WoodEMA

Bioeconomy Moves Forward: Perspectives on Wood Product Markets

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PERSPECTIVES ON WOOD PRODUCT MARKETS

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PREFACE

Is the bioeconomy moving forward? This question serves as the central theme of the 19th International Scientific Conference Bioeconomy Moves Forward: Perspectives on Wood Product Markets, held in Zvolen, Slovakia.

During the period since the team from Zvolen last organized a WoodEMA conference, the event has experienced remarkable growth. The number of papers published in the conference proceedings has increased more than fourfold, reflecting not only the dedication of our colleagues – members of the WoodEMA association and organizers of previous conferences – but also the growing scientific and societal interest in the forest-based bioeconomy, wood products, and their markets.

The papers collected in these proceedings demonstrate the breadth and international character of this research community. They present the work of scholars and practitioners from well beyond Europe who share a common commitment to advancing a sustainable bioeconomy founded on renewable forest resources, wood products, and the ecosystem services provided by forests.

Whether the bioeconomy is truly moving forward depends not only on technological innovation but also on society's willingness to rethink the way resources are produced, consumed, and managed. As awareness of environmental challenges continues to grow, industries are increasingly replacing fossil-based raw materials with renewable alternatives, improving production processes, and designing products according to circular economy principles so that materials can be reused, recycled, or recovered for energy at the end of their life cycle.

The research presented in these proceedings offers evidence that this transformation is underway. It addresses emerging challenges and opportunities in forest- and wood-based value chains, providing new knowledge that supports innovation, sustainable markets, and evidence-based decision-making. Together, these contributions represent another step toward a more resilient and competitive bioeconomy.

We sincerely thank all authors, reviewers, members of the Scientific and Organizing Committees, and all participants whose efforts have made this conference possible. We hope that the ideas presented in these proceedings will inspire further research, strengthen international collaboration, and contribute to shaping the future of the forest-based bioeconomy.

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CHAPTER A
INVITED PAPERS

THE IMPACT OF CREATING SPECIFIC STOCKS OF LUMBER ON THE PERFORMANCE AND QUALITY OF SUPPLY AND STORAGE PROCESSES IN WOOD PROCESSING ENTERPRISES IN SLOVAKIA

Pavol Gejdoš, Ľubica Simanová

Abstract: The aim of the paper is to present scientific and practical knowledge focused on the creation of stocks in wood processing enterprises in Slovakia and their impact on the performance and quality of supply and storage processes. The specific properties of wood raw materials in general, the properties of its type, as well as the drying schedule are factors that distinguish the supply and storage of wood processing enterprises from other enterprises. The model example is aimed at presenting the complexity of the creation of technological stocks of softwood depending on the natural drying schedule. The specifics of wood, the time required for the natural drying process and the uneven volumes of dried lumber in individual months of the year are factors affecting the overall performance and quality of the supply and storage processes.
Keywords: performance, quality, lumber stocks, supply, and storage processes

1. INTRODUCTION

The supply and storage logistics of wood processing enterprises - sawmills is demanding, especially due to the specific properties of wood raw materials, which require special management of technological and non-technological processes. Neglecting these factors can lead to material deterioration and a decrease in its qualitative properties. The concept of quality is often associated with the idea of exceptional or above-standard products and services. In Slovak, the term quality is also used, which also denotes the level of product or service characteristics in relation to customer expectations (Križanová, 2020). The article analyses and describes the specifics of sawmill logistics with an emphasis on the impact of the natural wood drying process on supply and storage logistics. To achieve strategic operations, it is essential that the planning of the operational configuration of storage considers the strategies of operations and the main reasons for storage (Boysen et al., 2019, Makaci et al., 2017). The effective functioning of supply chains is a complex problem that should consider material and financial resources, as well as economic, environmental, technological, structural and other factors (Zimon et al., 2019). The warehousing process in the logistics chain allows to bridge space and time. Great emphasis is placed on the amount of insurance and technological stocks. Technological stocks represent the period during which a company should hold stocks in case the material cannot be used immediately after delivery and during this period the product acquires the required properties. This also applies in the woodworking industry when drying lumber before its further processing into dimensional goods for furniture purposes (Trebuňa et al., 2012). A typical example of the creation of technological stocks are sawmills, which must have these stocks due to the natural drying of wood in the form of lumber. Seasonal stocks serve to cover consumption that is consumed throughout the year. They can only be replenished during a certain period - in the season. The condition for the creation of seasonal stocks at sawmills is sufficient storage space and the ability to ensure the protection of individual types of wood. Economic analyses evaluating the increase in costs for the protection

of wood raw materials, supplies of wood raw materials at more favourable prices in the season and the decision on natural or artificial drying are attributes that affect the number of technological stocks (Kotlínová and Simanová, 2011). In the business practice of the woodworking industry, insurance, seasonal and technological stocks are essential for further logistics, they affect the quality of the material and the performance of the company. The condition is a sufficiently large and correct distribution of warehouses and the amount of wood raw materials.

2. MATERIALS AND METHODS

2.1. Methodology of creating technological stocks in a sawmill

The natural drying of wood as a method of drying in open spaces is characterized by a drying environment, which is atmospheric air. External drying conditions are characterized by the temperature, the humidity, and the flow rate. The tables of approximate natural drying times according to Trebula and Klement (2002) show the average number of days, in which the lumber is dried from the initial humidity, of about 80%, to different degrees of humidity, to 20% and to 30% humidity required by customers or technological requirements for further processing. Table 1 shows the different time in the schedule of natural drying of spruce sawn wood at a thickness of 15 - 19 mm, on which the drying time depends. The methodology for determining the time of the natural drying of the spruce sawn wood for the calculation of the technological stock: to determine the target moisture requirements and the spruce sawn wood thickness to determine the length of the drying process, to determine natural drying times (in days) according to the relevant month of the year for selected spruce lumber with a thickness of 15–19 mm and a desired target moisture content of 20%, to determine the day of the month when the sawn wood in the prescribed form of the cage will be stored in the warehouse (day 10 - for the model situation),to add mathematically the number of days of the natural drying in the 10th day, and to calculate the day and the month of the completion of the drying process, and to record the volumes of the dried spruce sawn wood for the purposes of further processing or dispatch in the stock plan, and to calculate the amount of the technological stock during a year. In enterprises of the wood processing industry, the inventory management takes place in conditions of uncertainty, therefore it is necessary to create insurance stocks mainly for a period of 15 - 25 days, these stocks are referred as normative stocks in the sawmill enterprises. Methodology of calculation of individual types of stocks according to Kotlínová and Simanová (2011) and Rosová et al. (2010).

3. RESULTS

3.1 Results of the analysis of warehousing and supply logistics in sawmills

The process of supply and storage in woodworking enterprises from the point of view of logistical division or division of stocks in the production process is influenced by the capacity of storage facilities and their equipment. Older sawmills usually have sufficient storage space for storing raw wood or for storing sawn timber, which also allows them to use the more economically advantageous natural drying. The basic task of supply and storage logistics in sawmills is to ensure the continuity of production and determine the optimal level of stock standards. This level is influenced by the raw material possibilities of the gravity area, the capacity parameters of the sawmill, the spatial possibilities of the warehouse, the degree of mechanization used in handling raw materials in the warehouse, as well as the level of supplier-

customer relations. The logistical chain of sawmill production for primary wood processing processes is shown in Figure 1.

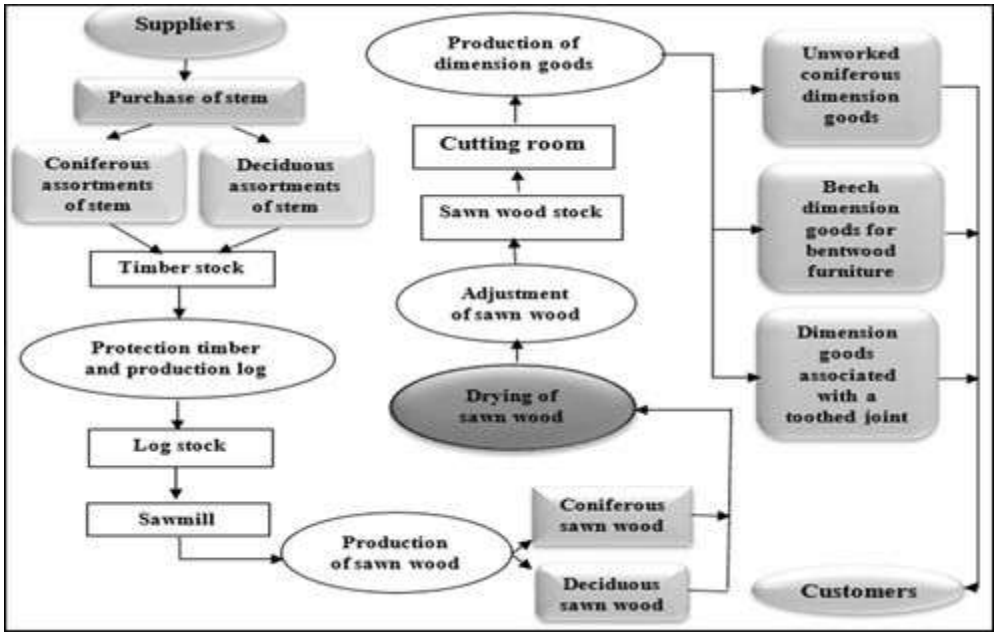


Figure 1. Scheme of the logistics chain of the sawmill production

The method of storage and protection is different for coniferous and deciduous wood and the preparation of lumber for further processing.

3.2. Specifics of creating sawn wood stocks in sawmills

In sawmills, stocks of stem need to be secured during the harvesting period to cover the needs of sawn wood production throughout the year in connection with the drying process. The logistics of supply and the creation of sawn wood stocks in these enterprises are influenced by the specifics that can be seen in Table 1.

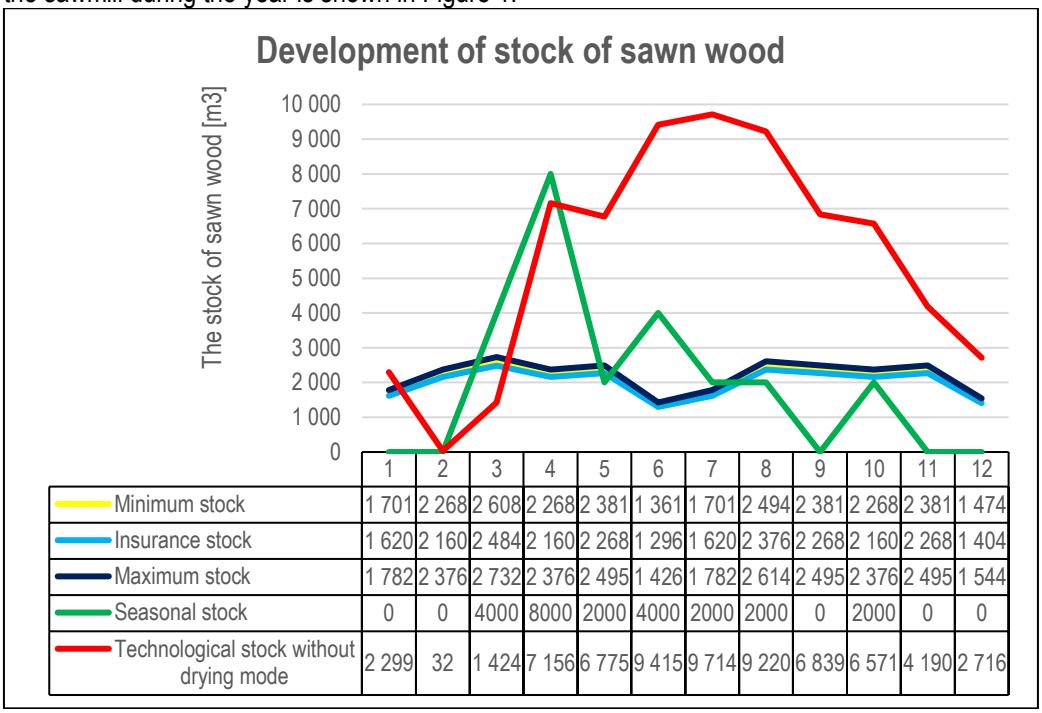
Table 1. Specifics of sawn wood stocks in a sawmill.

Type of stock	Specifics of stocks
Current	Limited stocks of dried sawn wood in the winter
Seasonal	Creation of stocks of dried sawn wood in the summer
Insurance	Need for stocks of dried sawn wood in the winter
Technological	Need for stocks due to the long-time of natural drying of sawn wood

The total volume of technological stocks is gradually changing. The most demanding link in the logistics chain in a sawmill is the creation of stocks dependent on the drying of lumber, which for technological reasons must be stored for a certain period of time so that semi-finished products and products achieve the required properties.

3.3. Analysis of the effect of natural drying of spruce sawn wood on the amount of technological stock

In the specific case of a sawmill, we demonstrate the impact of an uneven amount of dried spruce lumber in a natural drying schedule during the year on the volatility of technological stocks. The initial requirements for calculating the natural drying time of spruce lumber were as follows: required thickness 15 - 19 mm, input moisture content approx. 80% ± 10%, output moisture content approx. 20% ± 2%, annual volume of spruce lumber 24,000 m3 (sawmill capacity), average monthly volume of dried spruce lumber was 2,000 m3 to continuously meet the needs of further processing or direct shipment of dried spruce lumber to the customer. The drying time could only be determined approximately due to changing climatic conditions. Differences in drying times were taken into account in the amount of safety stock for a specific month of the year. On the 10th of each month, 2000 m3 of spruce sawn timber with a moisture content of approximately 80% was considered for natural drying. The development of stocks in the sawmill during the year is shown in Figure 1.



	1	2	3	4	5	6	7	8	9	10	11	12
Minimum stock	1 701	2 268	2 608	2 268	2 381	1 361	1 701	2 494	2 381	2 268	2 381	1 474
Insurance stock	1 620	2 160	2 484	2 160	2 268	1 296	1 620	2 376	2 268	2 160	2 268	1 404
Maximum stock	1 782	2 376	2 732	2 376	2 495	1 426	1 782	2 614	2 495	2 376	2 495	1 544
Seasonal stock	0	0	4000	8000	2000	4000	2000	2000	0	2000	0	0
Technological stock without drying mode	2 299	32	1 424	7 156	6 775	9 415	9 714	9 220	6 839	6 571	4 190	2 716

Figure 1. Development of stocks of dried sawn wood during the year.

4. DISCUSSION

When planning stocks of logs and sawn timber, it is necessary to take into account the winter and summer harvesting periods, supplier possibilities and transport conditions (Klementová, 2014). For each type of stock, a monthly nominal time fund was considered. The minimum stock of spruce sawn timber copies the monthly need for this assortment in the range from 1,701 to 2,381 m3 intended for various uses, whether it is further processing in the form of furniture semi-finished products or sale to other entities. It takes into account the 25-day recommended safety stock. The maximum stock of dried spruce sawn timber was determined with regard to the planned delivery interval and the safety stock. The safety stock was derived

from the need for the annual amount of dried spruce sawn timber and based on recommendations for creating a safety stock for a period of 25 days. The optimal normative stock of sawn timber for the needs of a sawmill in Slovak conditions is recommended for 15 - 25 days (Klement, Detvaj, 2007). The seasonal stock of dried spruce sawn timber depends on the natural drying schedule, the specifics of the sawmill, climatic conditions and the size of the sawmill's storage capacity. Seasonal stocks in individual months are formed based on respecting the drying schedule, which is carried out directly in the sawmill. As can be seen in Figure 3, fluctuations in seasonal stocks of dried timber occur mainly in the winter months, when they are drawn from summer stocks. The dispersion of these stocks is from 0 to 8000 m3 and their amount affects the amount of technological stocks during the year. When determining the number of technological stocks depending on the drying period, an initial stock of dried timber of 4,000 m3 was calculated at the beginning of the year, which was to cover the need for dried timber during the first two months and ensure its further processing or sale. A significant increase in technological stocks after the end of the drying schedule was recorded in the months of March to August. In connection with the results of a specific example of the formation of stocks of dried spruce lumber, we can state that the calculation of individual stocks according to general rules and formulas is possible in sawmill conditions only if the natural drying schedule of lumber is not taken into account, but is purchased or used by artificial drying. The formation of technological stocks depending on the natural drying of lumber is difficult in terms of managing the logistics of supply, storage and their subsequent use, the binding of financial resources to stocks, climatic conditions, but also the level of internal logistics services in the process of natural drying of spruce lumber.

5. CONCLUSION

When planning inventories, woodworking companies must consider the production capacity of the sawmill, the area capacity of natural drying warehouses, as well as the needs and requirements for subsequent use, which is a prerequisite for reducing tied-up financial resources in inventories. Although natural drying of lumber is a disadvantage in terms of tied-up financial resources, under certain conditions it is an advantage for the company in the form of lower energy costs, the company's certainty in its own inventories and increased quality and efficiency of processes. The contribution is based on the general principles of logistics and their application in primary wood processing companies, while considering the wood processing technology and its specificities from the processes of logging to the distribution of dried lumber. The results point to the specifics of the creation of individual types of inventories in sawmills of the wood processing industry in Slovakia.

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REFERENCES

1. Boysen, N.; De Koster, R.; Weidinger, F. (2019): Warehousing in the e-commerce era: A survey. European Journal of Operational Research, 396–411. https://doi.org/10.1016/j.ejor.2018.08.023.

2. Klement, I.; Detvaj, J. (2007):Technology of first-degree processing of wood. Technical university, Zvolen. 325.
3. Klementová, J. (2014): Analysis of supply and storage logistics processes for a wood processing company using natural drying. In: New trends in logistics - lean logistics. Technical university, Zvolen. 52-59.
4. Kotlínová, M.; Simanová, Ľ**. (**2011): Logistics. Technical University, Zvolen. 81.
5. Križanová, A. et al. (2020): Quality Management. Bratislava: Wolters Kluwer. pp. 45–80.
6. Makaci, M.; Reaidy, P.; Evrard-Samuel, K;. Botta - Genoulaz, V.; Monteiro T. (2017): Pooled warehouse management: An empirical study. Computers & Industrial Engineering. 526-536. https://doi.org/10.1016/j.cie.2017.03.005
7. Rosová, A.; Šaderová, J ; Hudymačová, J. (2010): Determining the structure and level of inventory in the company. Transport and logistics. 55-65.
8. Trebula, P.; Klement, I., (2002): Drying and hydrothermal treatment of wood. Zvolen: Technical University. 449.
9. Trebuňa, P.; Fiľo, M.; Pekarčíková, M. (2012): Supply and distribution logistics in examples Košice: TU in Košice. 212.
10. Zavadský, J. et al. (2021): Quality management systems and performance of Slovak enterprises. In: Quality Innovation Prosperity, 25: pp. 1–15.
11. Zimon, D.; Madzik, P.; Sroufe, R. (2019): Management systems and improving supply chain processes: Perspectives of focal companies and logistics service providers. International Journal of Retail and Distribution Management 48(9), 939–961. https://doi.org/10.1108/IJRDM-04- 2019-0107.

Authors address:

Pavol Gejdoš 1*, Ľubica Simanová 2*
[1]Department of Economics, Management and Business, Faculty of wood sciences and technology, Technical University in Zvolen, T. G. Masaryka 24, Zvolen, Slovak Republic; Email: gejdosp@tuzvo.sk
[2]Department of Economics, Management and Business, Faculty of wood sciences and technology, Technical University in Zvolen, T. G. Masaryka 24, Zvolen, Slovak Republic; Email: lubica.simanova@tuzvo.sk
*Corresponding author: gejdosp@tuzvo.sk

EMBEDDING ECO-INNOVATIONS IN WOOD-PROCESSING COMPANIES

Ján Parobek, Zuzana Kapsdorferová, Michal Dzian, Dominika Čeryová, Hana Maťová

Abstract: The integration of ecological innovations into innovation processes is an essential driver of sustainable development and competitiveness within the evolving bioeconomy. In the context of wood product markets, where increasing environmental requirements and shifting demand patterns are reshaping industry dynamics, eco-innovations play a pivotal role in advancing value creation. This study examines the key determinants influencing the adoption and implementation of eco-innovations in wood-processing companies. Eco-innovations—defined as new or significantly improved products, processes, organizational methods, or marketing solutions that reduce environmental impact—constitute a core mechanism through which firms respond to bioeconomy transitions. The analysis identifies both internal and external factors shaping their integration, including organizational capabilities, regulatory pressures, and market demand for sustainable wood products. The findings indicate that effective implementation requires a systemic approach in which environmental considerations are embedded across all stages of the innovation process, from idea generation to commercialization. By linking eco-innovation practices with market-oriented outcomes, the study demonstrates that wood-processing companies can enhance their competitive position, respond to evolving wood product market demands, and strengthen resilience within the advancing bioeconomy.
Keywords: Eco-innovations, wood processing companies, bioeconomy

1. INTRODUCTION

The transition toward a bioeconomy has increased the importance of eco-innovations as a strategic tool for sustainable industrial development. Eco-innovations are generally defined as new or significantly improved products, processes, organizational methods, or marketing solutions that reduce environmental impacts while maintaining or enhancing economic performance (OECD, 2005; OECD, 2009). Unlike conventional innovations, eco-innovations combine competitiveness with environmental responsibility and therefore play a critical role in supporting sustainable economic growth and the transition toward a greener economy (Rennings, 2000; Carrillo-Hermosilla et al., 2009).

The concept of eco-innovation emerged from broader discussions on sustainable development following the 1992 Rio Earth Summit and has since become increasingly important in addressing contemporary environmental challenges such as climate change, resource depletion, and biodiversity loss. Growing international commitments, including the Kyoto Protocol, the Paris Climate Agreement, and the United Nations Sustainable Development Goals, have further emphasized the need for environmentally sustainable production systems and technological transformations across industries (Ahmad & Wu, 2022; Qin, 2021).

Within the wood-processing industry, eco-innovations are particularly relevant because firms operate in a sector directly dependent on natural resources and increasingly influenced by sustainability requirements. As consumer demand for environmentally responsible products grows and environmental regulations become more stringent, wood-processing companies face increasing pressure to improve resource efficiency, reduce emissions, minimize waste, and develop sustainable wood-based products (Horbach, 2016; Bossle et al., 2016). At the

same time, eco-innovations create opportunities for firms to strengthen their competitiveness through cost savings, improved productivity, market differentiation, and access to new customer segments (UNEP, 2014; Porter & van der Linde, 1995).

Previous research suggests that the successful implementation of eco-innovations depends on a combination of internal and external determinants. Internal factors include organizational capabilities, environmental leadership, human resources, technological competencies, and environmental management systems, while external drivers involve regulatory pressures, market demand, technological opportunities, collaboration networks, and government support mechanisms (Horbach, 2008; Bossle et al., 2016). Understanding the interaction of these determinants is essential for explaining differences in eco-innovation performance across firms and industries.

This study examines the key determinants influencing the adoption and implementation of eco-innovations in wood-processing companies. Eco-innovations are viewed as a core mechanism through which firms respond to bioeconomy transitions and increasing sustainability demands. The study focuses on the role of organizational capabilities, regulatory pressures, and market demand for sustainable wood products in shaping eco-innovation activities. Furthermore, it argues that effective implementation requires a systemic approach in which environmental considerations are integrated throughout the entire innovation process, from idea generation and research and development to commercialization and market diffusion (Charter & Clark, 2007; Bossle et al., 2016). By linking eco-innovation practices with market-oriented outcomes, the study demonstrates how wood-processing companies can enhance their competitive position, improve resilience, and contribute to the development of a sustainable bioeconomy.

2. METHODOLOGY

The study focuses on identifying the key factors influencing the adoption and implementation of eco-innovations in wood-processing companies in Slovakia. The methodological framework is based on the assumption that eco-innovation represents an important instrument for achieving sustainability objectives while maintaining the competitiveness of firms operating within the emerging bioeconomy.

The research combines secondary and primary data collection methods. The first stage consisted of a comprehensive literature review of domestic and international scientific publications addressing eco-innovation, sustainability, and innovation determinants. Particular attention was devoted to studies examining internal and external drivers of eco-innovation, including organizational capabilities, human resources, environmental management practices, market demand, regulatory pressures, and collaboration networks. The findings from previous empirical studies were synthesized to establish a theoretical framework for the identification of eco-innovation determinants in the wood-processing sector.

The empirical part of the research was based on primary data collected through a questionnaire survey administered to Slovak wood-processing companies. The questionnaire was designed to capture information regarding the importance of various factors influencing eco-innovation activities. The investigated determinants were grouped into internal factors, such as environmental leadership, employee competencies, environmental culture, technological capabilities, research and development activities, and resource efficiency, and external factors, including environmental regulations, customer demand for sustainable wood

products, cooperation with external stakeholders, access to financial support, and technological opportunities.

Descriptive statistics were employed to characterize the sample and evaluate the relative importance of individual determinants. This approach enabled the identification of the most significant factors affecting eco-innovation implementation within the wood-processing industry. The methodological approach therefore combines theoretical knowledge with empirical evidence to provide a comprehensive understanding of the drivers and barriers influencing eco-innovation adoption in Slovak wood-processing companies.

3. RESULTS

Eco-innovation emerged from discussions on sustainable development and green economic growth. It is commonly associated with technological improvements that simultaneously enhance environmental and economic performance. However, modern approaches recognize that eco-innovation extends beyond technology and includes organizational changes, new business models, environmental management systems, and marketing innovations. The distinguishing feature of eco-innovation is its contribution to environmental improvement, whether intentional or not. Furthermore, eco-innovations often extend beyond individual firms and influence broader social and institutional systems. Within the bioeconomy, eco-innovation supports the efficient use of renewable biological resources while reducing dependence on fossil-based materials and energy sources. Wood-processing companies are particularly well positioned to contribute to this transition because wood is a renewable material that can replace more carbon-intensive alternatives. Consequently, eco-innovation has become an important driver of competitiveness and sustainability within the sector. A key characteristic of successful eco-innovation is the integration of sustainability considerations throughout the entire innovation process. Environmental objectives must be embedded from idea generation and research and development through production, commercialization, and market diffusion. From the perspective of wood-processing companies, internal determinants primarily determine the firm's ability to implement eco-innovations, while external determinants create the motivation and pressure for adoption. The literature suggests that successful eco-innovation implementation occurs when strong internal capabilities (leadership, skills, R&D, environmental culture) are combined with favorable external conditions (market demand, regulatory support, cooperation networks, and technological opportunities). Conversely, weaknesses in either dimension may significantly reduce eco-innovation performance.

3.1. Internal Determinants of Eco-Innovation Adoption

The implementation of eco-innovations is strongly influenced by internal organizational factors. These determinants shape a company's capacity to identify opportunities, develop innovative solutions, and successfully integrate sustainability into business activities. One of the most important drivers of eco-innovation is the availability of qualified human resources. Employees contribute knowledge, creativity, technical skills, and innovative ideas necessary for the development and implementation of environmentally friendly solutions. Firms with highly skilled personnel are better able to recognize sustainability opportunities, adopt advanced technologies, and manage complex innovation processes.Continuous employee training and education are particularly important because eco-innovation often requires new competencies related to environmental management, resource efficiency, and sustainable production.

Furthermore, employee involvement in decision-making processes can enhance innovation outcomes by encouraging the exchange of ideas and fostering organizational commitment to sustainability.

Management commitment plays a critical role in eco-innovation adoption. Environmental leadership influences organizational priorities and shapes the strategic direction of innovation activities. Managers who actively support sustainability objectives create conditions that encourage environmental responsibility across the organization. Corporate environmental culture is another significant determinant. Companies with strong environmental values are more likely to integrate sustainability considerations into their operations and innovation strategies. Such organizations typically demonstrate higher levels of environmental awareness, stronger employee engagement, and greater willingness to invest in long-term eco-innovation projects.

Investments in research and development (R&D) represent a key source of eco-innovation. R&D activities facilitate the development of cleaner technologies, improved production processes, and environmentally friendly products. Firms with stronger technological capabilities generally exhibit higher eco-innovation performance. Resource efficiency also serves as a major internal motivation. Companies can reduce costs through lower material consumption, improved energy efficiency, waste minimization, and optimized production processes. In wood-processing companies, where raw material utilization significantly affects profitability, resource-saving innovations provide both environmental and economic benefits. As a result, certified companies often demonstrate greater readiness to introduce eco-innovative solutions and maintain long-term sustainability commitments.

3.2. External Determinants of Eco-Innovation Adoption

While internal capabilities determine a firm's ability to innovate, external factors often create the conditions and incentives necessary for eco-innovation adoption.Environmental regulations are among the most influential external drivers of eco-innovation. Governments increasingly use environmental legislation, emission standards, environmental taxes, and sustainability requirements to encourage firms to reduce environmental impacts. Regulatory pressure is particularly important because many environmental challenges do not generate sufficient market incentives on their own. Compliance with environmental regulations often motivates companies to develop cleaner technologies and adopt innovative production methods. In many cases, firms that proactively implement eco-innovations gain advantages by adapting to future regulatory requirements before competitors. Next factor - market demand for sustainable wood products can be consider as key factor. Changing consumer preferences represent another critical determinant. Growing environmental awareness among customers has increased demand for sustainable and environmentally certified wood products. Consumers increasingly evaluate products based not only on quality and price but also on environmental performance. For wood-processing companies, this trend creates opportunities to access new market segments and strengthen customer relationships. Firms that successfully integrate eco-innovations into their product portfolios can differentiate themselves from competitors and respond more effectively to evolving market expectations. The increasing importance of sustainability in procurement policies and supply chains further reinforces market demand. Business customers, retailers, and public institutions increasingly require suppliers to demonstrate environmental responsibility and compliance with sustainability standards.

External cooperation significantly enhances eco-innovation performance. Research indicates that environmentally innovative firms collaborate more extensively with external partners than other companies. Important partners include suppliers, customers, universities, research institutions, consultants, and technology centers. Such collaboration facilitates knowledge transfer, access to technological expertise, and the sharing of innovation risks. In the wood-processing sector, partnerships can support the development of advanced processing technologies, circular economy solutions, and sustainable product innovations.

Public policies and financial support mechanisms can accelerate eco-innovation adoption. Subsidies, grants, tax incentives, and environmental funding programs help companies overcome financial barriers associated with innovation investments. Government support is particularly important because eco-innovations often require substantial initial investments and involve higher levels of uncertainty than conventional innovations. Financial incentives can therefore reduce risks and encourage firms to pursue environmentally beneficial projects.

Eco-innovations can generate substantial economic benefits for wood-processing companies. Key advantages include improved resource efficiency, lower production costs, enhanced productivity, access to new markets, stronger brand reputation, and increased competitiveness. Studies indicate that eco-innovation can improve profitability through reduced material and energy consumption, waste reduction, and process optimization. Sustainable products may also command premium prices and attract environmentally conscious customers. Furthermore, companies that invest in eco-innovation often strengthen their technological capabilities and innovation capacity. However, the implementation of eco-innovations is not without challenges. Common barriers include high investment costs, limited access to financing, insufficient technical knowledge, lack of qualified personnel, regulatory uncertainty, and weak market demand. Small and medium-sized enterprises frequently face greater difficulties because of limited financial and organizational resources. Therefore, successful implementation requires careful strategic planning and alignment between environmental and business objectives.

3. CONCLUSION

The adoption and implementation of eco-innovations in wood-processing companies are shaped by a complex interaction of internal and external determinants. Internal factors such as organizational capabilities, environmental leadership, skilled human resources, research and development activities, and environmental management systems influence a firm's capacity to innovate. External drivers, including regulatory pressures, market demand for sustainable wood products, collaborative networks, and government support, create incentives and opportunities for eco-innovation adoption. The findings highlight that successful eco-innovation implementation requires a systemic approach in which environmental considerations are integrated throughout the entire innovation process, from idea generation to commercialization. Such integration enables firms to simultaneously achieve environmental improvements and business objectives. By linking eco-innovation practices with market-oriented outcomes, wood-processing companies can strengthen their competitive position, respond effectively to evolving customer expectations, and enhance resilience within the emerging bioeconomy. Consequently, eco-innovation should be viewed not only as an environmental responsibility but also as a strategic instrument for long-term competitiveness and sustainable growth.

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REFERENCES

1. Ahmad, M.; Wu, Y. (2022): Combined role of green productivity growth, economic globalization and eco-innovation in achieving ecological sustainability for OECD economies. Journal of Environmental Management 302: 113980.
2. Bossle, M.B.; de Barcellos, M.D.; Vieira, L.M.; Sauvée, L. (2016): The drivers for adoption of eco-innovation. Journal of Cleaner Production 113: pp. 861–872.
3. Carrillo-Hermosilla, J.; del Río, P.; Könnölä, T. (2009): Eco-Innovation: When Sustainability and Competitiveness Shake Hands. Palgrave Macmillan, London. 223 p.
4. Charter, M.; Clark, T. (2007): Sustainable Innovation: Key Conclusions from Sustainable Innovation Conferences 2003–2006 Organised by The Centre for Sustainable Design. The Centre for Sustainable Design, University College for the Creative Arts, Farnham.
5. Horbach, J. (2008): Determinants of Environmental Innovation – New Evidence from German Panel Data Sources. Research Policy 37 (1): pp. 163–173.
6. Horbach, J. (2016): Empirical Determinants of Eco-Innovation in European Countries Using the Community Innovation Survey. Environmental Innovation and Societal Transitions 19: pp. 1–14.
8. OECD (2005): Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data. 3rd Edition. Organisation for Economic Co-operation and Development, Paris.
9. OECD (2009): Sustainable Manufacturing and Eco-Innovation: Framework, Practices and Measurement. Organisation for Economic Co-operation and Development, Paris.
10. Porter, M.E.; van der Linde, C. (1995): Green and competitive: Ending the stalemate. Harvard Business Review, 73 (5), pp. 120–134
11. Qin, L.; Kirikkaleli, D.; Hou, Y.; Miao, X.; Tufail, M. (2021): Carbon neutrality target for G7 economies: Examining the role of environmental policy, green innovation and composite risk index, Journal of Environmental Management, 295.
12. Rennings, K. (2000): Redefining Innovation – Eco-Innovation Research and the Contribution from Ecological Economics. Ecological Economics 32 (2): pp. 319–332.
13. UNEP (2014): The Business Case for Eco-Innovation. United Nations Environment Programme, Paris. 52 p.

Authors address:
Parobek, J.[1*]; Kapsdorferová, Z[2]., Dzian, M[1].; Čeryová D[2]., Maťová, H.[1]
[1] Department of Marketing, Trade and World Forestry; Faculty of Wood Sciences and Technology; Technical University in Zvolen; Slovakia
[2]Institute of Economics and Management; Faculty of Economics and Management; Slovak Agricultural University in Nitra; Slovakia

*Corresponding author: parobek@tuzvo.sk

EXPORT PRACTICES AND MARKET ORIENTATION OF SLOVENIAN WOOD AND FURNITURE COMPANIES

Matej Jošt, Leon Oblak, Jože Kropivšek, Luka Goropečnik, Anton Zupančič, Teja Bizjak Govedič, Bernard Likar, Erika Valentinčič

Abstract: Paper analyses the export practices and market orientation of Slovenian wood and furniture companies, focusing on a selected group of established exporters. The analysis is based on survey data collected in early 2026 from companies meeting two key criteria: at least 10 employees and a minimum of 10% of total revenues generated from exports. The study examines export intensity, geographical market focus, product-related export structures, and key constraints affecting sectors' international performance. The results show that the analysed companies are strongly export-oriented, with exports representing a significant share of turnover. Export activity is primarily concentrated in European Union markets, especially neighbouring and Northern European countries, due to proximity, regulatory alignment, and logistical efficiency. At the same time, several companies are active in selected non-European markets, particularly in the Middle East, North America, and parts of Asia, where demand for sustainable wood-based products is increasing.
Keywords: wood products, Slovenia, export

1. INTRODUCTION

The wood and furniture industry is an important segment of the Slovenian economy, with significant development potential due to the country's high forest cover and long tradition of wood processing. The sector is often regarded as strategically important, as it combines the use of a renewable raw material, job creation in manufacturing and substantial export potential (Lukiewska & Brelik, 2021). At the European level, the production of furniture and wood products remains economically significant; however, competitiveness varies considerably among individual countries, depending on production potential, export share, labour productivity and the level of innovation. In Slovenia, there are approximately 1,440 companies with at least one employee operating in activities C16 (wood processing) and C31 (furniture manufacturing), of which 270 have at least 10 employees. In total, the industry employs more than 12,000 people, making it a significant part of Slovenia's manufacturing sector (Ebonitete.si, 2026).

Despite the relatively large number of companies, the sector has been under considerable pressure in recent years. The economic environment has recently been marked by an energy crisis, inflation and reduced demand in key export markets (Kropivšek et al., 2025). In 2023, industrial production in Slovenia fell by 5.3%, with the decline in the wood and furniture industry even more pronounced. These negative trends continued into 2024, when revenue, profitability and investment declined further.

From an export perspective, the sector is distinctly international in nature, generating more than half of its revenue in foreign markets. This structure implies a high degree of dependence on conditions in the international environment, while at the same time enabling

integration into global value chains. However, export-oriented activities are also the most exposed to external shocks, such as changes in energy prices, logistical disruptions and fluctuations in demand.

The export orientation of companies is understood as a key component of the internationalisation process (Calheiros-Lobo et al., 2023; Vahlne & Johanson, 2017). Classical models emphasise gradual expansion into geographically and culturally proximate markets, a pattern also characteristic of Slovenian companies, which have traditionally been strongly focused on the European market. In today's environment, however, competition is increasingly shifting from price-based to value-based, with the following key differentiators: sustainable production and low-carbon materials, innovation and digitalisation, higher added value of products and certified quality (Calvano et al., 2025).The wood and furniture industry plays an important strategic role in this regard, as it contributes significantly to the transition to a low-carbon economy (Pirc Barčić, 2023). At the same time companies are facing a decline in competitiveness due to external shocks, such as intensified global competition, trade barriers, recession-induced shocks to demand, and pressures in the raw materials sector, combined with internal structural constraints, including low levels of innovation, dependence on labor costs, weak design and branding capabilities, fragmented supply chains, and rigidities in policies and organizational structures (Epede & Wang, 2022).

The purpose of this article is to analyse the export orientation of Slovenian companies in the wood and furniture industry that are already actively exporting, and to identify their main characteristics, market orientations, and challenges in the context of the current economic environment. The findings could also provide useful insights and guidance for other Slovenian wood and furniture companies that are not yet present in foreign markets but are considering international expansion. This would help them better understand export opportunities, the requirements of individual markets, and potential barriers to entering foreign markets.

2. METHODS

The study is based on an analysis of data collected through an online survey conducted between February and May 2026. The sample included companies that met the following criteria: at least 10 employees and at least 10% of their revenue from exports. This selection allows a focus on companies that actively operate in international markets.

In 2026 approximately 270 companies with at least 10 employees were identified in the Slovenian wood and furniture industry. Of these, 162 companies also met the criterion of at least a 10% share of exports in revenue; therefore, they were included in the survey and received a link to the online questionnaire using 1ka.si platform.

A total of 34 companies fully completed the survey, representing a response rate of approximately 21%. Given the study's objective and the specialised target group, this response rate can be considered satisfactory, as it includes companies of various sizes and from different production segments of the wood and furniture industry.

The questionnaire covered the share of exports in revenue, the geographic distribution of markets, product structure, export strategies, key challenges, and competitive advantages. Descriptive statistics were used to analyse the results, with an emphasis on identifying patterns of export performance and the international orientation of the participating companies.

3. RESULTS AND DISCUSION

3.1. Companies by product type

Export-oriented companies specialise in specific segments of the wood and furniture industry. The structure of the participating companies shows that furniture manufacturers predominate among Slovenian export-oriented wood and furniture companies. 41% of companies generate the bulk of their revenue in the furniture segment, which includes manufacturers of furniture for residential and commercial spaces, as well as interior furnishings for hotels, shops, and other facilities. This confirms the important role of the furniture industry as one of the key segments of Slovenia's wood and furniture sector with higher added value.

The second-largest group consists of companies dealing in sawn and planed lumber, which account for 19% of the sample. These companies operate primarily in primary wood processing and represent an important link in the subsequent stages of the wood-processing chain.

Window and door manufacturers account for 12% of the companies. The group of companies engaged in wooden structures (prefabricated houses, wooden halls, bridges, and other structures) also accounts for 12%. Both groups are linked to the construction sector and produce products with relatively high added value.

A smaller share of companies (4%) operates in the field of wooden construction elements, which includes structural timber, load-bearing elements, and other semi-finished products for the construction industry.

This structure is largely consistent with reports on the performance of the wood and furniture industry prepared by the Wood industry cluster at the Chamber of Commerce and Industry of Slovenia (Likar & Valentinčič, 2025). The report show that the largest share of economic activity in the sector is generated by activities C16 (wood processing and manufacturing) and C31 (furniture manufacturing), with building carpentry and joinery, as well as furniture manufacturing, standing out among the more significant segments. The survey results further indicate that exporters are disproportionately represented by companies operating in higher-value-added segments, such as furniture, interior design, architectural joinery, and wooden structures.

This suggests that success in international markets is increasingly less based on exports of basic wood products and more on the supply of more complex products and comprehensive solutions (FAO, 2025). Export-oriented companies are therefore increasingly focusing on products with a higher degree of processing, greater flexibility for customers, and higher added value, which is also one of the key development priorities of the Slovenian wood and furniture industry.

3.2 Current export markets

Survey results show that Slovenian wood and furniture companies remain strongly focused on European markets. The most important export destinations include Austria, Germany, Italy, Switzerland, the United Kingdom, and Croatia. Austria, Germany, and Italy, in particular, are traditional export markets where most of the participating companies are active.

In addition to the core markets of the European Union, companies are increasingly seeking opportunities outside Europe. Survey responses frequently mention Arab countries and the broader Middle East and North Africa (MENA) region, including the United Arab

Emirates, Egypt, and Algeria. Individual companies also export to North America, primarily to the United States and Canada, as well as to selected Asian markets, such as China and Japan.

This geographic diversification indicates a gradual broadening of export activities. While the European Union remains the foundation of business for most companies, the MENA, North American, and Asian markets represent a significant development opportunity for future growth and for reducing dependence on individual European economies.

3.3 Key challenges and competitive advantages in exporting

Slovenian export-oriented wood and furniture companies face numerous challenges when entering international markets, but at the same time, they possess competitive advantages that enable them to successfully integrate into international value chains.

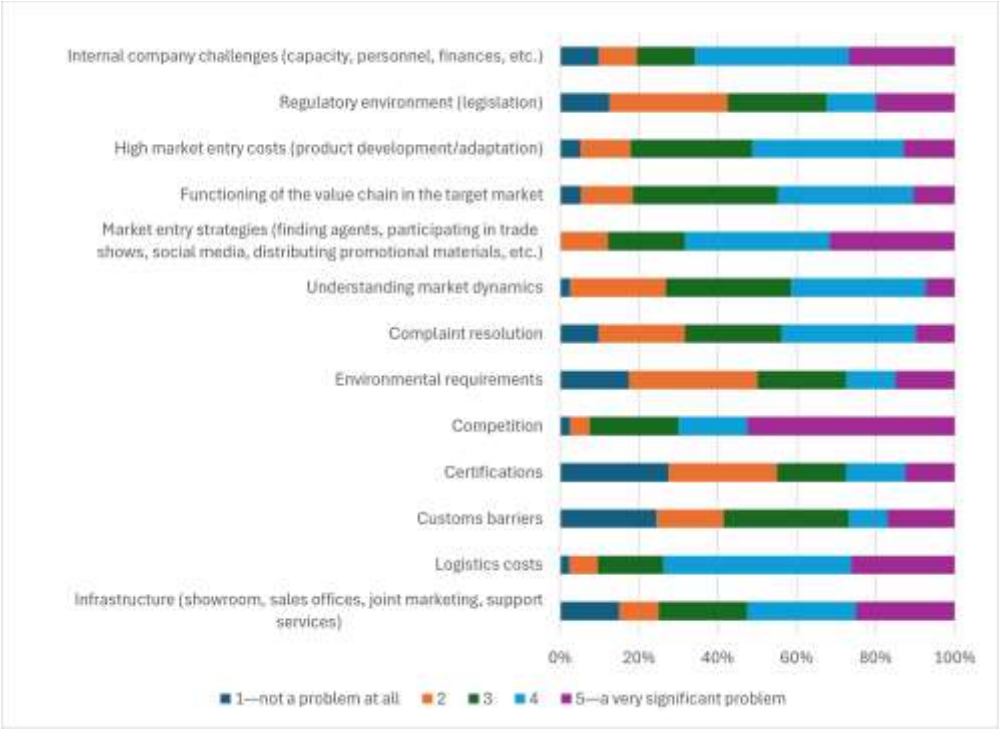

Figure 1. Main challenges in exporting (n=34)

Among the most significant challenges (Figure 1), competitive environment stands out, with the majority of surveyed companies rating it as a very significant challenge. The results show that competitive pressure is one of the key factors influencing the operations of Slovenian companies in foreign markets. Companies face not only price competition but also competition in terms of technological advancement, innovation, and the breadth of their product offerings.

Logistics costs are also rated very highly and represent one of the most significant operational barriers to exporting. Many companies rate them 4 or 5, indicating the substantial impact of transportation costs and supply chain efficiency on their international competitiveness. Similar barriers have been identified among exporting SMEs.

Significant challenges are also associated with the internationalisation process itself. Among these, high market entry costs, the method of market entry, understanding market dynamics and the functioning of the value chain in the target market stand out. The results show that successful entry into new export markets requires significant investment in product adaptation, sales channel development, finding distributors and establishing long-term business partnerships.

Internal challenges faced by companies are also rated relatively highly, particularly staff shortages, limited production capacity and financial resources. These factors can significantly limit the expansion of export activities, especially for small and medium-sized enterprises.

Challenges of moderate importance include customs barriers, certifications, environmental requirements and the regulatory environment, which become particularly significant when exporting to markets outside the European Union. Although companies do not view them as the main obstacles, they represent additional costs and administrative burdens when operating in foreign markets.

Figure 2. Competitive advantages in export markets (n=34)

Despite numerous challenges, the results show that Slovenian wood and furniture companies possess several significant competitive advantages (Figure 2). The most prominent of these is product quality, which nearly all companies rate as an important or very important advantage, with the highest rating being the most common. This confirms that Slovenian companies base their international competitiveness primarily on product quality and supply reliability.

Product innovation also stands out among the most important competitive advantages. Most companies rate it 4 or 5, which indicates the important role played by new product development, adaptation to specific customer requirements and the introduction of new technological solutions.

A approach focused on sustainability is also rated highly, as it is becoming an increasingly important factor in competitiveness in the modern business environment. Companies recognise that customers are increasingly demanding sustainably sourced materials, environmentally friendly production processes and certified products.

Delivery speed and a thorough understanding of the business culture in target markets are also important competitive advantages. Both areas enable companies to collaborate more effectively with customers and adapt more quickly to their needs, which is particularly important in demanding international markets.

Additional services, such as installation, maintenance, after-sales activities and technical support, are also viewed positively. The results show that companies are increasingly competing with comprehensive solutions rather than simply through product sales.

Complaint resolution also emerges as a significant advantage, confirming the importance of long-term customer relationships and high-quality after-sales support.

On the other hand, price ranks among the less pronounced competitive advantages. Although companies generally view it as an advantage, ratings of 3 and 4 predominate, they still rate it lower than quality, innovation, or a sustainable approach. This suggests that Slovenian companies base their competitiveness primarily on differentiation, quality and customised solutions, rather than on price competition.

3.4 Expansion into new markets

Approximately 60% of the surveyed companies plan to expand their operations into new export markets, confirming the continued internationalisation of Slovenian wood and furniture companies despite challenging economic conditions. In their expansion efforts, companies are not focusing solely on existing European markets but are also seeking opportunities in new and more distant markets.

Among the targeted markets, Germany, Italy, and Austria predominate, with most companies expecting these markets to contribute up to 20% of their revenue in the future. In addition to those markets, companies mainly focus on the United Kingdom, the United States, Switzerland, France, and Croatia as promising destinations, as well as the following countries: China, Japan, Saudi Arabia, the United Arab Emirates, Australia, Poland, the Netherlands, and other countries outside the European Union. The results show that companies are increasingly seeking opportunities beyond traditional European markets and striving to reduce their dependence on individual countries or regions. Of particular note is the interest in countries in the Middle East and Asia, where companies recognise opportunities for long-term growth in demand for wood products, interior furnishings, and wood-based construction solutions.

Companies also assessed the reasons why they view certain markets as attractive for future expansion (Figure 3). The results show that purchasing power, market size, and market niches stand out as the most important factors.

Purchasing power received the highest ratings, indicating that when selecting new markets, companies focus primarily on countries with higher levels of economic development and customers' ability to buy higher-quality products with greater added value. Market size is similarly important, as larger markets enable higher sales volumes and faster business growth.

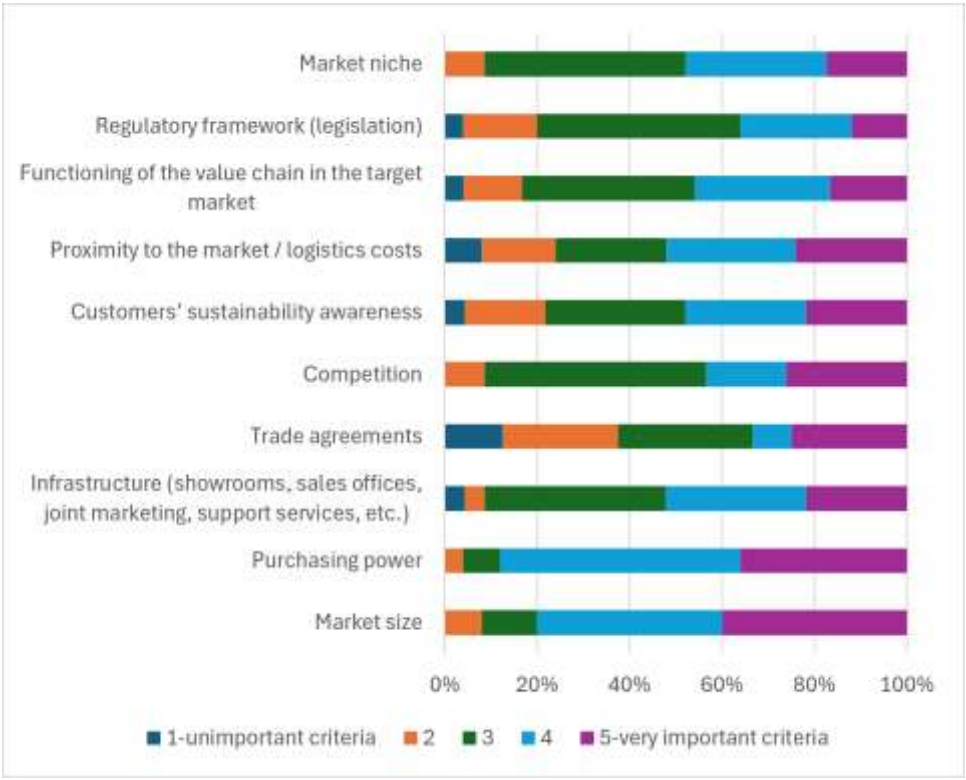

Figure 3. Criteria affecting the choice of specific markets (n=25)

Market niches also represent an important motivation for expansion, as companies recognise the opportunity to differentiate themselves from the competition and leverage their specialised expertise. This is particularly important for manufacturers of furniture, interior furnishings, wooden structures, and other products with a higher degree of processing.

Factors related to infrastructure in target markets, the functioning of the value chain, and the regulatory framework of the business environment also received relatively high ratings. This indicates that, in addition to market potential, companies also consider the stability of legislation, the availability of business partners, and opportunities for effective product distribution.

Customer sustainability awareness and market proximity also play important roles, although companies generally rate them slightly lower than purchasing power or market size. This suggests that companies are aware of the importance of sustainability trends but still prioritise economic factors that directly impact sales results.

Among the less important but still relevant factors are trade agreements and the level of competition in a given market. Although companies perceive competition as a significant business challenge, it is a somewhat less decisive criteria in the selection of new markets than market potential and purchasing power.

The results thus show that Slovenian wood and furniture companies primarily follow a market-oriented strategy when planning international expansion. When selecting new markets, they focus mainly on market size, purchasing power, and identified market niches, while

administrative and institutional factors represent secondary decision-making criteria. This orientation indicates the companies' ambition to enter markets with higher added value and greater long-term development potential.

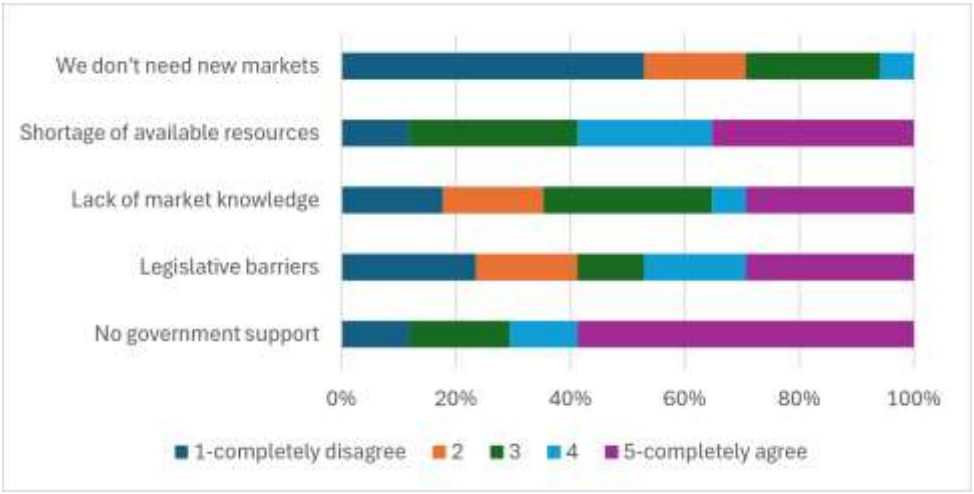

Figure 4. Reasons why not to expand to new markets (n=17)

On the other hand, 40% of companies stated that they do not plan to enter new markets in the near future. The results show that the reasons for this decision vary, ranging from internal constraints within the companies to the assessment that further geographical expansion is not currently necessary (Figure 4).

Surprisingly, the least significant reason for not expanding is the assertion that companies do not need new markets. Most respondents either disagree with this statement or consider it a less important factor, which suggests that companies generally recognise the importance of exports and internationalisation for their further development.

Among the more significant reasons, the lack of available resources, particularly human, financial, and organisational capacities stands out. Many companies believe that expanding into new markets would require additional investment that they are currently unable to provide. This finding is consistent with the results of an analysis of export challenges, in which internal constraints were identified as one of the most significant factors limiting export growth.

A lack of market knowledge and regulatory barriers are also important factors. Companies point out that entering new markets requires a thorough understanding of the local business environment, legislation, business culture, and distribution channels, which entails additional risk and cost. This is particularly pronounced in markets outside the European Union, where regulatory procedures are often more complex.

The results also show that the most important reason is insufficient systemic government support for expansion into new markets. In this regard, companies primarily highlight the need for greater support in entering distant markets, finding business partners, conducting promotional activities, and reducing administrative barriers.

Particularly interesting is the response from one company, which cited sustainability considerations as the reason for not expanding. The company stated that "Due to sustainable business models, they have decided to phase out operations in distant markets and now

operate within a 500 km radius of the company." This response is an interesting example of a different kind of strategic thinking based not on continuous geographical expansion, but on limiting transport flows, reducing the carbon footprint, and strengthening local and regional supply chains. Although this is an isolated case in the study, it suggests that sustainability considerations can also influence decisions regarding the extent of a company's internationalisation.

4. CONCLUSIONS

The results of the study confirm that Slovenian wood and furniture companies are internationally oriented. The strong export orientation observed among Slovenian companies is consistent with findings reported for medium and large furniture manufacturers in other Central European countries (Grzegorzewska & Stasiak-Betlejewska, 2023). Exporters are predominantly companies that manufacture higher value-added products, primarily furniture, architectural woodwork, wooden structures, and other more complex wood-based solutions.

The European Union remains the most important export market, particularly Germany, Austria, and Italy. At the same time, companies are increasingly seeking opportunities in the Middle East, North America, and Asia, indicating efforts towards geographic diversification of exports.

Companies highlight product quality, innovation, approach focus on sustainability, delivery speed, and additional services as their most important competitive advantages. Price does not appear to be a key factor in competitiveness, which confirms the companies' focus on differentiation strategies and creating higher added value.

On the other hand, significant challenges remain, primarily strong international competition, high logistics costs, the difficulty of entering new markets, and companies' limited human and financial resources. Companies also cite regulatory requirements, certification, and administrative procedures as additional constraints.

Approximately 60% of the surveyed companies plan to expand into new markets, driven primarily by market size, customer purchasing power, and the presence of market niches. In contrast, approximately 40% of companies do not plan to expand, primarily due to a lack of resources, unfamiliarity with new markets, and regulatory barriers.

Based on the companies' responses, competitiveness is perceived to depend more on quality, innovation, sustainability, and the ability to operate effectively in international markets than on price competitiveness. At the same time, new sustainability-oriented business models are emerging that combine an international presence with regional supply chains and a reduction in the environmental impacts of business operations.

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REFERENCES

1. Calheiros-Lobo, N., Vasconcelos Ferreira, J., & Au-Yong-Oliveira, M. (2023). SME Internationalization and Export Performance: A Systematic Review with Bibliometric Analysis. Sustainability (Switzerland), 15(11), 8473. https://doi.org/10.3390/su15118473
2. Calvano, S., Negro, F., Blanc, S., Bruzzese, S., Brun, F., & Zanuttini, R. (2025). Adding Value to Wood-Based Products: A Systematic Literature Review on Drivers. Forests, 16(4), 590. https://doi.org/10.3390/F16040590
3. Ebonitete.si. (2026). Database of Slovenian companies and financial information. https://www.ebonitete.si/
4. Epede, M. B., & Wang, D. (2022). Competitiveness and upgrading in global value chains: A multiple-country analysis of the wooden furniture industry. Forest Policy and Economics, 140, 102737. https://doi.org/10.1016/J.FORPOL.2022.102737
5. FAO. (2025, December 23). Global forest products facts and figures 2024. Global Forest Products Facts and Figures 2024. https://doi.org/10.4060/CD8005EN
6. Grzegorzewska, E., & Stasiak-Betlejewska, R. (2023). Models and forms of internationalization of medium and large Polish furniture companies - selected aspects in the light of the empirical research findings. In R. Dudík (Ed.), Current trends and challenges for forest-based sector: Carbon neutrality and bioeconomy: Proceedings of Scientific Papers, 78–81.
7. Kropivšek, J., Oblak, L., Goropečnik, L., Jošt, M., Remic, K., Gačo Jež, A., & Zupančič, A. (2025). Trends and main challenges in the wood industry in Slovenia. In Ž. Meloska & M. Miloshevska Janakieska (Eds.), Wood for the future: integrating sustainability across industries, 13–20.
8. Likar, B., & Valentinčič, E. (2025). Information on the operations of the wood and furniture industry in 2024.
9. Lukiewska, K., & Brelik, A. (2021). A Model for Measuring the International Competitiveness of Furniture Industry in the European Union Countries. European Research Studies Journal, 24(3), 334–350. https://doi.org/10.35808/ERSJ/2432
10. Pirc Barčić, A. (2023). Contribution and Importance of Wood-Based Sector Towards Carbon Neutrality and Bioeconomy. In R. Dudík (Ed.), Current trends and challenges for forest-based sector: Carbon neutrality and bioeconomy, 17–21.
11. Vahlne, J.-E., & Johanson, J. (2017). From internationalization to evolution: The Uppsala model at 40 years. Journal of International Business Studies, 48(9), 1087–1102. http://www.jstor.org/stable/45149364

Authors address:
Jošt, M.[1*]; Oblak, L.[1]; Kropivšek, J.[1]; Goropečnik, L.[1]; Zupančič, A.[1]; Bizjak Govedič, T.[1]; Likar, B.[2]; Valentinčič, E.[2]
[1] Chair of Management and Economics of Wood Companies, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia
[2] Wood Industry Cluster, Ljubljana, Slovenia
[*]Corresponding author: matej.jost@bf.uni-lj.si

CHAPTER B
SUSTAINABILITY, CIRCULAR ECONOMY AND BIOECONOMY

BIOTECHNOLOGIES IN THE WOODWORKING AND FURNITURE INDUSTRY IN THE REPUBLIC OF BULGARIA – CURRENT PROBLEMS OF THEIR ACCOUNTING PRESENTATION

Roumiana Pozharevska Snejana Bacheva

Abstract: Globally and nationally, innovations and their products are a driving force in the furniture and woodworking industry. However, they are not visibly highlighted or are not presented in the financial statements of Bulgarian enterprises. The reasons are multifaceted, the leading ones being that biotechnologies and the innovative products generated by them are not determined as accounting objects and do not actually participate in the business valuation of the reporting units. In order to overcome this negative trend and determine the new accounting assets, the authors conducted a scientific study and present the results in their report on the nature, types and legal protection of biotechnology in the woodworking and furniture industries in the Republic of Bulgaria. The identification was carried out in a symbiotic ecological and industrial environment of bio, eco and circular economy. Modern biotechnology and innovative products (such as bio-based materials and adhesives, wood waste processing technologies, application of biological protection agents, integration of new technologies and products, etc.) can ensure sustainable eco-development, protection of natural resources and competitiveness of the sector. Nationally, the rights to innovative products are regulated by law and have been scientifically studied by specialists in the field of intellectual property. The issue has not been treated so adequately from the standpoint of accounting theory and practice in the country. The rights to biotechnology and its products are not within the scope of accounting objects and assets, respectively. This is the motive of the authors to explore the possibilities for their accounting presentation in the financial statements of enterprises in the context of the current accounting standards, directives and regulations of the EU. Problem areas have been identified and an attempt has been made to propose solutions and models in these areas.
Keywords: biotechnology, innovation, woodworking industry, furniture industry, accounting, financial statement

1. INTRODUCTION

The issues related to the development and use of biotechnologies in enterprises within the wood-processing and furniture industries can be examined from various perspectives: ensuring the availability of sufficient high-quality raw materials and resources; developing new technologies for the sustainable use of terrestrial ecosystems; recognizing and reporting them as strategic assets in financial statements; and enhancing the competitiveness of reporting entities.

Deforestation and climate change are progressing at a rate that nature can no longer cope with on its own. The development and application of biotechnologies represent one of the options for addressing the United Nations Sustainable Development Goal 15. The long generation cycles of most tree species mean that traditional breeding methods are unable to improve trees at a pace sufficient to meet continually evolving commercial and environmental demands. Plant biotechnology and other forms of biotechnology provide a valuable approach for facilitating significant breakthroughs in tree improvement and related industries. Advances in plant biotechnology are opening up transformative opportunities for ecosystems and the forestry sector in the following key areas: **(a) Enhanced carbon sequestration** (companies such as Living Carbon are optimizing the enzyme RuBisCo to develop trees that absorb greater

amounts of CO_2 and reach maturity more rapidly; **(b) Optimized wood processing** – through genetic engineering, it is now possible to modify the structure of lignin to facilitate wood processing, thereby reducing production costs and minimizing industrial waste; **(c) Climate resilience** – the accumulation and integration of desirable genetic traits make it possible to develop tree varieties capable of withstanding increasingly frequent droughts and other climate-related stresses.

Biotechnologies based on two approaches—namely, the use of microorganisms and the direct application of enzymes—represent a promising tool in the wood and pulp processing value chain. Modern biotechnologies and innovative products (such as bio-based materials and adhesives, wood-waste processing technologies, the application of biological protection agents, the integration of new technologies and products, among others) can contribute to sustainable ecological development, the conservation of natural resources, and the enhanced competitiveness of the sector. The challenge facing scientists and experts in these fields is to transform these scientific discoveries into strategic assets. The challenge for accounting theory, practice, and regulatory frameworks is to ensure that these strategic assets are adequately recognized and reported as intangible assets of enterprises.

Research Methods. The study employs retrospective analysis, the comparative method, and the methods of analysis and synthesis. To support the selected methods and to structure the objectives, tasks, and specific stages of the research, interdisciplinary, normative, historical-logical, systemic, inductive, and deductive approaches have also been applied.

Research assumption. The authors' assumption is that the development and utilization of biotechnologies as strategic assets for enterprises in the wood-processing and furniture industries, their legal protection as intellectual property, and their recognition and presentation in financial statements will not only enhance competitiveness and sustainability within the sector but will also increase the business value of each reporting entity.

2. LITERATURE REVIEW

At the national level, rights relating to innovative products, including biotechnologies, are regulated by law and have been extensively examined by specialists in the field of intellectual property. However, the issue has not been addressed with the same degree of adequacy from the perspective of accounting regulation, theory, and practice in this country. Rights related to biotechnologies and their products are either insufficiently represented or not represented at all as accounting objects and, consequently, as assets in the financial statements of enterprises operating in these two sectors of the economy. The annual financial statements prepared for the National Statistical Institute, which are identical to those used by the National Revenue Agency, do not provide sufficient information regarding innovations and research and development activities of an innovative nature. In the course of their research, the authors attempted to obtain statistical data on the biotechnologies developed and applied in enterprises within the wood-processing and furniture industries; however, these efforts did not yield positive results. The primary reason for the current lack of adequate accounting regulation and practice is that no clear necessity or demand for such information has yet been generated among either external or internal users of financial statements. Unfortunately, compared to leading European countries, Bulgaria still lags behind in terms of tax incentives, circular economy policies, and ESG regulations. The green finance market is still in its infancy, and access to sustainable financial instruments remains limited. Despite the clear commitment of the European Commission and the EU's targeted policies aimed at fostering innovation, competitiveness, and

climate neutrality over the past two decades, Bulgaria continues to rank second from last in the EU Innovation Index (2025) and remains in last place in the Eco-Innovation Index (2024).

To support their thesis and develop an accounting model for the recognition and presentation of biotechnologies in these two sectors, the authors adopted an interdisciplinary approach and conducted research in the following areas:

- The essential characteristics and types of biotechnologies applicable to enterprises in the wood-processing and furniture industries - Tapin-Lingua, S., Meyer, V., Petit-Conil, M. (2008); Tomova, A.,(2014); Olatokun, D., Shaw, D. (2026);
- The protection of biotechnologies as intellectual property of enterprises - Markova, M. (2024); Murphy, A., Noesen, D., Margenat, F., Lejeune, F., Avaux, J., Verbeeren, M., Cock, M., Roland, N., Campolini, Ph.,Thoumsin, P.Y. (2026); information from WIPO and from Patent Office BG;
- The green and circular economy, and sustainable development, in the context of the issues under investigation - Zhelyazkova, V. (2017), Blot, D. (2022); Bezuhanova, Sl, Angelieva, K., Marinov, M., Doneva, A., Kumanova, R., Osses R. (2025); documents from the European Parliament;
- Accounting aspects of the issues under investigation - Pojarevska, R. (2015); Mikol, A. (2017); Nikolova, N. (2017); Zhelyazkova, V. (2020); Bacheva, S., Pozharevska, R. (2023); Bachev, I. (2023), Georgieva, V. D. (2026); EU directives; international and national accounting standards.

3. SPECIFIC FEATURES OF BIOTECHNOLOGIES IN THE TWO SECTORS IN THE CONTEXT OF THE GREEN, CIRCULAR, AND SUSTAINABLE ECONOMY

The furniture and wood-processing industries are traditionally well-established sectors of the Bulgarian economy, contributing nearly 3% of the country's GDP (with a combined annual production value exceeding €1.3 billion). According to the Bulgarian Branch Chamber of Woodworking and Furniture Industries (BCWFI), the main factors slowing competitiveness and sustainable development processes over the past decade have been the limited availability and/or shortage of raw materials and resources, as well as the absence of a national strategy for the harvesting of timber. According to the BCWFI, an important factor for stimulating business activity is the potential for the development of a circular economy, which remains largely unrealized at present. Recycling and the reuse of materials require the development of appropriate technologies, substantial investment, and a strong strategic commitment. According to the BKDMP, the third direction for the development of these sectors is the creation of proprietary brands, which would open new opportunities for many Bulgarian manufacturers, the majority of whom currently operate as subcontractors producing goods for foreign brands under contract manufacturing arrangements. A solution to the above-mentioned challenges facing the two sectors may be provided through the development of innovations, including biotechnologies. Their legal protection is a crucial aspect, as it not only provides exclusivity and control but also creates the conditions for their recognition as accounting assets (meeting all criteria required by the relevant accounting standards) and for their inclusion among the intangible assets of enterprises.

The biotechnologies applicable to the furniture and wood-processing industries may originate either from traditional knowledge and skills or from research and development activities. In the development of biotechnologies for the production of products and processes, living organisms or their enzymes are utilized. Researchers employ a wide range of techniques

to manipulate millions of different species of plants, animals, and microorganisms, each of which possesses cells and molecules with unique characteristics. Biotechnologies are based on a variety of approaches, including fermentation, genetic engineering, and bioinformatics. Of particular relevance to the subject under investigation are the so-called "green" or plant biotechnologies and their four principal methods for transforming plant cells with foreign DNA, which are successfully used to produce transgenic plants. A leading direction for future development is the advancement of nanotechnologies as a modern multidisciplinary field of research and innovation.

To substantiate their thesis, the authors primarily examined the possibilities for recognizing and presenting biotechnologies as part of the intangible assets of reporting entities and as a significant component of their financial statements (i.e., as accounting assets). A mandatory prerequisite for this is the existence of control over the resources and the economic benefits arising from their use. Rights to biotechnological inventions (new products, new technologies, or new applications of existing ones) are protected under both national and international legal frameworks.[1] They may either incorporate traditional knowledge or exist independently of such knowledge - a classification that is of fundamental importance for the manner in which they are recognized for accounting purposes. The legislator prohibits the patenting of plant varieties and animal breeds, as well as essentially biological processes for their creation. This prohibition does not extend to microbiological processes or to products obtained through such processes (Article 7 para 3 of the Patent Act). Plant varieties and animal breeds may receive only the so-called *sui generis* protection under the provisions of national legislation [2]. Biological methods used for the creation of plant varieties and animal breeds are not patentable; however, they receive indirect protection through the *sui generis* protection granted to the respective plant variety or animal breed. Any higher taxonomic unit, other than a plant variety or animal breed, such as a species, genus, family, order, class, or phylum, may be patented as a biotechnological invention. The law does not state that products obtained through biological methods other than those used for the creation of plant varieties and animal breeds are not eligible for protection. Rather, it specifies which biological organisms, other than plant varieties and animal breeds, are not regarded as inventions for the purposes of patent protection. A microorganism may be either newly created or newly discovered, regardless of the form in which it exists. In order to be patented, a microorganism must be deposited in one of the international depository institutions for microorganisms recognized by the World Intellectual Property Organization (WIPO) [3]. Biotechnological inventions may also be realized in the form of a novel application of an existing product, process, or technology. In such cases, the inventive contribution lies in exerting an effect on an existing resource through the involvement of another biological entity, which may function as the object of the action, the means by which the action is carried out, or the result of the action itself.

[1] National legislation is represented by the provisions of specialized laws, such as the Patent Act and the Protection of New Plant Varieties and Animal Breeds Act. At the international level, the protection of biotechnological inventions is governed by the provisions of the European Patent Convention, Directive 98/44/EC, the Convention on Biological Diversity, the TRIPS Agreement, as well as the Budapest Treaty, which provides for the international recognition of the deposit of microorganisms for the purposes of patent procedures.

[2] Protection is granted in accordance with the provisions of the Protection of New Plant Varieties and Animal Breeds Act.

[3] For Bulgaria, this function is performed by the National Bank for Industrial Microorganisms and Cell Cultures (NBIMCC). Its activities and organization are regulated by the Rules of Procedure issued by the Ministry of Education and Science, promulgated in the State Gazette, No. 42/2000.

In summary, regardless of the type, method, or source of acquisition of biotechnologies and their products in the furniture and wood-processing industries, a mandatory prerequisite for their recognition as accounting assets and their inclusion among the intangible assets of enterprises is the simultaneous fulfillment of the fundamental accounting recognition criteria: the resource must be used in the entity's operations, be under the entity's control, be capable of generating future economic benefits, and have a value that can be measured reliably.

4. BIOTECHNOLOGIES AS INTANGIBLE ASSETS AND A FOUNDATION FOR THE DEVELOPMENT OF BUSINESS STRATEGIES IN THE TWO SECTORS

In the course of the study, the authors, as already noted, were unable to find official statistical data indicating the existence of biotechnology-related accounting assets, in any legal form, among any of the more than 4,000 enterprises operating in the wood-processing and furniture industries. According to the authors, the reasons for this situation may have different origins, including the absence of such assets; a lack of awareness of intellectual property rights (IPR) objects; difficulties in identifying such objects; and the lack of adequate accounting regulation, theory, and practice in this area. Rights to biotechnologies within an enterprise may be acquired from either external or internal sources. When acquired from external sources - such as research institutes or international and national companies operating in the relevant sectors - they may be obtained through licensing or franchising agreements, for a specified period and in exchange for agreed remuneration. In both cases, these rights constitute recognized objects of intellectual property rights (IPR).

Internally developed biotechnologies may be classified as different categories of intellectual property rights (IPR) objects. They may be recognized as patents or utility models**,** provided that they satisfy the legal requirements and criteria established by the applicable legislation. Alternatively, they may be recognized as new plant varieties or new animal breeds if they incorporate traditional knowledge and skills and do not meet the criteria required for patent protection. In INsome cases, enterprises choose not to patent their innovations in order to avoid the mandatory disclosure of the invention after the statutory protection period expires (typically 20 years). Under this approach, the biotechnology is classified as know-how. According to both national and international legislation, know-how is not recognized as an object of intellectual property rights and, consequently, cannot be recognized as an accounting asset, since the criterion of control over the resource is not considered to be fully satisfied. A final form of asset arises when enterprises choose to register their own brand incorporating the biotechnologies they have developed. In such cases, the biotechnology becomes embedded within the brand and may contribute to its value and market distinctiveness.

Two additional significant issues arise in connection with the recognition of internally generated biotechnologies. The first concerns the stage at which an innovative product should be recognized for accounting purposes. According to both national and international accounting standards, a distinction must be made between two phases: the research phase and the development phase**.** The recognition of an accounting asset should commence only once the development phase has been demonstrated and the relevant recognition criteria have been met. All expenditures incurred up to that point should be recognized as current expenses. This leads to the second major issue - the valuation of the newly developed product. In practice, such a valuation does not include all costs incurred from the beginning of the technology's development and therefore fails to meet the requirements of reliability and fair value

measurement. It is well known that biotechnologies require substantial investment over what is often a prolonged period, and the most significant expenditures are typically incurred during the research phase. According to the authors, these two significant issues can be addressed by accumulating costs from the very beginning of the creation process and initially treating them as deferred expenditures (costs attributable to future periods). In the event of a **successful outcome**, an intangible asset would be recognized, and the valuation of the acquired innovative product would reflect the actual costs incurred throughout its development. In the event of an unsuccessful outcome, where the research project does not result in the creation of an innovative product, the deferred expenditures would be amortized or allocated to future periods in accordance with a business-appropriate repayment or expense-recognition plan. This accounting model would also comply with the fundamental accounting principles of matching revenues with expenses and accrual accounting**.** The costs associated with the development of a biotechnological product would be reflected in the balance sheet from the outset as deferred expenditures relating to the acquisition or creation of intangible resources. Under the proposed model, all rights relating to biotechnologies, as well as the processes involved in their development, would be visible in the financial statements of enterprises in the wood-processing and furniture industries throughout each reporting period. The only exceptions would be know-how and show-how, where such assets are held by enterprises. In these cases, the decision not to seek formal legal protection—and consequently not to recognize them as accounting assets—rests with the enterprises themselves.

The identification of biotechnologies as objects of intellectual property rights (IPR) would also provide an opportunity to develop a model for managing the competitiveness of enterprises in the two sectors, with a particular focus on intellectual property, through the application of contemporary methods such as IP Profile and IP Score. According to the first method, intellectual property rights (IPR) are analyzed in a differentiated manner, distinguishing between intellectual property embedded in innovations and intellectual property embodied in business identifiers. Based on a comprehensive SWOT analysis**,** GE analysis**,** and the enterprise's intellectual property portfolio**,** management can formulate strategies founded on the rights it holds to biotechnologies and related intellectual property assets. The second method, IP Score**,** is a tool for evaluating all intellectual property rights (IPR) included in an enterprise's intellectual property portfolio. The application of these models should, of course, take into account the specific characteristics, needs, and strategic objectives of each enterprise.

4. CONCLUSION

In this paper, the authors have sought to present the main highlights and key findings of their scientific research. Of course, the topic of biotechnologies is multifaceted and encompasses a broad range of issues and areas of application. It is not possible, within the scope of this paper, to analyze all the issues involved or to provide detailed proposals for their resolution.

In conclusion, the authors would also like to highlight several additional challenges that hinder the full realization of the potential of enterprises in these two sectors, including difficulties in securing financing, limited human resources, restricted access to international networks, insufficient institutional commitment to green innovation and sustainable development, as well as challenges in collaborating with large businesses (Green Solutions for Bulgaria, 2025).

REFERENCES

1. Bachev, I. (2023). Challenges for auditors in relation to disclosure of sustainability information in financial statements, 13th International Conference on Application of Information and Communication Technology and Statistics in Economy and Education (ICAICTSEE – 2023), UNWE, Sofia, Bulgaria,. URL: https://www.ceeol.com/search/book-detail?id=1274210

2. Bacheva, S., Pozharevska,R. (2023). Opovestiavane na informatzia za ustoichivost vav finansovite otcheti – regulatzii i problemi. (Sustainability Disclosure in Financial Statements - Regulations and Issues) Nautcni troudove na UNSS (5); pp. 11-31. ISSN (print): 0861-9344 ISSN (online): 2534-8957. UNWE, Sofia; URL: https://unwe-research-papers.org/bg/journalissues/article/11515

3. Bezuhanova, Sl, Angelieva, K., Marinov, M., Doneva, A., Kumanova, R., Osses R. (2025). Green solutions from Bulgaria, focus Innovations. MOVE.BG. Sofia Bulgaria. (Bezukhanova, Sl, Angelieva, K., Marinov, M., Doneva, A., Kumanova,R., Osses R. (2025). Zelenite resheniya ot Bŭlgariya, fokus Inovatsii.).URL::https://www.ngobg.info/bg/documents/3412%D0%B4%D0%BE%D0%BA%D0%BB%D0%B0%D0%B4-%D0%B7%D0%B5%D0%BB%D0%B5%D0%BD%D0%B8%D1%80%D0%B5%D1%88%D0%B5%D0%BD%D0%B8%D1%8F-%D0%BE%D1%82 %D0%B1%D1%8A%D0%BB%D0%B3%D0%B0%D1%80%D0%B8%D1%8F-2025.html

4. Blot, D. (2022). Développement durable, économie circulaire et pratiques populaires: la relation entre société et environnement a-t-elle besoin de l'économie ? DOI:10.26754/ojs_ais/accioninvestigsoc.2022437427. URL:https://www.researchgate.net/publication/366527000_Developpement_durable_economie_circulaire_et_pratiques_populaires_la_relation_entre_societe_et_environnement_a-t-elle_besoin_de_l%27economie

5. Georgieva, V. D. (2026). Reliability of the research, development activity and innovation data of non-financial enterprises in Bulgaria, Prof. Marin Drinov Publishing House of Bulgarian Academy of Sciences, Sofia: ISBN 978-619-245-607-8; ISBN 978-619-245-608-5 (pdf)

6. Markova, M. (2024). Economic Dimensions of Intellectual Property - Approach, Characteristics and Management Models. Publishing complex ZIP Ltd; ISBN: 978-954-9369-75-5

7. Mikol, A. (2017). Audit des sociétés de biotechnologie. La revue française de comptabilité , N 515, décembre 2017. URL: https://revuefrancaisedecomptabilite.fr/audit-des-societes-de-biotechnologie/

8. Murphy, A., Noesen, D., Margenat, F., Lejeune, F., Avaux, J., Verbeeren, M., Cock, M., Roland, N., Campolini, Ph.,Thoumsin, P.Y. (2026). Les droits intellectuels en 2026 : défis et opportunités. ISBN : 9782807216594.

9. Nikolova, N. (2017). Printsip na kompensiraneto v schetovodstvoto - prilagane i izklyucheniya. "Ikonomikata na Bulgaria i Evropeĭskiya sŭyuz v globalniya svyat". Izd. na VUZF, Sofiya. ISBN: 978-954-8590-41-9. s. 403-406 (Principle of compensation in accounting - application and exceptions. "The Economy of Bulgaria and the European Union in the Global World". Publishing House of the VUZF, Sofia. ISBN: 978-954-8590-41-9; pp. 403-406)

10. Olatokun, D., Shaw, D. (2026). L'avenir des forêts passera-t-il par les biotechnologies. J A KEMP. URL:https://www.jakemp.com/knowledge-hub/lavenir-des-forets-passera-t-il-par-les biotechnologies/

11. Patent Office BG. URL:http://www.bpo.bg/index.php?option=com_content&task=view&id=718&Itemid=432

12. Pojarevska, R. (2015). Accounting aspects on biotechnology and their products (according to theory and practice in Bulgaria), USA -Chinese Business Review,USA *(ISSN 1537-1506)"* March 2015, Vol. 14, No. 3, doi: 10.17265/1537-1506/2015.03.001. pp 137-142

13. Tapin-Lingua, S., Meyer, V., Petit-Conil, M. (2008). Biotechnologies dans l'industrie papetière. Techniques de l'ingenieur. URL https://www.techniques-ingenieur.fr/base-documentaire/materiaux-th11/papiers-et-cartons-42832210/biotechnologies-dans-l-industrie-papetiere-bio4200/

14. Tomova, A.,(2014) Biotechnology as a means for creating ecologically clean industrial processes. Sofia University "St. Kliment Ohridski"). 2014-1-BG01-KA204-001645;
URL: https://uni-ecoaula.eu/images/Tables/biotechnology_1-formatted_BG.pdf
15. Zhelyazkova, V. (2017). Circular Economy. Financial Aspects, Sofia, St. Gr. Bogoslov Publishing House, ISBN:978-954-8590-42-6.
16. Zhelyazkova, V. (2020). Environmental Reporting: Principles and Main Challenges. Ecology & Safety, ISSN 1314- 7234, Volume 14, 2020, Journal of International Scientific Publications
URL: www.scientific-publications.net
17. ***: Commission Delegated Regulation (EU) 2023/2772 of 31 July 2023 supplementing Directive 2013/34/EU of the European Parliament and of the Council as regards sustainability reporting standards. URL: https://eur-lex.europa.eu/legal-content/BG/TXT/?uri=OJ:L_202302772
18. ***:International Financial Reporting Standards Foundation,
URL: https://www.ifrs. org/groups/international-sustainability-standards-board/
19. ***:Natsionalni sihetovodni standarti (National Accounting Standards).
URL: https://balans.bg/zakonodatelstvo/nss
20. ***:Natsionalen Zakon za schetovodstvo.. (National Accounting Law)
URL: http://top-account.net/zakoni/138-zakon-za-schetovodstvoto.html
21. *** Parlement Européen (2023). Économie circulaire : définition, importance et bénéfices URL::https://www.europarl.europa.eu/topics/fr/article/20151201STO05603/economie-circulaire-definition-importance-et-benefices
22. ***:United Nations. Department of Economic and Social Affairs. Sustainable Development. Goal 15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
URL https://sdgs.un.org/goals/goal15
23. ***:WIPO. La propriété intellectuelle au service de la croissance et du développement durable.
URL: https://www.wipo.int/edocs/pubdocs/fr/wipo_pub_1050_2021-chapter5.pdf

Authors address:
Pozharevska, R.[1]; Bacheva, S.[2] на
[1] Professor, PhD, Department of Accounting and Analysis, Financial and Accounting Faculty, University of National and World Economy, Sofia, Bulgaria.
[2] Professor, PhD, Department of Accounting and Analysis, Financial and Accounting Faculty, University of National and World Economy, Sofia, Bulgaria.
*Corresponding author: e-mail: r_pojarevska@unwe.bg; e-mail: sbasheva@unwe.bg

INDUSTRIAL PARKS AND CIRCULAR ECONOMY: ASSESSMENT OF RESOURCE EFFICIENCY IN THE FOREST SECTOR

Bozhidar Chaparov

Abstract: This study assesses the potential of industrial parks to increase resource efficiency in the forestry sector as part of the transition to a circular economy. The analysis focuses on identifying key factors that influence the effective implementation of circular practices, including optimization of material flow, waste reduction and use of by-products. infrastructure and inter-company cooperation to improve resource efficiency. The study examines selected practices and operational approaches applied in industrial parks, highlighting both favourable conditions and existing barriers to integration. Based on the results, a set of evaluation criteria and practical recommendations are proposed to support the development of more resource-efficient and sustainable industrial systems in the forest sector.
Key words: sustainable development, circular economy, industrial parks, forestry sector

INTRODUCTION

The transition to a circular economy is a key priority in sustainable development policies worldwide, driven by increasing pressures on natural resources, climate change and environmental degradation. In contrast to the linear take-make-throw model, the circular economy promotes the reuse, recycling and recovery of materials in order to reduce waste and improve resource efficiency.

The forestry sector is particularly important in this context, as it provides renewable raw materials that can replace non-renewable resources. However, despite their renewability, forest resources require sustainable management along the entire value chain. This includes optimizing production processes, reducing material losses, and using industrial by-products through closed systems.

Industrial parks can significantly support the implementation of the circular economy in the forest sector by allowing industrial symbiosis, shared infrastructure and cooperation between firms. In recent years, eco-industrial parks have attracted attention because of the integration of environmental and economic goals. They promote the efficient use of energy, water and materials while reducing environmental impacts. However, their success depends on factors such as infrastructure, regulation, technology, and inter-company collaboration.

Although the circular economy and industrial symbiosis have been extensively researched, less attention has been paid to the specific role of industrial parks in improving resource efficiency in the forest sector. Existing research often ignores sector-specific features such as cascading wood use and biomass use.

The author's aim is to assess how industrial parks can increase resource efficiency in the forest sector within the circular economy. Within the framework of the study, the influencing factors as well as some challenges and advantages were identified.

1. Literature review

The circular economy (CE) has emerged as a leading paradigm for sustainable development, aiming to keep products, materials, and resources in use for as long as possible through reuse, repair, remanufacturing, and recycling, rather than following the traditional extract-produce-consume-dispose model (Lazaridou et al., 2021; Aggestam & Giurca, 2022).

Resource efficiency, a core CE objective, is increasingly understood not merely as a technological issue but as a systemic process spanning production systems, business models, governance, and stakeholder collaboration, requiring companies to redesign value chains and integrate circular principles into product design and industrial cooperation in support of the Sustainable Development Goals and the European Green Deal (Lazaridou et al., 2021; Aggestam & Giurca, 2022). Industrial parks, in particular, are recognized as strategic platforms for implementing these principles: their geographic concentration of enterprises facilitates the evolution from traditional to eco-industrial parks, where shared infrastructure, utilities, and environmental management systems improve both economic and environmental performance (Mortensen et al., 2024).

A key mechanism that maintains circularity in industrial parks is industrial symbiosis. It is expressed in a collaborative relationship in which waste, by-products, energy, water or services of one enterprise become valuable inputs to another. Such exchanges reduce resource consumption, reduce production costs, minimize waste disposal and increase overall resource productivity. The geographical proximity of firms facilitates communication, trust, and long-term collaboration, which are essential prerequisites for successful industrial symbiosis (Shu et al., 2024). Recent research has shown that eco-industrial parks generate significant environmental and economic benefits through coordinated resource management, shared infrastructure and integrated waste management systems. However, their successful implementation depends on several factors, including institutional support, digital information systems, adequate infrastructure, regulatory frameworks, and effective governance. International experience further shows that co-management significantly improves recycling rates, material recovery, and resource circulation in industrial ecosystems (Mortensen et al., 2024; Shu et al., 2024).

The forest sector occupies an important place in the circular bioeconomy, as it provides renewable biological resources capable of replacing non-renewable resources. Wood products not only store carbon, but also have a high potential for reuse, recycling, and cascading use, making them essential components of circular production systems (Lazaridou et al., 2021).

Forestry industries produce significant amounts of secondary materials, including bark, sawdust, biomass residues, and wood ash. Modern circular economy approaches increasingly recognize these by-products as valuable resources that can be transformed into bioenergy, wood products, pulp and paper products, biobased chemicals, composite materials, and soil additives. Such practices reduce waste generation while creating additional economic value from existing biomass streams (Miassi & Dossa, 2024).

One of the most important concepts in the circular economy of the forest sector is the cascading use of wood resources, which puts the highest value applications of wood first before its final use for energy recovery, thus extending the life cycle of the product and maximizing resource productivity. This approach simultaneously contributes to climate change mitigation, efficient use of biomass and sustainable forest management (Aggestam & Giurca, 2022).

Despite these opportunities, a number of challenges continue to limit the implementation of circular economy principles in forest value chains. These include fragmented supply chains, insufficient cooperation between businesses, technological constraints, insufficient infrastructure for the exchange of by-products and inconsistent policy frameworks. Recent sustainability assessments further show significant variation among forestry companies in terms of integrating circular economy principles into their strategic management and sustainability reports, indicating significant potential for further development (Panori et al., 2024).

Although previous research has extensively examined the circular economy, industrial symbiosis and eco-industrial parks, relatively little attention has been paid to assessing how industrial parks contribute specifically to improving resource efficiency in the forest sector. Existing research mainly looks at manufacturing industries, focusing on individual aspects of the implementation of the circular economy, without taking into account the specific characteristics of the industrial systems of the forestry sector. (Lazaridou et al., 2021; Mortensen et al., 2024).

Furthermore, relatively little research integrates the combined effects of logistics, shared infrastructure, intercompany collaboration, material flow optimization and by-product use into a comprehensive framework for assessing resource efficiency in forestry industrial parks. Most existing assessment models remain sector-specific or concentrate on environmental indicators, without adequate inclusion of operational and management dimensions (Shu et al., 2024).

In order to overcome these limitations, the current study aims to develop an integrated assessment of the factors that affect the efficiency of resources in industrial parks serving the forest sector. By combining the concepts of circular economy, industrial ecology, industrial symbiosis, and sustainable forest management, the study offers evaluation criteria that can be useful in the design of efficient and sustainable industrial ecosystems, as well as in the management of industrial parks and forestry enterprises.

2. Methodology

The present study is based on a systematic review of existing scientific literature, analysis of conceptual models in the field of circular economy, industrial symbiosis and sustainable resource management in industrial parks. This approach allows the integration of different theoretical perspectives and the formation of a comprehensive analytical basis, with the limitation being that no primary empirical data are used.

The methodological framework is based on a systematic understanding of industrial parks as open production systems in which resource flows go through interconnected stages of entry, transformation, and output. Inputs include wood, biomass, energy, and water, while production processes encompass processing, logistics, and industrial operations. The resulting by-products and waste streams can subsequently be reused through mechanisms of industrial symbiosis. Where can be reused through mechanisms of industrial symbiosis. In this context, industrial parks are seen as integrated systems in which resource efficiency depends on the degree of connectivity and coordination between the enterprises involved. The analytical framework of the study is based on the relationship between: (1) inputs (wood, biomass, energy, water); (2) operational processes (production, logistics, processing); (3) symbiosis mechanisms (exchanges between companies, shared infrastructure); (4) outflows (products, waste, by-products); (5) results (resource efficiency, reduced waste, increased added value).

This structure allows the evaluation of industrial parks as integrated systems and not as isolated enterprises.

Based on the literature review, five main groups of factors are derived: (1) Optimization of material flows (efficiency of the use of raw materials and by-products); (2) Waste reduction (reuse, recycling and recovery); (3) Logistics and transport efficiency (cost reduction and carbon footprint); (4) Infrastructure support (availability of shared facilities and technologies); (5) Inter-company cooperation (levels of industrial symbiosis and exchange of resources).

Based on these factors, an integrated system of criteria for assessing resource efficiency in industrial parks of the forestry sector is developed. This system combines quantitative and

qualitative dimensions, allowing analysis of both material efficiency and organizational and managerial aspects of industrial interactions. In this way, the basis is created for a comparative assessment of different industrial parks, as well as for the identification of key barriers and opportunities for improvement in the direction of a higher degree of circularity.

In order to operationalize the proposed conceptual framework, a model for measuring resource efficiency is developed, based on a system of Key Performance Indicators (KPIs). The model aims to transform the identified factors into measurable quantities that allow comparative analysis between industrial parks in the forestry sector.

The indicator system is structured in five main groups, which correspond to the analytical framework of the study and to the derived influencing factors (Table 1)

Table 1. Indicator system of evaluation criteria

Category	Indicator
Material Flow Optimisation Indicators	✓Material Input Efficiency (MIE) ✓Yield Rate (%) ✓Material Loss Rate (%)
Waste and by-product use indicators	✓Recycling Rate (%) ✓By-product Utilization Rate (%) ✓Energy Recovery Rate from biomass (%)
Logistics performance indicators	✓Transport Cost per unit (€ / m³) ✓CO_2 emissions from logistics (kg CO_2 / ton-km) ✓Average transport distance (km)
Infrastructure performance indicators	✓Shared infrastructure utilization rate (%) ✓Energy consumption per unit of output (kWh / m³) ✓Water reuse rate (%)
Indicators of inter-company cooperation (industrial symbiosis)	✓ Number of inter-firm resource exchanges ✓ Symbiosis Intensity Index (SII) ✓ Share of inputs obtained from other firms in the park (%)

For the purposes of the overall assessment, the following **Composite Resource Efficiency Index (CREI)**:

$$CREI = \sum_{g=1}^{G} WgIg$$

where:

CREI – Composite Resource Efficiency Index;

wg – weight assigned to category g, where $\sum_{g=1}^{G} wg = 1$

Ig – normalized score of category g;

G – total number of indicator categories

The normalized category score is calculated as:

$$Ig = \frac{1}{ng} \sum_{i=1}^{ng} N(Xgi)$$

where:
n_g – number of indicators in category g;
$N(x_{gi})$ – normalized value of indicator i in category g.

Weights can be determined by expert assessment or multi-criteria analysis. Higher CREI values indicate a higher degree of circularity and resource efficiency in industrial parks. The model allows both internal analysis of individual parks and comparative studies between different industrial systems. To demonstrate the practical applicability of the proposed model, an illustrative assessment of a hypothetical forest-sector industrial park is presented in the Results and Discussion section.

For the purpose of systematizing the interrelationships between factors, a conceptual framework is used, which will be based on a multi-criteria approach to decision-making. This approach is not applied as a mathematical model with quantitative optimization, but as an analytical tool that allows structuring and comparative analysis of the different dimensions of resource efficiency. It provides a better understanding of the relative importance of individual factors and their impact on the overall sustainability of industrial systems.

3. Results and Discussion

The conducted analysis resulted in the development of an integrated framework for assessing resource efficiency in industrial parks operating within the forest sector. Unlike existing approaches that typically evaluate isolated aspects of circular economy implementation, the proposed framework combines material efficiency, logistics, infrastructure, waste utilization, and inter-company cooperation into a unified assessment model.
To illustrate the applicability of the proposed framework, a hypothetical industrial park operating within the forest sector was evaluated using the developed indicator system. The assessment is intended solely to demonstrate the calculation procedure and does not represent empirical results.

Table 2. Example evaluation of a hypothetical forest-sector industrial park

Indicator group	Normalized score
Material flow optimization	0.82
Waste reduction and by-product utilization	0.76
Logistics efficiency	0.69
Infrastructure support	0.85
Inter-company cooperation	0.71

For demonstration purposes, equal weights (wg = 0.20) were assigned to each indicator category. In practical applications, however, these weights may be determined through expert judgement or multi-criteria decision analysis (MCDA), depending on the specific characteristics and priorities of the industrial park. Accordingly, the Composite Resource Efficiency Index (CREI) is calculated as:

CREI = 0.20 × (0.82 + 0.76 + 0.69 + 0.85 + 0.71) = 0.77

The obtained value indicates a relatively high level of resource efficiency and circularity. The strongest performance is observed in infrastructure support and material flow optimization, reflecting efficient utilization of shared facilities and effective management of raw materials. Lower scores for logistics efficiency and inter-company cooperation suggest opportunities for

improving transport organization and strengthening industrial symbiosis among companies within the industrial park.

This simple example demonstrates how the proposed framework can support benchmarking and identify priority areas for improving circular economy performance in industrial parks serving the forest sector. Although hypothetical, the example illustrates the practical applicability of the proposed assessment framework and its potential use for benchmarking resource efficiency across industrial parks.

The first key result is the identification of five interconnected dimensions that determine resource efficiency in forest-sector industrial parks: material flow optimization, waste reduction and by-product utilization, logistics efficiency, infrastructure support, and industrial symbiosis. These dimensions reflect both operational performance and organizational capacity, providing a broader perspective than conventional environmental indicators alone.

The second major outcome is the establishment of a structured Key Performance Indicator (KPI) system. The proposed indicators enable resource efficiency to be measured quantitatively while simultaneously capturing qualitative aspects of cooperation between firms. The inclusion of indicators such as the Symbiosis Intensity Index and the share of inputs exchanged within the industrial park extends traditional resource efficiency assessments by explicitly considering collaborative resource management.

A further contribution of the study is the introduction of the Composite Resource Efficiency Index (CREI), which integrates all indicator categories into a single evaluation measure. The composite index provides a flexible tool for benchmarking industrial parks, identifying performance gaps, and supporting strategic decision-making. Because the weighting factors can be adapted through expert judgement or multi-criteria decision analysis, the model remains applicable under different industrial and regional conditions.

From the perspective of the circular economy, the framework highlights that resource efficiency is influenced not only by technological improvements but also by organizational interactions among companies. Industrial parks that facilitate resource exchange, shared infrastructure, and coordinated logistics are expected to achieve higher levels of material productivity while reducing waste generation and environmental impacts. These findings are consistent with recent research emphasizing the importance of industrial symbiosis and integrated resource management in eco-industrial parks.

The proposed framework also addresses several research gaps identified in the literature. Previous studies have generally focused either on environmental performance or on individual circular economy practices. By integrating operational, logistical, infrastructural, and managerial dimensions into a single assessment framework, the present study provides a more comprehensive basis for evaluating industrial parks in the forest sector.

Nevertheless, the study has several limitations. The framework has been developed through conceptual analysis and literature synthesis and has not yet been validated using empirical data from existing industrial parks. Consequently, the proposed indicators and weighting scheme should be considered as an analytical foundation rather than a finalized assessment instrument. Future research should apply the model to real industrial parks, compare different forestry clusters, and validate the Composite Resource Efficiency Index using quantitative datasets.

Overall, the results suggest that industrial parks can become important enablers of circular economy implementation in the forest sector when supported by appropriate infrastructure, governance mechanisms, and inter-company collaboration. The proposed

assessment framework offers both researchers and practitioners a practical basis for evaluating and improving resource efficiency within industrial ecosystems.

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References:

Aggestam, F., & Giurca, A. (2022). Implementing circular-bioeconomy principles across two value chains of the wood-based sector: A conceptual approach. *Land, 11*(11), 2037. https://doi.org/10.3390/land11112037

Lazaridou, D. C., Michailidis, A., & Trigkas, M. (2021). Exploring environmental and economic costs and benefits of a forest-based circular economy: A literature review. *Forests, 12*(4), 436. https://doi.org/10.3390/f12040436

Miassi, Y. E., & Dossa, K. F. (2024). Circular economy initiatives for forest-based bioeconomy: Harnessing the potential of non-wood biomaterials. *Waste Management Bulletin, 2*(2), 270–278. https://doi.org/10.1016/j.wmb.2024.05.006

Mortensen, L., Kørnøv, L., Gjerding, A. N., Rattigan, E., & Schlüter, L. (2024). Middle-out evolution of greenfield eco-industrial parks: The journey of GreenLab, Denmark. *Journal of Industrial Ecology, 28*, 1816–1829. https://doi.org/10.1111/jiec.13569

Panori, D., Papaspyropoulos, K. G., & Nikolaou, I. E. (2024). A forest companies typology regarding their contribution to circular economy: A sustainability reporting-based analysis. *Discover Sustainability, 5*, 120. https://doi.org/10.1007/s43621-024-00304-4

Shu, C., Feng, Z., Liang, C., Guo, J., Xu, F., Tian, J., & Chen, L. (2024). Whole-process and multi-stakeholder-based solid waste management framework construction for industrial parks: Toward circular economy development. *Journal of Industrial Ecology, 28*, 928–941. https://doi.org/10.1111/jiec.13508

Authors address:
Chaparov, B.
Business, Investments, Real Estate, University of Economics - Varna, Bulgaria
Corresponding author: bchaparov@ue-varna.bg

MATERIAL FLOWS ANALYSIS OF TIMBER AND WOOD-RESIDUE STREAMS IN BULGARIA: EVIDENCE FROM MFA AND SANKEY MODELLING

Nikolay Neykov, Todor Stoyanov, Emil Kitchoukov

Abstract: The sustainable use of forest biomass and circular bio-economy strategies increasingly demand a comprehensive understanding of material flows from timber extraction through wood processing to final waste or product streams. This study applies Material Flow Analysis (MFA) to the Bulgarian forest sector, covering logging, imports, primary and secondary processing, manufactured wood products, and wood-residue streams. By combining national harvesting data, industrial production statistics, trade and recycling records, we establish a mass-balanced flow model for the period 2014-2022. Results, visualized through Sankey diagrams, reveal the proportions of input timber converted into long-lived products, recycled wood materials, energy biomass and residual waste. Preliminary findings indicate substantial losses at primary sawmilling and low rates of residue valorization, while a significant share of wood residues remains unused or under-utilized. The analysis highlights key bottlenecks and potentials for increased circularity: improved residue recovery, higher recycling quotas, and integration with bio-based energy or material chains. We discuss implications for resource efficiency policies, sustainable forest management, and circular bio-economy strategies in Bulgaria. This work contributes to the research of lifecycle assessment, circular design and material-use efficiency in the forest sector's environment by providing empirical evidence on wood-material flows at national scale.
Keywords: Material Flow Analysis; wood-residue streams.

1. INTRODUCTION

The production and use of wood and wood-based products are central to the transition towards a more resource-efficient and circular bioeconomy. Wood is a renewable material with important environmental advantages, including carbon storage potential and substitution effects in relation to more carbon-intensive materials (Wang et al., 2025). In this context, material flow analysis (MFA) has become an important tool for quantifying material flows and stocks within defined systems and for assessing the efficiency of resource use (Brunner & Rechberger, 2016). MFA-based approaches are increasingly applied to wood resources in order to understand production, trade, processing, residue generation and opportunities for cascading use.

Recent studies show that wood-flow modelling still faces important methodological challenges, including inconsistent terminology, fragmented data sources, mixed measurement units and limited information on end-use allocation and residue utilization (Anspach et al., 2024; Wang et al., 2025). At the EU level, Sankey-based material-flow visualizations have been developed mainly for aggregated economy-wide monitoring, but they provide limited detail on specific wood-processing sectors and internal residue streams (Nuss et al., 2017). Existing wood MFA studies cover several European countries, including Germany, France, Portugal, Denmark, Slovakia and Slovenia, but Bulgaria has not been specifically addressed in a process-based MFA framework for industrial roundwood and wood-residue utilization over the period 2014–2022.

This study addresses this gap by developing a material flow model of industrial roundwood and wood-residue streams in Bulgaria for 2014 and 2022. The analysis combines FAOSTAT and JFSQ data with literature-based conversion coefficients and visualizes the results through Sankey modelling. The aim is to identify how industrial roundwood is allocated among major wood-processing activities and to assess the generation and reuse of key residues, including bark, sawmill by-products, forest residues, industrial residues and black liquor..

2. MATERIALS AND METHODS

This study applies Material Flow Analysis (MFA) to quantify the allocation of industrial roundwood and the generation of wood-processing residues in Bulgaria. The analysis follows the MFA principles proposed by Brunner and Rechberger (2016) and covers the Bulgarian wood-based industry in 2014 and 2022, including industrial roundwood production, imports, exports and the main wood-processing sectors (sawnwood, plywood, veneer sheets, fibreboard, particleboard and chemical wood pulp). Production, import and export data were obtained from the FAOSTAT Forestry Production and Trade Statistics database and converted into solid wood equivalent (SWE) using conversion factors from the Joint Forest Sector Questionnaire (JFSQ). Internal material flows were reconstructed using input-output coefficients developed by the European Commission Joint Research Centre (JRC), which describe the relationships between raw materials, primary products and secondary products, including bark, sawmill by-products, black liquor and other industrial residues. Since production statistics are reported in cubic metres and waste statistics in tonnes, JFSQ conversion coefficients were applied to express all material flows in SWE. The estimated quantities of generated residues were subsequently compared with Eurostat Waste Statistics for sectors A02 – Forestry and Logging and C16 – Manufacture of Wood and of Products of Wood and Cork. Finally, the material flows were visualized using Sankey diagrams, providing a comprehensive representation of industrial roundwood allocation and residue utilization. Unlike previous MFA studies based on aggregated national statistics, the proposed approach reconstructs process-level material flows within the Bulgarian wood-processing industry by combining official production statistics with JRC input-output coefficients. This makes it possible to estimate internal wood-residue streams and their cascading utilization, which are not directly available from official statistical databases.

3. RESULTS AND DISCUSSION

Table 1 summarizes the changes in production, imports and exports of the main wood-based products in Bulgaria between 2014 and 2022. The results reveal substantial structural changes in the forest-based sector, providing the background for the subsequent material flow analysis of industrial roundwood and wood-processing residues.

Table 1. Changes in production and international trade of selected wood products in Bulgaria (2014–2022)

Product	Production (%)	Import (%)	Export (%)
Industrial roundwood	+9.5	+94.0	−96.0
Sawnwood	−16.4	+367.0	−79.0
Plywood	−30.6	+46.3	−20.5
Veneer sheets	−19.2	−20.5	−47.6
Particleboard	+62.9	+92.5	+29.4
Fibreboards	+642.4	+64.5	+2961.0
Chemical wood pulp	+55.6	−86.8	−18.8

The results indicate considerable structural changes in the Bulgarian forest-based sector between 2014 and 2022. While industrial roundwood production increased by 9.5%, exports declined by 96%, suggesting greater domestic availability of raw material. The most significant growth was observed in the wood-based panel industry, particularly fibreboards (+642.4%) and particleboards (+62.9%), indicating increasing value-added processing. In contrast, sawnwood, plywood and veneer production declined during the study period despite rising imports. Chemical wood pulp production also increased (+55.6%), while imports decreased substantially (−86.8%), reflecting greater domestic production capacity. Overall, the results demonstrate a gradual shift towards higher-value added wood processing and provide the basis for the subsequent material flow analysis.

Figure 1 presents the Sankey diagram illustrating the allocation of industrial roundwood within the Bulgarian wood-processing industry in 2014. The diagram integrates primary material flows with the generation and cascading utilization of wood-processing residues, providing a comprehensive overview of resource use throughout the production chain.

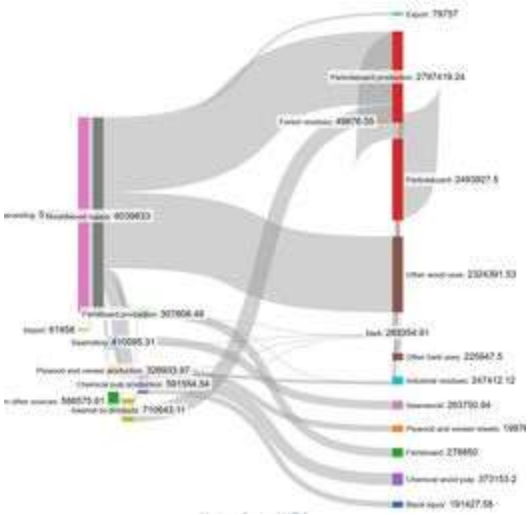

Figure 1. Sankey diagram for the 2014 Bulgarian forest-based sector material flows

The results indicate that 6.04 million m³ of industrial roundwood were available for domestic use, including domestic production and imports. Following exports, approximately 4.03 million m³ entered the analysed wood-processing industries, while 2.32 million m³

remained outside the scope of the model, representing other wood products, energy uses and stock changes not included in the analysed production chains. The largest share of industrial roundwood was allocated to particleboard production, requiring approximately 2.80 million m³ of raw materials, including primary roundwood and secondary wood residues. This confirms the central role of the particleboard industry in the cascading utilization of woody biomass. Chemical wood pulp production represented the second largest consumer of raw material, followed by sawmilling, plywood and veneer production, and fibreboard manufacturing.The Sankey diagram also demonstrates the importance of secondary material flows. Approximately 263 thousand m³ of bark and 711 thousand m³ of sawmill by-products were generated during processing. While a substantial proportion of sawmill by-products was reintroduced into fibreboard, particleboard and pulp production, only a relatively small fraction of bark was reused in particleboard manufacturing. The remaining bark and other industrial residues were directed to other applications outside the system boundary, indicating additional opportunities for improving cascading wood utilization and resource efficiency. Overall, the results demonstrate that the Bulgarian wood-processing sector already incorporates significant internal recycling of wood residues; however, considerable quantities of secondary biomass remain outside the analysed production system, highlighting further potential for circular bioeconomy development.

Figure 2 presents the material flow of industrial roundwood in Bulgaria in 2022, illustrating the allocation of primary raw materials together with the generation and utilization of wood-processing residues. Compared with 2014, the diagram reveals significant structural changes in the distribution of industrial roundwood among the major processing industries.

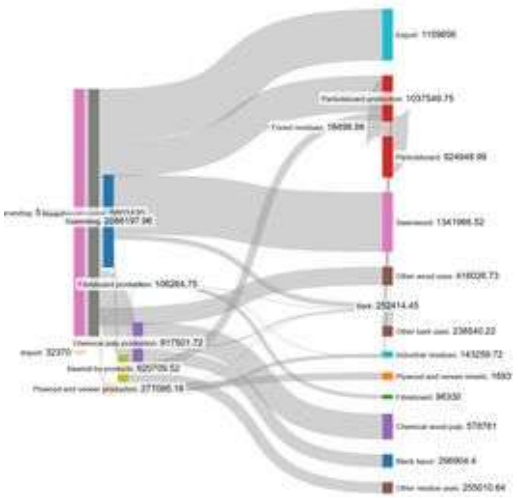

Figure 2. Sankey diagram for the 2022 Bulgarian forest-based sector material flows

The total industrial roundwood supply amounted to approximately 6.04 million m³, including domestic production and imports. After exports of only 79.8 thousand m³, approximately 3.64 million m³ entered the analysed production system, while 2.32 million m³ were allocated to other wood products and stock changes outside the system boundaries. The largest share of the available raw material was allocated to particleboard production, which required approximately 2.80 million m³ of wood resources. Besides primary roundwood, this production process incorporated 37.4 thousand m³ of bark, 49.9 thousand m³ of forest residues, and 498.8 thousand m³ of sawmill by-products. Consequently, secondary wood resources

represented approximately 21% of the total material input for particleboard manufacturing, confirming its central role in the cascading utilization of woody biomass. Fibreboard production also relied considerably on secondary raw materials, with approximately 122.7 thousand m³ of sawmill by-products accounting for about 40% of its total material input. The diagram further illustrates the generation of approximately 263.4 thousand m³ of bark, 247.4 thousand m³ of other industrial residues, 122.1 thousand m³ of sawmill by-products, and 191.4 thousand m³ of black liquor. Within the analysed system, bark, forest residues and sawmill by-products were partially reused as secondary raw materials, whereas the remaining quantities were allocated to processes outside the system boundaries. These results demonstrate the growing importance of cascading wood utilization in the Bulgarian forest-based sector, while also indicating the existence of additional secondary material streams that are not captured within the analysed production system and may represent further opportunities for improving resource efficiency and circular bioeconomy practices.

4. CONCLUSSION

This study developed the first process-based Material Flow Analysis (MFA) of industrial roundwood and wood-residue streams in Bulgaria for the period 2014–2022, combining official production statistics with JRC input-output coefficients and Sankey modelling. The results revealed significant structural changes in the Bulgarian forest-based sector, including a shift towards higher value-added wood processing and increasing production of wood-based panels. Particleboard production was identified as the largest consumer of both primary roundwood and secondary wood resources, demonstrating the importance of cascading wood utilization. Despite the increasing integration of secondary raw materials into manufacturing processes, considerable quantities of wood residues remain outside the analysed production system, indicating additional opportunities for improving resource efficiency and circular bioeconomy practices. The proposed methodology provides a reproducible framework for analysing wood-material flows and can support decision-making related to sustainable forest resource management and the development of circular value chains in Bulgaria.

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REFERENCES

1. Anspach, R.L.; Allen, S.R.; Lupton, R.C. (2024): *Robust modeling of material flows to end-uses under uncertainty: UK wood flows and material efficiency opportunities*. In: Journal of Industrial Ecology, 28(4), 953-965.
2. Besserer, A.; Troilo, S.; Girods, P.; Rogaume, Y.; Brosse, N. (2021): *Cascading recycling of wood waste: A review*. In: Polymers, 13(11), 1752.

3. Brunner, P.H.; Rechberger, H. (2016): *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*. 2nd ed. CRC Press. Boca Raton.
1. European Commission, Joint Research Centre (2026): *Input and output coefficients for the wood-based industry*. Dataset. DOI: 10.2905/JRC.E21X5FG. PID: http://data.europa.eu/89h/a1f94d36-748d-48ef-81bd-f936c64e5800
2. Gregg, J.S.; Jürgens, J.; Happel, M.K.; Strøm-Andersen, N.; Tanner, A.N.; Bolwig, S.; Klitkou, A. (2020): *Valorization of bio-residuals in the food and forestry sectors in support of a circular bioeconomy: A review*. In: Journal of Cleaner Production, 267, 122093.
3. Jarre, M.; Petit-Boix, A.; Priefer, C.; Meyer, R.; Leipold, S. (2020*): Transforming the bio-based sector towards a circular economy: What can we learn from wood cascading?* In: Forest Policy and Economics, 110, 101872.
4. Mair, C.; Stern, T. (2017): *Cascading utilization of wood: A matter of circular economy?* In: Current Forestry Reports, 3, 281-295.
5. Nuss, P.; Blengini, G.A.; Haas, W.; Mayer, A.; Nita, V.; Pennington, D. (2017): *Development of a Sankey diagram of material flows in the EU economy based on Eurostat data*. Publications Office of the European Union. Luxembourg.
6. UNECE; FAO (2026): *Joint Forest Sector Questionnaire (JFSQ): Definitions and Explanatory Notes for 2025 Data*. URL: https://unece.org/sites/default/files/2026-04/DEF-EN-JQ-for-2025-data.pdf
7. Wang, H.; Takano, A.; Winter, S. (2025): *Material Flow Analysis of Wood Resources: A Review of Current Practices in EU and Switzerland*. In: Sustainability, 17(21), 9808.
8. ***: FAOSTAT Forestry Production and Trade Statistics. Food and Agriculture Organization of the United Nations (FAO). URL: https://www.fao.org/faostat/en/#data/FO
9. ***: Eurostat (2026): Generation of waste by economic activity (env_wasgen). URL: https://ec.europa.eu/eurostat/databrowser/view/env_wasgen__custom_20625645/default/table

Authors address:
Neykov, N.[1]; StoyanovT[2]; Kitchoukov, E[3]
[1,3] Alternative Tourism, Ecology and landscape Architecture, University of Forestry, Sofia, Bulgaria
[2] Forest Ecology, Forest Research Institute, Sofia, Bulgaria
*Corresponding author: nkneykov@gmail.com

SUSTAINABLE MANAGEMENT AND CONTROL OF FOREST EXPLOITATION IN BULGARIA

Radka P. Ivanova, Zhivka Mateeva

Abstract: Forest exploitation in Bulgaria is a regulated process aimed at sustainable forest management, ecosystem protection, and the production of both timber and non-timber forest products. This study focuses on two of the principal aspects of forest exploitation in Bulgaria: sustainable forest management and the control of the forestry sector. On the one hand, the role of the Forest Stewardship Council (FSC) standards is of particular importance with regard to the principles of sustainable management and the conservation of forest resources. On the other hand, the control and protection of forest territories, exercised by the Executive Forest Agency—a legal entity funded through the state budget and operating under the Ministry of Agriculture and Food of the Republic of Bulgaria—is of critical importance for maintaining ecological balance, supporting the economy, and safeguarding public health.
The objective of this study is to analyse the extent of FSC implementation in Bulgaria, which establishes requirements for environmentally, socially, and economically responsible forest management, and to examine the role and significance of control mechanisms within the forestry sector as a primary instrument for the protection, sustainable management, and development of forest territories.
Keywords: management, control, standards, FSC, Executive Forest Agency

1. INTRODUCTION

The Forestry in Bulgaria operates within a complex legal framework characterized by a strong degree of public-law regulation, institutional centralization, and detailed normative provisions. At the same time, the global forestry sector has witnessed the growing importance of voluntary certification mechanisms, among which the Forest Stewardship Council (FSC) occupies a leading position.

2. THE STANDART FSC

The Forest Stewardship Council (FSC) was established in 1993 as an international non-governmental organization following the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992. The primary objective of the FSC is to promote the sustainable management of forest resources through certification and to provide a response to the growing threat of deforestation. An important feature highlighted in the literature is that the FSC is characterized by voluntariness, market orientation, and multi-stakeholder participation (Cashore et al., 2004; Auld et al., 2008).
The FSC framework is based on ten principles which, from a substantive perspective, can be grouped into four categories: legal and institutional principles; management and economic principles; ecological principles; and principles related to planning and monitoring. Each of these categories is characterized by a distinct focus and set of objectives (see Table 1).

Table 1. Principles of the Standard FSC

№	Category	Focus	Principles
1	Legal and institutional principles	FSC builds upon the existing Legal Framework	Principle 1: Compliance with Laws Principle 2: Workers' Rights and Employment Conditions Principle 3: Rights of the local communities (including indigenous people)
2	Management and Economic Principles	Sustainability and Economic Viability	Principle 4: Community Relations Principle 5: Benefits of the Forest
3	Ecological Principles	Biodiversity Conservation	Principle 6: Environmental Impact Principle 9: High Conservation Values
4	Planning and monitoring	Implementation of a Process-Based Approach and Accountability	Principle 7: Management planning Principle 8: Monitoring Principle 10: Implementation of Management Activities

The academic literature frequently discusses the FSC as an example of private governance or soft law in the field of environmental regulation. In this regard, Cashore et al. (2004) characterize the FSC as a form of non-state market-driven governance, whereby market mechanisms partially substitute for direct state intervention. At the same time, a number of scholars identify certification schemes of this type as innovative instruments for environmental governance and sustainability (Auld et al., 2008). Research has also demonstrated that the FSC establishes a global framework of principles and criteria that are subsequently adapted at the national level, thereby enabling the integration of universal standards with local and regional specificities (Overdevest & Zeitlin, 2012). In this context, certification systems may also be viewed as part of a broader process of transnational governance (Bartley, 2007; Bernstein & Cashore, 2007).

At the same time, the specialized literature emphasizes the interaction between public and private regulatory mechanisms, highlighting that the effectiveness of FSC certification depends largely on the national institutional context (Gulbrandsen, 2004; Keskitalo et al., 2009). In countries characterized by highly centralized forest governance systems, the role of voluntary standards tends to remain relatively limited. Furthermore, several critical studies have questioned the actual environmental impact of FSC certification, emphasizing that certification does not always result in the substantial improvements in management practices that are often anticipated (Blumröder et al., 2020; van der Ven & Cashore, 2018). Nevertheless, the FSC is generally recognized as an important instrument for promoting the sustainable management of forest resources (Rametsteiner & Simula, 2003; FAO, 2018).

FSC certification applies both to entities engaged in forest management and to participants throughout the forest-product supply chain. Accordingly, FSC certification is divided into two principal categories: Forest Management (FM) certification and Chain of Custody (CoC) certification. Consequently, FSC certification is relevant not only for forest owners and organizations responsible for the management of forest territories, but also for companies involved in the processing, manufacturing, and trade of timber products, as well as non-timber forest products such as paper, cork, and related materials. The Bulgarian FSC National Forest Stewardship Standard was approved in 2016 and became effective in 2017. According to data

published by the World Wide Fund for Nature (WWF), nearly 50% of Bulgaria's forests and approximately 400 companies engaged in wood processing and timber trade is currently FSC-certified (wwf.bg). Furthermore, a substantial proportion of the state-owned forest enterprises operating in the country have also obtained FSC certification.

3. CONTROL OVER THE PROTECTION OF FOREST TERRITORIES IN BULGARIA

The control over the protection of forest areas in Bulgaria is a strictly regulated process aimed at protecting forest resources from illegal activities, fires and diseases. The Executive Forest Agency (EFA) occupies a key place among the administrative bodies exercising control over the protection of forest areas. It is an administration included in the composition of the central executive power, according to Art. 38, para. 1, item 5 of the Administration Act (AA), assisting the executive director of the agency in the exercise of his powers and carrying out activities on administrative services to citizens and legal entities. The creation of agencies under the central executive authority is called the process of "agencification", starting in the late 20th and early 21st centuries with the advent of the New Public Management in Europe (Gyaurova-Vegertseder et al., 2022:19), and in Bulgarian administrative practice the term "agency" first appeared in 1990 (Pehlivanov, 2012:64). The Agency is a legal entity supported by the budget and is managed and represented by an executive director. It is a body of the executive authority within the meaning of Art. 19, para. 4, item 3 of the AA and is a secondary budget spending authority under the Minister of Agriculture and Food (MAF). It exercises its powers directly and through the regional forestry directorates and specialized territorial units of the Agency.

A specific and important activity of the EFA is the administrative control it carries out over the implementation of the Forestry Act (FA) and its implementing regulations. The control is regulated in Section Two of Chapter Thirteen of the FA and in Ordinance No. 1 of January 30, 2012 on the Control and Protection of Forest Territories (OCPFT). Its main functions are:

- **Preventive function**

It is of key importance for the sustainable management and control of forest territories in Bulgaria, as it protects the forest fund from illegal logging, fires, diseases and erosion. The main aspects of the preventive activities carried out by the EFA are expressed in **the protection of forest territories and protection from fires and diseases**.

Direct control over the activities carried out in the forest territories is carried out by employees of EFA and its structures (regional forest directorates), holding positions for which forestry education (higher and secondary) is required, as well as by employees appointed by order of the executive director of the agency. In order to prevent violations in the forest territories, checks (complex and permanent) are carried out on the entire territory of the country, which are carried out in accordance with the FA and the OCPFT. The protection and preservation of forest territories from forest fires and illegal encroachments is among the priorities of EFA. In this regard, EFA conducts annual information campaigns and joint inspections with the General Directorate "Fire Safety and Protection of the Population" for the prevention of forest areas from fires with a view to reducing human negligence, which is the main cause of more than 58% of forest fires in 2025 (EFA's Annual report for 2025, p. 35).

For the protection of the forest territories, the officers performing control functions use means and measures for public impact in relation to violators. In particular, forest officials have the following basic rights:

- **free access** – they have the right to access all objects and documentation subject to control under the FA.

- **request for information** - they have the right to request documents and receive the necessary information for the performance of their control functions.
- **inspection of means of transport** - they have the right to stop by signaling with a stop stick and to inspect road vehicles transporting wood and non-wood forest products. It is undisputed that this power is not limited to inspections related to the transport of timber and non-timber forest products. The officers have the right to establish the identity of the persons, to check the documents of the road vehicle and all documents related to the purpose of the check.
- seizure of property – they have the right to seize the property - subject of the violation, as well as the property that served to commit it. Confiscation in favor of the state is regulated in Art. 20 and Art. 21 of the Administrative Violations and Penalties Act (AVPA) as a secondary sanction that affects the property of the offender. The established rules under AVPA for the management and disposal of seized property should also comply with the provisions of the special law - FA. According to Art. 273, para. 1 of the FA, these properties are seized in favor of the state regardless of whose ownership they are. An exception to this rule is in cases where it is established that the properties were used independently or against the will of their owner. The inspection and control bodies are obliged to carry out detention of objects (for example, wood and non-wood forest products - the subject of the violation) when drawing up acts of establishing an administrative violation (AEAV) or with finding protocols under Art. 8, para. 2 of the OCPFT. Based on the drawn up protocol and the AEAV, administrative-criminal proceedings are initiated, which may end with the imposition of an administrative penalty on the violator. In this sense, the Supreme Administrative Court (SAC) accepts that the seizure and detention of objects is not an independent administrative proceeding for the application of a coercive administrative measure within the meaning of Art. 23 of the AVPA, but is an element of the administrative-criminal proceedings initiated on the basis of Art. 36, para. 2 of the AVPA (Decision No. 17272 of 17.12.2019 under adm. e. No. 11998/2019, V department of the SAC).
- forced removal, physical force and additional measures – they have the right to take offenders with an undetermined identity to the nearest regional department of the Ministry of Internal Affairs, in cases where they refuse to be accompanied voluntarily, as well as to use physical force and additional measures (handcuffs, electric shock batons, service animals as a check, horses, etc.) only when it is impossible to fulfill their official duties in another way (for example, when resisting or refusing to comply with a legal order). These rights are set out in Art. 200 of the FA and serve as a tool for prevention and control.
When performing their official duties of control regarding the protection of forest territories, forest officials prevent violations of the law by **stopping illegal activities, issuing orders and prescriptions**.
Stopping illegal activities in forest territories is a compulsory administrative measure (CAM) within the meaning of Art. 22 and 23 of the AVPA, which is imposed during control inspections. CAM is a type of administrative coercion without a sanctioning nature (Keremedchiev, 2004:42) and is one of the strongest in terms of its legal intensity. It can be imposed even when there is a danger of committing an administrative violation (Balabanova, 2004:95). Its purpose is to prevent, terminate or eliminate the harmful consequences of violations of the legislation on the protection of forest territories.
The authority to issue orders to impose CAM to prevent and terminate administrative violations under the FA is assigned to the MAF, the Executive Director of the EFA, the directors of the regional forest directorates, the directors of the state forest and hunting estates and the mayors of municipalities.

Orders that are in violation of the FA and the implementation of plans approved in violation of the law are suspended by the MAF, as well as by the Executive Director of the EFA. Upon detection of violations, the relevant director of a regional forestry directorate issues an order to suspend activities and construction in forest areas in order to prevent adverse consequences. Specifically, the provision of Art. 253, para. 3 of the FA provides that the directors of regional forestry directorates shall:

- suspend any activities in forest areas when violations of the regulations explicitly listed in the FA are detected with respect to illegal activity in a certain forest area, lack of regular documents or in the event of an immediate danger;
- suspend illegal construction in forest areas when it is carried out without the necessary documents (a project adopted in accordance with the relevant procedure), in violation of forest management plans and programs or is outside the scope of the issued permits.

In the context of forest protection legislation, these actions directly protect the forest fund by preventing the spread of environmental and material damage. The order for the imposition of a CAM also provides instructions for the prevention and elimination of the harmful consequences of the violations committed. The order for the imposition of a CAM, issued by the relevant director of a regional forest directorate, is an individual administrative act within the meaning of Art. 21 of the Administrative Procedure Code (APC). It is subject to immediate execution, since by its nature the CAM is suspensive - it prevents from now on an already initiated and ongoing violation of the legislation on the protection of forest territories.

- **Regulatory function**

This function ensures the sustainable management, protection and use of forest resources in Bulgaria. It is expressed in coordinating and controlling the implementation of forest legislation and state policy in the field of forestry. In this regard, the EFA acts as a regulatory authority in the forest sector. Specifically, its main powers are expressed in:

- **protection of the forest fund** - the EFA controls the implementation of the FA, plans for the development of forest territories and for the management of natural parks, as well as exercises general supervision and methodological guidance over the activities of all bodies and persons assigned obligations under the law.
- **issuing mandatory instructions** - the executive director of the EFA approves developments and instructions related to planning and conducting logging in forests. The instructions are binding for their addressees, directing them to specific behavior that they must implement and adhere to. They are approved by an order of the executive director, which is subject to appeal under the APC.

- **Penal (sanctioning) function**

The purpose of this function is to prevent, suppress and sanction violations of forest legislation with a view to protecting forest territories. Violations of the FA and the by-laws for its implementation are established by AEAV. In administrative law literature, these acts are not considered legal. They only establish and certify facts and circumstances of legal significance, which is why they do not constitute a statement of will. Their main functions are accusatory and adjudicative (Lazarov, 2008:17; Dermendzhiev, 2005:557), as they serve to initiate administrative-criminal proceedings, which may end with the imposition of an administrative penalty on the violator.

The authority to establish an administrative violation of the forest legislation is assigned to the relevant control bodies. The FA does not establish a category of employees who have the right to establish the violations committed (Stoyanov et al., 2011:377). Employees in the EFA and

its structures are among the category of control bodies established by Art. 274, para. 1 of the FA, which have the right to draw up acts to establish violations of the FA and the by-laws on its implementation.

For violating the forest legislation, the guilty persons are imposed an administrative penalty of a "fine" or a "property sanction" by a penal decree. The Executive Director of the EFA or officials authorized by him, as well as the directors of the regional forest directorates authorized by the MAF, are among the administrative sanctioning bodies that are tasked with issuing penal decrees under the FA and the by-laws for its implementation.

In the context of forest legislation, administrative sanctions aim to protect forest areas and ensure their sustainable development, prevent future violations (illegal logging, illegal extraction or transport of wood), punish unlawful actions against the rules for forest management and restore the damage caused to the forest fund. In this sense, administrative sanctions are an important means of ensuring compliance with forest legislation in Bulgaria.

4. CONCLUSION

In the context of increasingly complex and dynamic global climate change, the management of forests and forest resources requires regulatory frameworks that ensure their conservation while taking into account the interests of local communities, forestry sector employees, and timber consumers. This creates the need for specific legal regulations governing the activities and relationships within the forestry sector.

The FSC principles encompass legal, social, economic, and environmental dimensions, including compliance with legislation, protection of workers' rights, conservation of biodiversity, and effective management practices. However, given the voluntary nature of the FSC standard, these principles cannot be considered sufficient in themselves and should rather be viewed as complementary to the existing regulatory framework, contributing to the sustainability of forest management.

At the same time, the control exercised by the EFA plays a crucial role in the protection of the national forest estate, as it encompasses both preventive and subsequent forms of oversight. The control activities carried out by the EFA and its subordinate structures are based on clearly defined legal mechanisms established in the FA and the OCPFT. Forestry officials are vested with specific powers to stop, inspect, and sanction violations of forestry legislation. Nevertheless, in order to enhance the prevention of illegal logging activities, greater public transparency regarding conducted inspections and imposed sanctions should be ensured.

REFERENCES (alphabetical order)

1. Auld, G., Gulbrandsen, L.H. & McDermott, C.L. (2008). Certification schemes and the impacts on forests and forestry. Annual Review of Environment and Resources, 33, 187–211. https://doi.org/10.1146/annurev.environ.33.013007.103754
2. Balabanova, H. (2004). Administrativen kontrol. Varna: VSU „Chernorizets Hrabar"
3. Bartley, T. (2007). Institutional emergence in an era of globalization: The rise of transnational private regulation. American Journal of Sociology. https://doi.org/10.1086/518871
4. Bernstein, S. & Cashore, B. (2007). Can non-state global governance be legitimate? Regulation & Governance. https://doi.org/10.1111/j.1748-5991.2007.00021.x

5. Blumröder, J.S. et al. (2020). Clearcuts and related secondary dieback undermine the ecological effectiveness of FSC certification. Ecological Processes, 9(10). https://doi.org/10.1186/s13717-020-0214-4
6. Cashore, B., Auld, G. & Newsom, D. (2004). Governing through Markets: Forest Certification and the Emergence of Non-State Authority. Yale University Press.
7. Dermendzhiev, I. Administrativno pravo. Sofiya: Sv. Kliment Ohridski, seriya "Universitetska klasika", 2005
8. FAO (2018). Forest Certification and Sustainable Forest Management. Food and Agriculture Organization.
9. Gulbrandsen, L.H. (2004). Overlapping public and private governance: Can forest certification fill the gaps in the global forest regime? Global Environmental Politics, 4(2), 75–99. https://doi.org/10.1162/152638004323074200
10. Gyaurova-Vegertseder et al. (2022). Visshite publichni naznacheniya v izpalnitelnata vlast. Sofiya: Balgarski institut za pravni initsiativi, https://appointmentsboard.bg/wp-content/uploads/2022/09/%D0%9D%D0%B0%D7%BD%D0%B0%D1%87%D0%B5%D0%BD%D0%B8%D1%8F-%D0%98%D0%92-%D0%91%D0%98%D0%9F%D0%98.pdf
11. Keremedchiev, I. (2004). Prinuditelni administrativni merki v oblastta na zakonodatelstvoto po opazvane na okolnata sreda. Administrativno pravosadie, 4, 42-47
12. Keskitalo, E.C.H. et al. (2009). Institutional adaptation to forest certification in Europe. https://doi.org/10.1080/02827580903161739
13. Lazarov, K. (2008). Administrativen akt – ponyatie i vidove. Yuridicheski svyat, 1, 11-20
14. Ministerstvo na zemedelieto i hranite. IAG. (2026). Godishen otcheten doklad na IAG za 2025 g.,https://www.iag.bg/data/docs/Doklad25_01str_final_08.05.2026.pdf [05/31/2026]
15. Overdevest, C. & Zeitlin, J. (2012). Assembling an experimentalist regime: Transnational governance interactions in the forest sector. Regulation & Governance. https://doi.org/10.1111/j.1748-5991.2012.01133.x
16. Pehlivanov, K. (2012). Praven statut na agentsiite saglasno Zakona za administratsiyata i spetsialnite normativni aktove, De Jure, 4(1),62-73
17. Rametsteiner, E. & Simula, M. (2003). Forest certification—an instrument to promote sustainable forest management? Journal of Environmental Management. https://doi.org/10.1016/S0301-4797(02)00265-3
18. Stoyanov, V., Kurteva, S., Stoykova, Yu. (2011). Praven rezhim na zemedelskite zemi i gorskite teritorii. Sofiya: IK „Trud i pravo“
19. van der Ven, H. & Cashore, B. (2018). Forest certification: The challenge of measuring impacts. Current Opinion in Environmental Sustainability, 32, 104–111. https://doi.org/10.1016/j.cosust.2018.04.010
20. https://www.wwf.bg/?18867941/Balgaria-stana-chast-ot-globalnata-mrezha-FSC-za-ustoichivo-upravlenie-na-gorite [04/30/2026]

Authors address:
Ivanova, R.[1]; Mateeva, Zh.[2]
[1] Department of Management and Administration, Faculty of Management, University of Economics – Varna, Varna, Bulgaria
[2] Legal Studies Department, Faculty of Finance and Accounting, University of Economics – Varna, Varna, Bulgaria

ANALYSIS OF RESOURCE MANAGEMENT: WOOD WASTE TRENDS IN THE EU AND CROATIA AS A BASIS FOR CIRCULAR BUSINESS MODELS DEVELOPMENT

Andreja Pirc Barčić, Domagoj Kovačević, Jelena Crnojević, Ivana Perić, Kristina Klarić, Darko Motik, Karla Vukman, Denis Jelačić

Abstract: With increasing pressure on natural resources and the need to reduce the amount, the circular economy is becoming an important concept in the development of industrial systems. A special role in this process is played by the wood industry, which, due to the nature of its raw materials, has significant potential for efficient resource use and material reuse. The aim of this paper is to analyze wood waste trends in the European Union and Croatia and assess their significance for the development of circular business models in the wood industry. The research is based on the analysis of secondary data on wood waste quantities in the observed period, with special emphasis on comparing trends at the EU and Croatian levels. The results of the analysis indicate the importance of systematic monitoring and management of wood waste as a valuable secondary resource that can be re-incorporated into production processes..
Keywords: wood waste trends, secondary data, resource management, circular economy

1. INTRODUCTION

Increasing pressure on natural resources, climate change, and environmental concerns have intensified the need for sustainable resource management. In response, the circular economy has emerged as a key framework for improving resource efficiency, reducing waste generation, and extending the life cycle of materials through reuse, recycling, and recovery processes. Unlike the traditional linear model based on the “take–make–dispose” principle, circular economy strategies aim to retain the value of resources within the economy for as long as possible (European Parliament, 2023; Goldhahn *et al*., 2021).

Effective resource management is essential for achieving sustainability objectives and enhancing industrial competitiveness. In the wood industry, this is particularly important because growing demand for wood products places increasing pressure on forest resources and requires more efficient use of both primary and secondary raw materials (Kovačević, 2025).

The wood sector is a significant component of the European bioeconomy due to its reliance on renewable resources and its contribution to climate change mitigation. Wood products store carbon throughout their life cycle and can replace more carbon-intensive materials such as concrete and steel, thereby reducing greenhouse gas emissions (Gustavsson *et al*., 2006; Lundmark *et al*., 2014). Consequently, improving wood resource efficiency has become a strategic objective of European sustainability, bioeconomy, and circular economy policies (European Commission, 2018; European Commission, 2023).

Particular attention has been directed toward wood waste as a valuable secondary resource. Residues generated during processing, manufacturing, construction, and end-of-life product management can be reintroduced into production systems, reducing dependence on virgin raw materials and supporting circular material flows. Previous studies have highlighted the environmental and economic benefits of wood waste recovery, including reduced landfill

disposal, lower resource consumption, and increased resource efficiency (Jiang *et al*., 2018; Mi *et al*., 2020; Goldhahn *et al*., 2021).

The efficient utilization of wood waste is closely linked to the cascading use principle, which prioritizes long-life applications, reuse, and recycling before energy recovery (Höglmeier *et al*., 2015; Vis *et al*., 2016; Navare *et al*., 2022). This approach is increasingly recognized as an important element of sustainable resource management and circular business model development in the wood industry (Kovačević, 2025).

Within the European Union, substantial quantities of wood waste are generated annually, particularly in wood processing, construction, and furniture manufacturing, making these sectors important sources of secondary raw materials (Crnojević *et al*., 2026). Understanding long-term trends in wood waste generation is essential for evaluating resource efficiency, identifying opportunities for material recovery, and supporting circular business models.

As a country with a well-developed forestry and wood-processing sector, Croatia has significant potential to increase the valorisation of wood waste through circular production systems. Resource-efficient management of wood waste streams can reduce dependence on virgin materials, improve sustainability performance, and create additional economic value from secondary resources (Kovačević, 2025).

Therefore, the aim of this study is to analyse wood waste trends in the European Union and Croatia using secondary statistical data and compare developments at both levels. By providing an overview of wood waste generation patterns, the study contributes to a better understanding of the role of secondary wood resources in supporting circular economy objectives and the development of circular business models in the wood sector.

2. MATERIALS AND METHODS

This study is based on the analysis of secondary statistical data on wood waste generation in the European Union (EU) and Croatia. The aim is to identify and compare trends in wood waste quantities over time and assess their potential contribution to circular economy objectives and circular business models in the wood sector.

The analysis uses data from the Eurostat database (Eurostat, 2025), including harmonized information on wood waste generation from economic activities and households. Comparable data for the EU and Croatia were collected, organized, and analyzed using descriptive statistical methods. Annual quantities and percentage changes were examined to identify trends and differences between the EU and Croatia.

The results are presented through tables and graphical visualizations, highlighting key developments and their implications for resource management and the utilization of secondary wood resources. The study follows a descriptive analytical approach and does not include econometric or inferential statistical analyses.

3. RESULTS AND DISCUSSION

3.1 Trends in Wood Waste Generation in the European Union and Croatia

Figure 1 shows trends in wood waste generation in the European Union during 2004–2022. Wood waste quantities decreased from approximately 62.5 million tonnes in 2004 to around 47 million tonnes in 2022, representing a reduction of about 25%. The most pronounced decline occurred between 2008 and 2014, after which wood waste generation stabilized at

slightly below 50 million tonnes annually. The decline may reflect improvements in material efficiency, changes in production practices, and the increasing utilization of wood residues within industrial processes. In addition, the growing use of wood by-products for energy recovery and other valorisation pathways may have reduced the quantities reported as waste (Zbieć *et al*., 2022). Similar developments have been reported in studies on cascading wood use and circular resource management in the European wood sector (Vis *et al*., 2016; Crnojević *et al*., 2026).

A comparable trend was observed in Croatia (Figure 2), although on a much smaller scale. Wood waste generation declined from approximately 250 thousand tonnes in 2004 to below 100 thousand tonnes in 2012 and 2014, followed by a gradual increase to approximately 167 thousand tonnes in 2022. Compared with the relatively stable EU trend after 2014, Croatia exhibited greater fluctuations, likely reflecting changes in domestic wood-processing activities and the utilization of wood residues.

Despite considerable differences in absolute quantities, the EU and Croatia show similar long-term dynamics characterized by an initial decline in wood waste generation followed by stabilization or moderate growth. These trends suggest that wood waste management is increasingly influenced by circular economy principles aimed at improving resource efficiency and enhancing the utilization of secondary raw materials (Crnojević *et al*., 2026). According to Kovačević (2025), the integration of secondary raw materials into production processes is essential for circular business model development and sustainable resource management. Therefore, systematic monitoring of wood waste flows remains crucial for planning circular business models, improving material recovery systems, and increasing resource efficiency in both the European Union and Croatia

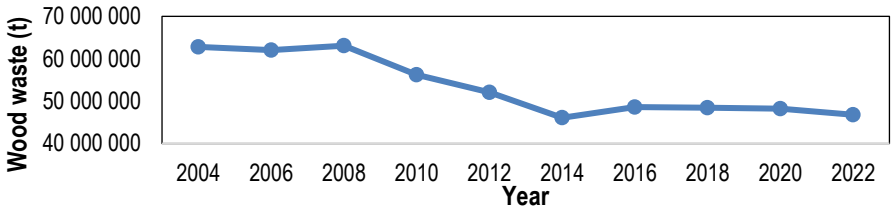

Figure 1. Trends in wood waste generation in the European Union (EU-27), 2004–2022 (tonnes).

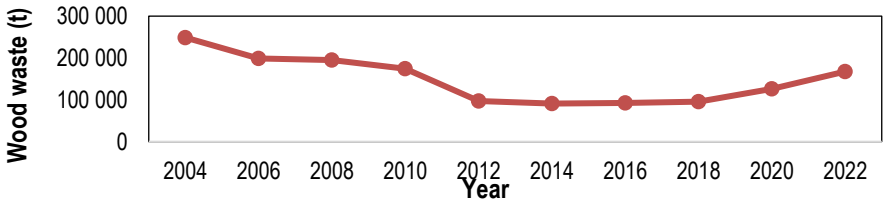

Figure 2.Trends in wood waste generation in Croatia, 2004–2022 (tonnes).

3.2 Sectoral Distribution of Wood Waste Generation

The distribution of wood waste generation across economic sectors reveals the activities that contribute most significantly to the availability of secondary wood resources. As shown in Table 1, manufacturing (NACE C) was the dominant source of wood waste generation in both the European Union and Croatia, accounting for 47.26% and 49.36% of total wood waste, respectively.

In the EU, the second-largest share was generated by the water supply, sewerage, waste management and remediation activities sector (NACE E), which accounted for 29.52%, followed by construction (NACE F) with 21.71%. In Croatia, sector E represented 42.71% of total wood waste generation, while construction contributed only 7.53%. The shares of all remaining sectors were below 1% in both cases.

The results indicate a strong concentration of wood waste generation within a limited number of economic activities, particularly manufacturing and waste management-related sectors. Compared with the EU average, Croatia exhibited a higher concentration of wood waste generation in these sectors and a substantially lower contribution from construction activities.

These findings confirm the importance of industrial activities as the principal source of secondary wood resources and highlight their relevance for circular economy implementation in the wood sector (Crnojević *et al*., 2026). Since manufacturing represents the largest source of wood waste generation in both observed regions, further analysis focuses on the contribution of the wood-processing industry within this sector, particularly NACE C16.

Table 1 Sectoral shares of total wood waste generation in the European Union (EU-27) and Croatia, based on average annual quantities for the period 2004–2022 (%)

Sector (NACE Rev. 2)	EU-27 (%)	Croatia (%)
A – Agriculture, forestry and fishing	0.76	0.33
B – Mining and quarrying	0.11	0.03
C – Manufacturing	47.26	49.36
D – Electricity, gas, steam and air conditioning supply	0.65	0.04
E – Water supply; sewerage, waste management and remediation activities	29.52	42.71
F – Construction	21.71	7.53
Total	**100.00**	**100.00**

3.3 Contribution of the wood products industry within manufacturing

To assess To assess the importance of the wood sector as a source of secondary wood resources, the contribution of NACE C16 (Manufacture of wood and wood products, except furniture) to manufacturing-related wood waste generation was analysed for 2022.

The results show that wood-processing activities represent the dominant source of manufacturing-related wood waste in both the European Union and Croatia. In the EU, the manufacture of wood and wood products generated 10.21 million tonnes of wood waste, accounting for 58.4% of total wood waste generated within the manufacturing sector. In Croatia, the concentration was even more pronounced, with 58,639 tonnes of wood waste originating from C16 activities, representing 83.7% of total manufacturing-related wood waste generation.

These findings confirm the strategic importance of the wood-processing industry as a generator of secondary wood resources. The substantially higher share recorded in Croatia reflects the strong specialization of its manufacturing sector in wood processing and indicates a greater dependence on the wood industry as a source of industrial wood residues. From a circular economy perspective, these residues should be regarded as valuable inputs for recycling, cascading use, and resource-efficient production systems, thereby supporting the

development of circular business models in the wood sector (Kovačević, 2025; Crnojević *et al*., 2026).

4. CONCLUSION

This study analysed wood waste generation trends in the European Union and Croatia using secondary statistical data, with the aim of assessing the role of wood waste as a resource for circular economy implementation and circular business model development. The results revealed a general decline in wood waste generation in both the EU and Croatia during the observed period, followed by stabilization or moderate growth in recent years. Sectoral analysis showed that manufacturing and waste management-related activities are the dominant sources of wood waste generation in both regions.

Particular attention was given to the manufacture of wood and wood products (NACE C16), which accounted for 58.4% of manufacturing-related wood waste generation in the EU and as much as 83.7% in Croatia in 2022. These findings confirm the strategic importance of the wood-processing industry as a major generator of secondary wood resources and highlight its potential contribution to circular resource management. The substantially higher share of C16 within manufacturing-related wood waste generation in Croatia compared to the EU average highlights the strategic importance of the wood-processing industry for circular resource management at the national level.

The study emphasizes that wood waste should be regarded not merely as a waste stream but as a valuable secondary raw material that can be reintegrated into production processes through recycling, cascading use, and other circular economy practices. Therefore, systematic monitoring of wood waste flows and the efficient utilization of wood residues represent important prerequisites for improving resource efficiency and supporting the development of circular business models in the wood sector.

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REFERENCES

1. Crnojević, J.; Pirc Barčić, A.; Tafro, A.; Vukman, K.; Klarić, K.; Kitek Kuzman, M.; Perić, I. (2026): EU Wood Products and Waste Markets: Trends, Trade Dynamics, and Sustainability Perspective. BioResources 21 (2): pp. 4953-4976. DOI: 10.15376/biores.21.2.4953-4976.
2. Kovačević, D. (2025): Analysis of Resource Management as a Basis for the Development of Circular Business Models in the Wood Industry. Master's Thesis. University of Zagreb, Faculty of Forestry and Wood Technology, Zagreb.
3. Goldhahn, C.; Cabane, E.; Chanana, M. (2021): Sustainability in Wood Materials Science: An Opinion about Current Material Development Techniques and the End of Lifetime Perspectives. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379 (2206): article 20200339. https://doi.org.10.1098/rsta.2020.0339
4. Gustavsson, L.; Pingoud, K.; Sathre, R. (2006): Carbon Dioxide Balance of Wood Substitution: Comparing Concrete and Wood Framed Buildings. Mitigation and Adaptation Strategies for Global Change 11 (3): pp. 667-691. https://doi.org.10.1007/s11027-006-7207-1
5. Höglmeier, K.; Steubing, B.; Weber-Blaschke, G.; Richter, K. (2015): LCA-based Optimization of Wood Utilization under Special Consideration of a Cascading Use of Wood.

Journal of Environmental Management 152: pp. 158-170. https://doi.org/10.1016/j.jenvman.2015.01.018
6. Jiang, F.; Hsieh, Y.; Wang, Y.; Song, J.; Li, T.; Kuang, Y.; Gan, W.; Das, S.; Hu, L. (2018): Wood-based Nanotechnologies toward Sustainability. Advanced Materials 30 (28): article 1703453. https://doi.org.10.1002/adma.201703453
7. Kuzman, M. K.; Glavonjić, B.; Pirc Barčić, A.; Obućina, M.; Haviarova, E.; Grošelj, P. (2024): Exploring Attitudes towards Extending Lifecycle of Wood Products by Cascading: A Case Study in Bosnia and Herzegovina, Croatia, Serbia, and Slovenia. Wood Material Science and Engineering 19 (3): pp. 752-761. https://doi.org.10.1080/17480272.2023.2294345
8. Lundmark, T.; Bergh, J.; Hofer, P.; Lundström, A.; Nordin, A.; Poudel, B. C.; Sathre, R.; Taverna, R.; Werner, F. (2014): Potential Roles of Swedish Forestry in the Context of Climate Change Mitigation. Forests 5 (4): pp. 557-578.
9. Mi, R., Li, Y., Kuang, Y., Liang, X., Chen, C., Hitz, E., Jiang, F., Huang, H., Li, T., and Hu, L. (2020). "A clear, strong, and thermally insulated transparent wood for energy efficient windows," Advanced Functional Materials 30(17), article 1907511. https://doi.org.10.1002/adfm.201907511 Navare, K.; Arts, W.; Faraca, G.; Van den Bossche, G.; Sels, B.; Van Acker, K. (2022): Environmental Impact Assessment of Cascading Use of Wood in Bio-fuels and Bio-chemicals. Resources, Conservation and Recycling 186: article 106588. https://doi.org/10.1016/j.resconrec.2022.106588
10. Vis, M.; Mantau, U.; Allen, B. (2016): Study on the Optimised Cascading Use of Wood. European Commission, Brussels. https://doi.org.10.2873/827106
11. Zbieć, M.; Franc-Dąbrowska, J.; Drejerska, N. (2022): Wood Waste Management in Europe through the Lens of the Circular Bioeconomy. Energies 15 (12): article 4352. https://doi.org/10.3390/en15124352
12. ***European Commission (2018): A Sustainable Bioeconomy for Europe – Strengthening the Connection between Economy, Society and the Environment. (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0673)
13. ***European Commission (2023): Circular Economy Action Plan. (https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en)
14. ***European Parliament (2023): Circular Economy: Definition, Importance and Benefits. (https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits)
15. ***Eurostat (2025): Generation of waste-by-waste category, hazardousness and NACE Rev. 2 activity (env_wasgen). (https://ec.europa.eu/eurostat/databrowser/view/env_wasgen__custom_21756514/default/table)

Authors address:

Pirc Barčić, Andreja[1*]; Kovačević, Domagoj[1]; Crnojević, Jelena[1]; Perić, Ivana[1]; Klarić, Kristina[1]; Motik, Darko[1]; Vukman, Karla[1]; Jelačić, Denis[1]
[1]Department for Production Organization, Faculty of Forestry and Wood Technology, University Zagreb, Zagreb, Croatia.
[*]Corresponding author: apirc@sumfak.unizg.hr

THE HISTORICAL AND CONTEMPORARY DEVELOPMENT OF THE FORESTRY SECTOR IN BULGARIA, A COMPARISON WITH OTHER BALKAN AND EUROPEAN COUNTRIES, AND OPPORTUNITIES FOR ITS FUTURE DEVELOPMENT

Gergana Slavova

Abstract: Our country possesses great natural wealth, based on its extensive forest resources and rich flora and fauna. The main objective of this report is to provide a comprehensive historical retrospective and comparison of Bulgaria's forestry sector with other Balkan and European countries, and to identify the key opportunities for the current and future development of the forestry sector in Bulgaria. The following methods were used: synthesis, induction, deduction, comparative analysis, retrospective analysis, and scientific comparison. The results successfully achieved in this study can be utilized by scientific institutes in the field of forestry, national and European forestry agencies, forestry officials and agronomists, forest engineers, research associates, scientists, and doctoral students working in the forestry sector.
Keywords: forestry sector, climate change, forest areas, development, agricultural sector, environmental, social, and economic impacts

1. A RETROSPECTIVE ON THE DEVELOPMENT OF THE FORESTRY SECTOR IN BULGARIA AND THE BALKAN PENINSULA

Before the Ottoman conquerors took over the territory of Bulgaria in the past, our land was covered with dense, in many places completely impassable virgin forests. During the Middle Ages, Western knights from the First and Second Crusades described their journey through Bulgarian lands as a passage through an endless forest massif. They called our land "Land Rich in Forests"—"Magna Silva Bulgarorum." The ancient forests in our lands at that time began at Belgrade, passed through Niš and Sofia, and reached all the way to Plovdiv and Thrace. In ancient times, ancient oak and beech forests predominated in our country, even in its lowlands. This is a rarity today (2026), as these areas are now farmland. The Bulgarian tsars used the forests as a strategic military advantage. They provided natural protection that shielded our ancestors from foreign attacks. The dense forests and mountain passes were transformed into fortifications that halted the Byzantine armies. Compared to later centuries, the population was smaller and concentrated in fortified towns and small villages, which allowed nature to dominate. Many of the forest areas were preserved as hunting grounds for the country's aristocracy or were owned by the major monasteries (such as the Rila Monastery), which protected them with strict rules.

1.1. Historical Development of the Forestry Sector in Bulgaria

During the Middle Ages (7th–14th centuries), the forests were managed by the Bulgarian kingdoms. It was precisely during this period that Bulgaria was one of the most forested regions

in Europe. The forest was not merely a backdrop of trees, but a strategic resource. The Bulgarian tsars—Omurtag,Telerig, Krum, Simeon, and Samuel, relied on the forests for their "ambushes."The well-known fortifications that served as barriers were constructed from felled centuries-old trees, which turned the mountain passes into impenetrable walls forthe Byzantine cavalry. During this period, Bulgaria exported to Byzantium and Venice not only grain, but also timber for shipbuilding, copper, and wax, also harvested in the forests. The tsars donated vast forest tracts to the monasteries. The forests located near monasteries and churches were considered "sacred" and were the first protected areas in our history (Alexandrov,2018).

Following the Liberation from Ottoman rule (1878–1890), a period of "unrestricted logging" began in our country. Peasants cut down forests on a massive scale to acquire land for farming. The young Kingdom of Bulgaria quickly realized the danger and established a forest protection service as early as 1881. This was also the time when strict laws related to the protection of Bulgaria's forests were enacted. During the reign of Tsar Ferdinand I, he had a keen interest in botany and ornithology. During his reign, the first state nurseries were established in our country, and the foundations of scientific afforestation were laid. It was then that the idea of a "Reforestation Festival" was first conceived. Today, this festival is known as "Forest Week," in which schoolchildren, students, and citizens participate.

Table 1. Key functions of forests in Bulgaria before and after the country's liberation from Ottoman rule

Period	Condition of the forests	Main functions of the forests
Middle Ages	Pristine forest tracts	Forests are used for defines, hunting, and the establishment of monastic forest districts
Ottoman Period	Deforestation and unregulated logging	They are mainly used as pastureland after being cleared; they are also used as fuel and for heating in Istanbul, as well as in shipbuilding
Third Bulgarian Kingdom	The forests are slowly beginning to recover	Forests are relied upon as an economic resource and have become a recognized symbol of national wealth

During the Ottoman Empire's rule over our lands, forests were primarily referred to as state forests and were intended for public use. Anyone could cut wood for firewood and construction without a plan or supervision. This led to severe deforestation in some areas. In addition, the Ottoman Empire consumed vast quantities of high-quality timber, primarily oak and pine from the Rila, Pirin, and Strandzha mountains, for the construction of the Ottoman fleet. Since livestock farming was the primary economic activity, forests were often deliberately set on fire to clear space for pastures. For the Bulgarians, however, the forest was a symbol of protection. It was the place where the haidouks hid, which often led to punitive actions and the clearing of entire forests along the roads by the Turkish authorities.

After the Liberation (1878), many areas, especially in the Pre-Balkan region and the Sredna Gora Mountains, had already been heavily deforested to meet the needs of the abajii's craft workshops. The timber was used to produce charcoal for the abajii industry. After 1878, large-scale construction of the new state began. Railways, telegraph poles, bridges, and houses began to be built. All of this required a great deal of timber. Immediately after the end of the war, peasants in Bulgaria began cutting down state-owned forests en masse, believing

that “freedom” meant the forest was their personal property. This led to the destruction of thousands of acres of centuries-old forests in just a few years. These facts became the main reason for the adoption of Bulgaria’s first Forest Act (1883): Just five years after the Liberation, the state realized that if logging was not stopped, Bulgaria would turn into a desert. Thus, the second law was also adopted, which protects forest areas and is the first law in Bulgaria to prohibit grazing in young forests. In the 1890s, the first forest nurseries were established, and reforestation began in the country. Why were forests so important for our territory? They are a source of photosynthesis, green energy (Radenksi, 1999), and clean air. They are the “lungs” of our country.

1.2. Comparison with other countries in Europe and the Balkan Peninsula

During this same period, deforestation was also observed in Greece. There are several reasons for this. The first is the increase in shipbuilding; since Greece has always been a maritime nation, timber from its forests has been used to build its fleet since ancient times. Another serious problem is goat herding, which is directly linked to the destruction of young saplings by the goats raised in the country. Unlike Bulgaria, Greece has a much more rugged terrain. This means that deforestation in such areas leads to much slower recovery, resulting in the country’s typical landscape today across all its Greek islands and mountains. Ferdinand I made a huge contribution to Bulgaria’s forests; as a passionate botanist, he played a major role in forest conservation and the creation of the first reserves to save Bulgaria’s flora and fauna. At the same time, Romania possessed a vast expanse of virgin forests, part of the Carpathians. In the regions of Wallachia and Moldavia, the forests remained in good condition because they were more difficult to access and less populated. After liberation from Ottoman rule—which occurred slightly earlier for Romania than for Bulgaria—the country began a massive export of timber to Central Europe. This was carried out primarily via the Danube River. In Romania, forests were often owned by aristocrats, who preserved them as hunting grounds, which, paradoxically, helped ensure their better preservation.

During this very same stage of economic development in Turkey, the Anatolian region—known as the “imperial desert” and the center of power—served as the primary source of firewood and charcoal for the vast city of Istanbul. This led to the near-total deforestation of northwestern Turkey as early as the 18th century. The construction of massive Ottoman armies and encampments required colossal amounts of timber, turning parts of inland Anatolia into semi-desert regions. The Ottoman Empire did not adopt its first modern forestry law until 1870. While it was influenced by the French model of forest management, implementing it in the vast and corrupt empire proved very difficult.

Table 2. Comparison of forest conditions among the countries of the Balkan Peninsula

Country	State of the Forests	Main reason
Bulgaria	Heavily damaged but preserved in the mountains	Banditry and crafts
Greece	Severe erosion and deforestation	Shipbuilding and goat herding
Romania	The best-preserved on the peninsula	Main reason

2. CURRENT DEVELOPMENTS IN THE FORESTRY SECTOR IN BULGARIA

Despite illegal and unregulated logging, Bulgaria has managed to preserve a large portion of its green forests and mountains. As of today (March 20, 2026), Bulgaria has a total of over 1,000 protected areas, divided into several categories, as shown in the following table 3(Forest Act, 2025)

Table 3. National parks, nature parks, reserves, protected areas, and natural landmarks in Bulgaria's forested regions

Type of protected area	Number	Names of some of the protected areas	Key characteristics	Location
National parks	3	"Rila," "Pirin," and "Central Balkan"	Exclusively state-owned	The Rila, Pirin, and Stara Planina
Nature parks	11	"Vitosha," "Strandzha," "Vrachanski Balkan," "Golden Sands, Rila Monastery," "Rousenski Lom," "Shumen Plateau," "Bulgarka," etc.	Controlled economic activity permitted.	Nationwide
Strict nature reserves	55	The oldest are "Siloviya" (1931), "Parangalitsa" (Rila), "Stento" (Central Balkan), "Boatin" (Central Balkan), etc.	Human interference is strictly prohibited in these areas.	Nationwide
Managed nature reserves	35	"Srebarna," "Atanasovsko Lake," "Baltata," "Patleina," "Persinski Marshes,"	Designed to protect specific ecosystems.	Nationwide
Protected areas	600	"Irakli," "Poda," "Silistar," "Rupite," "Kaylaka." They feature a distinctive landscape, flora, and fauna	Protected areas due to the presence of natural features	Nationwide
Natural landmarks	350	Iskar Waterfall, Gorge, Blue Pool, Snowdrop, Womb, Yagodinska Cave, Devetashka Cave, Prohodna, Krushuna Waterfalls	such as caves, waterfalls, and specific habitats of rare plants.	Nationwide

2.1. Forest areas in Bulgaria

Today, Bulgaria ranks among the leaders thanks to the forest areas in the Rila, Pirin, Rhodope, and Stara Planina mountains. About 35–37% of the country's territory is covered by forests. For example: "Parangalitsa" is one of the oldest nature reserves in Bulgaria (designated in 1933). It is located in the southwestern Rila Mountains and is home to some of the oldest and tallest spruce forests in Europe. Some trees are over 200 years old and reach heights of

over 60 meters. “Steneto” is home to centuries-old beech forests unique to Europe. It is part of the UNESCO site “Seventeen Centuries-Old Beech Forests in Europe.” Bayuvi Dupki – Dzhindzhiritsa (Pirin). One of the first nature reserves in Bulgaria is “Bayova Dupka,” established as early as 1934 and located in the northern part of Pirin. It preserves unique forests of white and black beech. Some of the beech trees are over 500 years old. In “Boatin,” located in the Central Balkan Mountains, there are preserved beech forests. These are among the oldest on the Balkan Peninsula. The forest is so dense and ancient that in some places it seems literally inaccessible to humans.

2.2. Forest areas in Europe

Today, Bulgaria, as one of the countries on the Balkan Peninsula, is second only to Montenegro and Slovenia in terms of forest area, and clearly outpaces Greece, Romania, Serbia, and Turkey in terms of the percentage of land covered by forests. Within the European Union, however, it ranks fourteenth in terms of forest cover. This means it is somewhere in the middle of the ranking of forest resources among EU member states. Our country is far behind the northern leaders such as Finland and Sweden, but is significantly ahead of economically highly developed Western countries such as Germany, France, and Italy. Regarding our country’s participation in the Natura 2000 network, it ranks in the top 3 in the EU, as Bulgaria leads in the proportion of its territory included in the Natura 2000 (Doichevska, 2024), ecological network (nearly 35% of our country’s land area is under European protection). Regarding the country’s forest cover as of today (March 20, 2026), Bulgaria ranks 5th among other countries (Yurukov, 2008), with 37% of its land area forested (Table 4)

Table 4. Percentage of forest cover in the countries of the Balkan Peninsula

Number	Country	Forest cover percentage
1.	Slovenia	62%
2.	Montenegro	60%
3.	Bosnia and Herzegovina	53%
4.	Croatia	47%
5.	BULGARIA	37%
6.	Greece	31%
7.	Romania	29%
8.	Serbia	28%

Slovenia leads the European region of the Balkan Peninsula under analysis, with only a small portion of its southern territory falling within the peninsula’s boundaries. Bulgaria, Montenegro, and Bosnia and Herzegovina are entirely within the Balkan Peninsula, but all three countries rank higher than ours in terms of forest cover. Croatia also ranks ahead of Bulgaria; only its southern and central parts (including Dalmatia) are on the Balkan Peninsula, while the northern parts of the country belong to Central Europe. Behind us in terms of forested area are Greece and Romania, which have parts outside the Balkan Peninsula. For Greece, these are all its islands, and for Romania, almost its entire territory, excluding the region of Romanian Dobruja. Behind Bulgaria in terms of forest cover are also Serbia and Turkey, with approximately equal shares of forested areas, with the difference that Turkey has a very small portion on the Balkan Peninsula—namely, the area around Istanbul and the country’s European territory. In reality, the Balkans are one of the greenest regions in Europe, and Bulgaria holds

a place of honor among the top five. Compared to the EU (27 countries), Bulgaria is slightly above the average, which is about 33–35% of the country's forested area; by comparison, northern countries such as Finland have 74% forested area, and Sweden has approximately 69%, followed by Slovenia with 62%, Estonia with nearly 54%, and Latvia with about 53% forested areas. Bulgaria ranks 14th in the EU. Although we appear to be in the middle of the pack, it is important to note that we rank ahead of countries with much more developed economies that have lost a large portion of their forests over the centuries. These include Germany (32%), France (31.5%), and Italy (31%). The Netherlands has the lowest forest cover in the entire EU, at nearly 11%.

3. CONCLUSION

Although Finland has more forests, Bulgaria ranks among the leaders in biodiversity. Our forests are the natural habitat of various species of birds, mammals, reptiles, and plants that have long since disappeared from Central and Northern Europe. Bulgaria is one of the few countries in Europe and the world where the forest cover has nearly doubled since the beginning of the 20th century (after the Liberation, it was around 17–20%). In the Natura 2000 ranking by forest area, we rank third in the EU, which means that our forests are not merely "trees for logging" but protected ecosystems. The total forest area in our country is nearly 4 million hectares. Bulgaria is home to over 1,450 ancient trees, which are strictly protected under the country's Forest Protection Act. In recent decades, the total forest area in Bulgaria has actually increased due to the natural regrowth of abandoned agricultural land and active reforestation campaigns.

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REFERENCES

1. Alexandrov, A. (2018) History of forest reseach institute-Bulgarian academy of sciences with a view of the 100th anniversary, Proceeding of the International Scientific Conference "90 Years Forest Research Institute – for the Society and Nature", 24-26 October 2018, Sofia, p.12-24, ISBN: 978-619-7379-28-0
1. Doichevska, K., (2024), "History and Development of Agricultural Management in Bulgaria," *Management and Sustainable Development* journal, published by the University of Forestry, 6/2024 (109), p. 59
2. Radenksi, A. (1999),The Bulgarian Forest: A Brief History of Forests in Bulgaria, 1999. Zemizdat Publishing House, Plovdiv, p. 8
3. Forest Act (2025), effective as of April 9, 2011. Data from past periods to the present (2026) –https://www.lex.bg/laws/ldoc/2135721295
4. Yurukov, S. (2008), "The Green Heart of Europe," *Gora*: Journal of Ecology and Forestry, No. 10, 2008, ISSN 0861-7570
5. ***: Executive Forestry Agency (EFA) – Annual Reports on the State of the Forest Resources in Bulgaria from 2000 to 2026 – https://www.iag.bg/docs/lang/1/cat/5/index

6. ***: Eurostat (Agriculture and Forestry Statistics) – За сравнителните анализи на България в ЕС.- https://ec.europa.eu/eurostat/web/products-statistical-books/-/ks-fk-20-001
7. ***: Strategic Plan for the Development of the Forestry Sector 2014–2023. Ministry of Agriculture and Food of the Republic of Bulgaria—Executive Forestry Agency of Bulgaria, (2026),https://www.iag.bg/data/docs/strategicheski_plan_za_razvitie_na_gsektor.pdf/20/03/2026

Authors address:
Slavova, G.[1]
[1] University of Economics-Varna,
Faculty of economics department “Agricultural economics”, Bulgaria
*Corresponding author: ggss@ue-varna.bg

FROM FORESTS TO FOOD SYSTEMS: ECOSYSTEM SERVICES AND THE RESILIENCE OF AGRICULTURAL LANDSCAPES IN BULGARIA

Mihaela Mihailova, Rumena Gandeva, Monika Kabadzhova

Abstract: This study examines the role of forest ecosystem services in enhancing the resilience of food systems in Bulgaria through a regional, integrated assessment of land-use dynamics. The analysis focuses on changes in land-use structure between 2010 and 2020, agricultural diversification patterns, and the condition of key environmental factors. A three-stage methodological framework is applied, including the evaluation of land-use changes, the calculation of a Simpson diversification index, and the construction of a composite Food Resilience Index integrating agricultural diversification, forest ecosystem coverage, and soil degradation pressure. The results reveal significant spatial heterogeneity in agricultural structures and food system resilience across regions. Findings indicate that diversification alone does not ensure resilience, which depends on the combined effects of ecological conditions and land-use patterns, highlighting the need for integrated land management policies.
Keywords: forest ecosystem services, food system resilience, food supply chains.

1. INTRODUCTION

Ensuring the long-term stability of global food systems has become a major challenge of the twenty-first century. Population growth, climate change, land degradation, and biodiversity loss increasingly threaten agricultural production and the ecosystems that sustain it. The ecosystem services framework has become an important approach for understanding the links between ecological systems and food production. Food security is therefore no longer viewed only through the lens of agricultural productivity, but also through the ecological processes supporting food systems (Poppy et al., 2014; Bommarco et al., 2013). The FAO report proves that soil health has major influence on the sustainability of ecosystems, but globally nearly one third of them are degraded (Smith et al., 2024). Healthy soils support nutrient cycling, microbial activity, and water retention, thereby improving crop productivity and resilience to climate variability (Kabato et al., 2025). Conversely, soil erosion reduces soil fertility and increases vulnerability to drought and extreme weather events, making it a major environmental threat to global food security and productivity (Gomiero, 2016). In addition, the ecosystems has key role in the global carbon sycle (Lal, 2010). According to the United Nations report (Millennium Ecosystem Assessment, 2005), significant environmental policy changes are needed to support ecosystems. In the scientific literature, there are “win-win” scenarios which can balance global food productivity and ecosystem sustainability (Power, 2010).

In agricultural landscapes, regulating services such as soil stabilization, water retention, and climate regulation are particularly important for sustaining productivity and reducing environmental risks. Research increasingly highlights the contribution of surrounding natural ecosystems, especially forests, to the resilience of agricultural systems. Forests play a key role in maintaining ecological stability within agricultural landscapes. Through vegetation cover, root systems, and organic matter inputs, forests contribute to soil stabilization and hydrological regulation, reducing erosion and improving water infiltration. They also support favorable microclimatic conditions for crop growth and act as natural buffers against environmental

degradation and climate variability. Consequently, forest ecosystem services are increasingly recognized as important for food security and rural livelihoods, particularly in landscapes where agriculture is closely connected to natural ecosystems (Varyvoda & Taren, 2022). At the same time, agricultural systems influence ecosystem functioning. Agricultural intensification and land-use change can reduce biodiversity and degrade soil resources, undermining the ecological foundations of food production (Carswell et al., 2025). In response, greater attention has been given to diversified agricultural systems that integrate ecological processes into farming practices. Agricultural diversification through crop rotations, mixed cropping, and diversified land use has been shown to improve soil quality, enhance biodiversity, and increase the resilience of food production systems (Raveloaritiana et al., 2026). Diverse systems also strengthen nutrient cycling, improve resistance to pests and environmental stress, and reduce dependence on single production pathways (Sanderson et al., 2013). Murrell et al. (2017) show that diversified and integrated production systems achieve results comparable to monocultures, while providing high ecological stability, more efficient use of resources, and greater adaptive capacity to climate and managed risks. Despite growing recognition of ecosystem services in food production, empirical research examining the relationships between forest ecosystems, soil degradation, and agricultural structure at the regional level remains limited. Existing studies often address agricultural productivity or ecosystem services separately, without fully exploring the interactions between land-use change, environmental conditions, and agricultural resilience.

The aim of this study is to provide an integrated assessment of the resilience of food systems in Bulgaria in the context of land-use changes at the regional level and forest ecosystems. The analysis encompasses the dynamics of land-use structure over the period 2010–2020, the degree and changes in agricultural diversification. Through the application of a composite index, the study seeks to evaluate the combined impact of agricultural structure, forest ecosystem coverage, and soil degradation pressure on the resilience of regional food production systems.

2. METHODOLOY

The empirical analysis proceeds in three stages.

• First, regional land-use changes between 2010 and 2020 are examined to identify spatial patterns in forest dynamics, agricultural land use, and urban expansion.
• Second, an agricultural diversification index (Simpson index) is calculated and its change over time is assessed in order to capture structural shifts in agricultural production systems.
• Third, a composite Food Resilience Index is constructed to evaluate the resilience of regional food systems by integrating three key dimensions: agricultural diversification, forest ecosystem coverage, and soil degradation pressure.

The Simpson diversification index, following Sanderson et al. (2013), is a statistical measure used to evaluate the degree of diversity within agricultural production systems. Higher values of the index reflect a more diversified and balanced land use structure, while lower values indicate strong specialization, which are associated with higher vulnerability of agrarian systems.

$$D_i = 1 - \sum_{k=1}^{n} s_{ki}^2 \quad (1)$$

where:

- Di represents the diversification index for region i
- s_{ki} represents the share of agricultural land allocated to crop category k
- n represents the number of crop categories.

Higher values of the index indicate more diversified agricultural systems.

The change in diversification between 2010 and 2020 is calculated as:

$$\Delta D_i = D_{i,2020} - D_{i,2010} \quad (2)$$

This measure captures structural shifts in agricultural production.

To evaluate the broader implications for food systems, a Food Resilience Index (FRI) was constructed based on three key dimensions:

- agricultural diversification
- forest ecosystem coverage
- soil degradation pressure.

The index is calculated using standardized variables:

$$\mathbf{FRI_i} = \frac{\mathbf{z(Diversification,i)+z(Foresarea,i)+z(Soilerosion,i)}}{\mathbf{3}} \quad (3)$$

where ***z*** denotes standardized values.

Higher index values indicate stronger resilience of regional food production systems. The use of composite indicators to assess food system resilience is common in sustainability and food security research (Rockström et al., 2017).

2. RESEARCH AND DISSCUSSION

To quantitatively capture the spatial differentiation of agricultural structure and production specialization, the analysis applies the Sanderson Specialization Index calculated for Bulgaria's economic regions in 2010 and 2020. Based on data, the agricultural structure of Bulgaria underwent substantial transformation characterized by both sectoral consolidation and regional differentiation in production diversification. Forest ecosystem services play a fundamental role in maintaining the ecological stability and long-term sustainability of agricultural production systems. Through processes such as soil stabilization, water regulation, carbon sequestration, and climate moderation, forests support the environmental conditions necessary for stable food production. Forest vegetation reduces soil erosion and improves water infiltration, thereby protecting agricultural land from degradation and increasing resilience to drought and extreme weather events. In addition, forest ecosystems contribute to biodiversity conservation by providing habitats for pollinators and other beneficial organisms that support agricultural productivity. Consequently, forest ecosystem services represent an essential ecological foundation for resilient food supply chains and sustainable land-use systems.

Table 1. Agricultural Specialization Index (Sanderson Index) by Economic Regions in Bulgaria, 2010–2020.

Economic Region	Sanderson Index 2010	Sanderson Index 2020	Change 2010–2020	Dominant Agricultural Structure
Bulgaria (total)	0.91	0.90	−0.01	High specialization and structural concentration
North-West	0.88	0.88	−0.01	Highly specialized cereal-based production
North Central	0.90	0.87	−0.04	Declining but still high specialization
North-East	0.90	0.88	−0.03	Strong specialization in cereals and oilseeds
South-East	0.91	0.89	−0.01	Mixed structure with dominant arable production
South-West	0.90	0.88	−0.02	More diversified agriculture and mixed systems
South Central	0.88	0.89	0.00	Lowest specialization and highest diversification

Source: authors' calculations based on Farm Structure Survey (FSS)

The analysis reveals a pronounced regional differentiation in the agricultural structure of Bulgaria, driven by varying degrees of production specialization and diversification. The northern economic regions are characterized by the dominance of large-scale cereal and oilseed production and a limited development of mixed farming systems. Despite high agricultural productivity, this model is associated with lower structural diversification and increased vulnerability to climatic variability, market fluctuations, and soil degradation processes.

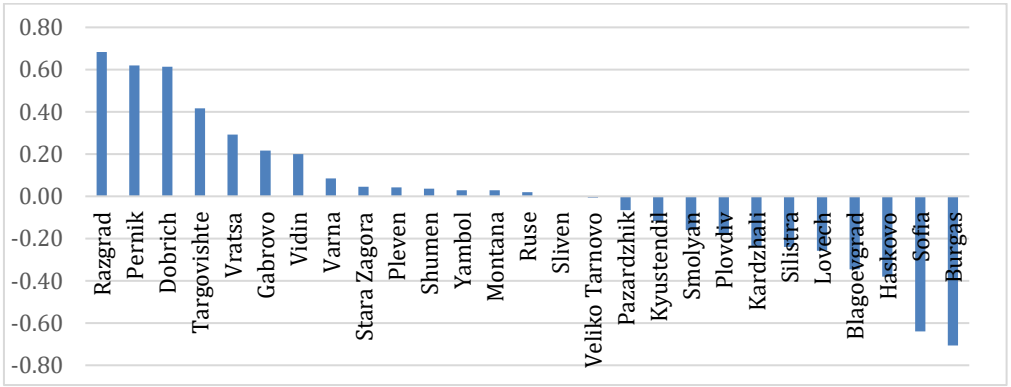
In contrast, the southern and south-western regions retain a more heterogeneous and functionally diversified agricultural structure based on the integration of crop production, livestock farming, perennial crops, and mixed production systems. The maintenance and expansion of these multifunctional agricultural models enhance the adaptive capacity and resilience of regional food systems by reducing dependence on single production pathways and strengthening ecological and economic flexibility. As a result, clear spatial differences emerge in the long-term sustainability potential of Bulgarian agriculture.

The Food Resilience Index (FRI) analisys reveals substantial regional differences in the resilience of agricultural and food production systems across Bulgaria. The index integrates three core dimensions: agricultural diversification, forest ecosystem dynamics, and soil degradation pressure. Regions with higher FRI values generally combine diversified agricultural structures, relatively stable ecosystem conditions, and lower environmental vulnerability, while regions with lower values are characterized by stronger production specialization, forest decline, or higher soil degradation risks.

The results of the FRI at the regional level reveal pronounced spatial heterogeneity and the absence of a single, coherent regional pattern of food system resilience in Bulgaria. The highest FRI values are observed in regions such as Razgrad, Pernik, and Dobrich, indicating a favorable combination of agricultural structure, ecosystem conditions, and comparatively lower

pressure from degradation processes. At the same time, a substantial share of regions exhibit low or negative index values, including both southern territories traditionally associated with higher levels of agricultural diversification and highly urbanized and economically developed areas. This finding demonstrates that a high degree of agricultural diversification alone does not guarantee high measured resilience, as its effects may be constrained or offset by ecosystem stress, urbanization processes, and natural resource degradation. The analysis highlights that food system resilience emerges from location-specific interactions between production structures and environmental context, making the regional level particularly suitable for identifying both vulnerable and resilient territories.

Figure 1. Regional variation of Food Resilience Index (FRI) in Bulgaria.



Source: authors' calculations based on Farm Structure Survey (FSS)

The discrepancy between agricultural diversification and measured food system resilience observed in the FRI results points to the need for land-use mechanisms that more effectively integrate ecological functions into production systems.

3. CONCLUSION

This study confirms that food system resilience emerges from complex interactions between agricultural structure and ecosystem conditions. The results reveal pronounced spatial differentiation in both agricultural specialization and resilience levels across Bulgaria, indicating that regions with higher diversification do not necessarily exhibit greater resilience. This finding can be attributed to the influence of additional factors, particularly soil degradation pressure and forest ecosystem dynamics. The analysis demonstrates that diversification alone is insufficient to ensure system stability when not supported by favorable ecological conditions. In this context, the results highlight the importance of adopting an integrated land-use management approach that simultaneously enhances economic performance and preserves key ecosystem functions essential for sustainable food production systems such as forest ecosystems.

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REFERENCES (alphabetical order)

1. Bommarco, R., Kleijn, D., & Potts, S. G. (2013). Ecological intensification: Harnessing ecosystem services for food security. Trends in Ecology & Evolution, 28(4), 230–238. https://doi.org/10.1016/j.tree.2012.10.012
2. Gomiero, T. (2016). Soil degradation, land scarcity and food security: Reviewing a complex challenge. Sustainability, 8(3), 281 https://doi.org/10.3390/su8030281
3. Lal, R. (2010). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. BioScience, 60(9), 708–721 https://bioone.org/journals/bioscience/volume-60/issue-9/bio.2010.60.9.8/Managing-Soils-and-Ecosystems-for-Mitigating-Anthropogenic-Carbon-Emissions-and/10.1525/bio.2010.60.9.8.short
4. Millennium ecosystem assessment, M. E. A. (2005). *Ecosystems and human well-being* (Vol. 5, p. 563). Washington, DC: Island press.https://www.millenniumassessment.org/en/Synthesis.html
5. Murrell, E. G., Schipanski, M. E., Finney, D. M., Hunter, M. C., Burgess, M., LaChance, J. C., ... & Kaye, J. P. (2017). Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. *Agronomy Journal*, *109*(1), 259-271. https://doi.org/10.2134/agronj2016.03.0174
6. Poppy, G. M., Chiotha, S., Eigenbrod, F., Harvey, C. A., Honzák, M., Hudson, M. D., Jarvis, A., Madise, N. J., Schreckenberg, K., Shackleton, C. M., Villa, F., & Dawson, T. P. (2014). Food security in a perfect storm: Using the ecosystem services framework to increase understanding. Philosophical Transactions of the Royal Society B: Biological Sciences, 369(1639), 20120288. https://doi.org/10.1098/rstb.2012.0288
7. Power, A. G. (2010). Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical transactions of the royal society B: biological sciences*, *365*(1554), 2959-2971. https://doi.org/10.1098/rstb.2010.0143
8. Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., ... & Falkenmark, M. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio, 46, 4–17. https://doi.org/10.1007/s13280-016-0793-6
9. Sanderson, M. A., Archer, D., Hendrickson, J., Kronberg, S., Liebig, M., Nichols, K., Schmer, M., Tanaka, D., & Aguilar, J. (2013). Diversification and ecosystem services for conservation agriculture: Outcomes from integrated crop–livestock systems. Renewable Agriculture and Food Systems, 28(2), 129–144 https://doi.org/10.1017/S1742170512000312
10. Smith, P., Poch, R. M., Lobb, D. A., Bhattacharyya, R., Alloush, G., Eudoxie, G. D., ... & Hallett, P. (2024). Status of the World's Soils. Annual review of environment and resources, 49(1), 73-104. https://doi.org/10.1146/annurev-environ-030323-075629
11. Kabato, W. S., Hailegnaw, N., Chaffamo, T. E., Samuel, A., De Silva, A. G. S. D., & Molnár, Z. (2025). Microalgae-Based Strategies for Soil Health and Crop Productivity: Mechanisms, Challenges, and Pathways to Climate-Resilient Agriculture. *Agronomy*, *15*(11), 2669. 10.3390/agronomy15112669
12. Varyvoda, Y., & Taren, D. (2022). Considering ecosystem services in food system resilience. *International Journal of Environmental Research and Public Health*, *19*(6), 3652. https://doi.org/10.3390/ijerph19063652
13. Carswell, A. M., Willcock, S., Blackwell, M. S., Upadhayay, H. R., Harris, P., McAuliffe, G., ... & Collins, A. L. (2025). Agricultural practices can threaten soil resilience through changing feedback loops. *npj Sustainable Agriculture*, *3*(1), 56. https://doi.org/10.1038/s44264-025-00098-6
14. Raveloaritiana, E., & Wanger, T. C. (2026). Long-term agricultural diversification increases financial profitability, biodiversity, and ecosystem services: a second-order meta-analysis. *Nature Communications*. https://doi.org/10.1038/s41467-025-67757-7

Authors address:
Mihailova, M.[1]; Gandeva, R.[2]; Kabadzhova, M.[3]
[1] Institute of Agricultural Economics, Agricultural Academy, Sofia, Bulgaria
[2] Fruit Growing Institute – Plovdiv, Agricultural Academy, Plovdiv, Bulgaria
[3] Institute of Agriculture – Kyustendil, Agricultural Academy, Kyustendil, Bulgaria
*Corresponding author: m.mihailova92@gmail.com

PRACTICES FOR INTEGRATING WOOD AND WOODY CROPS TO INCREASE THE SUSTAINABILITY OF AGRICULTURE

Damyan Kirechev, Antoaneta Stoyanova

Abstract: This study examines the potential of integrating wood products and tree plantings to enhance farm sustainability. A conceptual framework is presented that traces the relationship between sustainable agriculture, the integration of woody components, the provision of ecosystem services, and the enhancement of farms' environmental, economic, and social sustainability. The main practices for using wood products and tree plantings are analysed, along with their potential effects on resource efficiency, production risk management, and the competitiveness of agricultural production. An original multi-criteria matrix was developed to comparatively assess the applicability of individual practices under Bulgarian conditions. The results show that practices with moderate investment costs, high environmental efficiency, and broad applicability have the greatest potential for implementation. The study confirms that integrating the three components is a promising tool for adapting to climate change and enhancing the resilience of agricultural holdings.
Keywords: wood, woody crops, agriculture, integration of woodland components, sustainable agriculture

1. INTRODUCTION

Modern agriculture faces several challenges related to climate change, soil degradation, biodiversity loss, and the need for more efficient use of natural resources (FAO; European Environment Agency). In this context, European policies are increasingly promoting nature-based solutions, including carbon farming practices, organic farming, and the enhancement of ecosystem services in the agricultural sector (European Commission, CAP overview, European Commission, Carbon Farming Initiative). One promising way to achieve these goals is to integrate wood products and tree plantations into agricultural production systems. The integration of wood resources (timber, wood residues, and wood products) and tree plantings constitutes a set of practices aimed at improving resource efficiency, ecosystem services, and farm sustainability. Such practices can lead to reduced production costs, income diversification, and increased resilience of farms to climate and market risks.

In recent years, scientific interest has shifted from viewing tree components solely as elements of agroforestry to recognising their role as multifunctional resources that provide simultaneous ecological, economic, and social benefits. Such an integrated approach aligns with the concept of ecosystem services and the goal of building more sustainable and adaptive agricultural systems that meet the requirements of the European Union's current Common Agricultural Policy and Green Deal.

The aim of this study is to analyse the main practices for integrating wood and woody plantations into agriculture, to assess their contribution to the ecological, economic, and social sustainability of agricultural holdings, and—through an original multi-criteria assessment—to identify the practices with the highest potential for application in the Bulgarian context. The

scientific novelty of the study lies in the application of an original multi-criteria matrix to the comparative assessment of the potential to implement various practices on Bulgarian farms.

2. THEORETICAL BASIS

The concept of sustainable agriculture is based on a balanced combination of the environmental, economic, and social objectives of agricultural production. Modern agriculture must operate in ways that conserve natural resources and make effective use of available resource potential (Slavova & Georgieva, 2025) while ensuring the long-term viability of farms (Marinova Georgieva & Ventsislavova Georgieva, 2025). One approach to achieving these goals is the integration of wood products and woody plants into agricultural systems (Mosquera-Losada et al., 2018). Unlike the traditional understanding, which associates woody elements primarily with agroforestry systems, this study examines their role in a broader context—as functional components of agricultural production. Alongside traditional agroforestry systems, this includes the use of wood mulch, wood chips, biochar, living hedges, field protection belts, inter-row tree plantings, buffer strips, and other practices. The implementation of these practices increases the ecosystem services provided by agricultural systems (FAO; Cole et al., 2020). These include regulating services (reducing erosion, retaining moisture, improving the microclimate, sequestering carbon), supporting services (enhancing soil fertility and biodiversity), provisioning services (timber, fruit, biomass), and cultural services that improve the landscape and quality of life in rural areas. In this way, tree components perform multiple functions simultaneously and enhance the resource efficiency of agricultural holdings. Therefore, the integration of tree components can be viewed as a management decision that simultaneously improves the environmental, economic, and social sustainability of agricultural production. Within the present research framework, it is assumed that the sustainability of farms is shaped by a consistent cause-and-effect relationship between sustainable agriculture, the integration of tree components, the enhancement of ecosystem services, and the improvement of farm sustainability.

2.1. Integration Practices

Practices for integrating wood-based components can be divided into two main groups — the use of wood products in the production process and the integration of living tree stands into agricultural systems — with a summary presented in Table 1. Despite their different nature, both groups share a common goal — to increase the efficiency of natural resource use and improve the sustainability of farms. In contemporary agriculture, such practices can be successfully combined, enabling their implementation and the realisation of their benefits; however, it must be clear that their effectiveness will depend largely on natural conditions, the farm's specialisation, and its economic capacity.

Table 1. Key Practices for Integrating Woodland Components into Farms

Type	Practice	Main Application	Suitable Farms
Use of Wood Products	Wood mulch	Moisture retention, weed control	Vegetable and fruit farms
	Wood chips	Improving soil structure, mulching	All farms
	Biochar	Increasing fertility and carbon content	Intensive crops

	Compost made from wood residues	Organic fertilization	Mixed farms
	Woody biomass	Farm energy needs	Livestock farming
Integration of woody plantings	Shelterbelts	Protection against wind and erosion	Grain production
	Living hedges	Biodiversity and habitats	Organic and mixed
	Interrow trees	Microclimate and diversification	Vineyards and orchards
	Buffer strips	Water resource conservation	All farms
	Silvopastoral systems	Shade and forage	Livestock farming

Source: Author's summary

2.2. Effects on the Sustainability of Farms

The integration of wood products and tree plantings into agricultural farms has a multifaceted impact on the sustainability of production systems (Kaputa et al., 2025). Unlike traditional technological solutions that improve only a single production process, the practices under consideration generate simultaneous environmental, economic, and social benefits. This multifunctionality is at the heart of their growing role in policies for sustainable agricultural development and climate change adaptation.

From an environmental perspective, the use of wood-based products and the integration of tree plantings help improve soil and water resources. The application of wood mulch (Demo & Bogale, 2024), biochar (Shyam et al., 2025), and compost improves soil structure, increases organic matter content, and enhances water retention capacity. Shelterbelts (Enescu et al., 2025), living hedges (Kratschmer et al., 2024), and buffer strips (Cole et al., 2020) limit wind and water erosion, create a favourable microclimate, and support biodiversity conservation. At the same time, the tree components play an important role in sequestering carbon in biomass and soil, which is consistent with the principles of carbon farming and European targets for reducing greenhouse gas emissions.

The economic effects of these practices should be viewed not only as an opportunity to generate additional income, but above all as a tool for enhancing the economic resilience of farms (Marinova Georgieva & Georgieva, 2025). The use of wood mulch and wood chips can reduce costs associated with irrigation, tillage, and weed control. Improving soil fertility and water management creates conditions for more stable yields and reduced production losses under adverse climatic conditions. Some of these practices, such as intercropping and agroforestry systems, create opportunities for production diversification through the production of fruit, timber, biomass, or forage, which broadens income sources and enhances the farm's financial sustainability. The role of tree cover in mitigating production risks is particularly significant. The creation of windbreaks and hedgerows reduces the negative impacts of strong winds, drought, and extreme temperatures on crops, while improved soil conditions increase production resilience to climate fluctuations. In this way, part of the initial investment can be offset by reducing future costs associated with restoring production, stabilising yields, and decreasing dependence on external production resources. Consequently, the economic efficiency of the practices under consideration lies not in short-term gains but in enhancing the farm's ability to maintain its long-term productivity and competitiveness.

Social effects should not be underestimated either. The integration of woody elements improves the quality of the agricultural landscape, helps preserve traditional agricultural practices, and creates opportunities for new activities in forest resource management, biomass

production, and the provision of ecosystem services (Mihailova & Marinov, 2025). This helps increase the attractiveness of rural areas and creates conditions for the more sustainable development of local communities.

The effects of integrating wood-based components are multifaceted and manifest themselves simultaneously in environmental, economic, and social terms. Therefore, the integration of wood products and woody crops should not be viewed solely as an environmental initiative, but rather as a management and investment decision that increases resource efficiency, improves adaptability to climate change, and strengthens economic resilience and the long-term competitiveness of farms. It is precisely this combination of environmental, economic, and social effects that makes these practices a promising tool for the sustainable development of agriculture.

3. ASSESSMENT OF THE APPLICABILITY OF PRACTICES FOR INTEGRATING WOOD COMPONENTS

For the purposes of the comparative analysis, a proprietary multi-criteria matrix was developed, based on expert assessments across six criteria. Each criterion was rated on a five-point ordinal scale, where 1 represents the lowest and 5 the highest degree of compliance. The overall score was calculated as the arithmetic mean of the scores for the individual criteria. The matrix does not claim to be a universal quantitative model but serves as an expert tool for the comparative assessment of the feasibility of implementing various practices in Bulgarian agriculture. The resulting scores should not be viewed as absolute values but rather as a means of comparing the potential to apply the various practices (Table 2).

Table 2. Multi-criteria assessment of practices for integrating wood components

Practice	Investment Costs*	Return on Investment	Environmental Impact	Contribution to Economic Sustainability	Applicability to Different Types of Farms	Potential for CAP Support	Applicability Index
Wood mulch	5	5	4	4	5	3	**4,3**
Wood chips	4	4	4	4	5	3	**4,0**
Biochar	2	3	5	4	3	3	**3,3**
Field protection belts	3	4	5	4	5	5	**4,3**
Living hedges	4	4	5	3	5	4	**4,2**
Interrow tree plantings	3	4	5	5	4	4	**4,2**
Buffer strips	4	4	5	3	5	5	**4,3**
Silvopastoral systems	3	4	5	5	4	4	**4,2**

** Under the "Investment Costs" criterion, a higher score corresponds to lower initial investment and easier implementation of the practice.*

According to the comprehensive assessment, field protection belts, buffer strips, and wood mulch have the greatest potential for application under Bulgarian agricultural conditions and received the highest rating (4,3). Furthermore, they are applicable to a wide range of farms and can be supported through Common Agricultural Policy interventions. Hedgerows, inter-row tree plantings, and agroforestry systems score similarly (4,2). These practices are particularly

well-suited for mixed, fruit-growing, vineyard, and livestock farms, where they can generate both environmental and economic benefits. The use of biochar received the lowest overall rating (3,3). The main factors contributing to this are the higher initial investment and the longer time it takes to realise economic benefits. Nevertheless, this practice has significant potential to improve soil fertility, increase organic matter content, and sequester carbon, making it a promising investment for farms pursuing a long-term strategy for sustainable development.

Overall, the results of the multi-criteria assessment indicate that practices that combine moderate investment costs, high environmental effectiveness, and broad applicability have the greatest potential for implementation. This confirms that the integration of woody components should be viewed not only as a means of improving the environment but also as a strategic management decision that enhances the economic resilience, climate change adaptability, and competitiveness of agricultural holdings.

4. CONCLUSION

The integration of woody crops into agricultural holdings represents a promising approach to enhancing the resilience of agricultural production amid climate change, increasing pressure on natural resources, and the need for more effective management of production systems. The analysis shows that these practices provide comprehensive benefits by improving ecosystem services, reducing production risk, promoting more efficient resource use, and creating conditions to enhance the economic sustainability of farms. The multi-criteria matrix developed by the authors enables a comparative assessment of the potential to apply the various practices and shows that the most promising ones for Bulgarian conditions are those that combine high ecological efficiency, relatively low investment costs, and good applicability across different types of farms. The results confirm that the practices under consideration should be viewed not only as environmental measures but also as strategic tools for enhancing the adaptability, competitiveness, and long-term sustainability of agricultural production. This study can serve as a basis for future research aimed at quantitatively assessing the economic effects, modelling the return on investment for individual practices, and developing indicators for their applicability under various production and natural-climatic conditions.

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REFERENCES

1. Cole, L. J., Stockan, J., & Helliwell, R. (2020). Managing riparian buffer strips to optimise ecosystem services: A review. Agriculture, Ecosystems & Environment, 296, Article 106891. https://doi.org/10.1016/j.agee.2020.106891
2. Demo, A. H., & Asefa Bogale, G. (2024). Enhancing crop yield and conserving soil moisture through mulching practices in dryland agriculture. Frontiers in Agronomy, 6, Article 1361697. https://doi.org/10.3389/fagro.2024.1361697
3. European Commission, Directorate-General for Agriculture and Rural Development. Common agricultural policy — CAP overview.

4. European Commission, Directorate-General for Climate Action. Commission sets the carbon farming initiative in motion.
5. European Environment Agency. Agro-forestry and crop diversification. Climate-ADAPT.
6. Food and Agriculture Organization of the United Nations. Basic knowledge — Agroforestry module. FAO Sustainable Forest Management Toolbox.
7. Kaputa, V., Maťová, H., Táborecká, J., & Olšiaková, M. (2025). Wood-based circular bioeconomy and its promotion in Europe. Wood for the future: Integrating sustainability across industries — Proceedings of scientific papers, 18th International Scientific Conference WoodEMA 2025, pp. 21–29
8. Kratschmer, S., Hauer, J., Zaller, J. G., Dürr, A., & Weninger, T. (2024). Hedgerow structural diversity is key to promoting biodiversity and ecosystem services: A systematic review of Central European studies. Basic and Applied Ecology, 78, 28–45.
9. Marinova Georgieva, T., & Ventsislavova Georgieva, D. (2025). Innovation potential of low-technology sectors: The case study of the forestry sector and agribusiness in Bulgaria. Wood for the future: Integrating sustainability across industries — Proceedings of scientific papers, 18th International Scientific Conference WoodEMA 2025, pp. 169–174.
10. Mihailova, M., & Marinov, P. (2025). Small forest farms a path to sustainability in Bulgaria. Wood for the future: Integrating sustainability across industries — Proceedings of scientific papers, 18th International Scientific Conference WoodEMA 2025, pp. 87–94,.
11. Mosquera-Losada, M. R., Santiago-Freijanes, J. J., Pisanelli, A., et al. (2018). Agroforestry in the European Common Agricultural Policy. Agroforestry Systems, 92(4), 1117–1127.
12. Enescu, C. M., Mihalache, M., Ilie, L., Dinca, L., Constandache, C., & Murariu, G. (2025). Agricultural benefits of shelterbelts and windbreaks: A bibliometric analysis. Agriculture, 15(11), Article 1204. https://doi.org/10.3390/agriculture15111204
13. Shyam, S., Ahmed, S., Joshi, S. J., & Sarma, H. (2025). Biochar as a soil amendment: Implications for soil health, carbon sequestration, and climate resilience. Discover Soil, 2, Article 15. https://doi.org/10.1007/s44378-025-00041-8
14. Slavova, G., & Georgieva, T. (2025). Conceptual models for enhancing sustainable management in forestry and agricultural sectors. Wood for the future: Integrating sustainability across industries — Proceedings of scientific papers, 18th International Scientific Conference WoodEMA 2025, pp. 67–74.

Authors address:
[1] Department of Agricultural Economics, Faculty of Economics, University of Economics -- Varna, Varna, Bulgaria
[2] Department of Commodity Science, Faculty of Economics, University of Economics -- Varna, Varna, Bulgaria
*Corresponding author: dkirechev@ue-varna.bg

PHYTOPATHOGENIC RISKS IN BIOMASS-BASED HEATING: IMPLICATIONS FOR WOOD CHIP SUPPLY CHAINS AND REGULATORY FRAMEWORKS

Miloš Gejdoš, Marek Potkány

Abstract: The increasing use of forest biomass in urban heating systems requires a deeper understanding of biological risks associated with large-scale storage of wood chips. This study analyzes long-term phytopathogen occurrence within biomass supply chains, focusing on three municipal heating plants in central Slovakia. Each plant stores forest chips in large-capacity piles ranging from 4,000 to 5,000 m³, representing a typical operational model within the regional bioeconomy. Between 2019 and 2024, annual sampling was conducted from both the surface and a depth of 0.5 m within the piles. Laboratory analyses included moisture determination and accredited microbiological testing. The results show that average phytopathogen concentrations remained relatively stable over time. Species from the genera Penicillium and Aspergillus represented the highest numbers of colony-forming units, while Mycelia Sterilia, Penicillium sp., Aspergillus brasiliensis, Aspergillus unguis and yeasts were the most frequently identified organisms. These findings highlight a largely overlooked risk factor in the production and logistics of biomass fuels. The presence of phytopathogens may influence product quality, occupational health, and environmental safety. Therefore, the study emphasizes the need to develop national-level regulatory frameworks and standardized work procedures to ensure safe handling of biomass in heating plants. Addressing these risks is essential for sustainable bioeconomy development, risk management within wood-based value chains, and the protection of both workers and nearby residents..
Keywords: biomass, bioeconomy, wood chips, phytopathogens, risk management, regulations, occupational health

1. INTRODUCTION

District heating plants in Slovakia primarily serve as local sources of heat and electricity for small towns and municipalities. Biomass is frequently used as the main fuel input in these facilities (Mantau, 2018). Typically, biomass is stored in piles with a capacity corresponding to approximately two to three months of operation. During the heating season, these storage systems operate under continuous inflow of fresh material coupled with ongoing consumption (Cikic et al., 2021).

Biological processes occurring within large volumes of stored woody biomass lead to changes in temperature, moisture content, and energy properties of the material. At the same time, these conditions promote the growth of fungi and the formation of phytopathogenic spores (Anerud et al., 2021).

The generation of wood dust and the release of phytopathogenic spores during large-scale biomass storage represent significant health risks, particularly under long-term exposure. These factors may contribute to a range of adverse health effects, including allergic reactions, respiratory diseases, and other serious conditions, with potentially fatal outcomes in immunocompromised individuals (Barontini et al., 2014). Although the existence of these risks has been scientifically confirmed, relatively few studies provide detailed quantification,

exposure limits, or effective mitigation strategies, largely due to the complexity of assessing long-term health impacts.

From a legislative perspective, most phytopathogens are classified into risk group 2 under applicable regulations (Government Regulations No. 356/2006 Coll.; 83/2013 Coll.), indicating that they can cause human disease and pose a potential occupational hazard, but are unlikely to spread widely within the population, and effective prophylaxis or treatment is generally available. Many species occurring during biomass storage are also recognized as allergens (Government Regulation No. 333/2020 Coll.). However, Slovak legislation does not specify clear exposure limits for these biological agents. Occupational safety measures in outdoor industrial environments are limited, primarily requiring protective clothing and minimizing airborne release of particles. In practice, even these basic measures are often not consistently implemented. Furthermore, there are no regulations defining minimum distances between such facilities and residential areas, which can pose a potential health risk, especially in the case of district heating plants located within urban environments.

The aim of this study was to identify health risks associated with wood chip storage in district heating plants and to propose fundamental mitigation measures, including potential legislative adjustments, to improve the protection of both workers and residents living in their vicinity.

2. MATERIAL AND METHODS

2.1. Biomass Sampling

For the purpose of biomass sampling, three district heating plants located in the Banská Bystrica self-governing region in central Slovakia were selected. The facilities (referred to as Plants 1, 2, and 3) are situated within a radius of approximately 45 km. The selection was primarily based on the similarity of their operational conditions. All three plants are located in central urban areas of towns with comparable size and population, belong to the same operator, and are situated within a relatively small geographical area. Climatic and meteorological conditions across the sites are highly comparable. A specific characteristic of these facilities is their location within built-up areas, in close proximity to residential zones. Since most district heating plants in Slovakia operate under similar conditions, the obtained results can be considered representative for comparable facilities.

In all plants, forest wood chips derived from a mixture of coniferous and deciduous species are used as the primary fuel. The biomass is stored in large-capacity piles with volumes ranging from approximately 4,000 to 5,000 m³. Residential buildings were located at distances ranging from about 30 m (Fig. 1) to 200 m from the storage sites.

Sampling was conducted annually from 2019 to 2024, always during the last week of October. Five samples were collected from each storage site every year, taken from two vertical levels: two samples from a depth of approximately 0.5 m and three samples from the surface layer. This resulted in 15 samples per year and a total of 90 samples over the entire study period. The selection of two sampling depths was intended to capture differences in temperature and moisture conditions within the pile and to assess their influence on the production of phytopathogenic spores.

Due to continuous biomass inflow and outflow, the shape and volume of the storage piles changed over time, and therefore the exact sampling locations varied each year. Sampling

points were selected to ensure an even spatial distribution across the pile. Samples were collected using a metal shovel and stored in 2 L plastic bags.

Figure 1. Large-capacity wood chip pile located near a residential area

All sites are located in the same geographical region and therefore exhibit similar climatic characteristics. During the monitoring period, the mean annual air temperature ranged from 8.3 to 9.8 °C, and annual precipitation ranged from 833 mm to 1,071 mm. These conditions remained relatively consistent across all sites throughout the study period. At each sampling point, two subsamples were collected: one for microbiological analysis and the other for determining moisture content and energy properties.

2.2. Microbiological Analysis

Microbiological analyses were performed in an accredited laboratory of the Regional Public Health Authority in the Slovak Republic and consisted of two phases. Since 2019, the laboratory has been equipped to quantify individual phytopathogenic species, allowing species-level abundance evaluation from that year onward.

Laboratory procedures followed standardized methods defined by relevant standards (STN ISO 21527-2, STN ISO 7218, STN 56 0100). The total microbial load was determined as colony-forming units per gram of sample ($CFU \cdot g^{-1}$) in accordance with STN ISO 21527-2. The quantification of individual phytopathogenic groups was carried out according to STN 56 0100. Identification of genera and species was based on morphological and cultural characteristics using identification keys.

3. RESULTS

As the sampling points were predominantly located in the upper layers of the biomass piles, where the freshest material is expected, the measured relative moisture content was correspondingly high. The average moisture content reached 59.82%, with more than 90% of all samples falling within the 60–70% range. Only 11 out of the total 90 samples exhibited moisture values between 10% and 50%. These findings indicate that the highest absolute abundances of phytopathogenic spores were associated with moisture levels exceeding 60% (Fig. 2).

Figure 2 also demonstrates that Plants 2 and 3 exhibited very similar moisture characteristics and pathogen abundances. In contrast, Plant 1 showed greater variability both in moisture content and in the number of detected colonies. The distribution of total phytopathogen counts with respect to sampling site and year is presented in Figure 3. The graph highlights differences between Plants 2 and 3, particularly regarding the variation in colony counts between surface samples and those collected from a depth of 0.5 m. In terms of absolute values, the year 2023 stands out as anomalous compared to the rest of the monitoring period.

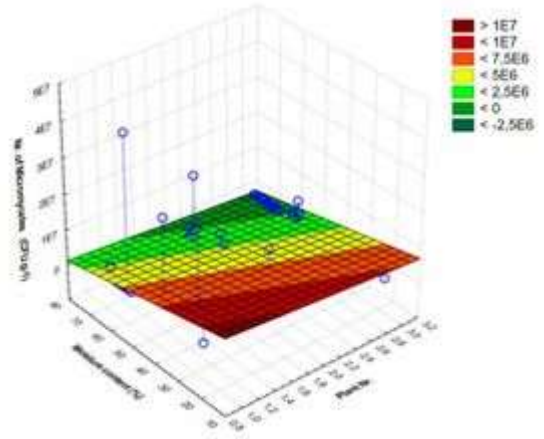

Figure 2. Colony counts (CFU·g⁻¹) as a function of moisture content and sampling location

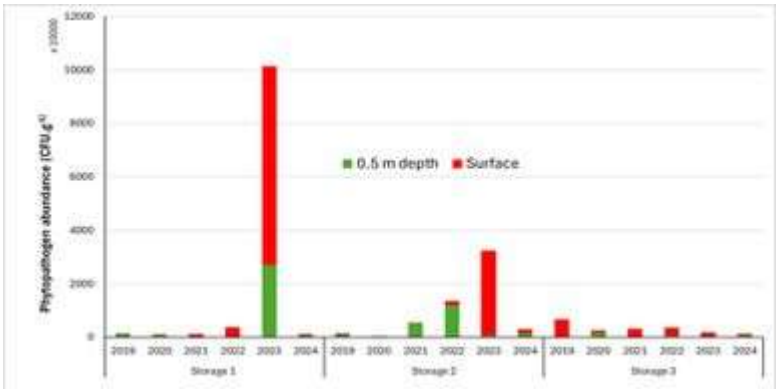

Figure 3. Phytopathogen abundance by year and sampling site

With the exception of the extreme values observed in 2023, the average number of colonies did not vary significantly between individual years. No clear explanation for this outlier could be established. Although sample contamination cannot be entirely ruled out, it is considered unlikely given the applied sampling and analytical procedures. A more plausible explanation is the origin of the biomass, which may have involved different processing, storage, or transport conditions. However, this assumption could not be verified.

After excluding extreme values, the overall concentration of phytopathogens in wood chips remained relatively stable across the study period, with only minor interannual differences. Although atmospheric conditions varied over time and were partially influenced by pandemic-related restrictions, these factors did not significantly affect microbial abundance.

The results suggest that, despite continuous biomass turnover within storage facilities, phytopathogenic spore concentrations remain consistently present, constituting a persistent potential health risk. This risk is primarily driven by the occurrence and concentration of specific species. This finding is consistent with previous studies (Barontini et al., 2014), which also reported stable microbial communities in long-term stored biomass.

Figure 4 presents the species with the highest overall abundance.

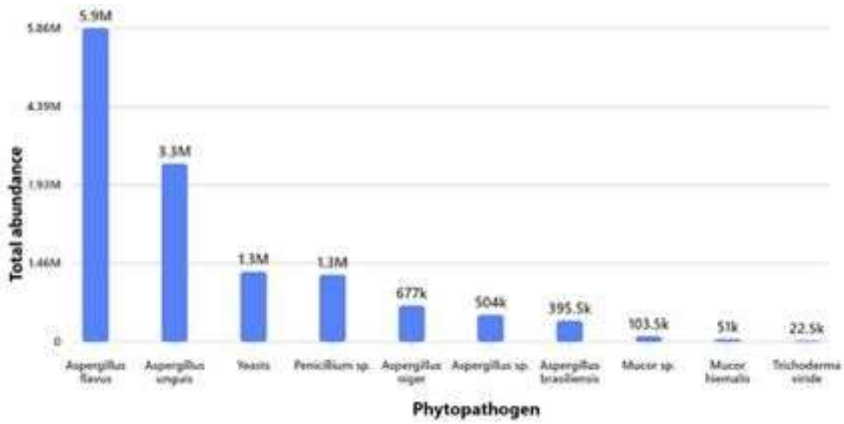

Figure 4. Most abundant phytopathogenic species (2019–2024)

The most dominant species was *Aspergillus flavus*, a major causative agent of aspergillosis. This disease primarily affects the respiratory system and may manifest as pneumonia, asthma, or bronchopneumonia. The species produces aflatoxins and other carcinogenic and toxic compounds, and its spores are highly allergenic. In severe cases, it may also affect blood vessels, leading to infarctions, posing a significant risk especially to immunocompromised individuals.

The second most frequently identified species was *Aspergillus unguis*, which is associated with allergic conditions affecting the skin and nails. It produces the mycotoxin sterigmatocystin, known for its strong carcinogenic and mutagenic properties. *Yeasts* also represented an important group, producing enzymes with invasive potential and causing serious health complications, particularly in partially immunocompromised individuals. Symptoms may include respiratory distress, dermatological conditions, urinary tract infections, and neurological manifestations.

The abundance of individual species largely corresponded with their frequency of occurrence throughout the monitoring period. An exception was Mycelia sterilia, which, although frequently detected, represents a comparatively lower health risk. Nevertheless, it may pose a threat to immunocompromised individuals, particularly due to its potential to cause systemic infections.

The significance of mycotoxins in human medicine remains underestimated, as patient samples are rarely tested for their presence despite well-documented mutagenic and carcinogenic effects. The results confirm that microorganisms associated with stored biomass persist over long periods and may contribute to a broad spectrum of health issues, potentially posing life-threatening risks for vulnerable populations.

4. CONCLUSION

Long-term monitoring of large-scale biomass storage in district heating plants has confirmed the persistent presence of phytopathogens, which represent a significant potential risk to human health. The identified risks also have economic implications, as demonstrated in previous work focused on the calculation of price and cost impacts of biomass storage risks (Gejdoš & Potkány, 2024). Despite this, the issue remains insufficiently addressed in industrial

practice. Current legislation does not define explicit exposure limits but primarily focuses on recommending the use of personal protective equipment. Compared to previous research, the identified persistence of phytopathogens confirms that storage conditions in municipal heating plants create a long-term stable environment for microbial growth. This suggests that the presence of phytopathogens is not just a short-term variation, but rather a stable and inherent feature of biomass storage.

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REFERENCES

1. Anerud, E.; Bergstrom, D.; Routa, J.; Eliasson, L. (2021): Fuel quality and dry matter losses of stored wood chips-Influence of cover material. Biomass Bioenerg. 2021, 150, 106109. doi: 10.1016/j.biombioe.2021.106109.
2. Barontini, M.; Crognale, S.; Scarfone, A.; Gallo, P.; Gallucci, F.; Petruccioli, M.; Pasciaroli, L.; Pari, L. (2014): Airborne fungi in biofuel wood chip storage sites. Int. Biodeter. Biodegr. 2014, 90, 17-22. doi: 10.1016/j.ibiod.2013.12.020.
3. Cikic, A.; Zdilar, S.; Misevic, P. (2021): The Effects of Biomass Availability and Preparation on the Sustainability of Power Plants in Croatia. Teh. Vjesn. 2021, 28(5), 1806-1812. doi: 10.17559/TV-20210707182728.
4. Gejdoš, M.; Potkány, M. (2024): Selected economic and health risks in the process of production and storage of biomass for energy purposes. In: Green Deal Initiatives, Sustainable Management, Market Demands, and New Production Perspectives in the Forestry-Based Sector: Proceedings of the 17th International Scientific Conference WoodEMA, Sofia, Bulgaria, May 15–17, 2024.
5. Mantau, U.; Doring, P.; Weimar, H.; Glasenapp, S. (2018): Utilization of wood resources in biomass heat and power plants in the context of market developments. In: Papers of the 26th European Biomass conference: Setting the course for a biobased economy, Copenhagen, Denmark, 14-17 May 2018.

Authors address:
Gejdoš, M[1,2]; Potkány, M[3]
[1] Department of Forest Harvesting, Logistics and Ameliorations, Faculty of Forestry, Technical University in Zvolen, Zvolen, Slovakia
[2] National Forest Centre, Zvolen, Slovakia
[3] Department of Economics, Management and Business, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia
*Corresponding author: gejdos@tuzvo.sk

STRUCTURAL CHANGES IN THE BIOECONOMY IN EU COUNTRIES

Martina Kánová, Petra Lesníková, Marek Potkány

Abstract: The bioeconomy is a key component of the European Union's economy. This paper examines structural changes in the bioeconomy across EU countries, focusing on the shift from labour-intensive sectors to higher value-added activities. Using data from the Joint Research Centre, the analysis explores differences in employment, value added, and productivity. The study also considers the role of research and development in supporting this transformation. The findings provide insights into the evolving structure of the bioeconomy in the EU.
Keywords: bioeconomy; employment; productivity; value added; R&D; EU countries

1. INTRODUCTION

The bioeconomy, aptly described as a new economic paradigm (Ronzon et al., 2022a) has become a key framework for several new EU policy initiatives and government strategies in the last decade (European Commission, 2012; European Commission, 2018; Kardung et al., 2021) such as the Sustainable Development Goals (UN, 2015); Paris Agreement (2015), European Green Deal (European Commission, 2019) and the Circular Economy Action Plan (European Commission, 2020). Several EU Member States have publicly released dedicated bioeconomy strategies, macro-regional and micro-regional bioeconomy initiatives have also been launched (Lusser et al., 2018). The bioeconomy focuses to achieve several objectives toward employment generation and growth, climate neutrality, food security, energy security, biodiversity and natural resource management (Wesseler & von Braun, 2017). Bioeconomy Strategy in 2012 and its subsequent revisions, the bioeconomy has been positioned as a key driver of green growth, competitiveness, and innovation (European Commission, 2025).

The EU Biomass Flows tool (Gurría et al., 2017) displays the harmonised data, the diagrams enable deeper analysis and comparison of the different countries and sectors across a defined time series. The most important changes of new release (Gurría Albusac et al., 2022) are among other focused on migration to EU27 aggregation and redesign of the flows for woody biomass. According to Mainar-Causapé et al. (2017), 40% of value added generated by bioeconomy value chains comes from biomass producing and manufacturing sectors (agriculture, the food industry and the manufacture of paper), 60% of this value added comes from up-stream and down-stream sectors (trading, transportation).

The structural transformation of the EU bioeconomy characterised Ronzon et al. (2020) by a gradual shift away from labour-intensive primary sectors such as agriculture and forestry towards higher value-added and more knowledge-intensive activities. Wood-processing industry plays an important role in fulfilment of Industry and Innovation Goal within SDGs (Agenda 2030) with a high potential for ensuring own sustainability and competitiveness (Lesníková & Kánová, 2020). Ronzon et al. (2022a) emphasise the growing decoupling between employment and value added within the EU bioeconomy.

The aim of this study was to examine structural changes in the bioeconomy across EU countries, with a particular focus on employment dynamics, value added creation, labour productivity and R&D, especially in the wood-processing industry sectors.

2. METHODOLOGY

In relation to the aim of the article, we formulated the following research questions:

RQ1: What structural changes are taking place in the EU bioeconomy, how are they reflected in employment, value added and productivity?

RQ2: What is the role of R&D in driving the transformation of the bioeconomy towards higher productivity and value-added activities?

Sectoral analyses based on NACE classification provide a useful framework for identifying structural differences and development patterns across economic activities (Gajdosikova et al., 2024). The analysed sectors were classified according to the NACE Rev. 2 classification used within the JRC monitoring framework. The bioeconomy aggregate was constructed by summing selected NACE Rev. 2 sectors included in the JRC output-based bioeconomy methodology (Lasarte-López et al, 2020; Lasarte-López et al, 2025), namely A01 Agriculture, A02 Forestry, A03 Fishing, C10; C11; C12 Food, beverage and tobacco industry, C13; C14; C15 Bio-based textiles, C16 Wood products, C31 Furniture products, C17 Paper and paper products, C20; C21; C22 Bio-based chemicals, pharmaceuticals and plastics (excl. biofuels).

Source data were included: Employment: number of employees in bioeconomy sectors; Gross Value Added (GVA): economic value in €; R&D expenditure: business expenditure R&D investment (BERD) in € (JRC, 2026; Eurostat, 2026). We applied methodology by Ronzon et al. (2020; 2022b) and by Wydra & Kroll (2024).

Variables calculated and analysed were Value-added growth, calculated as relative year-to-year change contribution in %; Labour productivity, calculated as GVA per employed person in €; R&D intensity, calculated as share of R&D in GVA in %.

The figures presented in the results show the development of selected indicators in the EU bioeconomy and in the wood processing sectors C16, C17, C31 in the period 2008 - 2023.

3. RESULTS AND DISCUSSION

The findings provide insights into the economic significance of the bioeconomy in the EU and the nature of its structural transformation over employment, productivity and R&D.

Figure 1 presents a declining employment trend across analysed sectors, as evidenced by the negative coefficients of the fitted linear trend functions. The most pronounced decline is observed in the aggregated bioeconomy. Among the individual sectors, C16 exhibits the highest employment levels, although employment decreased markedly. Despite some recovery after 2017, the overall trend remains negative. This decline may reflect increasing automation and efficiency gains in wood-processing activities. Sector C31 shows a similar pattern, with employment falling. The reduction is relatively gradual and is accompanied by minor fluctuations, suggesting a stable but contracting labour market. In contrast, C17 displays the greatest stability among the analysed sectors. Sector C17 is the only one of the analysed sectors with positive trend coefficient.

Figure 2 reveals a systematic upward trend in labour productivity across all sectors, as confirmed by the positive coefficients of the linear trend functions. This indicates a long-term

improvement in labour efficiency and value creation per employee. However, the magnitude of growth differs substantially between sectors. Sector C17 consistently exhibits the highest productivity levels, increasing from €55,000 to above €85,000 per person. The aggregate bioeconomy sector demonstrates a stable and continuous growth trajectory, rising from roughly €25,000 to nearly €47,000 per person.

Figure 3 illustrates the moderately increasing trends in R&D intensity across the sectors. The fitted linear trend functions indicate positive slopes for all variables. Sector C17 exhibits the highest R&D intensity throughout the period, fluctuating between 1.4% and 2.1%. Despite its leading position, this sector is characterized by considerable volatility what may reflect sensitivity to market conditions or cyclical investment patterns. The whole bioeconomy sector demonstrates a slightly higher R&D intensity 1.0% to 1.2%, and shows a more consistent upward trend, particularly after 2016. This suggests increasing strategic importance and policy support for bio-based innovation systems.

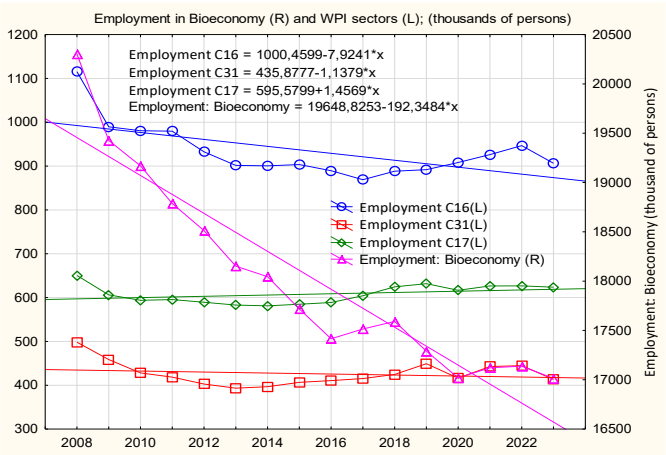

Figure 1. Employment in Bioeconomy and WPI sectors in EU countries (Source: own elaboration based on JRC and Eurostat data)

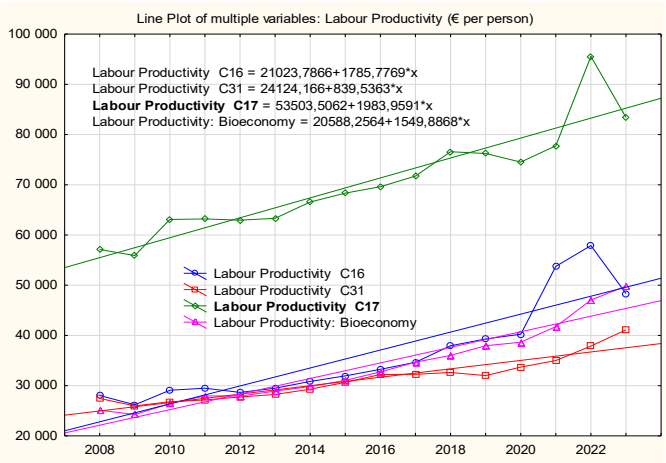

Figure 2. Labour Productivity in Bioeconomy and WPI sectors in EU countries (Source: own elaboration based on JRC and Eurostat data)

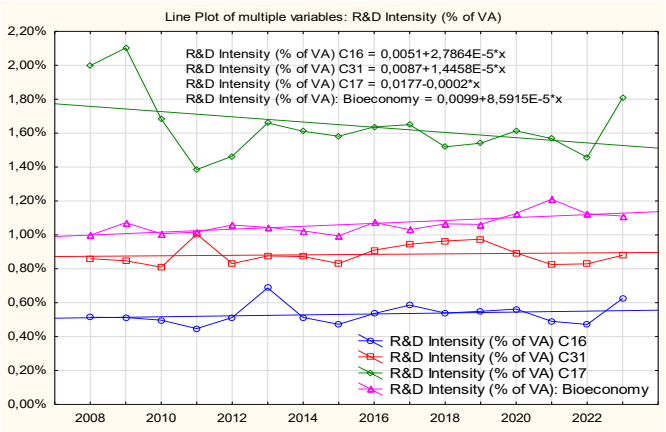

Figure 3. R&D Intensity in Bioeconomy and WPI sectors in EU countries (Source: own elaboration based on JRC and Eurostat data)

An important research result can be observed for the C17 Pulp and paper sector, characterised by significant productivity growth with above-average values, accompanied by a stable employment. In economic theory (Keynes, 1930; Solow, 1957; Acemoglu & Restrepo, 2019), productivity growth has often been associated with employment reduction. Contrary to the traditional expectation, sector C17 combines two frequently declared objectives: labour productivity growth and stable employment. This finding suggests that productivity was likely increased through technological innovation, organizational improvements, or growth in workforce skills, and not through reductions in the number of employees. From an economic policy perspective, sector C17 may therefore represent a particularly favourable model of successful structural transformation.

The results contribute to answering RQ1 by demonstrating that the EU bioeconomy is experiencing structural transformation characterised by increasing productivity and value added, while employment levels tend to stagnate or decline in several sectors. This indicates a gradual transition towards more efficient and higher-value production activities.

Concerning RQ2, the findings confirm that R&D intensity plays an important role in enhancing labour productivity within the EU bioeconomy (visible in C17 sector), however, not in the VA growth. This suggests that the R&D in bioeconomy transformation may occur primarily through productivity improvements rather than through direct short-term growth effects.

Evidence-based monitoring (Lasarte López et al., 2025; Ronzon et al., 2022a) at both national and regional levels remains crucial for tailoring policy interventions and supporting balanced bioeconomy development across the EU.

4. CONCLUSION

The figures in the aggregated EU bioeconomy highlight a process of employment contraction combined with productivity enhancement. Such developments are consistent with structural adjustments, where technological progress and innovation enable higher output and value creation despite a mostly declining workforce.

The observed development pattern in Pulp and paper sector C17 with significant productivity growth with above-average values, accompanied by stable employment may be

interpreted as being consistent with a successful process of technological upgrading and structural transformation. The findings may support policymakers in identifying bioeconomy sectors capable of combining productivity growth with employment stability.

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REFERENCES

1. Acemoglu, D., & Restrepo, P. (2019): Automation and new tasks: How technology displaces and reinstates labor. Journal of Economic Perspectives, 33(2), 3–30. https://doi.org/10.1257/jep.33.2.3
2. European Commission. (2012): Innovating for Sustainable Growth: A Bioeconomy for Europe. *Official Journal of the European Union*, 9. https://ec.europa.eu/research/bioeconomy/pdf/official-strategy_en.pdf.
3. European Commission. (2018): A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy *Official Journal of the European Union*, 107. https://doi.org/10.2777/792130.
4. European Commission. (2019): *The European Green Deal* (COM(2019) 640 final). EUR-Lex. europa.eu
5. European Commission. (2020): *A new Circular Economy Action Plan: For a cleaner and more competitive Europe* (COM/2020/98 final). EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098
6. European Commission. (2025): *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A strategic framework for a competitive and sustainable EU bioeconomy* (COM(2025) 960 final). EUR-Lex. https://eur-lex.europa.eu
7. Eurostat (2026): BERD by NACE Rev. 2 activity. URL: https://ec.europa.eu/eurostat/databrowser/view/rd_e_berdindr2/default/table?lang=en
8. Gajdosikova, D., Valaskova, K., Lopatka, A., & Lazaroiu, G. (2024): Corporate Debt Dynamics: Sectoral Clustering Analysis Using NACE Classification in Slovakia. Journal of Business Sectors, 2(1), 32–46. DOI:10.62222/FYUX6733
9. Gurría Albusac, P. et al. (2022): EU Biomass Flows, Publications Office of the European Union, Luxembourg. ISBN 978-92-76-49477-5, doi:10.2760/082220, JRC128384
10. Gurría, P., et al. (2017): Biomass flows in the European Union: The Sankey Biomass diagram- towards a cross-set integration of biomass, EUR 28565 EN, doi: 10.2760/22906
11. International Advisory Council on Global Bioeconomy. (2020): *Global Bioeconomy Policy Report (IV): A decade of bioeconomy policy development around the world* (p. 166). International Advisory Council on Global Bioeconomy.
12. Joint Research Centre (JRC). (2026): Business expenditure on Research and Development (R&D) on the EU bioeconomy (BERD) [Dataset]. https://doi.org/10.2905/JRC.9TCQ6AR

13. Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., et al. (2021): Development of the circular bioeconomy: Drivers and Indicators. *Sustainability, 13*(1), 413. https://doi.org/10.3390/su13010413
14. Keynes, J. M. (1930): Economic possibilities for our grandchildren. In J. M. Keynes, Essays in persuasion (pp. 321–332). Macmillan. (Original work published 1930)
15. Lasarte-Lopez, J., Mbarek, R., Ronzon, T., & Tamosiunas, S. (2020): EU Bioeconomy Monitoring System indicators update. Jobs and value added in the bioeconomy. https://publications.jrc.ec.europa.eu/repository/handle/JRC133484
16. Lasarte-López, J.; et al. (2025): Jobs and wealth in the EU bioeconomy. European Commission, JRC. http://data.europa.eu/89h/7d7d5481-2d02-4b36-8e79-697b04fa4278
17. Lesníková, P., & Kánová, M. (2020): Sustainable Development Goal Industry and Innovation: Challenge for Wood-Processing Industry in Slovakia. *Proceedings of Scientific Papers*, *165*.
18. Lusser, M., et al. (2018): Joint survey on bioeconomy policy developments in different countries. Brussels & Ispra: European Commission.
19. Mainar-Causapé et al. (2017): Analysis of structural patterns in highly disaggregated bioeconomy sectors by EU Member States using SAM/IO multipliers. EUR 28591. European Commission-Joint Research Centre. doi:10.2760/822918 T.
20. Paris Agreement (2015): United Nations Treaty Series, Dec. 12, 2015. unfccc.int
21. Ronzon, T., & M'Barek, R. (2018): Socioeconomic Indicators to Monitor the EU's Bioeconomy in Transition. *Sustainability*, *10*(6), 1745. DOI 10.3390/su10061745
22. Ronzon, T., Iost, S., & Philippidis, G. (2022a): Has the European Union entered a bioeconomy transition? Combining an output-based approach with a shift-share analysis. *Environment, Development and Sustainability*, *24*(6), 8195–8217.
23. Ronzon, T., Piotrowski, S., M'barek, R., Carus, M., & Tamošiūnas, S. (2022b): An output-based measurement of EU bioeconomy services: Marrying statistics with policy insight. *Structural Change and Economic Dynamics*, *60*, 290–301.
24. Ronzon, T., Piotrowski, S., Tamosiunas, S., Dammer, L., Carus, M., & M'barek, R. (2020): Developments of Economic Growth and Employment in Bioeconomy Sectors across the EU. *Sustainability*, *12*(11), 4507. DOI: 10.3390/su12114507.
25. Solow, R. M. (1957): Technical change and the aggregate production function. Review of Economics and Statistics, 39(3), 312–320. https://doi.org/10.2307/1926047
26. United Nations. (2015): *Transforming our world: The 2030 Agenda for Sustainable Development* (A/RES/70/1). United Nations Digital Library. https://sdgs.un.org/goals
27. Wesseler, J., & von Braun, J. (2017): Measuring the bioeconomy: Economics and policies. *Annual Review of Resource Economics, 9*, 275–298. https://doi.org/10.1146/annurev-resource-100516-053701
28. Wydra, S., & Kroll, H. (2024): *Methods to define indicators on research and innovation in the bioeconomy* (T. Ronzon, J. Lasarte Lopez, & R. M'barek, Eds.). Publications Office of the European Union. DOI 10.2760/63272.

Authors address:
Kánová, M.[1], Lesníková, P.[1], Potkány, M.[1]
[1] Department of Economics, Management and Business, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia
*Corresponding author: marek.potkany@tuzvo.sk

IS „CURRENT BIOECONOMY“ IN CZECHIA SUPPORTING THE FOREST-BASED SECTOR?

Petra Palátová, Roman Dudík, Miroslav Hájek

Abstract: The main aim of this contribution is to assess the recent development of bioeconomy in Czechia. First, evaluation related to the development of the national bioeconomy strategy is provided. Secondly, sectoral bioeconomy strategies are included and considered from the point of view on how the forest-based sector is considered within them. Part of the contribution deals with the findings from the CEE2ACT project (2022-2025, Horizon Europe), where Faculty of Forestry and Wood Sciences CZU Prague has been involved as a project partner and dealt with pathways towards national bioeconomy strategies in Central European (CEE) countries. The results include not only the current state of bioeconomy in the Czech Republic, but also its expected future development including bioeconomy contribution to the development of the forest-based sector.
Keywords: bioeconomy strategy, Czech Republic, CZU

1. INTRODUCTION

Bioeconomy in the forest-based sector has still been a widely discussed topic. Although in many countries sectors of forestry, pulp and paper industry, wood, wood products and furniture and bio-based industries are included in bioeconomy, the implementation of bioeconomy measures in practice widely differs among countries. There are 8 countries currently developing national bioeconomy strategy, including Czechia (EC, 2026a).

2. METHODS

The paper analyses data from Czech strategic documents based on literature review of the ministerial and governmental documents (only valid, publicly available documents in Czech language) and builds up on previous works published on this topic (Hájek, Palátová, 2025; Palátová et al., 2022). The documents were included into further analysis if they contain relevant key words (especially „forestry“, „wood“, „wood-processing“). Additionally, this contribution presents selected information from the CEE2ACT Horizon project (CEE2ACT, 2026a), namely data from the bioeconomy roadmaps (CEE2ACT, 2026b). These roadmaps are documents utilizing a bottom-up approach with national bioeconomy stakeholders (ensuring participatory approach through a series of 3 national-level workshops) where current state of bioeconomy and its future development was described by project partners at the national level.

3. BIOECONOMY IN THE CZECH REPUBLIC

3.1. Bioeconomy strategy in Czechia

The topic of bioeconomy has been indicated as important, but somewhat vaguely adopted in the translation towards national-level strategies in many European countries. Czechia has not yet (June 2026) implemented an official bioeconomy strategy. As presented in previous studies, even when the bioeconomy might not have been bordered in a single national-level document, its principles have already been included in several national-level strategies published by the ministries or Czech government (Palátová, Dudík, 2023; Palátová et al., 2022; Rinn et al., 2022; Hájek et al., 2021). Many of them have long-term goals but usually the strategies are not closely interlinked.

Between 2019-2024, the strategy entitled "Bioeconomy concept from the point of view of the Ministry of Agriculture" was in place (MZe, 2019). This concept itself was supporting the forest-based sector as it took a narrow approach to the topic of the bioeconomy, where key areas were biomass utilization, increased use of wood, forest ecosystems and research and investments. In 2025, evaluation of the Bioeconomy concept has been conducted, starting points for future are mostly: the need of mesi resort cooperation, increase international cooperation, gathering data for strategical decision-making, continuation in V4 macroregional cooperation, support and enlarge involvement of experts in international expert groups, interconnect academia and business (MZe, 2025).

3.2. Bioeconomy-related strategies in Czechia

Forestry belongs under the authority of the Ministry of Agriculture of the Czech Republic, the wood-processing belongs under the Ministry of Industry and Trade. Circular economy, as the closest concept has been published by the Ministry of Environment (MŽP, 2021). Bioeconomy is defined as a priority topic, but in connection with the food industry. The Action Plan for this strategy, currently in place for years 2022-2027, admittedly states in the first monitoring report (from December 2025) that forests are important in providing raw material, carbon sink, biodiversity, water regime, erosion regulation, social and recreational tasks so the strategy task is related to sustainable forest management (sustainable use of biomass, multi-story constructions, and perceiving wood as a strategic commodity). However, a direct defined target here is only related to food waste (MŽP, 2025). The other documents that are currently in place are (selected from Hájek, Palátová, 2025):

1. Research and Innovation Strategy for Smart Specialization of the Czech Republic (RIS3)

Bioeconomy is a part of the domain *Green technology, bioeconomy, sustainable food sources;* this domain is part *of Natural resources management, agriculture and forestry, food production, environment and biodiversity, construction and human settlements*. Bioeconomy is a strategic topic here (MIT, 2021).

2. *Implementation Document for the National Forestry Policy Concept through 2035 (2021)*

The document follows the Concept of the state forestry policy (MZe, 2020) with 4 aims:

- ensuring forest functions
- increase ecological stability and biodiversity

- ensure competitiveness of forestry and related sectors
- strengthen tole of consultation, education, research and Innovation in forestry

Partial fulfilment in 2026 tackles also the financial support of wood-processing companies, wood as a strategic commodity, minimal requirements for use of renewable sources in construction – with the preference of wood, carbon storage and education. The fulfilment of activities is not entirely in hands of the Ministry of Agriculture, but show interdisciplinarity - different ministerial support, forestry faculties and schools, state forestry enterprises, local administration etc. (MZe, 2021).

Many authors state that bioeconomy supports sustainability (e.g., Ferraz, Pyka, 2023; Srivastav et al., 2025) so also the following document has been included:

3. *Strategic framework Czech Republic 2030*

The Strategic framework contains 6 areas, including Resilient ecosystems, where subgoals mentioned are – Increase of ecological stability of forest stands, evaluation of ecosystem services and its inclusion into decision-making processes (12.2 and 12.4 subgoals; Gov, 2017).

Table 1. Summary of the strategies related to the forest-based bioeconomy (F-B BE)

Document	Validity	Supporting the F-B BE
RIS3	2021-2027	Yes
Concept of the state forestry policy	2020-2035	Yes
Strategic framework Czech Republic 2030	2017-2030	Yes (partially)

3.3. CEE2ACT project

CEE2ACT (Empowering the Central and Eastern European Countries to Develop Circular Bioeconomy Strategies and Action Plans, 2022-2025, Horizon CSA project led by Hungarian partner Geonardo Environmental Technologies Ltd.) united 17 partners from 17 countries utilizing participatory approach and involving bioeconomy stakeholders in project activities. The main aim was to transfer experience from countries that already run a national bioeconomy strategy to countries that are only on a way of the development. Czech University of Life Sciences Prague was among project partners and from the project results we could see that Czechia is in a similar position like Slovakia and Poland. Implementation barriers of bioeconomy in Czechia (as identified during 3 in-person and hybrid workshops with stakeholders held in Prague between 2023-2025) were financial barriers, legal barriers and lack of motivation of stakeholders. The bioeconomy here was not solely dedicated to forestry, but also to agriculture, crops and food; research and science-practice interlinkage.

3.4. Pathways towards bioeconomy deployment in Czechia

At this point, several parallel activities are taking place in Czechia – ministries are on their specific ways to develop strategies and action plans, research institutions are solving bioeconomy research topics, there have been project support through different funding schemes to support bioeconomy measures; bioeconomy has been included in the educational

activities. Still, there is not a complex attitude that would unite all relevant stakeholders, and the fragmented actions might or might not be included in the national strategy creation.

4. DISCUSSION

Bioeconomy strategy was firstly adopted at the European level in 2012. Shortly after this, national bioeconomy strategies have been developed, firstly in Finland (2014) and followed by other 11 European countries (Eliasson et al., 2025). The European level strategy has already been updated twice, with the newest strategy in late 2025 (EU, 2025). Some countries also already updated their initial strategies (Finland, Italy). Forestry is summarized as important namely in Germany and Spain; wood is emphasized in Austria (Eliasson et al., 2025). Forestry is also a key as it contributes to EU bioeconomy objectives – managing natural resources sustainably, mitigating and adapting to climate change, but also reducing dependence on unsustainable resources and food security (EC, 2026b). In Finland, the share of forest bioeconomy amounts up to 1/5 of people employed and 36% of bioeconomy output (LUKE, 2026). Europe is the main area where research on wood-based bioeconomy is being conducted. It focuses, e.g., on technologies utilizing wood-mixed biomass waste, forest residues. The environmental motivation is especially the waste reduction and fossil fuel displacement (Ali, Rusell, 2025).

Forest-based sector biomass and residues are important in Czechia. The Czech bioeconomy still has a great potential for its deployment, but many barriers persist. These are especially awareness barriers, lack of financial support and weak interinstitutional coordination as many of the bioeconomy activities are conducted solely. This is in line with information already presented and discussed with stakeholders during the CEE2ACT project (Hájek, Palátová, 2025). Situation in Slovakia and Poland (as indicated through CEE2ACT project activities) shows that there is probably more to be included into bioeconomy sources – especially waste and residues from different sectors. This result indicate that the topic is still important but needs to be considered interdisciplinary and with trust among involved stakeholders.

5. CONCLUSION

Coming back to the paper title and question mark – the answer is yes, the bioeconomy is supporting the forest-based sector, but in many cases only indirectly; or better-said, it does not specifically say that the steps that are being taken are directly linked to bioeconomy. Czech Republic has a huge potential of biomass utilization and forest-based value chains development. The future development will be largely dependent on the „power“ of bioeconomy actors and interconnection of measurable actions and progress tracking, but also heavily depends on increase of knowledge among stakeholders with decision-making power and professional and lay public.

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REFERENCES

1. Ali, A.; Russell, J.D. (2025). *Accelerating the Transition to Wood-Based Circular Bioeconomy: A Literature Review of Current State, Trends, Opportunities, and Priorities for Future Research*. Curr. For. Rep. 11, 23.
2. CEE2ACT, 2026a. CEE2ACT project. URL: https://www.cee2act.eu/.
3. CEE2ACT, 2026b. National bioeconomy roadmaps and policy papers. URL: https://www.cee2act.eu/national-bioeconomy-roadmaps-and-policy-papers/.
4. Eliasson, A.; Bozracchiello, M. T.; Camia, A.; Girardi, I.; Spartico, G. (2025). National bioeconomy strategies in Europe - State of play September 2025, European Commission, Ispra, JRC143845.
5. EC, 2026a. EU Bioeconomy Monitoring System. URL: https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en.
6. EC, 2026b. The bioeconomy in different countries. URL: https://knowledge4policy.ec.europa.eu/visualisation/bioeconomy-different-countries_enr policy.
7. EU, 2025. Document 52025DC0960. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52025DC0960.
8. Ferraz, D., Pyka, A. (2023). *Circular economy, bioeconomy, and sustainable development goals: a systematic literature review*. Environ Sci Pollut Res. DOI:10.1007/s11356-023-29632-0.
9. Gov, 2017. Strategický rámec Česká republika 2030. [Government of the Czech Republic. Strategic framework Czech Republic 2030]. URL: https://www.cr2030.cz/udrzitelny-rozvoj-v-ceske-republice/strategicky-ramec-ceska-republika-2030.
10. Hájek, M.; Holecová, M.; Smolová, H.; Jeřábek, L.; Frébort, I. (2021). *Current state and future directions of bioeconomy in the Czech Republic*. New Biotechnology, Vol. 61, pp. 1-8.
11. Hájek, M.; Palátová, P. (2025). T6.3 Bioeconomy roadmap/Plán pro bioekonomiku. URL: CEE2ACT-roadmap-CZ_2026-pdf.pdf
12. LUKE, 2026. Bioeconomy in numbers. URL: https://www.luke.fi/en/statistics/indicators/bioeconomy-innumbers
13. MZe, 2019. Koncepce biohospodářství. [Bioeconomy concept from the point of view of the Ministry of Agriculture of the Czech Republic]. URL: https://mze.gov.cz/public/portal/-q330521---vlH6qrbW/koncepce-biohospodarstvi-v-cr-z-pohledu
14. MZe, 2025. Hodnotící zpráva o plnění koncepce biohospodářství v České republice z pohledu Ministerstva zemědělství na léta 2019-2024. [Evaluation Report on the Implementation of the Bioeconomy Strategy in the Czech Republic from the Perspective of the Ministry of Agriculture for 2019–2024Evaluation Report on the Implementation of the Bioeconomy Strategy in the Czech Republic from the Perspective of the Ministry of Agriculture for 2019–2024]. URL: https://mze.gov.cz/public/portal/mze/-a82808---NdhlYpqm/hodnotici-zprava-o-plneni-koncepce-biohospodarstvi-v-ceske-republice-z-pohledu-ministerstva-zemedelstvi-na-leta-2019-2024?_linka=a684332.
15. MIT, 2021. URL: https://ris3.gov.cz/en.
16. MZe, 2020. Koncepce státní lesnické politiky do roku 2035. [Concept of the state forestry policy until 2035]. URL: https://mze.gov.cz/public/portal/mze/lesy/lesnictvi/koncepce-a-strategie/koncepce-statni-lesnicke-politiky-do.

17. MZe, 2021. Aplikační dokument ke Koncepci státní lesnické politiky do roku 2035. . [Application document to the Concept of the state forestry policy until 2035]. URL: https://mze.gov.cz/public/portal/mze/-q321949---GqaUgNDi/aplikacni-dokument-ke-koncepci-statni?_linka=a235677.
18. MŽP, 2021. Strategický rámec Cirkulární Česko 2040. [Strategic framework Circular Czechia 2040]. URL: https://mzp.gov.cz/cz/agenda/odpadove-hospodarstvi-a-cirkularni-ekonomika/cirkularni-ekonomika/cirkularni-cesko-0.
19. MŽP, 2025. Zpráva o plnění cílů Akčního plánu Cirkulární Česko 2040 za období 2022–2024. [Report on the Implementation of the Objectives of the Circular Czech Republic 2040 Action Plan for the Period 2022–2024]. URL: https://mzp.gov.cz/system/files/2026-02/OCEO-1_Monitorovaci_zprava_CC_2040-20260223.pdf.
20. Palátová, P.; Dudík, R., (2023). Circularity and forest bioeconomy in the Czech Republic. In *16th Annual International Scientific Conference WoodEMA – Current Trends and Challenges for Forest-Based Sector: Carbon Neutrality and Bioeconomy*, pp. 1-5, Prague, 14.-16.6.2023.
21. Palátová, P.; Purwestri, R.C.; Marcineková, L. (2022). *Forest bioeconomy in three European countries: Finland,the Czech Republic and the Slovak Republic*. International Forestry Review, 24(4), pp. 594-606.
22. Rinn, R.; Palátová, P.; Kalábová, M.; Jarský, V. (2023). *Forest Bioeconomy from the Perspectives of Different EU Countries and Its Potential for Measuring Sustainability*. Forests, 14, 33.
23. Srivastav, A.L.; Bagherian, A. & Ghosh, D. (2025). *The circular bioeconomy: pathways to sustainability and resource optimization*. Clean Techn Environ Policy 27, 815–832. https://doi.org/10.1007/s10098-024-03060-1.

Authors address:
Palátová, P.[1*]; Dudík, R.[2]; Hájek, M.[3]
[1,2,3] Department of Forestry and Wood Economics, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Czech Republic
[*]Corresponding author: petpalatova@gmail.com

ENHANCING WATER FOOTPRINT COMMUNICATION IN THE WOOD-PROCESSING INDUSTRY THROUGH GAMIFICATION

Teodor Daskalov, Neviana Krasteva, Aleksey Potebnya

Abstract: This study examines whether gamified communication of water-footprint information is more effective than a standard non-gamified format in shaping consumer evaluations and behavioural intentions toward household wood products. A pretest-posttest experimental design with two communication conditions was employed: a gamified simulation and a non-gamified informational format presenting identical factual content. The sample consisted of 75 fourth-year marketing students used as an established proxy sample in consumer experiments. The study measured perceived sustainability, perceived credibility, subjective and objective comprehension, engagement, purchase intention, and willingness to pay for products with a lower water footprint. Positive change was observed in both conditions, but the gamified format produced higher posttest scores for perceived credibility, comprehension, engagement, purchase intention, and willingness to pay. On the objective water-footprint items, the share of correct answers reached 81.6% in the experimental group, compared with 75.7% in the control group. The findings suggest that interactive communication of water-footprint information can make environmental messages more understandable, more credible, and more market-relevant for the wood-processing industry. The results contribute to bioeconomy transition strategies by improving market acceptance of lower-impact wood products. Findings provide actionable insights for managers and marketers in forest-based industries.
Keywords: water footprint communication; gamification; household wood products; perceived credibility; purchase intention; willingness to pay

1. INTRODUCTION

Increasing pressure on freshwater resources has made water stress a strategic issue for resource-dependent industries, including the wood-processing sector. Forest ecosystems provide raw materials and regulate hydrological processes through water retention, infiltration and ecosystem stability; therefore, sustainable forest management is closely connected with regional water security (Food and Agriculture Organization of the United Nations (FAO), n.d.).

For wood-processing firms, the challenge is not limited to measuring environmental impacts. Consumers must also be able to interpret environmental indicators as credible and relevant product information. The water footprint is useful in this respect because it captures direct and indirect freshwater use across supply chains, including green, blue and grey water components (Hoekstra et al., 2011). However, its multidimensional and spatially distributed nature makes it difficult for consumers to understand without adequate communication design.

Previous evidence shows that a substantial part of the water footprint of wood products is embedded in international supply chains and may be externalised to water-scarce regions (Cazcarro et al., 2022; Schyns et al., 2017). This creates a gap between environmental accounting and consumer interpretation. The present study therefore asks whether gamified communication of water-footprint information enhances consumer comprehension, perceived credibility and behavioural intentions compared with traditional non-gamified disclosure formats. While gamification has been widely examined in sustainability contexts, its application

to water-footprint communication in forest-based product systems remains underexplored. The contribution of this study lies in testing gamification as a communication format for a supply-chain embedded indicator in household wood products, while keeping factual environmental content constant.

2. LITERATURE REVIEW AND HYPOTHESES

Environmental communication research suggests that transparent, specific and credible information can reduce information asymmetry and support consumer trust (Atkinson & Rosenthal, 2014; Delmas & Burbano, 2011; Testa et al., 2015). Sustainability labels usually improve attitudes and willingness to pay, but their effectiveness depends on clarity, design and interpretability (Majer et al., 2022). Eco-label knowledge and trust are particularly important for pro-environmental consumer behaviour, while sustainable-behaviour research shows that communication works better when information is specific, actionable and personally relevant (Taufique et al., 2017; White et al., 2019). Recent evidence on origin-related environmental disclosure also indicates that disclosure alone is not sufficient unless consumers perceive the information as diagnostic for purchase decisions (Xiang & Liu, 2024). In wood-product and furniture markets, eco-information, certification and eco-label credibility have been associated with higher value perceptions, purchase intention and willingness to pay (Cai et al., 2017; Higgins et al., 2020; Holopainen et al., 2014; Morone et al., 2021; Veisten, 2007).

Gamification, defined as the use of game-design elements in non-game contexts, can improve engagement with complex information by adding interaction, feedback and progress cues (Deterding et al., 2011). Reviews report positive effects on engagement and motivation, although effects depend on context and design quality (Hamari et al., 2014). Recent sustainability-related studies also suggest that gamified learning can support understanding, motivation and sustainable purchasing (Mabalay, 2025; Zafar et al., 2024). However, this positive view should be treated cautiously. Although gamification can increase engagement, excessive game elements may reduce the perceived seriousness of environmental information or create superficial involvement without deeper behavioural change.

In this study, gamification is not treated as a separate sustainability claim. It is conceptualised as a communication-enhancement mechanism that keeps the factual environmental content constant while improving its cognitive accessibility, perceived relevance and credibility. The experimental model is deliberately limited to measured variables: perceived sustainability, perceived credibility, engagement, purchase intention, willingness to pay, subjective comprehension and objective comprehension.

H1. Water-footprint communication improves consumer evaluations of household wood products from pretest to posttest.

H2. Gamified water-footprint communication produces stronger gains in perceived credibility, engagement, purchase intention and willingness to pay than non-gamified communication.

H3. Gamified communication produces higher objective comprehension than non-gamified communication, although the expected effect is smaller than for attitudinal and behavioural outcomes.

3. METHODOLOGY

The study used a controlled pretest-posttest experiment with two communication conditions. Participants were randomly assigned either to a non-gamified informational disclosure or to a gamified interactive simulation. Both stimuli presented identical factual

information about the water footprint of household wood products; the only manipulation concerned the communication format.

The final sample consisted of 75 fourth-year marketing students: 37 in the non-gamified control group and 38 in the gamified experimental group. The sample should be interpreted as a controlled adult student-consumer sample rather than as a representative consumer population. Participation was voluntary and the experiment was conducted in a classroom setting. Although this limits external validity, the sample is appropriate for controlled theory-testing focused on relative treatment effects rather than population-level market estimation. The results should therefore be generalised to the communication mechanism, not to actual market demand.

All constructs were measured with composite indicators adapted from sustainability communication, eco-label and consumer-behaviour research. Seven-point Likert scales were used for perceived sustainability, perceived credibility, engagement, purchase intention, willingness to pay and subjective comprehension. Objective comprehension was assessed through a three-item knowledge test. Pretest-posttest changes were analysed using a mixed repeated-measures logic. In the results tables, p-values refer to the time × group interaction effect, and partial eta squared (ηp^2) is reported as the effect-size indicator.

Table 1. Experimental logic and measurement

Component	Operationalisation	Measurement / role
Communication input	Water-footprint information for household wood products	Identical factual content in both conditions
Format manipulation	Non-gamified disclosure vs gamified simulation	Between-subjects factor
Sample	75 fourth-year marketing students	Control n = 37; gamified n = 38
Outcomes	Credibility, engagement, sustainability, intention, WTP, comprehension	Pretest-posttest comparison
Statistical focus	Change over time and time × group interaction	Primary test of added gamification effect

Source: Authors` contribution

4. RESULTS

Both communication formats improved responses after exposure, which supports H1 at a descriptive level. However, the gamified condition produced stronger gains across the central attitudinal and behavioural outcomes. The largest differences were observed for purchase intention, willingness to pay, perceived credibility and engagement.

Table 2. Main scale indicators: posttest comparison and interaction diagnostics

Indicator	C Post M (SD)	G Post M (SD)	Δ C	Δ G	p	ηp^2
Perceived sustainability	4.52 (0.64)	5.05 (0.66)	+0.43	+0.99	0.018	0.08
Perceived credibility	4.63 (0.65)	5.54 (0.62)	+0.51	+1.44	0.004	0.12
Engagement	4.36 (0.70)	5.07 (0.67)	+0.44	+1.18	0.006	0.11
Purchase intention	4.57 (0.68)	5.61 (0.63)	+0.55	+1.63	0.002	0.15
Willingness to pay index	4.22 (0.76)	5.35 (0.71)	+0.51	+1.59	0.003	0.14
Subjective comprehension	4.48 (0.66)	5.12 (0.64)	+0.53	+1.20	0.011	0.09
Manipulation check	3.18 (0.80)	5.46 (0.72)	+0.38	+2.68	<0.001	0.32

Note. C = non-gamified control group, n = 37; G = gamified experimental group, n = 38. p-values refer to the time × group interaction effect. Source: Authors` contribution

The manipulation check confirms that the treatment was perceived as substantially more interactive and game-like. This supports the internal validity of the experiment because the factual information was held constant while the presentation format differed.

Objective comprehension improved in both groups, but the gamified group reached higher posttest accuracy. The advantage was positive but modest, which supports H3 only partially and confirms that gamification operated more strongly through interpretive and motivational mechanisms than through factual recall alone.

Table 3. Objective water-footprint comprehension

Indicator	C Post	G Post	Δ C	Δ G	p
Objective index (0-3), M (SD)	2.27 (0.71)	2.45 (0.64)	+0.24	+0.45	0.048
Q1. Meaning of water footprint	75.7% (28/37)	81.6% (31/38)	+10.8 p.p.	+15.8 p.p.	0.052
Q2. Meaning of lower water footprint	75.7% (28/37)	81.6% (31/38)	+8.1 p.p.	+15.8 p.p.	0.046
Q3. Indicator interpretation	75.7% (28/37)	81.6% (31/38)	+5.4 p.p.	+13.2 p.p.	0.041

Note. Percentages and frequencies in parentheses report correct answers within each group. p.p. = percentage points. Source: Authors` contribution

Table 4. Posttest distribution of willingness to pay a higher price

Price premium category	Non-gamified C n (%)	Gamified G n (%)
I would not pay more	6 (16.2)	1 (2.6)
Up to 5% more	12 (32.4)	5 (13.2)
6% to 10% more	10 (27.0)	9 (23.7)
11% to 15% more	6 (16.2)	13 (34.2)
More than 15% more	3 (8.1)	10 (26.3)
Total	37 (100.0)	38 (100.0)

The posttest distribution shows a stronger shift toward higher price-premium categories in the gamified condition, $\chi^2(4) = 12.84$, $p = 0.012$. Source: Authors` contribution

5. DISCUSSION

The main contribution of this study is demonstrating that gamification enhances environmental communication primarily by improving interpretation and trust rather than knowledge acquisition.The results are consistent with signalling theory: the credibility of an environmental signal depends not only on its factual accuracy but also on whether consumers can process it as understandable, relevant and trustworthy.

The strongest effects were observed for perceived credibility, purchase intention and willingness to pay. This suggests that gamified environments can convert complex environmental information into a more meaningful consumer signal. The smaller objective-comprehension effect indicates that gamification does not work mainly by increasing factual recall. Rather, it improves engagement, interpretive accessibility and perceived credibility, which are closer to behavioural readiness. This pattern suggests that gamification operated mainly through motivational and interpretive pathways, functioning as a sense-making and engagement mechanism rather than as a purely educational tool for factual recall.

Managerially, the results imply that static disclosure may be insufficient for complex sustainability indicators. Wood-processing firms can improve the market relevance of water-

footprint information by using interactive product-comparison tools, immediate feedback and simple scenario-based communication without changing the factual environmental claim.

6. LIMITATIONS AND FUTURE RESEARCH

The study has several limitations. The sample consisted of fourth-year marketing students and cannot be treated as representative of the wider consumer population. The experiment measured immediate post-exposure reactions rather than delayed behaviour or actual purchases. A related limitation is the possible novelty effect: participants may have responded positively because the gamified format was new and interactive, not necessarily because its effects would remain stable over time. The conference-paper format also reports composite scale indicators and summary-level statistics; a full journal version should include item-level reliability diagnostics and robustness checks. Future research should replicate the design with larger consumer samples, delayed posttests and real or simulated product-choice tasks. Intention and willingness-to-pay indicators are therefore treated as comparative measures of communication effectiveness, not as proxies for actual purchases. Future research should test delayed effects through simulated choice tasks, field experiments or retail-like decision settings.

7. CONCLUSION

This study shows that gamified communication can enhance the effectiveness of water-footprint disclosure for household wood products. Both communication formats improved consumer evaluations, but the gamified format produced stronger gains in perceived credibility, engagement, purchase intention and willingness to pay. Objective comprehension also improved, although the effect was more modest.

The contribution of the study is to position water-footprint communication not only as environmental accounting but also as a strategic marketing instrument. More specifically, gamification appears to increase not so much factual knowledge as trust, interpretive accessibility and perceived relevance of complex environmental information. It can therefore support the translation of water-footprint indicators into more actionable consumer signals for lower-impact wood products.

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REFERENCES

1. Atkinson, L.; Rosenthal, S. (2014): Signaling the green sell: The influence of eco-label source, argument specificity, and product involvement on consumer trust. Journal of Advertising 43 (1): pp. 33-45. https://doi.org/10.1080/00913367.2013.834803
2. Cai, Z.; Xie, Y.; Aguilar, F. X. (2017): Eco-label credibility and retailer effects on green product purchasing intentions. Forest Policy and Economics 80: pp. 200-208. https://doi.org/10.1016/j.forpol.2017.04.001
3. Cazcarro, I.; Schyns, J. F.; Arto, I.; Sanz, M. J. (2022): Nations' water footprints and virtual water trade of wood products. Advances in Water Resources 164: 104188. https://doi.org/10.1016/j.advwatres.2022.104188
4. Delmas, M. A.; Burbano, V. C. (2011): The drivers of greenwashing. California Management Review 54 (1): pp. 64-87. https://doi.org/10.1525/cmr.2011.54.1.64
5. Deterding, S.; Dixon, D.; Khaled, R.; Nacke, L. (2011): From game design elements to gamefulness: Defining "gamification". In: Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments. Association for Computing Machinery, pp. 9-15. https://doi.org/10.1145/2181037.2181040
6. ***: Food and Agriculture Organization of the United Nations (n.d.): Forest and Water Programme. URL: https://www.fao.org/in-action/forest-and-water-programme/en/

7. Hamari, J.; Koivisto, J.; Sarsa, H. (2014): Does gamification work? A literature review of empirical studies on gamification. In: Proceedings of the 47th Hawaii International Conference on System Sciences. IEEE, pp. 3025-3034. https://doi.org/10.1109/HICSS.2014.377
8. Higgins, K.; Hutchinson, W. G.; Longo, A. (2020): Willingness-to-pay for eco-labelled forest products in Northern Ireland: An experimental auction approach. Journal of Behavioral and Experimental Economics 87: 101572. https://doi.org/10.1016/j.socec.2020.101572
9. Hoekstra, A. Y.; Chapagain, A. K.; Aldaya, M. M.; Mekonnen, M. M. (2011): The water footprint assessment manual: Setting the global standard. Earthscan.
10. Holopainen, J. M.; Häyrinen, L.; Toppinen, A. (2014): Consumer value dimensions for sustainable wood products: Results from the Finnish retail sector. Scandinavian Journal of Forest Research 29 (4): pp. 378-385. https://doi.org/10.1080/02827581.2014.925138
11. Mabalay, A. A. (2025): Gamification for sustainability: A systematic review of applications, trends, and opportunities. Computers in Human Behavior 165: 108529. https://doi.org/10.1016/j.chb.2024.108529
12. Majer, J. M.; Henscher, H. A.; Reuber, P.; Fischer-Kreer, D.; Fischer, D. (2022): The effects of visual sustainability labels on consumer perception and behavior: A systematic review of the empirical literature. Sustainable Production and Consumption 33: pp. 1-14. https://doi.org/10.1016/j.spc.2022.06.012
13. Morone, P.; Caferra, R.; D'Adamo, I.; Falcone, P. M.; Imbert, E.; Morone, A. (2021): Consumer willingness to pay for bio-based products: Do certifications matter? International Journal of Production Economics 240: 108248. https://doi.org/10.1016/j.ijpe.2021.108248
14. Schyns, J. F.; Booij, M. J.; Hoekstra, A. Y. (2017): The water footprint of wood for lumber, pulp, paper, fuel and firewood. Advances in Water Resources 107: pp. 490-501. https://doi.org/10.1016/j.advwatres.2017.05.013
15. Taufique, K. M. R.; Vocino, A.; Polonsky, M. J. (2017): The influence of eco-label knowledge and trust on pro-environmental consumer behaviour in an emerging market. Journal of Strategic Marketing 25 (7): pp. 511-529. https://doi.org/10.1080/0965254X.2016.1240219
16. Testa, F.; Iraldo, F.; Vaccari, A.; Ferrari, E. (2015): Why eco-labels can be effective marketing tools: Evidence from a study on Italian consumers. Business Strategy and the Environment 24 (4): pp. 252-265. https://doi.org/10.1002/bse.1821
17. Veisten, K. (2007): Willingness to pay for eco-labelled wood furniture: Choice-based conjoint analysis versus open-ended contingent valuation. Journal of Forest Economics 13 (1): pp. 29-48. https://doi.org/10.1016/j.jfe.2006.10.002
18. White, K.; Habib, R.; Hardisty, D. J. (2019): How to SHIFT consumer behaviors to be more sustainable: A literature review and guiding framework. Journal of Marketing 83 (3): pp. 22-49. https://doi.org/10.1177/0022242919825649
19. Xiang, P.; Liu, Z. (2024): Is it both sufficient and necessary to disclose environmental information regarding the origin on consumer purchases? Sustainability 16 (12): 5017. https://doi.org/10.3390/su16125017
20. Zafar, A. U.; Shahzad, M.; Shahzad, K.; Appolloni, A.; Elgammal, I. (2024): Gamification and sustainable development: Role of gamified learning in sustainable purchasing. Technological Forecasting and Social Change 198: 122968. https://doi.org/10.1016/j.techfore.2023.122968

Authors address:

Daskalov, T.*; Krasteva, N.; Potebnya, A.
Faculty of Economics and Business Administration, Sofia University "St. Kliment Ohridski", Sofia, Bulgaria
*Corresponding author: tdaskalov@feb.uni-sofia.bg

BIOECONOMY AND GREEN ECONOMY: PERSPECTIVES, EDUCATION AND APPLICATION IN THE FOREST INDUSTRY

Daniela Todorova, PhD, Nina Gergova, PhD, Miryana Evtimova, PhD

Abstract:
The article examines the interrelationship between the development of the bioeconomy and the green economy with a focus on their application in the forest industry in the context of the growing demands for sustainable development and circular economy. The role of the sector as a key source of renewable resources, bio-based products and innovations with high added value is analyzed. Special attention is paid to the dynamics of product markets in the forest sector and the growing importance of sustainable management of forest resources.
The emphasis is placed on the role of higher education as a factor in preparing highly qualified specialists capable of meeting the challenges of the green transformation in the forest industry. The importance of modern education for promoting scientific research, innovation and the implementation of sustainable and resource-efficient practices in wood processing and related sectors is examined.
In conclusion, it is emphasized that improving the quality and practical orientation of higher education is essential for increasing the competitiveness of the forest industry in the conditions of globalized and environmentally oriented markets.

Keywords: bioeconomy, green economy, circular economy, forest industry, sustainable forest management, bio-based products, education, green transition

1. INTRODUCTION

The effects The first European Union (EU) Action Plan for a Circular Economy dates back to 2015. The transition to a more circular economy, where the value of goods, materials and resources is retained in the economy for as long as possible and waste generation is minimised, is the basis for building a sustainable, low-carbon and competitive resource-efficient economy [1]. The “2030 Decade of Action” announced by the United Nations (UN) in 2019 to achieve the global Sustainable Development Goals requires mobilisation at all levels – global, local and personal. Therefore, the prediction that “There is only one planet, but by 2050 the world will consume as many resources as if there were three planets” requires a New Action Plan for the Circular Economy [2]. The need to build a circular economy to reduce the environmental footprint has also been explored in previous studies by the authors[4]. In 2020, the European Commission adopted a New Circular Economy Action Plan, which is one of the main building blocks of the European Green Deal, the new European agenda for sustainable growth . A 2021

[4] Todorova, D. and Evtimova, M. Circular Economy and Ecological Security. Mechanics Transport Communications, ISSN 1312-3823, volume 15, issue 3, 2017, article No. 1479. (IX-1)-(IX-6) pp., Todorova, D. and Evtimova, M. Circular Economy: Gross Domestic Product and Ecological Footprint. Mechanics Transport Communications, ISSN 1312-3823, Volume 17, Issue 3, 2019, Article No. 1865. (IX-1)-(IX-6) pp.

report on the new Circular Economy Action Plan by the Committee on the Environment, Public Health and Food Safety and other associated committees to the European Parliament highlighted the following facts: the circular economy, combined with the zero-pollution ambition to achieve a non-toxic environment, is key to reducing the overall environmental footprint of European consumption and production, respecting planetary boundaries, protecting human health, while ensuring a competitive and innovative economy; the circular economy can make a major contribution to achieving the objectives of the Paris Agreement, the Convention on Biological Diversity and the UN Sustainable Development Goals[5]. Therefore, the report will examine and analyze the main challenges, overcoming which will achieve the expansion of the scope of the circular economy, the bioeconomy and the green economy, education with an emphasis on their application in the forest industry.

1. Expanding the scope of the circular economy: key highlights

By addressing the entire life cycle of products, the new action plan aims to prepare the economy for a green future, strengthen competitiveness while protecting the environment and providing new rights for consumers. The main focuses of the circular economy in relation to the forest-based industry are provided in Figure 1.

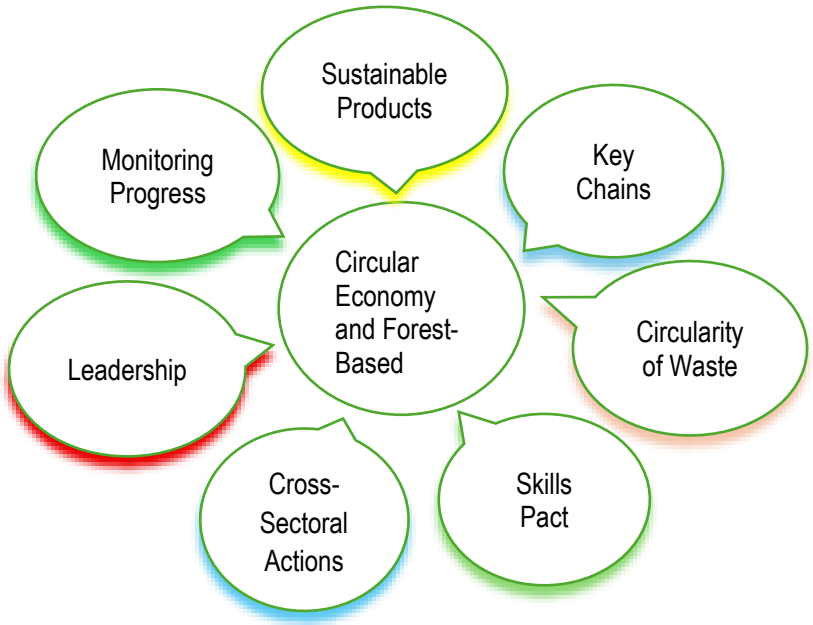

Fig. 1. - Main highlights of the circular economy, in relation to the forest industry

The sustainability aspects of the bioeconomy and the green economy, with a focus on their application in the forest-based industry, are to some extent addressed in certain initiatives and legislation such as the Ecodesign Directive, which contains provisions on energy efficiency and certain circular characteristics of energy products. There is still no comprehensive set of

[5] Committee on the Environment, Public Health and Food Safety of the European Parliament. REPORT on the new Circular Economy Action Plan (2024/2077(INI)) A9-0008/2025

requirements to ensure that all products placed on the EU market become increasingly sustainable and circular. It is therefore necessary to establish sustainability principles and other appropriate ways to regulate different aspects such as: improving the durability of products, their reusability and their upgradeability and repairability; addressing the presence of hazardous chemicals in products and increasing the energy and resource efficiency of products; increasing the recycled content of products while ensuring their efficiency and safety; reducing carbon emissions and environmental footprint; providing incentives for products based on their respective sustainability performance, including by offering incentives for high efficiency, the bioeconomy, the green economy, the forest-based industry, training, etc. Circularity is a key aspect of the broad industrial transition towards climate neutrality and long-term competitiveness. It can lead to significant material savings at all levels of value chains and production processes, generate additional value and create economic opportunities. The sustainability challenge posed by key value chains requires urgent, comprehensive and coordinated action, which will form an integral part of the sustainable products policy framework. Electrical and electronic equipment (as part of ICT - information and communication technologies) generates some of the fastest growing waste streams in the EU, with an annual growth rate currently of 2%. Estimates suggest that the recycling rate of e-waste in the EU is below 40%.

Other key product value chains requiring sectoral action include: packaging, plastics, textiles, construction and buildings, food, water and nutrients. All of these have an impact on the environment and the forest-based industry. The amount of waste generated by all economic activities in the EU is 2.5 billion tonnes per year, or 5 tonnes per capita, with each citizen producing on average almost half a tonne of municipal waste [6]. Actions that need to be taken are focused on the following areas: a more effective waste policy aimed at waste prevention and supporting its circular nature; increasing circularity in non-toxic environments, forest-based industries and the gradual development of harmonised systems for tracking and managing information on substances; creating a well-functioning EU market for secondary raw materials and taking measures in relation to waste exports from the EU. Between 2018 and 2025, the number of jobs in the EU related to the circular economy increased by 5% to around 4 million. Circularity can be expected to have a positive net effect on job creation, provided that workers acquire the skills needed for the transition to a green economy. In this regard, the European Commission is developing a European Skills Agenda for Sustainable Competitiveness, Social Fairness and Resilience [7]. It sets ambitious quantitative targets for upskilling (improving existing skills) and reskilling (acquiring new skills) to be achieved over the next five years. Education plays a key role in achieving these targets, providing the necessary knowledge, competences and practical skills for the successful implementation of the green transition. Higher education institutions are particularly important in preparing highly qualified specialists capable of meeting the growing demands of the circular economy and sustainable resource management. In addition to training future professionals, universities also contribute to the development of scientific research, innovation and technological solutions aimed at increasing

[6] communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions a new action plan on the circular economy for a cleaner and more competitive europe. brussels.

[7] European Skills Agenda for Sustainable Competitiveness, Social Fairness and Resilience. Brussels, https://ec.europa.eu/commission/presscorner/detail/bg/ip_20_1196

resource efficiency and sustainability of production processes. The role of higher education is important as a factor in preparing highly qualified specialists capable of meeting the challenges of the green transformation in the forest industry. The importance of modern education is related to promoting scientific research, innovation and the implementation of sustainable and resource-efficient practices in wood processing and related sectors. Skills for jobs in the green and digital economy should be developed through the implementation of key activities set out in the European Skills Agenda. A significant place among them is occupied by measures aimed at modernizing education and training, promoting lifelong learning, as well as strengthening partnerships between educational institutions and business. In this context, education is seen as a key mechanism for forming competencies necessary for the successful transition to a circular, green and digital economy. The role of higher education institutions is particularly important, as they not only prepare highly qualified specialists, but also create conditions for the development of scientific research, innovation and knowledge transfer to practice. In this way, they contribute to the development of human capital capable of meeting the growing demands of sustainable development and green transformation of industries, including the forestry and wood processing sector. Developing skills for jobs in the green and digital economy will be implemented through twelve key actions of the European Union. These include the Pact for Skills, improving the analysis of skills needs and supporting national skills development strategies. An important focus is placed on vocational education and training, the development of European Universities and the promotion of skills needed for the green and digital transition. The measures also include increasing the number of graduates in the fields of science, technology, engineering and mathematics (STEM), the development of entrepreneurial and life skills, as well as the introduction of individual learning accounts and micro-qualifications. The Europass platform is further developed and the framework for mobilising investment in human capital is improved.

2. The role of education and higher education in developing the circular economy, innovation and green transformation in the forest industry

Circularity as a prerequisite for climate neutrality, which can be achieved by strengthening the synergies between circularity and the reduction of greenhouse gas emissions. To this end, a number of measures need to be taken, such as an analysis of ways to systematically measure the impact of circularity on climate change mitigation and adaptation, etc. In addition to reducing greenhouse gas emissions, achieving climate neutrality will also require absorbing the carbon released into the atmosphere, using it in the economy without releasing it, and storing it for longer periods of time. Building a proper economy and accelerating the transition to a green economy requires careful but decisive measures to direct funding towards more sustainable production and consumption models, such as the Circular Economy Financial Support Platform. The transition is based on the development of scientific research, innovation, digitalization and training of human resources. To this end, various programmes can support the acquisition of new skills, upskilling, lifelong learning and mobility of researchers and specialists in this field. Investment in education and training is a key factor in preparing personnel capable of developing and implementing innovative solutions aimed at sustainable use of resources and the development of a circular economy. Particular attention should be paid to promoting innovations to reduce CO_2 emissions from transport activities and logistics processes, which are an integral part of the supply chain in the forest industry. At the same time, it is necessary to develop competences in the field of environmental technologies, energy

efficiency, automation and digital solutions. Thanks to digital technologies, it is possible to trace the origin and movement of wood, as well as the path of products, components and materials along the entire production chain, while ensuring secure access to the data generated. This creates the prerequisites for more efficient resource management, increasing transparency and ensuring the sustainability of production processes. In the context of the green and digital transformation of the forest industry, there is a growing need for specialists with interdisciplinary training combining knowledge in the fields of forestry, wood processing, digital technologies, data management, engineering sciences and sustainable development[8], . Therefore, modern higher education and vocational training play a key role in developing the competencies needed to implement innovations, develop circular business models and increase the competitiveness of enterprises in the forest sector in the context of the green and digital transition. To support the global transition to a circular economy, the EU will play a leading role in efforts at international level. The main initiatives in this direction are the creation of a global circular economy alliance to identify gaps in knowledge and governance in order to make progress in building a global circular economy; defining a "safety margin" for the use of natural resources and the possibility of reaching an international agreement on the management of natural resources. To achieve the objectives of the European Green Deal [9], it is necessary to update the framework for monitoring the circular economy. Indicators on resource use, including consumption impacts and the footprint on raw materials, will be further developed to account for raw material consumption and the environmental impact of production and consumption patterns, and will be linked to monitoring and assessing progress towards decoupling economic growth from resource use and the related impacts in the EU and beyond. [10] In this context, the role of education and higher education institutions in developing the circular economy, innovation and green transformation in the forest industry is also essential, as they prepare highly qualified specialists capable of applying modern methods for sustainable resource management and implementing innovative and resource-efficient solutions.

CONCLUSION

The transition to a circular, green and digital economy places new demands on businesses, the workforce and educational institutions and would be successful if it is systematic, comprehensive and radical. Its implementation through research, innovation and digitalization, as one of the main cross-sectoral actions, is a major challenge for education in the knowledge economy. In conclusion, the transition to a circular economy depends not only on the implementation of innovative technologies and digital solutions, but also on the availability of highly qualified specialists capable of applying the principles of sustainable development in practice. In this context, education and training are established as key factors for forming the necessary knowledge, skills and competencies to meet the changing needs of

[8] Lambovska, M. R. (2018). Control on teams: A model and empirical evidence from Bulgaria. Serbian Journal of Management, 13(2), 311–322. https://doi.org/10.5937/sjm13-14633

[9] Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions The European Green Deal Brussels

[10] Angelova-Stanimirova, A. (2025). Essential Components of Management Control Systems in the Forestry-Based Sector. WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers, 279–284.

the labor market. For the forest industry, these processes are of particular importance, as the sector makes a significant contribution to the development of the bioeconomy, the efficient use of natural resources and the reduction of the carbon footprint. The implementation of innovations, the digitalization of production and logistics processes, as well as the implementation of sustainable practices require specialists with interdisciplinary training and readiness for continuous improvement of knowledge. Therefore, higher education institutions should take a leading role in training personnel, developing scientific research and promoting cooperation between education, science and business. Therefore, investments in education, training and human capital development are a strategic prerequisite for increasing the competitiveness, sustainability and innovation potential of the forest industry in the context of green and digital transformation.

REFERENCES

1. Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions A new Action Plan on the Circular Economy For a cleaner and more competitive Europe. Brussels.
2. Todorova, D. and Evtimova, M. Circular Economy and Ecological Security. Mechanics Transport Communications, ISSN 1312-3823, volume 15, issue 3, 2017, article No. 1479. (IX-1)-(IX-6) pp.
3. Todorova, D. and Evtimova, M. Circular Economy: Gross Domestic Product and Ecological Footprint. Mechanics Transport Communications, ISSN 1312-3823, Volume 17, Issue 3, 2019, Article No. 1865. (IX-1)-(IX-6) pp.
4. Committee on the Environment, Public Health and Food Safety of the European Parliament. REPORT on the new Circular Economy Action Plan (2024/2077(INI)) A9-0008/2025
5. European Skills Agenda for Sustainable Competitiveness, Social Fairness and Resilience. Brussels, https://ec.europa.eu/commission/presscorner/detail/bg/ip_20_1196
6. The Pact for Skills: mobilising all partners to invest in skills.
7. https://ec.europa.eu/social/main.jsp?langId=bg&catId=1517&furtherNews=yes&newsId=9827
8. Lambovska, M. R. (2018). Control on teams: A model and empirical evidence from Bulgaria. Serbian Journal of Management, 13(2), 311–322. https://doi.org/10.5937/sjm13-14633
9. Angelova-Stanimirova, A. (2025). Essential Components of Management Control Systems in the Forestry-Based Sector. WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers, 279–284.

Authors address:
Daniela Todorova, Professor, PhD, Department “Transport Economy and Accounting”, Faculty of Transport Management, Todor Kableshkov Transport University, dtodorova@vtu.bg
Nina Gergova, Assoc. Professor, PhD, Department “Transport Economy and Accounting”, Faculty of Transport Management, Todor Kableshkov Transport University, ninagergova@vtu.bg
Miryana Evtimova, Assoc. Professor, PhD, Faculty of Engineering and Construction Technologies in Transport, Department of "Transport equipment", Todor Kableshkov Transport University, mevtimova@vtu.bg

THE TWIN TRANSITION IN FORESTRY AND AGRIBUSINESS: WORKFORCE CAPACITY AS CATALYST OR CONSTRAINT?

Sonia Mileva

Abstract: This paper examines the role of workforce capacity in the twin transition in forestry and agribusiness, understood as the parallel processes of digital transformation and the shift towards sustainable, low-carbon practices. It explores whether the current workforce profile functions as a catalyst for these transformations or as a constraint on their effective implementation. Methodologically, the paper combines contextual evidence from a nationally representative survey of innovation potential in Bulgarian agriculture with an exploratory pilot questionnaire survey among companies in forestry and agribusiness. The analysis focuses on skills gaps, reskilling and upskilling needs, demographic pressures in rural areas, and the organisational conditions required for the adoption of Industry 4.0 technologies and sustainability-oriented practices. The preliminary findings suggest that technology acquisition alone does not guarantee transformation. Without targeted investment in training, institutional cooperation and organisational adaptation, workforce capacity may become a bottleneck for innovation. The paper argues that workforce capacity should be treated as a strategic transition resource and outlines directions for public-private partnerships and education reforms aimed at strengthening the human dimension of the bioeconomy.
Keywords: twin transition, forestry, agribusiness, workforce capacity, skills, digitalisation, green transition

1. INTRODUCTION

Forestry and agribusiness are increasingly shaped by the twin transition: the combined pressure to digitalise production and management systems while simultaneously adopting more sustainable, resource-efficient and low-carbon practices. In both sectors, competitiveness is no longer defined only by access to land, timber, machinery or markets. It is also conditioned by the ability of companies to absorb new knowledge, use digital tools effectively, comply with environmental requirements and reorganise work around new technological and regulatory realities [2, 6, 8].

This challenge is particularly visible in sectors that have long been characterised as low-technology or medium-low-technology end users of innovation. In such contexts, renewal rarely depends on internally generated research alone. More often, new solutions enter through suppliers, service providers, software platforms, advisers and value-chain partners, while companies themselves must develop the organisational and human capacity to apply them productively [3, 4, 9, 10]. As a result, the question is no longer whether technology is available, but whether the workforce is able to turn it into measurable economic and environmental gains.

Against this background, the paper examines whether workforce capacity in forestry and agribusiness functions as a catalyst for the twin transition or rather emerges as a structural constraint. The contribution is twofold. First, it conceptualises workforce capacity not simply as labour availability, but as a combination of sector-specific knowledge, digital literacy, sustainability-related competences, adaptability and learning capability. Second, it uses

preliminary empirical evidence to identify the conditions under which workforce-related factors accelerate, delay or even block the transformation process.

2. WORKFORCE CAPACITY AS AN ANALYTICAL LENS

For the purposes of this paper, workforce capacity is understood as a multidimensional construct that combines the quantity and quality of labour with the ability of firms to mobilise, upgrade and retain relevant competences. In the context of forestry and agribusiness, this capacity cannot be reduced to formal qualifications alone. It also includes practical knowledge of production processes, the ability to work with data, the capability to interpret environmental requirements, and readiness to adapt to new organisational routines.

This perspective is important because the twin transition generates demand for hybrid competence profiles. Precision farming, automated forest-resource management, remote sensing, digital traceability, predictive maintenance, energy-efficiency measures and circular-bioeconomy practices require workers and managers who can combine sector-specific expertise with technological literacy and ecological awareness [1, 2, 6, 9]. The more complex the innovation, the more relevant become communication, teamwork and problem-solving skills, since new technologies often reconfigure workflows across the entire enterprise.

Table 1. Workforce capacity in the twin transition: key analytical dimensions

Dimension	Constraint signal	Catalyst signal
Skills profile	Fragmented competences; weak combination of operational, digital and sustainability knowledge	Hybrid skills; ability to use data, digital tools and environmental standards in daily work
Demography	Ageing staff, labour shortages, high turnover, limited rural attractiveness	Generational renewal, mentoring and stronger retention of younger specialists
Training culture	Ad hoc or supplier-led training; low investment in continuous learning	Regular upskilling and reskilling linked to technology and process change
Institutional linkages	Weak cooperation with VET, universities and advisory structures	Active partnerships that support knowledge transfer and curriculum relevance
Organisational readiness	Resistance to change; compliance-only approach	Innovation-oriented culture and internal knowledge sharing

Source: own elaboration

In this sense, workforce capacity mediates between technology availability and actual transition outcomes. Even when firms invest in machinery, software or environmental upgrades, weak absorptive capacity may reduce the return on these investments. Conversely, firms with stronger learning cultures, internal knowledge transfer and external partnerships are more likely to translate digital and green investments into productivity gains, compliance advantages and improved resilience. The catalyst-or-constraint dilemma therefore depends not only on the state of the labour market, but also on the way firms organise competence development and interact with the surrounding innovation ecosystem.

3. METHODOLOGY

The analysis combines two empirical layers. The first is contextual evidence from a nationally representative survey of innovation potential in Bulgarian agriculture conducted in April–May 2025. The survey covered 522 enterprises and used a two-stage stratified sampling design by region, specialisation and enterprise size. It provides a broader picture of innovation behaviour, process renewal and the sources of technological change in agribusiness [4]. In the present paper, these data are used not as a direct test of the forestry dimension, but as a robust contextual benchmark for understanding sectoral innovation conditions.

The second empirical layer is a pilot questionnaire survey among companies from forestry and agribusiness focused specifically on workforce-related aspects of the twin transition. The pilot captures employer self-assessments of workforce readiness, skills gaps, reskilling and upskilling needs, demographic pressures, and cooperation with educational and training institutions. Because the study is exploratory, it does not aim at statistical representativeness. Its value lies in identifying emerging patterns, perceived bottlenecks and practical transition needs at company level.

Analytically, the paper treats company responses as evidence of perceived readiness rather than as an objective measurement of individual competences. This distinction is important. The findings illuminate how firms interpret their own workforce-related constraints, what types of skills they consider scarce, and which organisational conditions they see as necessary for moving from technology adoption to effective transformation.

4. PRELIMINARY FINDINGS AND DISCUSSION

The discussion below is organised around the analytical dimensions introduced in Table 1, moving from skills profile and demography to training culture, institutional linkages and organisational readiness. The contextual agribusiness evidence suggests that process modernisation is already under way, but not always accompanied by comparable progress in workforce development. TIn the national agricultural survey, nearly 57% of enterprises reported renewal of machinery and equipment during the preceding three years, while more than 56% used specialised software, mostly for financial and administrative management [5]. At the same time, the survey showed that firms relied only to a limited extent on research organisations and universities when accessing new knowledge. This indicates a pattern in which technological acquisition may advance faster than the development of deeper organisational learning and science-based competence support.

The pilot survey points in the same direction. A first recurring theme is the shortage of hybrid skills. Respondents tend to distinguish between traditional sectoral know-how and the newer capacities needed for data-based decision making, digital monitoring, traceability systems, environmental reporting and resource optimisation. In other words, firms may have operational experience, but still lack the competence mix required to use digital and green tools strategically. This makes workforce capacity a transition constraint even in companies that have already invested in hardware or software.

This echoes the argument that Industry 4.0 in agriculture and forestry depends less on the technologies themselves than on the hybrid competence profiles needed to operate them [1, 2], and is consistent with the observation that low- and medium-technology sectors absorb innovation primarily through external partners rather than internal research [3, 8].

A second theme concerns demographic and territorial pressures. Employers identify ageing workforces, limited attractiveness of rural employment, difficulties in recruiting younger specialists and uneven access to training opportunities outside major urban centres as structural challenges. These pressures are especially relevant for forestry and agribusiness because many activities remain territorially embedded, seasonal or physically demanding. Under such conditions, the twin transition is not only a technology issue; it is also a labour-market issue linked to generational renewal and the social sustainability of rural work.

A third theme is organisational culture. Pilot responses suggest that workforce development is still frequently treated as a secondary or reactive function rather than as a strategic investment. Training is often supplier-led, short-term or compliance-driven, and less often embedded in a broader learning strategy. This limits the firm's ability to diffuse knowledge internally, create hybrid roles or sustain change once a specific project or subsidy period ends. As a result, transformation risks remaining fragmented: new tools are introduced, but routines, responsibilities and incentives remain largely unchanged.

Finally, the pilot survey highlights the importance of institutional linkages. Companies that maintain more active relationships with universities, vocational providers, consultants, branch organisations or cluster-type structures are better positioned to identify emerging skills needs and to translate innovation into everyday practice. Where such linkages are weak, firms depend heavily on private suppliers for knowledge, which may support technology uptake but not necessarily broader workforce development. This is a critical distinction for the twin transition, where successful adaptation requires not only equipment and compliance, but also continuous learning and cross-sector knowledge exchange.

Two limitations should be noted. First, the pilot is exploratory and non-representative; its findings indicate perceived rather than objectively measured workforce conditions, and they should be read as hypotheses for further testing.

Second, the contextual survey covers agriculture rather than forestry directly, so its evidence is used as a sectoral benchmark rather than as a substitute for forestry-specific data.

5. CONCLUSION

Reading these outcomes against the dimensions in Table 1 clarifies where the balance tips. Workforce capacity acts as a catalyst where hybrid skills, generational renewal, embedded learning cultures and active institutional linkages reinforce one another. It becomes a constraint where competences remain fragmented, demographic pressures go unaddressed, training stays supplier-led and ad hoc, and cooperation with education and advisory structures is weak. The decisive factor is therefore not the presence of technology, but the alignment of these workforce conditions around it.

The paper argues that workforce capacity occupies a pivotal position in the twin transition of forestry and agribusiness. It is neither a secondary background variable nor a purely labour-market issue. Rather, it is the mechanism through which digital and green ambitions are translated into concrete organisational change. When companies can attract, develop and retain workers with hybrid competences, workforce capacity becomes a catalyst for transformation. When skills gaps, demographic decline, weak training cultures and limited institutional cooperation dominate, the same capacity becomes a bottleneck.

For this reason, transition policies should go beyond technology funding alone. They should support practice-oriented training, modular upskilling and reskilling, stronger links

between companies and education providers, and place-based solutions adapted to rural and peripheral contexts. For firms, the implication is equally clear: workforce development should be integrated into innovation strategy rather than treated as an afterthought. The pilot evidence reported here is preliminary, but it indicates that the success of the twin transition in forestry and agribusiness will depend as much on people, learning and organisational adaptation as on machines, software and regulation.

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REFERENCES (ALPHABETICAL ORDER)

1. Bernhardt, H., Bozkurt, M., Brunsch, R., Colangelo, E., Herrmann, A., Horstmann, J., Kraft, M., Marquering, J., Steckel, T., Tapken, H., Weltzien, C., & Westerkamp, C. (2021). Challenges for Agriculture through Industry 4.0. Agronomy, 11(10), 1935. https://doi.org/10.3390/agronomy11101935
2. Bjerke, L.; Johansson, S. Innovation in Agriculture: An Analysis of Swedish Agricultural and Non-Agricultural Firms. Food Policy 109 (2022), 102269. https://doi.org/10.1016/j.foodpol.2022.102269
3. Fieldsend, A. F., Cronin, E., Varga, E., Biró, S., & Rogge, E. (2020). Organisational Innovation Systems for multi-actor co-innovation in European agriculture, forestry and related sectors: Diversity and common attributes. NJAS: Wageningen Journal of Life Sciences, 92(1), 1–11. https://doi.org/10.1016/j.njas.2020.100335
4. Georgieva, T. M. Innovation Activity in Agriculture: Main Drivers and Enabling Factors. In: Proceedings of the 19th International Scientific Conference WoodEMA 2026, forthcoming.
5. Iordanis, P.; Emvalomatis, G.; Läpple, D.; Thorne, F.; Wallace, M. (2024):The Contribution of Innovation to Farm-Level Productivity. Journal of Productivity Analysis 62, 239–255. https://doi.org/10.1007/s11123-024-00728-0
6. Mileva, S., Georgieva, T. (2022): Sectoral innovation system of agribusiness in Bulgaria – main challenges and perspectives. Access to science, business, innovation in digital economy, ACCESS Press, 3(3): 307-338. https://doi.org/10.46656/access.2022.3.3(9)
7. Żemigała, M. (2018):Tendencies in Research on Innovation in Low-Technology Sectors. Operations Research and Decisions 4. https://doi.org/10.5277/ord180408
8. *** McKinsey (2020), Goedde, L. et al. Agriculture's Connected Future: How Technology Can Yield New Growth. McKinsey Center for Advanced Connectivity and Agriculture Practice, https://www.mckinsey.com/industries/agriculture/our-insights/agricultures-connected-future-how-technology-can-yield-new-growth
9. *** World Economic Forum. (2024, September). Mainstreaming food innovation: A roadmap for stakeholders (White paper). World Economic Forum; Boston Consulting Group. https://www3.weforum.org/docs/WEF_Mainstreaming_Food_Innovation_2024.pdf
10. ***: World Bank (2012): Agricultural Innovation Systems: An Investment Sourcebook. ISBN 978-0-8213-8944-7. https://doi.org/10.1596/978-0-8213-8684-2

Author's address:
Sonia Mileva
Faculty of Economics and Business Administration, Sofia University "St. Kliment Ohridski"
1113 Sofia, Bulgaria
smileva@feb.uni-sofia.bg

INCREASING URBAN TREE PLANTING SUCCESS UNDER CLIMATE CHANGE THROUGH SMART FARMING TECHNOLOGIES

Svetla Markova

Abstract: With cities expected to house more than two thirds of the population by 2050, urban tree planting becomes critical for mitigating climate change, urban heat and air quality, as well as the health and resilience of the population in cities. The long-term success of urban tree planting programs depends substantially on the availability of climate-resilient trees capable of surviving and performing under both current and future environmental stress. To improve post-transplant establishment and long-term robustness, tree nurseries must be able to expose saplings to conditions that approximate the unfavourable environments they are likely to encounter after planting. This review examines the role of smart farming solutions in the cultivation of tree saplings in greenhouse nurseries, focusing on their capacity to simulate future stress conditions associated with climate change and urban anthropogenic pressure. By assessing the usage of smart farming solutions in tree sapling greenhouses in the Netherlands and South Africa, the research evaluates the potential of such technologies to support long-term urban tree planting strategies, improve plantation success, and reduce associated costs, for countries with differing environmental and economical contexts.
Keywords: urban tree planting, smart farming technologies, climate-resilient trees, climate change adaptation, Netherlands, South Africa

1. INTRODUCTION

By 2050, 68% of the global population is expected to live in urban areas. With climate change, environmental challenges like extreme heat, drought and increased flooding are expected to intensify. Tree planting can significantly cool cities through canopy shading, reduced heat emission from urban surfaces, and transpiration, helping to dissipate heated air. Bowler et al. (2010) point out that urban green areas are cooler than built-up surroundings. Alonzo et al. (2025) confirm that urban trees mitigate extreme heat through shading and evapotranspiration. Thus, trees should no longer be viewed only as decorative urban elements – if carefully pre-conditioned, maintained and able to survive the post-planting stress and urban conditions, they can function as cooling infrastructure, helping the cities to cope with rising heat.

Smart farming greenhouse technologies can guide and control this adaptation process, making it precise, measurable and repeatable. Existing research addresses nursery establishment practices and smart greenhouse production separately. Limited attention has been paid to how smart greenhouse technologies could intentionally prepare urban tree saplings for future climate stress, across different national contexts. This paper reviews evidence on the use of smart farming technologies in nursery production, focusing on the Netherlands and South Africa as countries with extensive greenhouse experience but different climate challenges. It also evaluates the potential of such technologies to support long-term urban tree planting strategies by reducing associated costs.

2. METHODS

This paper uses a mixed-methods approach, combining a review of relevant scientific literature, examination of publicly available website data with regard to smart farming technologies, commercial and research greenhouse projects and discussions with experts in

the field. The collected data were analysed and compared using descriptive statistical methods to allow key patterns, similarities, and differences to be identified across the selected sources.

3. RESULTS AND DISCUSSION

Producing tree saplings capable of surviving under changing climate conditions requires growth-environment management and control, exposing plants to the stress factors they are likely to encounter after planting. This approach can be implemented through smart farming greenhouse solutions. In this paper, the term refers to technologies that combine sensors, IoT, automation, data analytics and decision support tools to monitor and control growing conditions, aiming to improving resource efficiency, crop performance and resilience (Bersani et al., 2022)

Among the main climate change factors causing stress and low survival rates of planted tree saplings are drought, heat, overwatering and compacted soils caused by floods and excessive rainfall, and excessive salinity of the irrigation water. Scientific studies show that exposing plants to controlled drought can improve drought tolerance, although the effect depends on how the stress is managed. Guarnaschelli et al. (2006) conclude that drought conditioning improves water status and survival of Eucalyptus seedlings. Vilagrosa et al. (2003) show that drought preconditioning as a nursery technique enables drought-hardened seedlings to be less water-stressed than seedlings experiencing drought for the first time and post-transplanting survival is higher. In greenhouse nurseries, smart sensor-based control can expose plants to controlled drought while recording the intensity and duration of drought periods, improving post-planting resilience without being lethal for the saplings.

Heat stress, induced via exposure to increased temperatures before planting can also improve heat tolerance. Heat preconditioning activates protective mechanisms, including the production of heat-shock proteins. Chopra et al. (2025) conclude that thermopriming enhances plant resilience and prepares them for future heat stress. Ladjal et al. (2000) reveal that heat-preconditioned seedlings of three Mediterranean cedar species show higher tolerance to heat stress compared to unconditioned ones. Zhang et al. (2025) point out that plant thermotolerance can be improved through prior exposure to short-term, mild, or moderate heat shock. In greenhouse conditions, smart farming solutions can precisely regulate temperature, create heat shock, and measure plant response.

Waterlogging is another stress factor for plants. Occasional but severe flood events, expected to become more frequent under climate changes, result in compacted soils, affecting root growth by reducing oxygen in the root zone, limiting water uptake and nutrient absorption. Controlled preconditioning in greenhouses can help plants survive waterlogging stress. Feng et al. (2022) show that waterlogging priming enhances waterlogging tolerance in wheat. Yamauchi et al. (2018) describe adventitious roots and barriers to radial oxygen loss as key traits involved in plant acclimation to waterlogged soils. Smart farming solutions can simulate waterlogging in tree-sapling nurseries as a controlled and measurable stress treatment through automated irrigation, drainage control, root-zone sensors, and climate monitoring.

Climate change is expected to increase soil salinisation in many regions due to higher evapotranspiration and sea-level rise. Building salinity tolerance depends on mechanisms that can be activated before severe exposure. Llanes et al. (2021) explain that in woody plants important salt-tolerance mechanisms include ion compartmentalization, synthesis of protective proteins and activation of stress-related transcription factors. Preconditioning activates these responses gradually, so the sapling is not shocked. Gupta and Huang (2014) describe salt

tolerance as a complex response involving physiological traits and metabolic pathways. Therefore, salinity-preconditioned saplings may survive better because they have already started adjusting their stress-defence systems before being planted in adverse field conditions.

Smart farming technologies can support the preconditioning of tree saplings for region-specific climate change stress factors while making the process controlled, measurable and repeatable. Al-Najadi et al. (2026) state that a smart greenhouse typically consists of microcontrollers, actuators, and sensors. Sensors collect critical data on soil, plant, and climatic conditions to support data-driven decisions, while actuators manage control mechanisms within the system. Thus, soil moisture can be regulated through sensor-based automated irrigation, while irrigation and fertigation can be adjusted according to temperature, humidity, light, and other environmental parameters. By mapping the pre-conditioning needs of the trees to the potential of smart greenhouse solutions, we see in Table 1 how each preconditioning need can be addressed by smart farming technologies, ensuring a measurable and repeatable result.

Table 1. Handling of preconditioning needs by smart farming technologies in nurseries

Stress factor	Preconditioning need	Smart farming technology used
Drought	Controlled exposure to water deficit	Soil moisture sensors-based irrigation, irrigation and environmental parameters log and data analytics
Heat	Preconditioning for heat	Air temperature and humidity sensor-based climate control, environmental parameters log and data analytics
Waterlogging	Controlled irrigation	Soil sensor-based irrigation, irrigation and environmental parameters log and data analytics
Salinity	Irrigation water EC control	EC sensor-based control of irrigation water, irrigation and EC sensor historical data log and analytics
Overall plant stress	Controlled stress, without being lethal	Plant wellbeing monitoring via NDVI indices, NDVI historical data and analytics mapped to other sensor data

Applying moderate drought, heat, salinity or other stress increases the overall resilience of the plant to adverse conditions. Scientific literature confirms that drought hardening results in improved water-use efficiency, root growth potential, and stress resistance (Gupta & Huang, 2014). Drought-preconditioned seedlings are able to maintain higher heat tolerance than unconditioned ones (Von Moler & Nelson, 2021), showing that one controlled stress can increase tolerance to another. Smart farming technologies can thus act as a practical nursery tool for producing resilient tree saplings by "training" them before moving to urban environment.

Greenhouses play a central role in global food security, sustainability goals and climate adaptation. The Netherlands and South Africa are leaders on their continents, with the first holding 30% in the European greenhouse market while South Africa accounts for 35–40% of the horticulture value in Africa. Both countries are greenhouse innovators but operate in different economic and ecological contexts. Thus, their experience with using smart greenhouse solutions for crop adaptation can be reviewed to draw broader conclusions.

In the Netherlands, evidence from innovation projects like Plantar and Compas Agro show that water and fertilizer resources are being optimised in tree and horticulture nurseries with smart farming technologies like sensor-based irrigation and fertigation, soil/substrate moisture sensors, weather stations, plant-stress sensing and AI-based forecasting. Research institutions like WUR and commercial suppliers like Priva and Ridder are showcasing the usage of AI, cameras, climate monitoring and forecasting for autonomous greenhouse cultivation. The examples relate to growing vegetables, ornamental or container plants, but they focus on controlling the same variables - irrigation, fertigation, temperature, humidity, plant stress, etc. and this the technologies may also be applied to tree saplings. In South Africa, the successful usage of smart farming solutions in the tree nursery sector is demonstrated in Sappi research centre's smart nurseries (SA Forestry, 2024), the automated irrigation and precise fertigation solutions in Mondi's sapling nurseries (ONDO, 2026), Netafim South Africa greenhouses with precision irrigation, fertigation and climate control, BCC's nursery automation equipment. Not all examples are being used in explicit tree sapling greenhouses, but they are directly relevant to sapling production due to their ability to control key variables related to preconditioning the tree saplings - soil moisture, nutrients, air temperature and humidity and overall plant stress.

As the above evidence shows, smart farming solutions in both the Netherlands and South Africa are already controlling the climate and soil parameters in nurseries, and those technologies can be used for preconditioning nursery tree saplings. The exact technologies used vary between the two countries based on the climate specifics and needs. Compared with South Africa, the Netherlands faces a wetter and coastal climate risk while South Africa is challenged by increased heat and drought, as well as water stress.

Table 2. Climate change stress factor relevance – Netherlands and South Africa

Stress factor	Relevance for The Netherlands	Relevance for South Africa
Drought	**High.** Drought risk getting higher in dry summers	**Very high.** Drought is a major risk, increased dry period duration
Increased heat	**High.** Climate warmed by about **2°C since the early 20th century**	**High.** Climate warmed by **1.04 – 1.44°C for 1961–2015,** trend persists
Irregular rainfall	**High.** Wetter winters, drier summers, extreme rainfall	**Very high.** Overall trend toward **drier conditions**, but regional variation
Waterlogging	**Very high.** Flat terrain and exposure to sea rise	**High.** Intense rainfall floods linked to climate change
Soil salinity	**Very high.** Major national risks, linked to rising sea level.	**Mid.** Coastal areas are exposed but no country-wide impact expected

Source: Dutch Climate Risk (2026), Royal Netherlands Meteorological Institute (2023), Department of Forestry (2026), World Weather Attribution (2022)

Smart farming technologies can also reduce the long-term costs of urban tree plantation by improving the quality, survival rate and predictability of saplings planted in stressful urban environments. A major cost of urban tree planting is related to the maintenance, replacement of dead trees, labour and the delayed loss of ecosystem benefits when trees fail to establish (Forest Research, 2019). Sensor-based irrigation and precise fertigation, data-driven climate control and stress conditioning in nurseries and greenhouses enables the growth of saplings with stronger root systems and greater tolerance to drought, heat or other stress factors. Research on greenhouse and nursery crops shows that sensor-controlled irrigation reduced

production time and crop losses by more than half compared with standard practice (Lichtenberg et al., 2013). Thus, smart nursery production can reduce the probability of post-transplant survival failure and lower the demand for replanting and intensive aftercare. Although the initial investment in sensors, controllers and automation can be significant, these technologies may generate savings over the full plantation cycle by reducing sapling waste, improving labour efficiency, extending the lifespan of urban trees and thus increasing the overall ecological and social benefit for the urban environment as a whole.

Preconditioning tree saplings comes with ecological and social benefits. However, these benefits must be weighed against the costs of sensors, automation, software, training and system maintenance. At present, there is still limited direct evidence showing whether smart-conditioned urban tree saplings reduce total life-cycle costs in practice. Future studies should therefore combine nursery monitoring, post-planting survival data and economic assessment to determine whether resilience-oriented production can deliver measurable long-term benefits.

4. CONCLUSIONS

This review demonstrates that nursery production for the urban tree sector necessitates adaptation to climate changes and the increasingly stressful urban environments. Saplings intended for city planting should therefore be preconditioned for stress tolerance and resilience for the specific adverse, climate-change-related conditions they are likely to face after transplanting. Smart farming technologies can support this process by allowing nurseries to apply controlled, measurable and reproducible conditioning regimes through precise and traceable control of the irrigation, fertigation and climate parameters. However, such pre-conditioning of the young trees must be carefully designed around local climate projections, and species-specific thresholds and responses, in order to enhance resilience without compromising plant quality, establishment potential or long-term well-being.

The comparison between the Netherlands and South Africa suggests that smart nursery solutions may need to address different, region-specific climate challenges. The economic value of smart-conditioned saplings lies in savings from lower mortality, fewer replacements, reduced replanting labour and maintenance, and greater ecosystem benefits. Further empirical evidence is needed on whether preconditioning reduces costs in practice, particularly when the investment and operational cost of smart greenhouse technologies are accounted for.

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REFERENCES (alphabetical order)

1. Al-Najadi, R.; Al-Mulla, Y.; Goher, K. (2026): *Advances in intelligent and autonomous greenhouse systems: A comprehensive review of internet of things, artificial intelligence, and robotics integration.* Smart Agricultural Technology 13: 101670
2. Alonzo, M.; Ibsen, P. C.; Locke, D. H. (2025): *Urban trees and cooling: A review of the recent literature (2018 to 2024)*. Arboriculture & Urban Forestry 51 (5): pp. 420-444.
3. Bersani, C.; Ruggiero, C.; Sacile, R.; Soussi, A., Zero, E. (2022): *Internet of Things Approaches for Monitoring and Control of Smart Greenhouses.* Energies, 15 (10): 3834
4. Bowler, D. E.; Buyung-Ali, L.; Knight, T. M.; Pullin, A. S. (2010): *Urban greening to cool towns and cities: A systematic review.* Landscape and Urban Planning 97(3): pp. 147–155.

5. Chopra, P., Sapia, N., et al. (2025): *Priming thermotolerance: Unlocking heat resilience for climate-smart crops.* Philosophical Transactions of the Royal Society 380.
6. Feng, K.; Wang, X. (2022): *Waterlogging priming enhances hypoxia stress tolerance of wheat offspring plants by regulating root phenotypic.* Plants 11 (15): 1969.
7. Guarnaschelli, A. B.; Prystupa, P.; Lemcoff, J. H. (2006). *Drought conditioning improves water status, stomatal conductance and survival of Eucalyptus globulus subsp. bicostata seedlings.* Annals of Forest Science 63 (8): pp. 941–950.
8. Gupta, B.; Huang, B. (2014): *Mechanism of salinity tolerance in plants: Physiological, biochemical, and molecular characterization.* International Journal of Genomics 2014.
9. Ladjal, M.; Epron, D.; Ducrey, M. (2000): *Effects of drought preconditioning on thermotolerance of photosystem II and susceptibility of photosynthesis to heat stress in cedar.* Tree Physiology 20 (18): pp. 1235–1241.
10. Lichtenberg, E.; Majsztrik, J.; Saavoss, M. (2013): *Profitability of sensor-based irrigation in greenhouse and nursery crops.* Hort Technology 23 (6): pp. 770–774.
11. Llanes, A.; Palchetti, M. V.; Vilo, C.; Ibañez, C. (2021): *Molecular control to salt tolerance mechanisms of woody plants.* Annals of Forest Science 78 (96) 2021.
12. Vilagrosa, A.; Cortina, J.; Gil-Pelegrín. E.; Bellot, J. (2003): *Suitability of drought-preconditioning techniques in Mediterranean climate.* Ecology 11 (2): pp. 208–216.
13. Von Moler, E. R.; Nelson, A. S. (2021): *Perspectives on drought preconditioning treatments with a case study using western larch.* Frontiers in Plant Science 12: Article 741027.
14. Yamauchi, T.; Colmer, T. D.; Pedersen, O.; Nakazono, M. (2018): *Regulation of root traits for internal aeration and tolerance to soil waterlogging-flooding stress*. Plant Physiology, 176(2): pp. 1118–1130.
15. Zhang, X.; Rossi, S.; Zhuang, L.; Dodd, I. C.; Huang, B. (2025): *Stress priming mechanisms that enhance plant temperature tolerance.* Environmental and Experimental Botany 237: Article 106208.
16. *** Forest Research (2019). URL: https://cdn.forestresearch.gov.uk/2019/06/frrn039.pdf
17. *** SA Forestry (2024). URL: https://saforestryonline.co.za/articles/silviculture/sappi-builds-smart-nurseries-for-a-changing-environment/
18. *** ONDO (2026). URL: https://ondo.io/ondo-success-mondi-south-africa/
19. *** Dutch Climate Risk (2026). URL: https://dutchclimaterisk.nl/climate-risk/dutch-climate-scenarios/
20. *** Royal Netherlands Meteorological Institute (2023). URL: https://openresearch.amsterdam/
21. *** Department of Forestry (2026). URL: https://nccis.environment.gov.za/climate-services/climate-projections
22. *** World Weather Attribution (2022). URL: https://www.worldweatherattribution.org

Authors address:
Markova, S. [1]
[1] Department of Industrial Economics and Management, Faculty of Economics and Business Administration, Sofia University “St. Kliment Ohridski”, Sofia, Bulgaria
*Corresponding author: sivanovam@uni-sofia.bg

BIOECONOMY IN ACTION: PROSPECTS FOR THE UTILIZATION OF FOREST RESIDUES

Violeta Blazheva

Abstract: Forests are a natural ecosystem. They provide oxygen, regulate the climate and conservation over 80% of biodiversity. Sustainable management of forests as a resource is of strategic importance. Forests perform multiple functions: ecosystem function; climate regulation function; social function; economic function. According to publicly available data, the forest area worldwide amounts to about 32% of the earth's surface. At the European level, forests make up 47% of the territory of the European Union. An EU Forest Strategy to 2030 has been developed for sustainable forest management. At the national level, this percentage ranges from 33-39%. It is claimed that over the past 60 years, the area of forests in Bulgaria has increased by nearly 23%, and the wood stock has increased threefold. The above draws attention to forest residues as a residual (branches, twigs and tops of trees), a by-product of wood obtained during logging and harvesting of wood material (timber harvesting). The quantities of residual, by-products of wood depend on a number of factors such as: type of forest, age of trees, intensity of logging and other factors. In the conditions of bioeconomy, the possibility of utilizing the forest residues is important, namely in the search for ways for its quantitative use as a valuable resource for: energy purposes; reproductive purposes; economic purposes and other purposes. For decision-making, respectively, perspectives on the markets of wood products, models for added value and sustainability are used. The goal is to achieve a balance by combining economic growth and environmental protection (as a result of the utilized quantities of forest residues).

Keywords: forest residues, slash, harvesting of wood material

1. INTRODUCTION

In the context of the bioeconomy, biological resources are used to produce food, energy, materials and products. The aim is to achieve and ensure sustainability by using resources without destroying their ability to regenerate.

The distribution of forest areas worldwide is as follows (Table 1):

Table 1. Forest area of land area, by region, 2025

Region	Forest area		
	Total (1 000 ha)	% of world forest area	% of land area
Africa	662 630	16	22
Asia	630 029	15	20
Europe	1 038 911	25	47
North and Central America	776 162	19	37
Oceania	183 898	4	22
South America	848 587	20	49
World	**4 140 217**	**100**	**32**

Source: FAO

Structures and organizations that monitor and permanently report on the state of forests are: Eurostat, the International Tropical Timber Organization and the United Nations Economic Commission for Europe, and others.

Globally, public ownership of forests prevails – 71%; followed by private ownership of forests – 4.24% and the remainder, categorized as “unknown” or “other” ownership – 24.76%.

In the period 1990-2020, forest management has shown a trend of decreasing the share of forests owned by public administrations, from 94% to 81%, and increasing the share of public forests managed by economic entities, from 4% to 15%. The share of public forests managed by the local population has increased from 2% to 3%.

Information on the use of forest and wood resources helps to compare their actual state.

Forest biomass per unit area has increased by 10.5 tons per hectare globally between 1990 and 2025. This represents an increase of 7%.

The use of forest residues allows the transformation of by-products into a resource.

Attention is drawn to the so-called logging residues or slash. These are logging residues that do not have a commercial form - tree tops, twigs, limbs, branches, bark, and stumps.

The term slash in forestry refers to wood waste, the so-called forest biomass, which is classified into:

- "coarse" wood waste - thick branches, tree tops;
- "fine" wood waste - leaves, needles, thin twigs.

The top is a residual wood product obtained from felling and processing wood. It includes branches, twigs and top parts of trees that are not suitable for primary wood material.

Outside the scope of the concept remains sawdust, a by-product or waste from wood processing obtained after cutting, planing, milling or grinding.

2. DIRECTIONS FOR FOREST USE

2.1. Production of wood and non-wood forest products

Globally, 30% of the total forest area is used for the production of wood and non-wood forest products. The leader in this area is Europe - 548 million hectares (Table 2).

Table 2. Forest area for production, by region, 2025

Region	Forest area for production	
	Total (1 000 ha)	% of total forest area
Africa	111 589	17
Asia	192 200	32
Europe	547 958	54
North and Central America	221 840	29
Oceania	9 639	5
South America	121 765	15
World	1 204 990	**30**

Source: FAO

2.2. Biodiversity conservatio

The world's forests for biodiversity conservation amount to 482 million hectares – 12% of the total forest area (Table 3).

Table 3. Forest area for biodiversity conservation, by region, 2025

Region	Forest area for biodiversity conservation	
	Total (1 000 ha)	% of total forest area
Africa	130 050	20
Asia	79 481	13
Europe	43 591	4
North and Central America	79 894	10
Oceania	29 316	16
South America	119 972	14
World	482 305	**12**

Source: FAO

2.3. Soil and water protection

Globally, 386 million hectares of forests are primarily dedicated to soil and water protection – 10% of the total forest area. Europe has a leading position in soil and water protection, 173 million hectares (17% of the total forest area) - Table 4.

Table 4. Forest area for soil and water protection, by region, 2025

Region	Forest area for soil and water protection	
	Total (1 000 ha)	% of total forest area
Africa	28 453	5
Asia	123 876	21
Europe	173 491	17
North and Central America	16 092	2
Oceania	1 797	4
South America	42 348	6
World	386 055	**10**

Source: FAO

2.4. Social services

About 221 million hectares of forests worldwide are designated for social services such as recreation, tourism, education, research, and the preservation of cultural and spiritual sites – 5% (Table 5).

Table 5. Forest area for soil and water protection, by region, 2025

Region	Forest area for soil and water protection	
	Total (1 000 ha)	% of total forest area
Africa	4 441	1
Asia	25 704	4
Europe	19 168	2
North and Central America	17 988	2
Oceania	0	0
South America	153 505	23
World	220 806	**6**

Source: FAO

The data presented is an indicator for searching for sources of information to cover forest areas, categorized as: unknown; no designation; other.

3. CONCLUSION

The utilization of forest residues as a residual, by-product requires their management. Their use is possible in the following directions:

- Conversion of forest residues into renewable energy - Wood waste is a source of lignocellulosic biomass;
- Controlled burning of large quantities of forest residues - To prevent the occurrence of forest fires;
- Achieving ecological balance - Leaving quantities of wood residues in the forest - a source of nutrients for the soil and habitat for local species.

According to publicly available data, logging residues vary within 66/34, i.e. the wood/waste ratio is 66% - wood and 34% - forest residue.

The volume of felled forest wood is an indicator of the priority economic and social role of forest resources in national economies. Revenues from harvested wood are the largest source of revenue from forests.

In the context of bioeconomy, the possibility of utilizing the quantities of sawn wood in search of prospects for its use as a resource is important - the application of technologies for transforming sawn wood into a higher-value product, or rather into a model for sustainability.

For this purpose, more detailed information is needed to allow the construction of an economic model to assess the effect of realizing the quantities of sawn wood. This model is of fundamental importance for decision-making.

Testing the economic model will allow checking its reliability, accuracy and applicability in a real environment. This stage turns the theoretical concept into a practical tool through empirical verification and analysis of the results.

In conclusion, forests are a complex ecosystem with multifaceted significance: economic significance; ecological and climatic significance; social significance.

Forest residues is a valuable resource that is used mainly for energy purposes and in forestry. Its sustainable management is of strategic importance - for maintaining global carbon cycles and long-term ecological stability.

REFERENCES

1. FAO (2025): Global Forest Resources Assessment 2025. Rome. https://doi.org/10.4060/cd6709en
2. Koopmans, A; Koppejan, J. (1997): Agricultural and Forest Residues Generation, Utilization and Availability. Regional Consultation on Modern Applications of Biomass Energy, 6-10 January 1997, Kuala Lumpur, Malaysia: p. 3.
3. Petrova, S. (2025): Analyzing E-Commerce of Small and Medium-Sized Enterprises in the European Union: Dependencies and Trends in the Context of Digitalization. Environment. Technology. Resources. Rezekne, Latvia, Proceedings of the 16th International Scientific and Practical Conference, 2025, Volume II, pp. 265-270.

Author address:
Blazheva, V.
[1] Department of Agricultural Economics, Faculty of Industry and Commerce, Tsenov Academy of Economics, Svishtov, Bulgaria
*Corresponding author: v.blazheva@uni-svishtov.bg

THE FORESTRY AND WOOD-BASED SECTOR IN THE EUROPEAN BIOECONOMY: A COUNTRY COMPARISON BASED ON GROSS ADDED VALUE

Vladislav Kaputa, Martin Synák-Varga

Abstract: In light of the growing importance of bioeconomy sectors in European Union strategies, this paper focuses on assessing the economic value currently generated by subsectors of the forestry and wood-based sector in selected EU countries. We use the gross value added of specific bioeconomy subsectors, classified according to the NACE Revision 2 categorization, as a tool. The total value of the measure depends on several factors (e.g. the availability of resources in a given country or the volume of processing capacities), but it interestingly highlights the contribution of value created by the wood processing branches to the total value created by the given economy. The results highlight differences in the structure and economic contribution of this bioeconomy sector across countries, with Slovakia possessing untapped potential in the area of final processing of wood products.
Keywords: gross value added, bioeconomy, forest-based sector, wood processing

1. INTRODUCTION

The bioeconomy, as a component of the economic development of EU member states, is increasingly coming to the forefront as a tool for implementing environmental objectives and enhancing competitiveness in international trade. One of its key sectors is the forest-based sector (FBS), which combines the economic utilisation of renewable natural resources with the social and environmental goals of European countries. Its significance is growing in the context of the EU's ambitious green economy targets and sustainable development objectives. In addition to forestry and logging activities, Palátová et al. (2023) stated that the processing of wood and downstream industries using wood as input is vital to the economic development in many (rural) regions. Across the literature, primary forestry usually contributes a modest share of GDP or GVA, while wood processing, paper, furniture, and broader forest-based bioeconomy activities account for much larger value creation and stronger multipliers (Li et al., 2019; Vineta Tetere et al., 2024; Chang-kee Lee et al., 2022). The share of the NACE divisions under review within the sector in question varies depending on the conditions in each country and their international market environment. For example, Sujová (2023) points to the theoretical and logical premise that the furniture industry should achieve a higher value-added rate than the timber industry. Slovakia had the strongest comparative advantage in the trade of industrial coniferous roundwood due to its sufficient wood resources and competitive prices (Parobek et al., 2016). The competitiveness of the Slovakian forest-based sector is insufficient and reflects the low level of wood processing.

2. METHODOLOGY

This study analyses the gross value added (GVA) of the sector referred to as the forest-based sector (FBS), a broader term that also encompasses the wood-based sector. GVA was

selected as the primary quantitative indicator owing to its capacity to express the real contribution of individual industries to the economy without distortion caused by intermediate consumption costs. It is calculated as the value of output minus intermediate consumption.

Selected European Union countries are compared on the basis of gross value added expressed in current prices. Following an analysis of a broader set of countries, the study includes: Austria (AT), Czechia (CZ), Finland (FI), Germany (DE), Italy (IT), Latvia (LV), Poland (PL), Slovakia (SK), Slovenia (SI), and Sweden (SE). Czechia and Slovenia serve as suitable comparative benchmarks for Slovakia – Czechia due to its strong historical and economic developmental context, and Slovenia together with Latvia due to the inclusion of smaller economies, a shared starting point represented by EU accession (participation in the Single European Market), and the significance of the FBS for their respective national economies. Germany, Italy, and Poland are major producers of wood-based products (e.g. furniture), while countries such as Finland and Austria (including Germany) exhibit a substantial share of forestry and wood processing within their national economies.

Data for NACE division 31 (manufacture of furniture) were retrieved from national statistical databases. This was necessitated by the fact that Eurostat does not publish data separately for NACE division 31, but only in aggregate for divisions NACE 31–32, which is logically inconsistent given that NACE 32 covers other product categories (non-furniture). Data sourced from national statistical databases for Czechia required conversion using average annual exchange rates, as they were reported in the national currency. The study compares the FBS share of individual countries based on data from the period 2022–2024 – the post-COVID period characterised by evident price increases in this sector. However, for some countries, 2024 data for the analysed NACE divisions were not yet available, even from national databases. The share of the forest-based sector is expressed as the sum of selected NACE divisions relative to the total gross value added (GVA) of the assessed countries. Specifically, the following NACE divisions are included:

- 02: Forestry and logging
- 16: Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
- 17: Manufacture of paper and paper products
- 31: Manufacture of furniture

These data are also analysed separately for each country, with an assessment of the relative contribution of individual FBS divisions. While no direct cross-country comparison is performed at this level, the shares are evaluated for the reference year 2023, for which data are available across all countries.

2. RESULTS

2.1. Total gross value added of the forest-based sector

Across all countries, a clear declining trend is observable from 2022 to 2023 – the GVA of the forest-based sector as a percentage of total GVA is decreasing. This decline reflects a combination of structural changes (growth of other sectors) and cyclical factors, such as the pan-European slowdown in the wood-processing industry – driven, for instance, by the construction sector crisis and shifts in post-COVID demand for paper and packaging, timber, and furniture. An analysis covering a longer time horizon (not presented here) would, however,

suggest that in several of the studied countries, this represents little more than a reversion to pre-COVID levels.

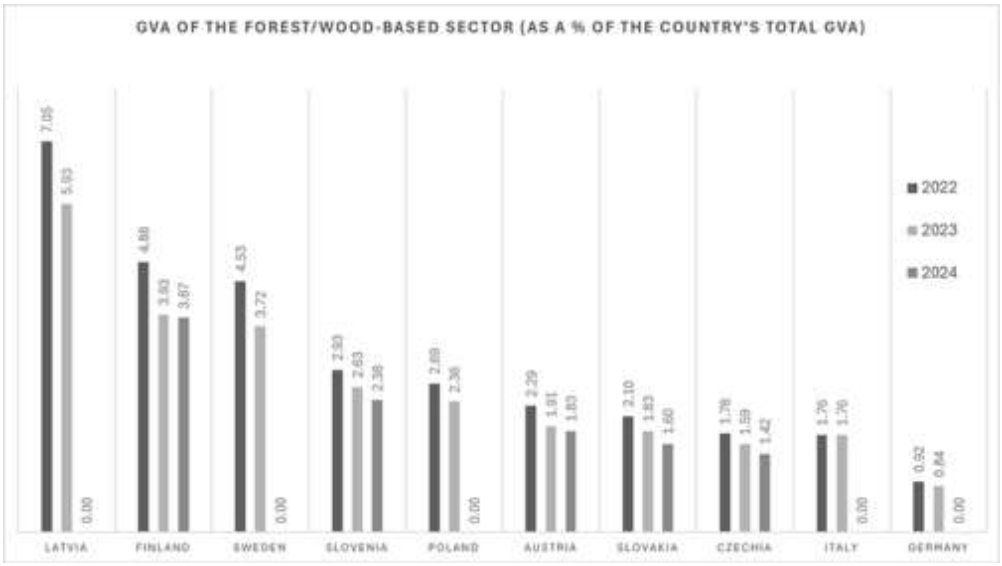

Table 1. GVA of the Forest/Wood-based sector (as a % of the country's total GVA). Note: 0.00 means data not available for 2024 (Source: own elaboration)

Latvia records by far the highest share (7.05% in 2022), reflecting the Baltic economy's traditional dependence on forestry and its export-oriented wood-processing industry. The sharp decline of 1.12 percentage points (pp) in 2023 is the most pronounced in the European context. Finland and Sweden belong to the classic "forest economies" of Northern Europe, characterised by well-developed pulp and paper and timber sectors. Slovakia, with a value of 2.10% in 2022, exhibits an above-average share among Central European countries. However, it declines to 1.60% in 2024 — a cumulative decrease of 0.50 pp over two years, which is relatively substantial. Czechia registers a more moderate decline over the same 2022–2024 period (−0.36 pp). Italy is an exception, the decline between 2022 and 2023 is nearly negligible (−0.004 pp), suggesting that its furniture and wood-processing industry demonstrated greater resilience to the cyclical downturn. Germany records the lowest share among the studied countries (0.84% in 2023), consistent with its highly diversified economy, in which the forest-based sector plays a relatively (!) marginal role in national economic performance.

2.2. Share of GVA by NACE divisions

The Figure 2 contains 2023 data on the share of the Forest-Based Sector (FBS) in the total gross value added (GVA) of selected European countries. The selection of countries is justified in the methodology. The diversity in the economic size of the countries provides a good framework for evaluating the significance of the FBS. Germany dominates with a total GVA of almost EUR 3,854 billion, and Italy is the second-largest economy in the dataset with a GVA of EUR 1,924.9 billion. They are followed by Sweden (EUR 478 bn), Finland (EUR 239 bn), and Poland (EUR 679 bn). Slovakia (EUR 113 bn), Slovenia (EUR 57 bn), and Lithuania (EUR 35 bn) are significantly smaller economies.

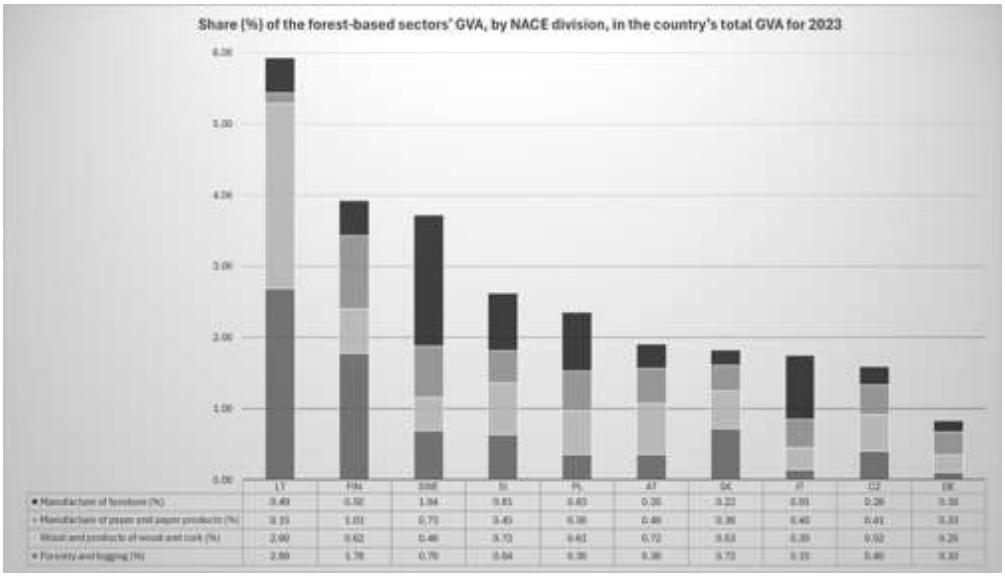

Figure 2. Share (%) of the forest-based sectors' GVA, by NACE division, in the country's total GVA for 2023 (Source: own elaboration)

Lithuania exhibits the highest share of the forest-based sector (5.93%), making it the country with the strongest economic dependence on this sector. It is followed by Finland (3.93%), Sweden (3.72%), and Slovenia (2.63%). Slovakia, with a value of 1.83%, is below the average of the monitored countries, followed by Italy with 1.76%, while Germany has the lowest share (0.84%). We can see that the size of the economy and the sector's share are not directly correlated.

In the following evaluation, it is important to note that the share values do not represent a basis for ranking the countries- it is always an assessment of the NACE division's share in the given country's total GVA. The most significant share in the division NACE 02 – Forestry and logging is in Lithuania (2.69%) and Finland (1.78%), reflecting high forest cover and the traditional orientation of these economies toward logging. Slovakia (0.72%) and Sweden (0.70%) are at a comparable level, while Italy (0.15%), Germany (0.10%), and Poland (0.36%) exhibit the lowest shares. NACE 16 – Manufacture of wood, cork, and straw products is most significantly represented in Lithuania with a share of 2.60%, signalling a strong link between logging and wood processing in this country. Austria (0.72%), Slovenia (0.72%), Finland (0.62%), and Poland (0.61%) show above-average shares, whereas Italy (0.30%) and Germany (0.25%) are at an intermediate level. Slovakia reaches 0.53%. The division NACE 17 – Manufacture of paper and paper products is significant in Finland (1.03%) and Sweden (0.73%), where the paper industry historically forms a key export segment. Poland (0.56%), Italy (0.40%), and Germany (0.33%) follow, with Slovakia (0.36%) and the Czech Republic (0.41%) at a similar level. In terms of absolute value (EUR 7,673 million), it is even the second-largest country in this division right after Germany. Lithuania, with a value of only 0.15%, strongly contrasts with its marked share of forestry here. Sweden has the highest share of the furniture industry's GVA (NACE 31 – Manufacture of furniture) in its national GVA (1.84%), which is influenced by the presence of global players in this segment. It is also a key division

for Italy, with a share of 0.91%. The absolute value of EUR 17,485 million is by far the highest in the entire set of countries, demonstrating the dominance of Italian furniture manufacturing at the European level. Italy is a specific case here, where furniture accounts for more than half of the total FBS share (0.91 out of 1.76%), representing the highest ratio of furniture to the total FBS among all examined countries. Poland (0.83%) and Slovenia (0.81%) are significantly above average, reflecting a strong export-oriented furniture industry. Slovakia exhibits the lowest share among the monitored countries (0.22%), matching Germany (0.16%).

3. CONCLUSIONS

It is evident that the size of the economy plays a relatively significant role in the sector's share. Decisive factors include the raw material base and the development level of the wood processing sector in the context of the maturity of other sectors in the national economy. The share of individual FBS components also varies significantly across the monitored countries. In connection with the complex of environmental factors of the country, as well as the markets where the production is realized (both domestic and international markets), the share of the examined NACE divisions varies – it is specific to each country.

A comparison of countries' GVA figures shows that the forest-based sector has the greatest relative weight in the more forested and traditionally timber-oriented economies of Northern and Central Europe, particularly in Latvia, Finland, and Sweden. Conversely, in large and diversified economies such as Germany and Italy, its share is lower.

Three types of countries can be identified: forestry-dominant (LT, FIN – driven by divisions 02 and 17), comprehensively balanced (SI, AT, PL – relatively even representation of all divisions), and furniture-dominant (SWE, IT, PL – significant share of NACE 31). Slovakia has relatively the weakest furniture industry compared to neighbouring countries, while forestry and logging dominate.

An analysis of gross value added in the forestry and wood products sector leads to the conclusion that forestry alone has a small to moderate impact, but the broader system (the entire wood processing chain) generates much greater value added (Vineta Tetere et al., 2024; Li et al., 2019; Aruna, 1997). That is, when secondary production sectors, domestic supply chains, and multiplier effects are taken into account. National strategic plans should adopt this approach to the components of the bioeconomy and set the course for their complementary development.

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REFERENCES

1. Aruna, P., Cubbage, F., Abt, K., & Redmond, C. (1997). Regional economic contributions of the forest-based industries in the South. Forest Products Journal, 47, 35-45.
2. Li, Y., Mei, B., & Linhares-Juvenal, T. (2019). The economic contribution of the world's forest sector. Forest Policy and Economics. https://doi.org/10.1016/j.forpol.2019.01.004.

3. Tetere, V., & Peerlings, J. (2024). Measuring the forest-based bioeconomy in Estonia, Latvia, Lithuania, and Finland. Scandinavian Journal of Forest Research, 39, 226 - 231. https://doi.org/10.1080/02827581.2024.2362216.
4. Lee, C.-K., & Kim, K.-D. (2022). Effects of the forest industry on the South Korean national economy: evidence from an Input-Output analysis based on the special classification for the forest industry. Forest Science and Technology, 18, 56 - 66. https://doi.org/10.1080/21580103.2022.2075474.
5. Sujová, A. J., Marcineková, K., & Kupčák, V. (2023). Impacts of Foreign Trade on the Economy of Wood-Based Sectors Generating Different Levels of Value Added in the Slovak and Czech Republics. Forests. https://doi.org/10.3390/f14051029.
6. Parobek, J., Paluš, H., Kalamárová, M., Loučanová, E., Križanová, A., Repková-Štofková, K. (2016). Comparative analysis of wood and semi-finished wood product trade of Slovakia and its Central European trading partners. In Drewno. ISSN 1644-3985, 2016, vol. 59, nr. 196, s. 183-194.
7. Palátová, P., Rinn, R., Machoň, M., Paluš, H., Purwestri, R. C., Jarský, V. (2023). Sharing economy in the forestry sector: opportunities and barriers. In Forest policy and economics. ISSN 1389-9341, 2023, vol. 154, art. no. 103000.

Authors address:
Kaputa, V.[1*]; Synák-Varga, M[2]
[1] Department of Marketing, Trade and World Forestry, Technical University in Zvolen, Slovakia
[2] Department of Economics, Management and Business, Technical University in Zvolen, Slovakia
[*]Corresponding author: kaputa@tuzvo.sk

THE FOREST IN CONFLICT WITH ECOLOGY: A NEED TO VERIFY DEVELOPMENT PRIORITIES OR JUST AN ECOLOGICAL FOREST ECONOMY?

Władysław Kusiak, Łukasz Sarniak, Leszek Wanat

Abstract: This paper addresses the growing conflict between the paradigm of "Ecological Forest Economy" and the postulates of deep ecology and integral development. In the era of forest digitalisation (Big Data) and market pressure, the forest has become an object of algorithmic optimisation, sparking opposition from socio-humanistic perspectives. Based on original CAWI survey data (N=120) collected from engineering and humanities students, the study reveals significant discrepancies in the perception of forest functions. While future engineers identify the forest primarily as an efficient bio-asset within the Circular Economy framework, media students perceive forest commercialisation as an ethical threat and a form of greenwashing. Interestingly, both groups converge in acknowledging that digitalisation primarily serves industrial optimisation rather than biodiversity. The findings underscore the urgent need to verify development priorities and implement an interdisciplinary model that bridges resource efficiency with ethical sensitivity.
Keywords: forest economy, bioeconomy, conflict, forest sociology, circular economy, Big Data.

1. INTRODUCTION

The contemporary debate on the role of forests in the global economy and local social structures is undergoing a significant evolution, shifting focus from raw material extraction toward a multidimensional bioeconomy [2, 6]. Forests are no longer regarded merely as timber warehouses but as essential pillars of human integral development and vital spaces for clinical support [5, 13]. Historical case studies, such as the forest parks surrounding psychiatric hospitals in Kobierzyn or Kulparków, demonstrate that natural environments have functioned as critical tools for revalorisation and therapeutic assistance for over a century [4, 8, 11]. Recent systematic reviews further confirm the measurable, evidence-based benefits of forest therapy for adult mental health, positioning these environments as indispensable in modern psychiatry [7]. However, this transition toward a contemporary bioeconomy model is not free from fundamental contradictions. While the "Ecological Forest Economy" is often promoted as a sustainable solution, it frequently generates conflicts between traditional industrial forestry interests and broader social, spiritual, and ecological needs [6, 12]. As explored in the landscape economics framework, the "pathfinders" of such transitions must navigate the tension between purely economic efficiency and the irreplaceable value of the human-forest relationship [10, 13]. This tension is intensified by the discourse on "greenwashing", where sustainable labels may mask intense commercialisation [3, 9].

In the Polish context, research into the "people-forest-wood" nexus has identified significant inclusive integration models that leverage urban forest parks to provide targeted therapeutic benefits [11, 12]. Yet, there remains a persistent gap in understanding how future experts - those who will eventually manage these landscapes-perceive these priorities. As

noted in recent meta-analyses, stakeholder perceptions in European forestry remain deeply polarised, often split between biodiversity protection and commodity production [1]. The search for new paradigms requires moving beyond mere technological optimisation to recognise the dignity of labor and the intrinsic value of natural settings [2, 10, 13, 14].

2. MATERIAL AND METHODOLOGICAL BACKGROUND OF THE STUDY

The interdisciplinary nature of this study, positioned at the intersection of materials engineering, forest sociology, and clinical psychology, necessitated a mixed-methods approach grounded in the "people–forest–wood" integration model [12]. To explore the conflict between the technological optimisation of bio-resources and the preservation of social and spiritual values, we conducted a purposive, contrastive survey.

The research was conducted between March and April 2026 using the CAWI (Computer-Assisted Web Interview) method, yielding N=120 valid responses. The sample was purposively selected to reflect two distinct professional and educational paradigms. The cohort consisted of 60 students from the Faculty of Forestry and Wood Technology at the Poznań University of Life Sciences (UPP) - specifically 30 students of Forestry and 30 students of Wood Technology - representing the technical-industrial paradigm. The second cohort comprised 60 students from the Pontifical University of John Paul II in Krakow (UPJPII) - specifically 30 students of Journalism and Social Communication and 30 students of Digital Media - representing the socio-humanistic and media-critical paradigm. The analysis aimed to verify the intensity of the "paradigm conflict" between the engineering-based approach to the Circular Economy and the critical perception of forest commodification. This stratification was deliberate, aiming to capture the friction between a resource-oriented and a society-oriented view of forest ecosystems.

2.1. Research Instrument and Variables

The primary tool was an original, structured questionnaire based on a 5-point Likert scale (1: 'strongly disagree' to 5: 'strongly agree'). The survey was divided into four diagnostic sections corresponding to the research hypotheses:

1. The Paradigm of Circular Economy: Evaluating whether wood production should remain the primary focus of forest management.
2. The Greenwashing Dilemma: Assessing scepticism towards the term "Ecological Forest Economy" and the risk of market exploitation.
3. Technological vs. Ecological Agency: Analysing whether Big Data and AI in forestry serve nature or industrial optimisation.
4. Social vs. Economic Priorities: Testing the preference for social or spiritual forest functions over economic extraction.

The questionnaire was validated via a pilot phase to ensure terminology was accessible to both engineers and humanists. Data analysis employed structural comparative statistics, focusing on the variance between engineering and social science cohorts to identify the sources of the "paradigm conflict" highlighted in the literature [1, 6, 9, 14].

3. SELECTED RESULTS

This section presents findings from the March - April 2026 comparative survey, elucidating cognitive divergence between technical-industrial and socio-humanistic students. Moving beyond descriptive statistics, it highlights variance in attitudes towards the forest as a commodity versus a relational space. The data in Tables 1 and 2 verify the hypotheses, providing a basis for discussing the bioeconomy's "paradigm conflict".

3.1. Analytical Approach

Moving beyond descriptive snapshots of central tendencies, this study employed comparative variance assessment and thematic mapping. We utilised mean scores (Table 1) and percentage distributions (Table 2) as proxies for "cognitive distance" between the cohorts. Identifying significant deviations from the neutral Likert midpoint (3.0) enabled us to verify the paradigm conflict hypotheses.

Table 1. Mean evaluation scores (scale 1–5, where 5 = strongly agree)

Student group	Paradigm	Concept criticism	Digitalisation	Priorities
Forestry (UPP)	4.85	1.40	3.85	4.35
Wood Technology (UPP)	4.35	1.05	4.15	4.35
Journalism (UPJPII)	2.05	4.05	2.80	3.20
Digital Media (UPJPII)	1.35	3.65	3.70	2.50
Overall mean	**3.15**	**2.54**	**3.63**	**3.60**

Note: The percentage values have been converted to a 5-point scale (where 5 corresponds to 100%, 4 = 75%, 3 = 50%, 2 = 25%, 1 = 0%).
Source: Own elaboration.

Table 2. Distribution of affirmative responses by subgroup (%)

Field of study	Sample size (N)	Paradigm (CE)	Concept criticism (Greenwashing)	Digitalisation (Industrial)	Priorities (Social)
Forestry	30	97%	10%	73%	70%
Wood technology	30	87%	1%	79%	67%
Journalism	30	40%	85%	55%	62%
Digital Media	30	28%	69%	75%	52%
TOTAL	**120**	**63%**	**41%**	**70%**	**63%**

Source: Own elaboration.

The data presented in Tables 1 and 2 demonstrate that whilst engineers identify the forest as an efficient bio-asset (Paradigm 4.85), Digital Media students subject this narrative to rigorous deconstruction (Criticism 3.65–4.05), which constitutes a significant point of conflict in the debate over development priorities (see: Figure 1). As illustrated in Figure 1, the engineering students (UPP) demonstrate a pronounced right-skewed distribution, scoring above 4.0 on three of the four axes. This pattern indicates a predominantly efficiency-driven

and technological paradigm. In contrast, the humanities and media students (UPJPII) present an almost mirrored profile; they peak sharply at 3.85 for Concept Criticism, yet remain below 2.9 on the economic and priority axes. These findings empirically confirm a substantial cognitive divergence between the two academic groups. Such technological optimism among future engineers aligns with the rapid integration of machine learning into biomass supply chain management [14].

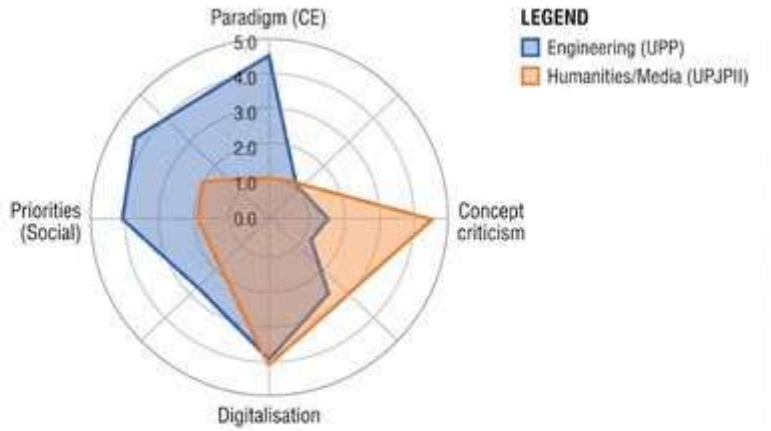


Figure 1. The 'Paradigm Conflict' map: A comparative radar chart of student perceptions. Note: The chart illustrates the cognitive divergence between the engineering cohort (UPP) and the humanities/media cohort (UPJPII) across four dimensions. The spatial area between the two polygons represents the 'cognitive distance', highlighting the fundamental conflict of paradigms regarding the definition of forest value, sustainable development priorities, and the role of digitalisation in the forest-based sector. Source: Own elaboration based on survey data (March–April 2026).

Figure 1. The 'Paradigm Conflict' map – a comparative radar chart of student perception

However, the critical stance of the humanities cohort underscores that data-driven tools must transcend mere industrial optimisation and actively support collaborative governance to ensure genuine ecological restoration [9].

3.2. Verification of Research Hypotheses

The data confirm a distinct divergence in perceptions, validating the hypotheses as follows:

- H1 (Circular Economy Paradigm): Strongly supported among UPP students (M>4.3), where efficiency is viewed as a developmental imperative. Conversely, UPJPII students display significant scepticism (M<2.05), suggesting that the CE model is perceived by them as an extension of industrial exploitation rather than a solution.
- H2 (The Greenwashing Dilemma): This hypothesis is confirmed by the sharp polarisation: UPP students reject the existence of "greenwashing" (1–10%), whereas UPJPII students view it as a systemic issue (69–85%). This suggests that the term "Ecological Forest Economy" acts as a semantic battlefield.
- H3 (Digitalisation of Forestry): This is the only point of convergence. Both cohorts perceive forestry AI as an industrial optimisation tool (65%–79%). The critical consensus is that digitalisation serves production rather than biodiversity.
- H4 (Social Priorities): Supported by the majority (63% total), though engineering students surprisingly prioritise social functions (>67%) alongside production,

suggesting a "dual-purpose" management vision, whereas humanities students emphasise social values exclusively.

3.3. Discussion: The Conflict of Paradigms

The discrepancy between the UPP and UPJPII groups reveals a deeper epistemological rupture. Engineering students operate within a technocratic paradigm, viewing the forest as a "bio-asset" to be optimised. In contrast, the UPJPII group adheres to a humanistic-critical paradigm, conceptualising the forest as a "relational space". Their convergence on digitalisation (H3) is particularly alarming: both groups recognise that technology distances forest management from traditional interaction with nature. This suggests the "Ecological Forest Economy" remains a top-down construct rather than a socially accepted consensus.

4. CONCLUSIONS

Based on the obtained results, it is concluded that a profound cognitive dissonance exists between future forestry engineers and media professionals regarding the modern bioeconomy paradigm. Whilst technical students view the forest primarily as an efficient bio-asset to be managed through circular economy principles, humanities students perceive it as a relational space, expressing severe scepticism towards 'Ecological Forest Economy' narratives, which they frequently identify as greenwashing. Interestingly, the mutual consensus that digitalisation serves industrial optimisation rather than biodiversity highlights a shared concern over the technocratic alienation of forest management. To bridge this epistemological gap, it is strongly recommended that academic curricula integrate interdisciplinary modules, exposing engineering students to media criticism and environmental ethics, whilst providing humanities students with foundational knowledge of sustainable resource mechanics.

The primary limitation of this study lies in its purposive, geographically restricted sample comprising merely two Polish universities, alongside the inherent constraints of a cross-sectional CAWI survey, which limits the generalisability of the findings. Consequently, future research should expand the geographical scope to include international cohorts and employ qualitative methods, such as in-depth interviews, to better understand the underlying motivations driving these divergent paradigms. Furthermore, incorporating established industry professionals into the comparative matrix would provide valuable insights into how these early-career perceptions evolve with practical experience.

REFERENCES

1. Brancalion, P. H., Hua, F., Joyce, F. H., Antonelli, A., Holl, K. D. (2025). Moving biodiversity from an afterthought to a key outcome of forest restoration. *Nature Reviews Biodiversity*, 1(4), 248-261.
2. Candelier, K., Brancheriau, L., Gérard, J., Thévenon, M. F., Zoveda, F., de Prado Viargues, L. (2026). Pathways to increase supply of sustainable wood from planted forests and trees to address bioeconomy needs: A review. *iForest: Biogeosciences and Forestry*, 19, 168-185.

3. Kiziridis, D. A., Salonikidou, E., Eleftheriadou, N., Fotakis, D. (2025). Balancing Non-Timber Services with Biomass Production via Sustainable Forest Management: A Review of Conflicting Demands and Suggested Approaches. *Forests*, 16(2), 348.
4. Klimek, J. (2019). Duszpasterstwo w kobierzyńskiej kapelanii na przestrzeni wieków (Pastoral care at the Kobierzyn chaplaincy over the centuries), Kraków.
5. Kotte, D., Li, Q.; Shin, W. S.; Michalsen, A. (Eds.). (2019). International handbook of forest therapy. Cambridge Scholars Publishing.
6. Melnykovych, M., Nijnik, M., Soshenskyi, O. et al. (2026). Pathways for Ukraine's post-war nature recovery: Focus on forest socio-ecological systems. *Ambio*, 55, 817–843. DOI: 10.1007/s13280-025-02263-0.
7. Shang, X., Lu, J., Tao, M., Fei, C., Fei, J. (2025). Benefits of forest therapy for adult mental health: a systematic review and meta-analysis based on the Profile of Mood States (POMS). *Frontiers in Psychology*, 16, 1670804. DOI: 10.3389/fpsyg.2025.1670804.
8. Staniewska, A., Petryshyn, H., Lukashchuk, H., Kliusa, T., Koprynia, K. (2021). Values of the Historical Parks and Gardens of Psychiatric Hospitals in Kulparków and Kobierzyn as the Basis for Their Revalorisation. *Wiadomości Konserwatorskie - Journal of Heritage Conservation*, 67, 22–34.
9. Sun, Y., Gong, Q. (2026). Digital economy empowering low-carbon collaborative governance and ecological restoration in forestry. *Journal of Forestry Research*, 37(1), 40.
10. Wanat, L. (2024). Kazimierza Zimniewicza drogowskazy ekonomii krajobrazu (Kazimierz Zimniewicz's pathfinders of landscape economics). *Biuletyn Parków Krajobrazowych Wielkopolski*, 31: 11-14.
11. Wanat, L. (2024). Selected creating factors of the integrated urban forest - the case of Kobierzyn garden in the Kraków metropolitan area in Poland. In: D. Jelačić (ed.), Achieving sustainability in forest-based industry, WoodEMA, i.a., Zagreb, pp. 59-68.
12. Wanat, L., Klimek, J., Kusiak, W., Sarniak, Ł. (2025). People - forest - wood: inclusive integration models. The case of the Kobierzyn urban forest park in the Kraków metropolitan area in Poland. In: Ž. Meloska, M. Miloshevska Janakieska (eds.), Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA, WoodEMA, i.a., Ohrid, pp. 307-312.
13. Wąchol, G., Wanat, L. (2023). Perspektywa λόγος i ἀρετή w procesie integracji osób z dysfunkcjami psychicznymi (The λόγος and ἀρετή perspective in the integration process of people with mental dysfunctions). *Paideia / Παιδεία*, 5: 67-88.
14. Zhao, J., Wang, J., Anderson, N. (2024). Machine learning applications in forest and biomass supply chain management: A review. *International Journal of Forest Engineering*, 35(3), 371-380.

Authors address:
Kusiak, W. [1]; Sarniak, Ł. [2]; Wanat, L. [3*].
[1] Department of Forest Engineering, Faculty of Forestry and Wood Technology, Poznań University of Life Sciences, Poznań, Poland.
[2] Department of Finance and Accounting, Faculty of Economics, Poznań University of Life Sciences, Poznań, Poland.
[3] Department of Social Sciences, Kozminski University, Warsaw, Poland, and Department of Theology and Pastoral Psychology, The Pontifical University of John Paul II in Kraków, Poland.
[*] Corresponding author: leszek.wanat@kozminski.edu.pl .

RETHINKING WOOD: DEVELOPMENT STRATEGIES IN THE BIOECONOMY ERA – THE CASE OF THE WOOD-BASED SECTOR IN POLAND

Łukasz Sarniak, Marek Wieruszewski, Leszek Wanat

Abstract: This study evaluates adaptive strategies - specifically supply chain logistics, biomass barriers, and greenwashing risks - within the Polish forest-based sector's transition to a circular bioeconomy. A mixed-methods approach transposed structured Individual In-Depth Interviews (IDI) from a purposive sample (N=50) of forestry and industry professionals into a quantitative matrix. Findings expose a severe circular economy implementation gap, where ambiguous resource classification and extreme price volatility force actors to rely heavily on informal networking, highlighting profound vulnerability to tokenistic eco-innovation. Securing long-term resilience demands a definitive paradigm shift: rethinking wood as a strategic bio-asset through transparent, data-driven governance.
Keywords: circular bioeconomy, wood-based sector, greenwashing, supply chain resilience, forestry.

1. INTRODUCTION

Driven by permanent economic uncertainty and climate change, forestry faces a systemic transformation [30]. The circular bioeconomy replaces linear extraction, demanding sustainable business models [5, 8, 21]. "Rethinking wood" is essential: timber is a strategic bio-asset for global supply chains [19] and socio-economic resilience [7, 9]. Integrating the Circular Economy (CE) requires advanced resource recovery and biomass production [17, 23], where wood by-products and stumps offer significant market opportunities [18]. Furthermore, AI and data-driven tools optimise supply chains and manage CE complexities [2, 6, 13], defining future management practices [15, 28]. Poland's state monopoly must adapt to the EU Forest Strategy 2030 and technological shifts [4]. While intersectoral cooperation mitigates market uncertainties [16, 26, 31], balancing economic extraction with non-substitutable ecosystem values [22, 24, 25] and urban forestry [27] creates structural friction. Stakeholders navigate intense biomass production, non-timber services, and biodiversity restoration [1, 3, 14] amidst market volatility [12]. Rising greenwashing risks [11] urgently necessitate holistic life cycle sustainability assessments [10, 32] and robust chain-of-custody certifications [20] for genuine eco-innovation. Consequently, this paper evaluates the Polish forest-based sector's adaptive strategies, addressing three tasks: (1) assessing CE integration in supply chain logistics; (2) identifying barriers to optimal wood biomass utilisation; and (3) examining market navigation between authentic eco-innovation and greenwashing risks.

2. MATERIAL AND METHODOLOGICAL BACKGROUND OF THE STUDY

To evaluate the Polish forest-based sector's adaptive strategies amidst the bioeconomy transition, a purely quantitative approach proved insufficient. Therefore, the research employed

a mixed-methods design using qualitative Individual In-Depth Interviews (IDI) - a proven method for assessing strategic decisions under crisis [30]. For objective assessment, qualitative insights were systematically coded into a quantitative matrix. Using purposive sampling to capture inter-sectoral friction, 100 inquiries yielded a validated cohort of exactly N=50 experts. For comparative symmetry, the sample comprised two equal sub-cohorts: (A) Wood Industry Managers (n=25) from the sawmill and furniture sectors, and (B) Forestry Professionals (n=25) managing state timber trade with direct industrial contact.

To guarantee exploratory depth, IDI scenarios evaluated three problem areas: (1) Circular Economy Integration (PB1): the operational integration of closed-loop principles; (2) Biomass Utilisation Barriers (PB2): institutional constraints hampering optimal wood biomass use and resource degradation risks [18]; and (3) Eco-innovation vs. Greenwashing (PB3): how stakeholders navigate between authentic eco-innovation and image-driven greenwashing [11]. Narrative data was transposed onto a 5-point Likert scale (1='strongly disagree', 5='strongly agree') to calculate mean scores and distributions. These metrics served as proxies to assess cognitive distance and inter-sectoral cooperation consensus [16, 26], enabling precise mapping of systemic vulnerabilities.

3. SELECTED RESULTS

The IDI protocols (N=50) highlight structural friction and cognitive divergence within the primary wood market. Evaluating Circular Economy implementation (PB1), both groups report an operational gap: practical execution of theoretical strategies is severely hindered (Overall Mean: 4.38), prompting foresters to advocate domestic industrial cooperation over short-term profit (M=4.48). Regarding biomass utilisation (PB2), institutional bottlenecks emerge: foresters warn unclear energy wood classification degrades high-quality materials (M=4.72), whilst industry faces opaque purchasing criteria and extreme price volatility (M=4.88), paralysing long-term strategic planning (see Table 1).

Table 1. Evaluation of bioeconomy transition factors and institutional barriers.
Note: FP=Forestry Professionals, WIM=Wood Industry Managers, OM=Overall Mean.

Evaluated Variable / Thematic Statement	FP (n=25)	WIM (n=25)	OM (N=50)
PB1: CE Implementation Gap: Theoretical bioeconomy strategies face severe practical barriers.	4.64	4.12	**4.38**
PB1: Domestic Integration: Prioritising domestic industrial cooperation outweighs short-term profit.	4.48	4.80	**4.64**
PB2: Resource Degradation: Unclear energy wood classification wastes high-quality materials.	4.72	4.28	**4.50**
PB2: Market Instability: Opaque purchasing and price volatility paralyse strategic planning.	3.44	4.88	**4.16**

Source: Own elaboration.

Data on PB3 reveals alarming institutional vulnerabilities: 80% of the sample perceives corporate environmental policies as fluid and image-driven rather than structural. Moreover, permanent market uncertainty has institutionalised informal networking. An overwhelming 94%

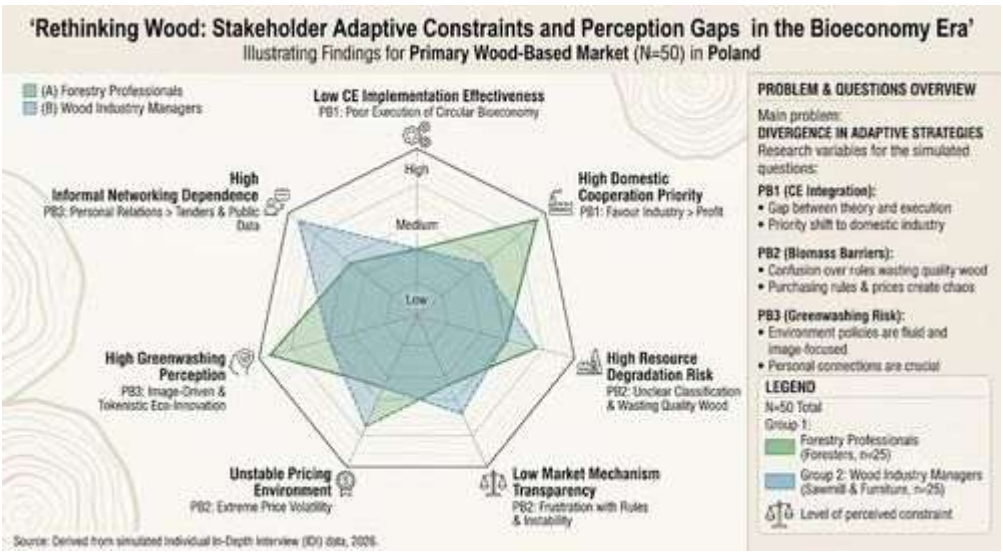
of respondents (96% industry, 92% foresters) admit personal contacts are significantly more effective for securing resources than official tenders or public data (see Table 2).

Table 2. Market navigation and greenwashing risks (% 'agree' / 'strongly agree'). Note: FP=Forestry Professionals, WIM=Wood Industry Managers.

Evaluated Variable / Thematic Statement	FP (n=25)	WIM (n=25)	Total (N=50)
PB3: The Greenwashing Dilemma: Environmental strategies are fluid, primarily serving image-building rather than structural eco-innovation.	84%	76%	**80%**
PB3: Informal Networking Dominance: Personal relationships are more effective for market navigation than official tenders or public data.	92%	96%	**94%**

Source: Own elaboration.

Figure 1 maps the sector's "paradigm conflict" and low CE integration effectiveness, illustrating that Poland's bioeconomy transition relies on tactical relationships over transparent governance. This informal networking, combined with high greenwashing risks, indicates



a state of reactive survival rather than proactive development. Furthermore, divergent perceived constraints - foresters citing resource degradation, whilst industry cites pricing chaos - underscore a highly fragmented value chain. To genuinely "rethink wood" and ensure long-term resilience, policymakers must dismantle the natural monopoly's rigidities. The sector urgently requires data-driven classification frameworks and robust chain-of-custody certification to bridge the gap between resource efficiency and ethical market practices.

Figure 1. Stakeholder Adaptive Constraints and Perception Gaps in the Bioeconomy Era.

4. CONCLUSIONS

The empirical investigation into the Polish forest-based sector confirms that the transition towards a multidimensional bioeconomy is currently paralysed by profound structural friction. Addressing the primary research questions, the study reveals that while the theoretical framework for circular economy integration is established, practical supply chain logistics fail to support domestic industrial cooperation, resulting in a severe implementation gap. Furthermore, the optimal utilisation of wood biomass is critically hampered by opaque institutional regulations, specifically ambiguous classification criteria that risk degrading high-quality raw materials, alongside extreme price volatility. Consequently, market stakeholders are forced to navigate the perilous boundary between authentic eco-innovation and corporate greenwashing by relying overwhelmingly on informal, tactical networking rather than transparent, systemic governance.

To overcome these systemic vulnerabilities, it is imperative to implement transparent, data-driven classification frameworks and robust chain-of-custody certification models that dismantle the current rigidities of the natural monopoly. This urgent institutional reform constitutes the very essence of "rethinking wood". It demands a definitive paradigm shift where timber is no longer perceived merely as an extractive, linear commodity, but is redefined as a strategic, multifaceted bio-asset. Ultimately, rethinking wood means replacing reactive survival tactics and tokenistic environmental policies with authentic industrial symbiosis, ensuring that the sector delivers both long-term economic resilience and genuine ecological restoration.

REFERENCES

1. Achim, F., Dinca, L., Chira, D., Raducu, R., Chirca, A., Murariu, G. (2025). Sustainable management of willow forest landscapes: A review of ecosystem functions and conservation strategies. *Land*, 14(8), 1593.
2. Berntzen, L., Johannessen, M. R., Collalti, A., Morichetti, M., Mitter, H., Linser, S., Cheval, S. (2026). Designing a Data-Driven Decision Support System for Sustainable and Climate Resilient Forest Management: Lessons Learned from the OptForEU Project. In: ICDS 2026: The Twentieth International Conference on Digital Society (pp. 23-28). IARIA.
3. Brancalion, P. H., Hua, F., Joyce, F. H., Antonelli, A., Holl, K. D. (2025). Moving biodiversity from an afterthought to a key outcome of forest restoration. *Nature Reviews Biodiversity*, 1(4), 248-261.
4. Brożek, J., Kożuch, A., Wieruszewski, M., Adamowicz, K. (2025). Verification of the Assumptions of the Polish State Forest Policy in the Context of the New EU Forest Strategy 2030. *Sustainability*, 17(6), 2398.
5. Candelier, K., Brancheriau, L., Gérard, J., Thévenon, M. F., Zoveda, F., de Prado Viargues, L. (2026). Pathways to increase supply of sustainable wood from planted forests and trees to address bioeconomy needs: A review. *iForest: Biogeosciences and Forestry*, 19, 168-185.
6. Cao, C., Zhuang, J., Wu, J. J., Zhou, W. (2026). Impact of Progress of AI on Circular Bioeconomy: Applications, Challenges, and Future Directions. In: Handbook of Circular Bioeconomy (pp. 397-440). Cham: Springer Nature Switzerland.

7. Carmenta, R., McKinley, K., Akamany, K., Delgado-Serrano, M. M., Larson, A., Allen, C., Swiderska, K. (2025). Options for Enhancing the Contributions of Forests to Social and Economic Resilience. *Forests as Pillars of Social and Economic Resilience*, 159-201.
8. Dorrego-Viera, J. I., Urbinati, A., Hansen, E. G., Lazzarotti, V. (2026). Open innovation for circular and sustainable business models: Case evidence from the bioeconomy sector. *Innovation*, 28(1), 124-162.
9. Ferreira, J., Izquierdo-Tort, S., Delgado-Serrano, M. M., Akamani, K., Dhyani, S., Djenontin, I. N., Pulhin, J. M. (2025). Relationships between forests and social and economic resilience. Forests as Pillars of Social and Economic Resilience. A Global Assessment Report, 45.
10. Ghose, A., Pizzol, M. (2024). Data sharing-challenges and opportunities for LCA. In SETAC Europe 26th LCA Symposium: Making LCA Meaningful: Good Data, Better Models, Sustainable Decisions.
11. Gottinger, A., zu Jeddeloh, S. (2026). Seeing beyond Europe's nose: a critical interpretive synthesis of negative impacts of the European bioeconomy transition. *Journal of Environmental Policy & Planning*, 1-34.
12. Hosseininasr, S., Tajdini, A., Pourmousa, S. (2026). Identifying the gaps between customers' expectations and perceptions of sales service quality dimensions in wooden home furniture companies. *Iranian Journal of Wood and Paper Science Research,* 41(1):15-31.
13. Kannamma, R., Khan, M., Senthil Ragavan, V. K., Ambhika, C. (2026). Data-Driven Decision Making: Utilizing Big Data for Forest Health. In: Smart Forestry 5.0 for Powered AI Sustainable Environment and Climate (pp. 201-214). Cham: Springer Nature.
14. Kiziridis, D. A., Salonikidou, E., Eleftheriadou, N., Fotakis, D. (2025). Balancing Non-Timber Services with Biomass Production via Sustainable Forest Management: A Review of Conflicting Demands and Suggested Approaches. *Forests*, 16(2), 348.
15. Kumar, S., Kumar, P. (2026). Innovations Sustainable Management Practices and Future Perspectives in Forest Management. In: Harnessing AI for Invasive Species Management and Biodiversity Conservation (pp. 219-252). IGI Global Scientific Publishing.
16. Kusiak, W., Mikołajczak, E., Wanat, L. (2018). Institutional and Industrial Symbiosis Case Study of Cooperation for Development in Forestry and Wood-Based Sector. In: Increasing the use of wood in the global bio-economy. Glavonjic B. (ed.), September 26th-28th, 2018, University of Belgrade, Belgrade, Serbia, 388-399.
17. Kusiak, W., Wanat, L., Klus, S., Styma-Sarniak, K. (2019). Circular Economy from the Perspective of Scientific Research Papers in the Forestry and Wood-Based Sector in Poland. [In:] Chobanova R.(ed.) Digitalisation and Circular Economy: forestry and forestry based industry implications, USB and WoodEMA, i.a., 33-38.
18. Majchrzak, L., Wanat, L., Kusiak, W., Sikora, J., Sarniak, Ł. (2025). The Economic Potential of Stump Wood as an Energy Resource - A Polish Regional Case Study. Forests, 16(8), 1243. https://doi.org/10.3390/f16081243 .
19. Mensah, P., Pimenta, A. S., de Melo, R. R., Amponsah, J., Tuo, G., Chakurah, I., de Medeiros, P. L. (2025). The global supply chain of wood products: A literature review. *Forests*, 16(7), 1036.
20. Paluš, H., Parobek, J., Vlosky, R. P., Motik, D., Oblak, L., Jošt, M., Glavonjić, B., Dudík, R., Wanat, L. (2018). The status of chain-of-custody certification in the countries of Central and South Europe. *European Journal of Wood and Wood Products*, 76(2), 669-710.

21. Rosário, A. T., Lopes, P., Rosário, F. S. (2024). Sustainability and the circular economy business development. *Sustainability*, 16(14), 6092.
22. Szary, S. (2020). Las i jego nie-zastępowalność w integralnym rozwoju człowieka (Forest and its non-substitutability in integral human development), *Przegląd Leśniczy*, 10: 18-20.
23. Tkáč, F., Moravčíková, D., Billík, D. (2026). Evaluation of bioeconomy status in Visegrad countries: A comparative benchmarking. *Sustainable Environment*, 12(1), 2693335.
24. Wanat, L. (2016). Gospodarka leśna: zrównoważona czy integralna? Dylematy badawcze z perspektywy polskiego rynku drewna okrągłego (Forest Economy: Sustainable or Integral? Research Dilemmas from the Perspective of the Polish Roundwood Market). *Przegląd Leśniczy*, 26(09), 26-27.
25. Wanat, L. (2023). The Idea of Sylvicultura Oeconomica as a Tool to the University Renew and Promotion Forest Sciences for the Bioeconomy Development. In: R. Dudik (ed.), Current Trends and Challenges for Forest-Based Sector: Carbon Neutrality And Bioeconomy, WoodEMA, i.a. and Czech University of Life Sciences, Prague, 201-205.
26. Wanat, L. (2024). Kazimierza Zimniewicza drogowskazy ekonomii krajobrazu (Kazimierz Zimniewicz's pathfinders of landscape economics). *Biuletyn Parków Krajobrazowych Wielkopolski*, 31: 11-14.
27. Wanat, L. (2024). Selected creating factors of the integrated urban forest - the case of Kobierzyn garden in the Kraków metropolitan area in Poland. In: D. Jelačić (ed.), Achieving sustainability in forest-based industry, WoodEMA, i.a., Zagreb, pp. 59-68.
28. Wanat, L. (2025). Integrated development of forest and wood-based sciences on the background of the university idea. In: Ž. Meloska, M. Miloshevska Janakieska (eds.), Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA, i.a., Ohrid, pp. 325-330.
29. Wanat L., Potkański T., Chudobiecki J., Mikołajczak E., Mydlarz K. (2018). Intersectoral and Intermunicipal Cooperation as a Tool for Supporting Local Economic Development: Prospects for the Forest and Wood-Based Sector in Poland. *Forests* 9 (9), 531, 1.
30. Wanat, L., Sarniak, Ł., Sikora, J., Kusiak, W., Wieruszewski, M., Czarnecki, R., Smętkiewicz, K., Kaputa, V. (2026). Development programming in the forest-based sector under economic uncertainty - the case of Poland during the pandemic and post-pandemic crisis. *Economics and Environment*, 96(1), 928. DOI: 10.34659/eis.2026.96.1.928.
31. Wanat, L.; Sikora, J.; Majchrzak, L.; Sarniak, Ł.; Czarnecki, R.; Smętkiewicz, K.; Ornoch, M. (2025). The Economic and Technological Challenges of the Agri-Development Implementation Model in the Case of the Wielkopolska Region in Poland. Agriculture, 15, 412. DOI: https://doi.org/10.3390/agriculture15040412 .
32. Zeug, W., Bezama, A., Thrän, D. (2020). Towards a holistic and integrated Life Cycle Sustainability Assessment of the bioeconomy: Background on concepts, visions and measurements (No. 7/2020). UFZ Discussion Paper.

Authors address:

Sarniak, Ł.[1]; Wieruszewski, M.[2]; Wanat, L.[3*].
[1] Department of Finance and Accounting, Faculty of Economics, Poznań University of Life Sciences, Poznań, Poland.
[2] Department of Wood-Based Materials, Faculty of Forestry and Wood Technology, Poznań University of Life Sciences, Poznań, Poland.
[3] Department of Social Sciences, Kozminski University, Warsaw, Poland.
[*] Corresponding author: leszek.wanat@kozminski.edu.pl .

CHAPTER C
ECONOMICS, FINANCE AND INVESTMENT

CONTRIBUTION OF WOOD PRODUCTS TRADE TO ECONOMIC DEVELOPMENT: EVIDENCE FROM EUROPEAN UNION COUNTRIES IN THE CONTEXT OF THE BIOECONOMY

Simeonka Petrova

Abstract: The European forest-based bioeconomy has a significant impact on the generation of added value and Gross Domestic Product, maintaining a sustainable trade balance, regional employment and socio-economic footprint. The main objective of this study is to analyze the contribution of trade in wood products to the economic development of the European Union countries during the period 2014-2024. As a dependent variable measuring the economic development of the studied countries, the indicator for Gross Domestic Product of the studied countries was used, and as an independent variable allowing the presentation of trade in wood products – the indicator for exports of roundwood. The methodological framework of the study includes the application of the method of linear regression and correlation, implemented using the software product IBM SPSS Statistics. The values of the two evaluated variables were obtained on the basis of Eurostat data. The results obtained allow the identification of a positive correlation between the analyzed variables, with trade in wood products being identified as a determinant of economic development within the European bioeconomy.
Keywords: European forest-based bioeconomy, trade in wood products, Gross Domestic Product of European Union member states

1. INTRODUCTION

In recent decades, the importance of the bioeconomy concept has increased as an approach to overcoming the challenges associated with excessive dependence on non-renewable natural resources. Initially, the understanding of the bioeconomy focused on resource substitution and biotechnology (Birner, 2018). Subsequently, the concept has expanded to encompass aspects of sustainability, services and circularity (Heimann, 2019). The modern definition of the bioeconomy is associated with the production, consumption, conservation and regeneration of biological resources in order to provide sustainable solutions – information, products, processes and services, in all economic sectors, enabling the transformation towards a sustainable (European Bioeconomy University, 2025)economy .(Blazheva, 2025)

Within the European Union, the forest-based industry is essential for the circular bioeconomy model. Forests are natural systems that make an important contribution to the economy and employment creation in the 27 Member States of the Community, including climate regulation and biodiversity conservation. Data for 2022 show that the GVA generated by the wood-processing industry exceeds 144 billion euros, which represents over 7.50% of the total value added generated by the European Union industry sector (Eurostat, 2023). In the same year, the number of employees in the industry under study amounted to more than 3.10 million people, which is over 10.50% of those employed in the manufacturing sector. A

major share of employment is created in the sub-sectors of the production of wood and wood products.

By reducing greenhouse gas emissions and substituting materials and energy, wood-based products contribute to climate change mitigation. Such substitution involves using wood instead of materials such as: steel, concrete, plastics. This reduces emissions throughout the life cycle of the products (Sathre & O'Connor, 2010). The wood and wood-processing industry is investing in the development of innovative products designed as alternatives to conventional materials (Hassegawa, Karlberg, Hertzberg, & Verkerk, 2022). New developments demonstrate high potential for industrial use in the production of bio-based textile fibers, green chemistry platforms, functional packaging and advanced biocomposites.

Patterns of trade in wood products illustrate the level of integration within the single market. Interpreting trends in this direction provides important information on the import and export of wood products in the European Union. The data show that the majority of trade is internal, i.e. over 82% of total imports of firewood and industrial roundwood are carried out in the 27 Member States of the European Union (Eurostat, 2024). This indicates regional security of supply and relatively limited dependence on external suppliers.

Studies conducted among European countries on trade in products of the timber and wood processing industry focus on the opportunities for increasing the trade competitiveness of European countries by optimizing the management of vertical supply chains (Bojnec & Ferto, 2014). (Verter & Grega, 2019)In this regard, environmental certificates and innovative materials - such as CLT (Cross - Laminated Timber) Timber panels, create competitive advantages and make products more difficult to replace.

Analyses confirm that in the future, better market positions can be occupied by enterprises in the forest-based industry that implement innovative green technologies (Rembiasz, Borowiec, & Czajkowski, 2024). In the context of the bioeconomy, ecological production contributes to sustainable development and serves as a barrier to entry for non-certified competitors in the sector.

The presented findings related to the European forest-based industry and its importance for the circular bioeconomy model determine the research interest. This paper adopts the view that the transition to the bioeconomy poses a number of challenges for the logging and wood processing industries of the European Union countries. Some of these challenges are related to the redirection of resources towards increasing trade competitiveness through the optimization of vertical supply chains and the implementation of innovative technological solutions.

At the same time, the presented study considers the relevance of the statement that at the macroeconomic level roundwood – round logs – is defined as a primary raw material resource with the lowest degree of economic value in the entire forest chain (Ning & Sun, 2014). Therefore, roundwood is significant as a foundation of the supply chain, but ensuring the long-term competitiveness of a modern European economy should be based on transformation through technology and innovation into products from the forest segment, considering the requirements and principles of the bioeconomy. In addition, the study considers that in the forest sector of the European Union, security of supply is predominantly guaranteed autonomously. This can be brought into line with the modern paradigm in international trade, which replaces the concept of globalization with regionalization of supply chains for the purpose of higher flexibility (Chatzinikolaou & Viados, 2026).

Thus, the main objective of the study is to analyze the contribution of trade in wood products to the economic development of the countries of the European Union during the period 2014-2024, providing evidence in the context of the bioeconomy. On this basis, more significant dependencies are established and emerging similarities and differences between the individual Member States of the European Union are highlighted.

2. METHODOLOGY

The presented study is aimed at analyzing and assessing the relationship between the economic development of the European Union member states and the trade in wood products. In the constructed methodological framework, the level of economic development of the studied European countries is measured by the dependent variable "value of Gross Domestic Product of the European Union countries". The indicator "value of roundwood exports of the European Union countries" was chosen as the independent variable. In this sense, this study interprets the extent to which the economic development of the studied European countries depends on the export of roundwood.

The methodological tools of the study are based on the method of linear regression and correlation. The statistical processing of the empirical data is implemented using the capabilities the software product for econometric data analysis IBM SPSS Statistics, as well as the Excel program. The quantitative measurement of the researched indicators is based on official data from Eurostat for the period 2012-2022.

3. RESULTS AND DISCUSSION

In order to fulfill the basic objective, set in this study, the following statement interprets the strength of the relationship between the selected dependent variable "value of Gross Domestic Product of the European Union countries" and the independent variable "value of roundwood exports of the European Union countries". The regression and correlation analysis refer to the ten-year period 2012-2022.

The empirical data collected for the last year of the analyzed period allow visualization of the realized export of roundwood from the 27-member states of the European Union (Eurostat, 2023): see Fig. 1. According to the data illustrated with the help of figure, the comparison between the 27 Member States of the European Union, carried out for 2022, allows us to establish that the export of roundwood is largely geographically concentrated. The highest exports are reported by certain countries from Central Europe - Germany, the Czech Republic and Poland, followed by France, as a country from Western Europe. The four highlighted countries form over 50.00% of the total value of roundwood exports in the Community (Eurostat, 2024). In the same year, among the leading countries in exports, Sweden, Finland and Latvia from Northern Europe stand out, reporting an average of over 7.00% to 12.00% relative share in the total value of exports (Eurostat, 2023).

The indicated countries have significant forest areas and wood reserves. This allows them to be among the key players in the market and to determine the trends of roundwood exports for the entire European Union.

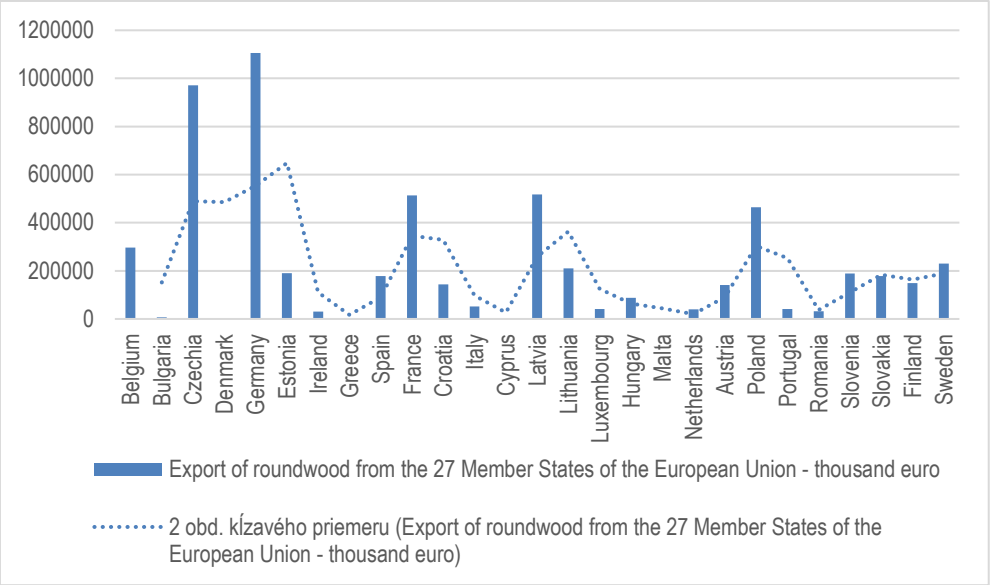


Figure 1. Roundwood exports from the 27 Member States of the European Union in 2022 (in thousands of euros), (data for certain countries not available).

The Member States with the relatively lowest results on the analyzed indicator include Malta and Cyprus. Among the factors with a determining impact on the reported data for the European forest-based economy, and specifically for the export of roundwood, the following can be highlighted: available forest areas, current regulations, market price dynamics, economic and trade sanctions imposed during the period, energy crises, environmental problems and others.

In accordance with the research objective set in this paper, the applied regression model yields the following results, characterizing the relationship between the dependent variable "value of Gross Domestic Product of the European Union countries" and the independent variable "value of roundwood exports of the European Union countries": see Table 1.

Table 1. Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0,823	0,678	0,642	675207,415

Based on the data presented in Table 1, it is reported that the correlation coefficient (R) takes the value of 0.823 and indicates a strong, positive and statistically significant relationship between the outcome variable "value of Gross Domestic Product of the European Union countries" and the factor variable "value of roundwood exports of the European Union countries". The established proportional linear relationship confirms that the increase in the value of roundwood exports is closely related to higher levels of GDP in the European countries under consideration, and in accordance with the specifics of the method of unit regression and correlation, the simultaneous influence of other market and macroeconomic factors is not

considered. The correlation coefficient ($R^2 = 0.678$) shows that nearly 68.00% of the variation in the realized "value of Gross Domestic Product of the European Union countries" is explained by the dynamics and value of roundwood exports. The interpretation of the adjusted coefficient of determination (0.642 or 64.20%) considers the number of variables and the sample size, confirming that the model remains highly robust.

Based on the presented scatter diagram with a linear trend line, the results of the regression model analyzed in this paper are confirmed: see Fig. 2.

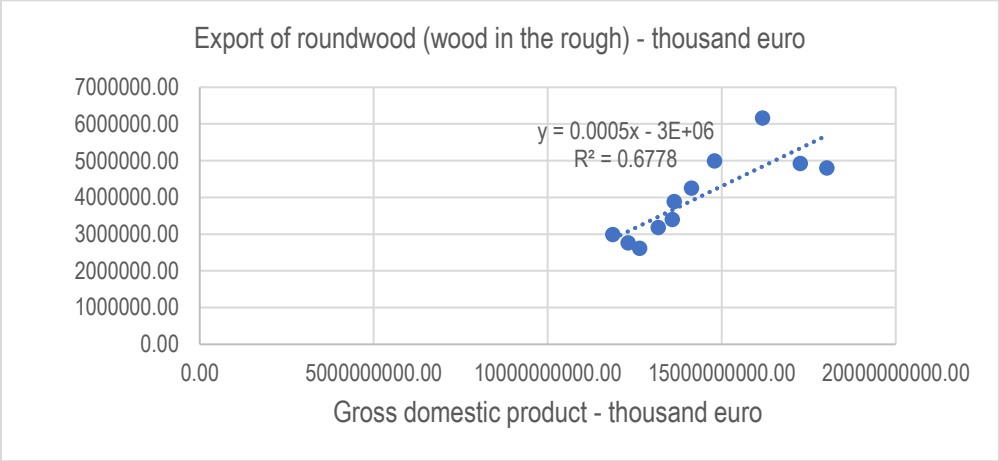


Figure 2. Dynamics of the "value size of Gross Domestic Product" of the European Union countries" and the "value of roundwood exports" of the European Union countries" during the period 2012-2022, in thousands of euros

During the period under study 2012-2022, a trend line with a pronounced upward slope to the right is outlined. This illustrates the distribution of empirical data for the 27 Member States of the European Union according to the reported “value of Gross Domestic Product” and “value of roundwood exports”. The graphical clustering of the analyzed values proves the formation of relatively homogeneous groups of European economies based on their export intensity of traded roundwood. This clustering is determined by similarities in macroeconomic development and GDP generation.

4. CONCLUSION

Based on the presented theoretical considerations related to the European forest-based industry and its importance for the bioeconomy model, as well as considering the results obtained from the regression model, more important conclusions can be formulated. The forest sector of the European Union is defined as one of the fundamental pillars of bioeconomy. The harvested wood biomass is a sustainable terrestrial source of renewable resources. The long-term competitiveness of the European economy is to a certain extent synchronized with the transformation of the forest sector through technology and innovation, considering the requirements and principles of the bioeconomy.

The developed trade in roundwood is linked to the GDP of the European Union countries. This is cited as empirical evidence that the bioeconomy can generate real economic development. Empirical data confirm the clear demarcation and formation of relatively homogeneous groups of European economies with similar export intensity regarding roundwood. Therefore, in a macroeconomic aspect, trade in wood products should not be analyzed in isolation, but fully integrated with the dynamics and level of economic development of the European Union countries.

REFERENCES

1. Birner, R. (2018). Bioeconomy Concepts. Springer International Publishing: Cham, Switzerland.
2. Blazheva, V. (2025). The Human Resources - a Factor for a Sustainable Agricultural Sector. *Environment. Technology. Resources. Rezekne, LatviaProceedings of the 16th International Scientific and Practical Conference. 2025. Volume I*, pp. 89-95.
3. Bojnec, S., & Ferto, I. (2014). Forestry industry trade by degree of wood processing in the enlarged European Union countries. *Forest Policy and Economics,* pp. 31-39.
4. Chatzinikolaou, D., & Viados, C. (2026). From Hyperglobalization to "New Globalization": Transnational Corporations, *Geopolitical Shocks, and Resilient Global Value Chains.* Mercados y Negocios, pp. 49-80.
5. European Bioeconomy University. (2025). The EU Circular Bioeconomy: How to fully develop its potential within the next 10 years? *The EBU Alliance position paper* – June 2025.
6. Eurostat. (2023). Wood products - production and trade. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_-_production_and_trade
7. Eurostat. (2024). Forests, forestry and logging. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Forests,_forestry_and_logging
8. Hassegawa, M., Karlberg, A., Hertzberg, M., & Verkerk, P. (2022). Innovative Forest Products in the Circular Bioeconomy. 2, p. 19.
9. Heimann, T. (2019). Bioeconomy and SDGs: Does the Bioeconomy Support the Achievement of the SDGs? *Earth's Future,* pp. 43–57.
10. Ning, Z., & Sun, C. (2014). Vertical price transmission in timber and lumber markets. *Journal of Forest Economics,* pp. 17-32.
11. Rembiasz, M., Borowiec, A., & Czajkowski, P. (2024). Competitiveness of Companies Producing Wood-Based Panels as an Example of the Sustainable Development. *European Research Studies Journal,* pp. 531-547.
12. Sathre, R., & O'Connor, J. (2010). Meta-Analysis of Greenhouse Gas Displacement Factors of Wood Product Substitution, *Environ. Sci. Policy.* pp. 104-114.
13. Verter, N., & Grega, L. (2019). Export performance and competitiveness in wood products in the Czech Republic and Austria. *Ekonomski pregled,* pp. 743-764.

Authors address:
Petrova, S.[1]
[1] Department of Commerce, Faculty of Industry and Commerce, Tsenov Academy of Economics, Svishtov, Bulgaria
*Corresponding author: s.petrova@uni-svishtov.bg

WOOD PROCESSING FINANCIAL SUSTAINABILITY IN CIRCULAR BIOECONOMY

Galina Sabcheva

Abstract: In today`s dynamic economic environment, the transition to sustainability involves overcoming a number of challenges facing the woodworking sector. It is essential to strike a balance between resource efficiency and financial stability. The aim of this report is to examine the financial sustainability of woodworking enterprises that apply circular economy principles by utilizing significant amounts of waste alongside primary raw materials. The study focuses on two of the leading enterprises in Bulgaria – "Kronospan Bulgaria" EOOD and "Kastamonu Bulgaria" AD. A comparative financial analysis is applied, based on data from financial statements, activity reports, and environmental reports for the period 2020-2024. The focus was on key financial indicators for resource efficiency, liquidity, and capital adequacy, which are used to assess how the cascading utilization of biomass changes the company`s financial profile.
Keywords: financial sustainability, wood processing, circular economy, analysis

1. INTRODUCTION

The 2020-2024 period was marked by unprecedented dynamics in the woodworking sector, resulting from a confluence of global economic disruptions (COVID-19 pandemic, high inflation, raw material shortage and rising energy costs). Following the COVID-19 crisis, demand stimulated the sector. The ensuing geopolitical changes beginning in 2022 and the sanctions imposed by European Union led to a shift in demand toward engineered wood and price increase of over 100%. At the same time, the energy crisis has driven electricity prices to record levels, which are of vital importance for energy-intensive industries such as wood processing. Against the backdrop of record inflation, the transition of cascading biomass utilization has become a critical tool for maintaining the financial sustainability of the sector`s two leading companies, "Kastamonu Bulgaria" AD and "Kronospan Bulgaria" EOOD.

In this economic context, the aim of this report is to examine how the cascading utilisation of biomass affects the financial sustainability of wood-processing enterprises. To achieve this aim, the following objectives have been set:

1) To formulate a hybrid conceptual framework integrating financial sustainability and cascade biomass utilization indicators.
2) To conduct a comparative empirical financial analysis of "Kastamonu Bulgaria" AD and "Kronospan Bulgaria" EOOD for 2020–2024.
3) To identify the circular business archetypes of both companies and provide practical optimization guidelines.

The empirical study is based on publicly available data from annual financial statements, audit reports and annual activity reports published in the Commercial Register, as well as on the annual environmental reports of the wood-processing companies analysed. The data were manually collected and calculated for the purposes of this report.

2. THEORETICAL FRAMEWORK

In the specialist literature, there are differing views on the nature of financial sustainability. This report adopts the contemporary understanding of Gleißner et al. (2022, p.474), who state that financial sustainability represents the ability of an enterprise to achieve current financial success without jeopardising its long-term viability and future financial performance under the influence of various factors. This approach successfully integrates the Brundtland Commission's basic idea of sustainable development into a financial context. According to the authors, financial sustainability is viewed as a dynamic system, measured by the simultaneous fulfilment of four mandatory conditions: firm growth, survivability, risk exposure and an attractive risk profile. On the other hand, the introduction of circular bioeconomy models and the measurement of the financial impact of structural changes in firms' business models require the application of specific hybrid models. In this context, *Baars et al. (2022)* argue in detail for the need to methodologically integrate material flow analysis (MFA) with micro-level financial assessments in order to eliminate the risk that the environmental benefits of resource efficiency might be offset by an economic deficit *(burden-shifting).*

Taking into account the dynamic economic environment in which the woodworking sector is developing during the analysed period 2020–2024, characterised by the COVID-19 pandemic, the ensuing high inflation, raw material shortages and the energy crisis (Trichkov, 2025), the financial sustainability of enterprises in the sector has become a challenge. Based on a review of the specialist literature (Baars et al., 2022; D'Amato et al., 2020; Emmanuel et al., 2026; Gleißner et al., 2022; Gursel et al., 2023; T. Manolov, 2025; T. L. Manolov, 2017; Moraga et al., 2019; Oliveira et al., 2021; Palea et al., 2023; Pauliuk, 2018; Pinho et al., 2025; Rondós-Casas et al., 2026; Saidani et al., 2019;), a conceptual hybrid framework for financial analysis is proposed in Table 1, which is based on the dynamic concept of Gleißner et al. (2022) for assessing financial sustainability, supplemented by hybrid indicators of resource efficiency:

Table 1. Conceptual hybrid framework for analysis

<table>
<tr><td colspan="4">Groups and indicators</td></tr>
<tr><td colspan="2">I. Financial ratios</td><td colspan="2">II. Resource ratios</td></tr>
<tr><td>III. Firm growth
Total asset turnover
Asset intensity</td><td>IV. Survivability
Net cash flow of operations ratio
Current ratio
Quick ratio
Solvency ratio
Long leverage ratio
Asset coverage ratio</td><td rowspan="2">V. Recourse intensity
Wood intensity
Waste intensity
Water intensity
Wood-waste ratio</td><td rowspan="2">VI. Energy intensity and autonomy
Energy intensity
Energy autonomy</td></tr>
<tr><td>VII. Earnings risk exposure
Material intensity
Leverage ratio
Intangibles turnover</td><td>VIII. Attractive risk profile
Return on assets
Return on sales</td></tr>
</table>

The ratios grouped in Table 1 have been applied in turn to the two timber-processing companies analysed: "Kastamonu Bulgaria" AD and "Kronospan Bulgaria" EOOD. The inventory turnover plays a crucial role as a link between the different groups of ratios. On the one hand, the funds tied up in higher levels of inventories have a direct impact on the company's liquidity and its ability to cover its liabilities immediately. In conditions of raw material shortages

and high inflation, higher levels of inventory can ensure the continuity of the production process and a steady flow of sales revenue. At the same time, the inventory turnover acts as the link between physical raw materials and working capital management.

3. EMPIRICAL RESULTS AND DISCUSSION

The calculated values of the ratios listed in Table 1 are presented in Table 2 below:

Table 2. Results of the ratio analysis

Company	Kastamonu Bulgaria AD ratios					Kronospan Bulgaria EOOD				
Indicator	2020	2021	2022	2023	2024	2020	2021	2022	2023	2024
Total asset turnover	0,65	0,92	1,02	0,69	0,70	0,31	0,46	0,53	0,45	0,58
Asset intensity	1,12	0,79	0,61	0,86	0,98	3,12	2,03	1,78	1,92	1,47
OCF ratio	0,04	0,27	0,34	-0,29	0,25	0,19	0,00	0,13	0,17	-0,18
Current ratio	0,60	0,58	1,22	0,67	0,61	0,56	0,76	1,23	0,99	1,36
Quick ratio	0,21	0,22	0,56	0,23	0,17	0,19	0,22	0,30	0,17	0,35
Solvency ratio	1,47	1,46	1,30	1,44	1,35	1,52	1,45	1,40	2,13	2,12
Long leverage ratio	1,37	1,93	0,62	1,38	0,97	0,63	0,56	0,47	1,67	1,56
Asset cov. ratio	1,32	1,46	0,86	1,30	1,35	1,06	1,04	0,97	1,00	0,94
Material intensity	0,60	0,66	0,76	0,65	0,59	0,75	0,77	0,78	0,69	0,74
Leverage ratio	2,26	2,13	2,18	3,30	2,29	1,97	1,93	2,24	2,49	0,88
Inventory turnover	3,74	5,03	4,25	2,91	3,36	5,58	7,39	5,47	3,92	4,34
Return on assets	-0,02	-0,01	-0,03	-0,07	-0,08	-0,03	0,00	-0,01	-0,08	-0,05
Return on sales	-0,03	-0,02	-0,03	-0,11	-0,11	-0,09	0,00	-0,01	-0,18	-0,08
Wood intensity	0,38	0,51	0,68	0,60	0,66	0,40	0,58	0,88	0,98	1.22
Waste intensity	0,38	0,33	0,33	0,41	0,41	0,28	0,20	0,19	0,18	0,12
Water intensity	1,44	1,27	0,97	1,19	1,19	0,82	0,54	0,41	0,34	0,27
Wood-waste ratio	5,41	4,55	3,46	3,17	2,84	6,92	6,69	4,66	4,40	5,52
Energy intensity	0,28	0,23	0,19	0,23	0,21	0,40	0,28	0,20	0,18	0,14
Energy autonomy	0,85	0,84	0,85	0,85	0,86	0,77	0,76	0,80	0,81	0,82

The proposed interpretation of the financial and resource indicators for the two enterprises is based on the multi-component conceptual hybrid framework for analysis proposed above, which integrates the concepts of financial sustainability, resource analysis and circular business models. The “Kastamonu’s” asset utilization shows a nominal improvement in the period 2020–2022 as a result of higher inflation, and a slowdown in the period 2023–2024 due to a decline in market demand for wood-based panels. The asset intensity ratio remains at optimal levels throughout the entire analysed period. At “Kronospan”, the total asset turnover ratio also maintains a stable upward trend until 2022 as a result of increased demand, approximately doubling by 2024 compared with the 2020 figure. The company maintains a high asset intensity throughout the analysed period – consistently above

1, which is an indicator of a significant volume of long-term investments with a prolonged payback period.

Both companies operate with low current and quick liquidity ratios throughout most of the period, occasionally peaking in 2022 due to raw material overstocking following the geopolitical disruptions. This conclusion is also confirmed by the low values of the cash coverage ratio for short-term liabilities. “Kastamonu`s” solvency ratio remains at high levels throughout the period under review and is only marginally affected by accumulated losses. The asset coverage ratio fell below 1 only in 2022, when there raw materials overstocking occurred, but remained at consistently high levels throughout the period. The long-term leverage ratio fell below 1 in 2022 and 2024, influenced simultaneously by a decline in equity and an increase in debt, indicating a weakening of the equity position vis-à-vis long-term creditors.

“Kronospan`s” solvency and asset coverage ratios remain at optimal levels throughout the period, falling slightly as a result of the reduction in equity due to accumulated losses. The company operates at the threshold of the golden balance sheet rule. The long-term debt ratio shows an upward trend, which is an indicator of capital structure optimisation during the 2023–2024 period.

Both entities maintain a relatively stable and high material intensity per unit of revenue over the period. “Kastamonu” stands out due to volatility in the inventory turnover, which is attributable both to a steady increase in the carrying value of inventories and a more gradual rise in revenue. “Kronospan” also maintains a high turnover rate, whilst being less dependent on raw materials. Both companies recorded a peak in turnover following the pandemic, as a result of increased demand and inflation in 2021. The raw materials crisis, which has led to a rise in timber prices of over 100 % and energy prices (Trichkov, 2025), has resulted in an increase in inventory levels and a slowdown in inventory turnover. “Kronospan” increased the book value of its inventories over the period. “Kastamonu’s” leverage ratio, due to a decline in equity, remained at high levels throughout the entire analysed period (above 2), which is an indicator of a high-risk position vis-à-vis creditors and strong sensitivity to raw material and energy prices. “Kronospan” also maintained a high debt-to-equity ratio of around and above 2, but a sharp fall to below 1 was recorded in 2024. This trend resulted from a stabilised capital structure and indicated a reduction in credit risk towards external creditors.

Both companies generate systematic net losses throughout the entire period analysed, as a result of high capital expenditure, raw material shortages and inflation, which are not offset even by the cascading biomass utilisation models that have been introduced. This negative profile restricts access to market-based financing.

Both entities recorded a gradual decline in the total volume of processed timber during the 2020–2024 period. The reduction in the volumes of water and electricity used for technological purposes is proportional to the quantities of timber processed. As a result of the increase in revenue despite lower volumes of raw timber, higher revenue per cubic metre of processed timber has been calculated for both companies – ranging from 0.38 to 0.66 for “Kastamonu”and from 0.40 to 1.22 at “Kronospan” over the period. At “Kastamonu”, waste intensity has worsened, whilst at “Kronospan”it has improved. At the same time, water and energy intensity have decreased at both companies. At both entities, the amount of waste generated per tonne of processed timber has increased as a result of the deterioration in the quality of the processed timber following the 2022 embargo, a trend that is more pronounced at “Kastamonu” (the generation of 1 tonne of waste requires almost half the amount of raw timber). As a result of the introduction of cascading models for biomass utilisation (at

"Kronospan" and the diversification of input raw materials through the processing of old furniture and waste from furniture production), both companies have seen an improvement in their energy efficiency by supplying a significant proportion of their processes with thermal energy. During the period, "Kastamonu's" energy self-sufficiency was exceptionally high, improving from over 84 per cent to over 86 per cent, whilst "Kronospan's" rise from over 76 per cent to 82 per cent. High energy self-sufficiency is both an environmental advantage and a result of the higher proportion of waste per unit of raw material. The presence of systematic net losses demonstrates that energy efficiency is not sufficient to compensate for the high scrap rate resulting from the poor quality of the processed timber, particularly at "Kastamonu". To summarise the above, the circular model applied by "Kastamonu"is based on internal resource and energy efficiency, whilst that applied by "Kronospan" is based on external cascade material recycling.

An individual analysis of the two companies based on the proposed conceptual hybrid framework leads to the conclusion that the two companies maintain their financial sustainability in different ways. "Kastamonu" maintains high overall solvency and asset coverage, financed entirely by long-term capital, whilst the current market dynamics (inflation, raw material shortages, etc.) affect its liquidity and profitability. "Kronospan" also maintains a high overall solvency ratio, but the financing of its fixed assets is at the limit, which results in more optimised management of working capital, liquidity and long-term debt.

The empirical data unequivocally confirm that the two companies can be classified into two distinct circular archetypes, in accordance with the taxonomy set out at Bocken et al. (2014). The data for "Kastamonu" (processing of raw timber only, high waste rate, high energy efficiency) can be interpreted as evidence of a technological model based on the internal energy recovery of waste. The data for "Kronospan" (high inventory turnover and processing of both in-house and external waste) can be interpreted as evidence of a business model based on cascading material recycling. There is a causal link between the data from the environmental reports (the calculated resource utilization indicators) and the financial results achieved by the two entities. Both companies are situated in the 'technology' pillar according to the classification at Bocken et al. (2014), but differ in terms of value creation and delivery.

4. CONCLUSION

To improve the financial sustainability and resource utilization of the two entities, based on the analysis results the following recommendations could be made: "Kastamonu Bulgaria" AD should focus on diversifying raw materials (e.g. furniture waste) to reduce waste rates, optimize inventory levels, and subsequently improve liquidity and equity positions. "Kronospan Bulgaria" EOOD could invest in material recycling infrastructure to enhance energy autonomy. Additionally, optimizing inventory structures to accelerate turnover could improve quick liquidity and overall profitability.

REFERENCES

1. Baars, J., Rajaeifar, M. A., & Heidrich, O. (2022). Quo vadis MFA ? Integrated material flow analysis to support material efficiency Mohammad Ali Rajaeifar 1. *Journal of Industrial Ecology*, *26*, 1487–1503. https://doi.org/10.1111/jiec.13288

2. Bocken, N. M. P., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production*, *65*, 42–56.

https://doi.org/10.1016/j.jclepro.2013.11.039

3. D'Amato, D., Veijonaho, S., & Toppinen, A. (2020). Forest Policy and Economics Towards sustainability ? Forest-based circular bioeconomy business models in Finnish SMEs. *Forest Policy and Economics*, *110* (October 2018), 101848. https://doi.org/10.1016/j.forpol.2018.12.004

4. Dragomir, M., Dragomir, D., & Popescu, D. (2023). Assessing Circularity in the Wood Industry — Methodology , Tool and Results. *Forests*, *14*(1935), 1–13. https://doi.org/https://doi.org/10.3390/f14101935

5. Emmanuel, G. B., Kutus, M. O., & Gbegi, D. O. (2026). Circular Economy Accounting: Measuring the Financial Value of Waste to Wealth Initiatives. *Journal of Human Resources & Mgt. Science*, *11*(7), 94–109.

6. Gleißner, W., Günther, T., & Walkshäusl, C. (2022). Financial sustainability: measurement and empirical evidence. In *Journal of Business Economics* (Vol. 92, Issue 3). Springer Berlin Heidelberg. https://doi.org/10.1007/s11573-022-01081-0

7. Gursel, I. V., Elbersen, B., & Meesters, K. P. H. (2023). Resources , Conservation & Recycling Monitoring circular biobased economy – Systematic review of circularity indicators at the micro level. *Resources, Conservation & Recycling*, *197*(January), 107104. https://doi.org/10.1016/j.resconrec.2023.107104

8. Manolov, T. (2025). Application of financial analysis in the analysis of solvency risk. In D. Feschiyan, N. Nenovsky, P. Ricci, P. Tadeu, J. F. Batanero, I. Martinez, J. Boutant, G. Migliaccio, P. Pavone, & E. Gremi (Eds.), *International scientific conference 105th anniversary of the Departement of accouning and analysis Accountig, digitalization, sustainability - science and practice*. Sofia: Academic publishing house – UNWE.

9. Manolov, T. L. (2017). Analysis of creditwortness of enterprises in Varna region (Bulgaria) as a prerquisite xto devopment of an effective financial strategy. In *SCIENCE AND EDUCATION:Collection of scientific articles* (pp. 256–259). Verlag SWG imex GmbH.

10. Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Acker, K. Van, Meester, S. De, & Dewulf, J. (2019). Resources , Conservation & Recycling Circular economy indicators : What do they measure ? *Resources, Conservation & Recycling*, *146*(April), 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045

11. Oliveira, C. T. De, Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators : Assisting decision-makers in circularity assessments. *Sustainable Production and Consumption*, *26*, 455–468. https://doi.org/10.1016/j.spc.2020.11.024

12. Palea, V., Santhia, C., & Miazza, A. (2023). Are circular economy strategies economically successful ? Evidence from a longitudinal panel. *Journal of Environmental Management*, *337*(January), 1–12. https://doi.org/10.1016/j.jenvman.2023.117726

13. Pauliuk, S. (2018). Resources , Conservation & Recycling Critical appraisal of the circular economy standard BS 8001 : 2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation & Recycling*, *129*(September 2017), 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

14. Pinho, G. C. D. S., Calmon, J. L., Medeiros, D. L., & Pinho, C. (2025). Furniture Wood Waste Management Towards the Circular Economy. *Applied Sciences*, *15*(1360), 1–20. https://doi.org/https://doi.org/10.3390/app15031360

15. Rondós-Casas, E., Arimany-Serrat, N., Carreras-Simó, M., & Coenders, G. (2026). The use of financial and sustainability ratios to map a sector . An approach using compositional data. *Corporate Social Responsibility and Environmental Management*, 1–13. https://doi.org/https://doi.org/10.1002/csr.70412

16. Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, *207*, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

17. Trichkov, L. (2025). Dunamika na polzvaneto i tcenite na darvesinata za perioda 2019 – 2024. *Gora*, *3*, 4–9.

Authors address:

Sabcheva, Galina[1];
[1] Department of Accounting, Faculty of Finance and Accounting, University of economics - Varna, Varna, Bulgaria
*Corresponding author: sabcheva.galina@ue-varna.bg

BIOECONOMY INNOVATIONS: THE IMPACT OF ELECTRICITY MARKETS ON THE DEVELOPMENT OF BIOBASED WOOD PRODUCTS

Dimitar Blagoev

Abstract: This paper examines the interaction between innovation in the forest-based bioeconomy and the dynamics of electricity markets, with a particular focus on how electricity price fluctuations influence the development of biobased wood products. The bioeconomy is emerging as a key component of the transition toward a low-carbon economic model, and the forest sector plays a central role by providing renewable resources with high added value. At the same time, the wood-processing industry is highly energy-intensive, making it sensitive to volatility in electricity prices. This creates a need for an in-depth analysis of how technological, process, and product innovations can mitigate the negative effects of energy shocks and enhance the sector's competitiveness.

The paper combines a theoretical overview with an empirical analysis based on panel data from Bulgaria. An econometric model is employed, incorporating electricity prices, innovation indicators (R&D expenditures, number of patents, adoption of energy-efficient technologies), and control variables such as GDP, wood prices, and sectoral investment. An interaction term between innovation and electricity prices is included to assess whether innovative firms and economies demonstrate greater resilience to energy market fluctuations.

Results indicate that high electricity prices exert a statistically significant negative effect on the production and export of biobased wood products. At the same time, innovation has a positive and compensatory effect, reducing energy intensity, improving production efficiency, and stimulating the creation of higher value-added products. The interaction model confirms that innovation acts as a buffer against energy shocks, and countries with higher R&D investment exhibit greater resilience and lower dependence on electricity market volatility.

The paper concludes that innovation is a key driver of sustainable development in the forest-based bioeconomy and a critical factor enabling the sector to adapt to a changing energy environment. Based on these findings, the study proposes policy recommendations aimed at fostering technological investment, improving energy efficiency, and supporting enterprises in their transition toward more competitive and sustainable biobased products.

Keywords: innovation, bio-economy, electricity market price

1. ELECTRICITY PRICES, PRODUCTION DYNAMICS, AND INNOVATION IN THE BIOECONOMY AND FOREST-BASED INDUSTRIES

The contemporary transition toward a sustainable economic model has positioned the bioeconomy as a central paradigm for addressing climate change, resource scarcity, and the need for low-carbon industrial transformation. A growing body of research emphasizes that innovations—technological, organizational, and systemic—serve as the primary engine behind the development and scaling of bio-based solutions. The bioeconomy is broadly defined as the set of economic activities relying on renewable biological resources, biological processes, and eco-efficient technologies to produce food, materials, chemicals, and energy (German Bioeconomy Council, 2018, as cited in Proestou et al., 2023). This conceptualization underscores the dual ambition of the bioeconomy: economic competitiveness and environmental sustainability.

Recent studies highlight that innovation plays a decisive role in shaping bioeconomy trajectories. Zuniga-Gonzalez et al. (2024) argue that the bioeconomy is inherently dynamic and requires integrated theoretical models that capture causal relationships, state variables, and system boundaries.

At the policy level, bioeconomy strategies worldwide increasingly incorporate innovation as a core pillar. Proestou et al. (2023) analyze 78 national bioeconomy policy documents and identify three dominant visions: bioresource, biotechnology, and bioecology. Although economic growth remains the most salient policy goal, the study reveals that innovation is essential for enabling the shift from fossil-based to renewable resource systems. However, environmental considerations are often less emphasized, suggesting a gap between innovation rhetoric and sustainability outcomes.

The forest-based sector - comprising forestry, wood harvesting, and wood processing—occupies a central position in the emerging bioeconomy, where renewable biological resources are transformed into materials, chemicals, and energy. A consistent theme in the literature is that energy costs, particularly electricity prices, exert a significant influence on production efficiency, competitiveness, and the capacity for innovation within these industries. As wood processing is among the most energy-intensive branches of the bioeconomy, fluctuations in electricity markets directly shape technological upgrading, investment decisions, and long-term sustainability strategies.

Electricity is a critical input in sawmilling, drying, pelletizing, panel production, and biorefining. According to Ranta et al. (2020), energy expenditures can represent up to 30% of total production costs in certain wood-processing segments, making the sector highly sensitive to price volatility. When electricity prices rise, firms face pressure to optimize processes, adopt energy-efficient technologies, or shift to self-generation through biomass residues. This dynamic is confirmed by Hurmekoski et al. (2023), who argue that energy price shocks accelerate innovation adoption, especially in mills with access to forest biomass suitable for cogeneration.

The relationship between electricity prices and innovation is also emphasized in broader bioeconomy research. According to Hausmann et al. (2021), high energy costs can either constrain innovation—by reducing available capital—or stimulate it, by creating incentives for efficiency-enhancing technologies. In the forest sector, the latter effect is more common due to the availability of internal renewable energy sources. For example, Mola-Yudego et al. (2022) show that firms increasingly invest in electrification, automation, and digital monitoring systems when facing sustained energy price increases, as these innovations reduce long-term operational costs.

The literature also highlights the role of policy frameworks. The European Commission (2022) notes that electricity price volatility—exacerbated by geopolitical disruptions—has accelerated the transition toward renewable energy integration in industrial processes. Forest-based industries, due to their biomass residues, are well positioned to adopt circular energy models. This is supported by Ladu et al. (2020), who emphasize that policy incentives for renewable self-generation significantly increase innovation uptake in the wood sector.

From a technological perspective, innovations in drying technologies, biorefining, and process automation are strongly correlated with electricity price trends. According to Sandberg et al. (2021), modern high-frequency and heat-pump drying systems reduce electricity consumption by up to 40%, making them attractive investments during periods of high energy prices. Similarly, bio-refineries integrating lignocellulosic feedstocks rely heavily on stable

electricity supply; thus, price fluctuations influence both operational planning and R&D investment (Kougias et al., 2021).

Overall, the literature converges on several conclusions. First, electricity prices are a major determinant of production costs and innovation incentives in the forest-based bioeconomy. Second, high prices tend to stimulate energy-efficiency innovations and renewable energy integration, particularly in firms with access to biomass residues. Third, policy frameworks play a crucial role in mitigating risks and supporting innovation adoption. Finally, the interplay between electricity markets and technological development is central to the long-term competitiveness and sustainability of the bioeconomy.

2. RESEARCH METHODS AND DATA

The present study employs a combination of qualitative and quantitative research methods to examine the influence of electricity prices, innovation activity, and macroeconomic development on the production performance of enterprises in the forestry and wood-processing sector. The methodological framework is grounded in established empirical research practices and follows APA-style structuring.

Several research methods were applied: Observation Method; Field Research; Grouping and Analytical Method; Retrospective Analysis; Correlation Analysis; Comparative Analysis;

These methods collectively ensure a robust analytical foundation and allow for triangulation of findings, thereby increasing the validity of the empirical results.

Data Sources

The study relies on two primary data sources:

1. Independent Bulgarian Energy Exchange (IBEX) – day ahead market prices for industrial electricity consumers. Data availability begins in 2017, when IBEX commenced operation, making earlier industrial level electricity price data unavailable.

2. Eurostat and National Statistical Institute of Bulgaria (NSI) – annual data on: production and turnover volumes in the wood processing sector; Investments (incl. R&D expenditures (used as a proxy for innovation activity).

To ensure methodological consistency and trend reliability, the analysis covers a 10 year period (2015–2025).

Analytical Approach

From a methodological perspective, the study focuses on three analytical dimensions:

1. Trend Identification. The analysis examines whether the observed variables exhibit upward, downward, or fluctuating trends. Trend lines are estimated using linear functions, which provide the best fit for the dynamic statistical series under consideration.

2. Functional Dynamics. Linear trend functions are used to approximate the direction and magnitude of change in each variable.

3. Correlation Assessment. Pairwise correlations are calculated to determine the degree of association between electricity prices, investments in innovation, production output and turnover in wood sector.

3. RESULTS AND DISCUSION

At the beginning of the observed period, there was relative stability and even a decline in electricity prices. That is, it can be said that in this period 2017-2020 they are a significant factor

for innovation of companies in the sector (in particular in energy-saving technologies). In 2021 and 2022, under the influence of a number of force majeure circumstances (pandemic, military conflicts), there was a sharp increase in the price of energy resources and products. During this period, companies in the sector reacted with an increase in capital expenditures (despite increased current production costs) (Fig.1).

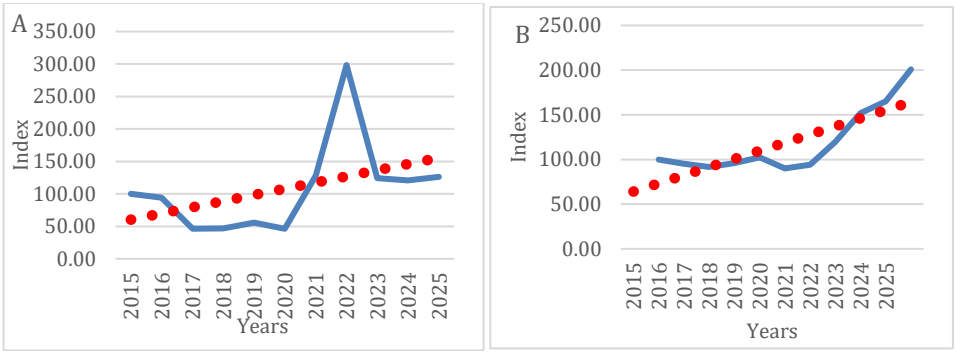


Figure 1. A. Electricity price index with base 2015=100 and B. Investment expenditure index (incl. innovation) with base 2015=100

The strong correlation suggests that the shock increase in energy prices forced the industry to invest rapidly in energy efficiency, renewable energy for its own needs and technological modernization in order to maintain competitiveness. Even after the partial calming of the energy market (2023–2025), investments continue to grow to 200.8 points in 2025, indicating a long-term commitment to cost restructuring.

Despite the general macroeconomic context, the two main sub-sectors demonstrate fundamentally different behavior. Wood production is in a state of structural crisis. Production volume has been steadily declining since 2015, collapsing to 74.3 points in 2023. Since turnover is also falling steadily (to 72.4 points in 2025), it is obvious that the decline is dictated by both contracted production and market factors – possibly loss of export markets or shortage of raw material (Fig.2).

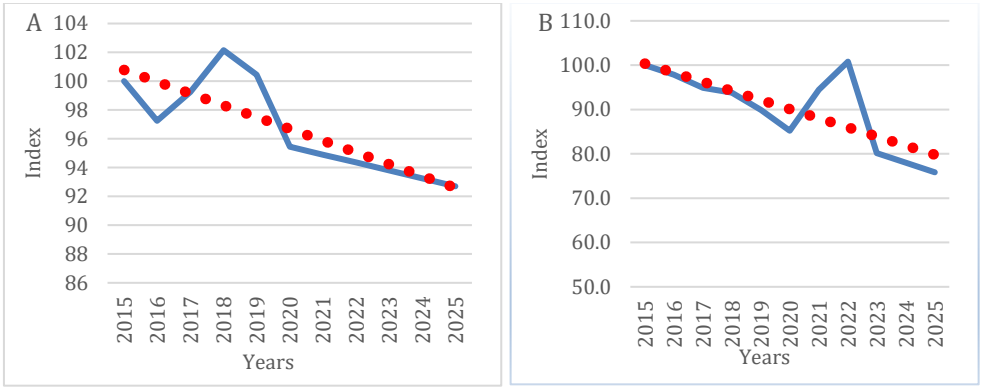


Figure 2. A. Index of turnover in wood industry with base 2015=100 and B. Index of production in Wood Industry with base 2015=100

The furniture manufacturing subsector shows significantly greater resilience and added value. Production volumes grew steadily until 2022, coinciding precisely with the energy crisis. Although production contracted in 2023 under the pressure of accumulated high production costs from previous years, the turnover of the subsector continued to grow linearly.

Table 1. Correlation Matrix (Pearson)

Variable	Electricity Price	Investment Costs	Turnover (Wood Industry)	Manufacturing (Wood Industry)
Electricity Price	1.00	0.91	–0.83	–0.88
Investment Costs	0.91	1.00	–0.74	–0.79
Turnover	–0.83	–0.74	1.00	0.96
Production	–0.88	–0.79	0.96	1.00

The results of the correlation analysis reveal several strong and economically significant patterns. The strongest positive correlation is observed between turnover and production (r = 0.96). Such a relationship is typical for sectors with low inventory buffers and high dependence on current production.

Electricity prices show a strong negative correlation with both production (r = –0.88) and turnover (r = –0.83). This suggests that rising electricity costs significantly dampen industrial activity in the wood processing sector. Since wood processing is energy-intensive, higher electricity prices directly increase variable costs, reduce profit margins and weaken competitiveness. The data clearly show that energy price shocks translate into lower production and reduced market performance.

A particularly interesting finding is the strong positive correlation between electricity prices and investment costs (r = 0.91). This confirms the conclusion made above based on the dynamics of the graphs that companies tend to increase their investments during periods of high energy costs. During such periods, they invest in innovations to modernize equipment to improve energy efficiency or to install renewable energy systems for their own consumption. These actions play the role of a strategic adaptation mechanism aimed at reducing long-term operating costs.

Investment spending also shows moderate negative correlations with production (r = –0.79) and turnover (r = –0.74). This trend suggests that firms invest more during downturns, likely to restore competitiveness or compensate for productivity declines. Such countercyclical investment behavior is common in industries where modernization is essential to maintain productivity.

4. CONCLUSIONS

The data provided outlines a clear causal relationship, in which the energy crisis of 2021–2022 acts as a catalyst for a large-scale investment wave in the Bulgarian industry, aimed at technological adaptation and cost optimization. Within the sector under consideration, a deep restructuring is observed along the value chain. The analysis shows the high sensitivity of the

wood processing industry to electricity prices and the central role of investments in innovation as a tool for adaptation. The growing investments in FTA by 2025 are a clear signal that the industry is betting on long-term modernization as the only way out of the negative situation of the sustainable increase in base costs.

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REFERENCES (alphabetical order)

1. Ambio. (2023). A global analysis of bioeconomy visions in governmental bioeconomy strategies. 53(3), 376–388. https://doi.org/10.1007/s13280-023-01958-6 (doi.org in Bing)
2. Zuniga-Gonzalez, C. A., Quiroga-Canaviri, J. L., Brambila-Paz, J. J., Ceballos-Pérez, S. G., & Rojas-Rojas, M. M. (2024). Formulation of an innovative model for the bioeconomy. PLOS ONE, 19(11), e0309358. https://doi.org/10.1371/journal.pone.0309358
3. ***: European Commission. (2022). EU Bioeconomy Strategy Progress Report. Publications Office of the European Union.
4. Hausmann, R., Hidalgo, C., & Yıldırım, M. A. (2021). Structural transformation and energy constraints in emerging bioeconomies. Energy Economics, 98, 105–122.
5. Hurmekoski, E., Lovrić, M., & Hetemäki, L. (2023). Drivers of innovation in the forest-based sector under energy market volatility. Forest Policy and Economics, 150, 102943.
6. Kougias, I., Taylor, N., & Monforti-Ferrario, F. (2021). Electricity market impacts on biorefinery competitiveness. Renewable Energy, 175, 1130–1142.
7. Ladu, L., Quitzow, R., & Morone, P. (2020). Policy mixes and innovation in the bioeconomy: The role of renewable energy incentives. Journal of Cleaner Production, 258, 120590.
8. Mola-Yudego, B., Sikkema, R., & Steierer, F. (2022). Energy efficiency and innovation responses of wood industries to electricity price fluctuations. Biomass and Bioenergy, 160, 106443.
9. Ranta, T., Laihanen, M., & Karhunen, A. (2020). Energy consumption patterns in wood processing industries. Energy Policy, 138, 111234.
10. Sandberg, D., Haller, P., & Jones, D. (2021). Innovations in wood drying technologies under rising energy prices. Wood Material Science & Engineering, 16(4), 245–258.
11. Independent Bulgarian Energy Exchange. (2017–2024). Day-ahead market data. IBEX. https://ibex.bg
12. National Statistical Institute of Bulgaria. (2014–2024). Annual enterprise statistics: Production, sales, and R&D expenditures. NSI. https://nsi.bg

Author address:
Blagoev, D.
Department “Industrial Business “, Business Faculty, University of National and World Economy, Sofia, Bulgaria
*Corresponding author: blagoev@unwe.bg

FINANCIAL SUPPORT FOR THE DEVELOPMENT OF FOREST BIOECONOMY: EU EXPERIENCE AND UKRAINIAN PRACTICE

Olena Yatsukh, Volodymyr Tsap, Irina Zhuravlova, Vasyl Borkovych

Abstract: The article examines the financial support for the development of the forest bioeconomy under conditions of green economic transformation, digitalization, and increasing environmental challenges. The role of financial mechanisms as a key instrument for ensuring sustainable development of the forestry sector, enhancing its competitiveness, and supporting the development of wood product markets within the European economic space is substantiated. The theoretical and methodological foundations of financial support for forest bioeconomy are revealed, including the integration of public and private financial resources, investment instruments, and international financial assistance.

The financial and economic performance of forestry enterprises in Ukraine is analyzed, including the structure of revenues and expenditures, financial results, and the efficiency of resource utilization. The importance of state and regional financial policy in shaping budget revenues, developing bioeconomic value chains, and ensuring the functioning of forest-based product markets is demonstrated. Particular attention is paid to international activities and Ukraine's integration into the European bioeconomy model, including the use of green finance instruments and the implementation of ESG approaches.

It is established that digitalization of financial management, including the implementation of accounting information systems, data analytics, and artificial intelligence technologies, acts as an important innovation driver for improving transparency and accountability of financial flows, enhancing managerial decision-making, and reducing the shadow economy. The study substantiates directions for improving financial support for forest bioeconomy development through harmonization with European financial instruments, development of public-private partnerships, stimulation of investment, support for innovation, and strengthening environmental responsibility.

Keywords: forest bioeconomy; sustainable development; green finance; investment; financial mechanisms; European Union; ESG; digitalization; artificial intelligence; forest sector financing

1. INTRODUCTION

In the context of the green transition, digitalization, and deepening European integration, financial support for the forest bioeconomy has become a strategic factor in enhancing the competitiveness of the forest sector and achieving sustainable development goals. Ukraine's adaptation to European approaches to forest resource management requires more effective financial mechanisms, broader access to investment resources, international support programs, and green finance instruments. Against this background, this study aims to analyze the current system of financial support for the forest bioeconomy, assess the financial performance of Ukraine's forest sector, compare it with European Union practices, and identify strategic mechanisms for strengthening financial support in the context of European integration.

2. FINANCIAL FOUNDATIONS FOR FOREST BIOECONOMY DEVELOPMENT

The forest bioeconomy is a key component of the bioeconomy, based on the sustainable use of forest resources to produce high value-added products, renewable energy, and ecosystem services while preserving natural capital. It promotes the transition from a resource-based economy to a circular and low-carbon model founded on innovation, resource efficiency,

and sustainable forest management. Beyond supplying timber and wood products, the forest sector provides essential ecosystem services, including carbon sequestration, biodiversity conservation, and climate resilience. Within the European Union, the forest bioeconomy is recognized as a strategic priority under the European Green Deal and the EU Bioeconomy Strategy. For Ukraine, its development has become increasingly important in the context of European integration, post-war economic recovery, and adaptation to environmental and climate challenges. Unlocking the potential of the forest bioeconomy can stimulate economic growth, strengthen regional development, create new employment opportunities, and enhance the competitiveness of forest-based industries.

Achieving these objectives requires an effective financial support system that promotes investment, innovation, forest restoration, and sustainable development. In the European Union, the forest sector benefits from an integrated financing framework combining public funding, investment programs, green finance instruments, and climate funds. In contrast, Ukraine's financing system is undergoing gradual transformation and alignment with European approaches. A comparative overview of the main financial instruments supporting the forest bioeconomy in Ukraine and the European Union is presented in table 1.

Table 1. Financial instruments supporting the forest bioeconomy in Ukraine and the European Union

Financial instrument	European Union	Ukraine
Public funding	National and EU funding programs (CAP, EAFRD, LIFE)	State budget programs
Investment support	Dedicated bioeconomy and circular economy investment funds	Enterprise own funds and selected investment projects
Green finance	Green bonds, climate funds, Sustainable Finance Framework	Emerging, with pilot projects
Grant programs	Horizon Europe, LIFE, Interreg, Innovation Fund	International donor and grant programs
Public–private partnerships	Widely applied for infrastructure and environmental projects	Limited implementation
ESG financing	Integrated into investment appraisal and corporate governance	Regulatory framework under development
Bank lending	Preferential financing for green and innovative projects	Limited access to finance
Carbon and climate mechanisms	Mature carbon markets and ecosystem service schemes	Early stage of development
Digital financial instruments	Digital platforms, Big Data, and AI for financial management	Selected digital solutions for accounting and monitoring

The comparison highlights clear differences in the financing models of the forest bioeconomy. The European Union applies an integrated approach that combines public funding, market-based instruments, and sustainable finance, whereas Ukraine's forest sector relies mainly on enterprise own funds, public funding, and international technical assistance. European integration is expanding access to green finance, ESG investment, and climate funds, strengthening the competitiveness and sustainable development of the forest sector.

3. RESEARCH RESULTS

3.1. Financial performance and development of Ukraine's forest sector

Financial support is a key driver of forest bioeconomy development, as it enables production modernization, forest restoration, innovation, and environmental protection. In Ukraine, financing of the forest sector is provided through public funding, investment programs of the State Agency of Forest Resources of Ukraine, bank lending, international financial institutions, and private investment. In contrast, the European Union applies a comprehensive multi-level financing framework that combines public funding, green finance instruments, innovation funds, and climate policy mechanisms. Key funding sources include the European Agricultural Fund for Rural Development, LIFE, Horizon Europe, Invest EU, and financing provided by the European Investment Bank, supporting projects in sustainable forest management, bioenergy, the circular economy, and decarbonization.

Table 2. Main sources and financial instruments supporting the forest bioeconomy in Ukraine and the European Union

Ukraine	Funding (€ million)	European Union	Program budget (€ billion)
State Budget of Ukraine	56.8	European Agricultural Fund for Rural Development	95.51
		Horizon Europe	95.5
Bank lending	23.5	LIFE	5.4
International financial institutions (EIB, World Bank)	19.8	Invest EU	26.2
		Just Transition Mechanism	>100
Private investment	33.0	European Investment Bank	>50 annually
State Agency of Forest Resources of Ukraine	12.8	European Green Deal Investment Plan	>1,000 (by 2030)

Note. *For Ukraine, the figures represent aggregated financing for the period 2019–2025. For the European Union, the figures refer to the budgets of the respective financial support programs for 2021–2027*

Substantial differences exist in the financing of the forest bioeconomy between Ukraine and the European Union. In Ukraine, the forest sector is financed mainly through public funding, investment programs of the State Agency of Forest Resources of Ukraine, bank lending, international financial institutions, and private investment. However, the overall scale of financial support remains limited compared with the European Union. This gap highlights the need to align Ukraine's financing framework with European practices by expanding green finance, strengthening public–private partnerships, and attracting investment. Diversifying funding sources would further enhance the financial resilience of the forest sector and reduce its dependence on public funding.

Beyond funding sources, it is equally important to assess the effectiveness of financial resource utilization. The performance of the forest sector can be evaluated through indicators such as revenue, profitability, investment activity, and budget contributions. A comparative analysis of the key financial indicators for Ukraine and the European Union is presented in table 3.

Table 3. Comparative financial indicators of the forest sector in Ukraine and the EU

Indicator	Ukraine (2024)	European Union (2024)
Net sales revenue	UAH 23.7 billion	> EUR 520 billion
Net profit	UAH 2.5 billion	> EUR 50 billion*
Taxes and mandatory budget payments	UAH 7.7 billion	> EUR 90 billion*
Capital investment	UAH 1.66 billion	> EUR 25 billion*
Share of GDP	1%	4–5%
Employment	>30 thousand persons	>3.5 million persons

Despite wartime challenges and limited public support, Ukraine's forest sector has maintained positive financial performance, generating UAH 23.7 billion in net sales revenue, UAH 2.5 billion in net profit, and UAH 7.7 billion in taxes and mandatory budget payments in 2024. Compared with the European Union, the sector operates on a considerably smaller scale because of differences in industrial capacity, value-added production, and financing systems. The European experience demonstrates that innovation and green finance can strengthen forest-based value chains and enhance the competitiveness of the forest bioeconomy.

3.2. European integration of Ukraine's forest sector

International cooperation and European integration are key drivers of the development of Ukraine's forest bioeconomy. In this context, aligning national forest policy with European Union requirements for sustainable forest management, climate neutrality, the circular economy, and biodiversity conservation has become a strategic priority. An essential component of this process is the adaptation of Ukraine's regulatory framework and forest governance to European standards. The main directions of this integration are summarized in table 4.

Table 4. Financial implications of aligning Ukraine's forest sector with EU policies

EU policy	Implementation priority	Required investment	Potential funding sources
European Green Deal	Decarbonization and climate neutrality	Low-carbon technologies and industrial modernization	LIFE, Invest EU, EIB
EU Forest Strategy for 2030	Sustainable forest management	Forest restoration, inventory, and digital monitoring	EAFRD, EU grants, state budget
EUDR	Timber traceability	Digital traceability systems, certification, and supply chain audits	Horizon Europe, private investment
EU Taxonomy & ESG Framework	Sustainable finance and ESG compliance	Environmental assessment, ESG reporting, and corporate governance	Green bonds, ESG funds, climate funds
Carbon Removal Certification Framework (CRCF)	Carbon sequestration and certification	Carbon accounting and verification systems	Carbon funds, private investment
Digital Europe & AI	Digital transformation	AI, Big Data, digital platforms, and satellite monitoring	Digital Europe, Horizon Europe, international grants

Unlike earlier stages of European integration, current EU policies influence not only the regulatory framework of the forest sector but also its financial requirements. Compliance with the European Green Deal, the EUDR, ESG standards, and carbon regulation requires investment in digitalization, certification, environmental monitoring, and technological modernization. At the same time, alignment with these policies expands access to European funding programs, green finance instruments, and international climate funds, creating new opportunities for the development of Ukraine's forest bioeconomy.

3.3. Prospective financial support mechanisms for forest bioeconomy development

The sustainable development of Ukraine's forest bioeconomy requires a more diversified financing framework capable of addressing the challenges of the green transition, digitalization, climate change, and European integration. The current financing model, based largely on enterprise own funds and limited public support, provides insufficient investment for modernization and innovation. Consequently, greater reliance on green finance, ESG investment, public–private partnerships, international financial institutions, and carbon markets is essential. Expanding access to European Union financial instruments would further accelerate investment in sustainable forest management and innovative bioeconomy projects. The proposed strategic financing mechanisms are presented in table 5.

Table 5. Strategic financial mechanisms for forest bioeconomy development in Ukraine

Financial mechanism	Key instruments	Expected outcome
Green finance	Green bonds, climate funds, ESG investment	Investment in forest restoration, bioenergy, and decarbonization
Public–private partnerships	Joint public and private investment projects	Modernization of production and forest infrastructure
European financial programs	EAFRD, Horizon Europe, LIFE, InvestEU, EIB	Access to grants, loans, and innovation funding
Carbon finance	Carbon credits, ecosystem services, carbon markets	New revenue streams and sustainable forest management
Innovation support	Research funding, start-ups, innovation projects	High value-added products and bio-based value chains
Digital financial management	AI, Big Data, GIS, digital platforms	More efficient and transparent financial management
Regional development funding	Local environmental funds, regional support programs	Regional development and stronger local financial capacity

A strategic financing framework for the forest bioeconomy should be based on diversified funding sources that combine public, private, and international capital. Unlike the traditional model, which relies primarily on public funding, it should integrate green and climate finance, public–private partnerships, European funding programs, and digital technologies. Greater access to European innovation and climate funds would accelerate the modernization of Ukraine's forest sector. Its successful implementation requires further alignment of Ukraine's financial policy with European Union standards and the expansion of sustainable finance instruments. Together, these measures will strengthen the financial resilience of the forest sector, stimulate investment, and support the sustainable development of Ukraine's forest bioeconomy.

4. DISCUSSION AND CONCLUSIONS

The findings confirm that financial support is a key driver of forest bioeconomy development and forest sector competitiveness. While the European Union applies an integrated financing framework combining public funding, green finance, investment programs, and public–private partnerships, Ukraine's forest sector continues to rely mainly on enterprise own funds, public support, and international assistance. Although the sector remains financially resilient, its long-term development requires greater access to European funding, innovative financial instruments, and sustainable finance. Further alignment with European Union standards and the wider application of ESG principles, carbon finance, and digital technologies will strengthen investment capacity and financial management.

The practical contribution of this study is the proposed strategic financing framework integrating green finance, public–private partnerships, European funding programs, carbon finance, and ESG-oriented investment. Its implementation will enhance the financial resilience and sustainable development of Ukraine's forest bioeconomy while supporting its European integration.

REFERENCES

1. State Agency of Forest Resources of Ukraine. (2026). *Public Report of the Head of the State Agency of Forest Resources of Ukraine for 2025*. Kyiv, Ukraine. https://forest.gov.ua
2. State Statistics Service of Ukraine. (2026). *Statistical Information: Agriculture, Forestry and Fisheries*. https://www.ukrstat.gov.ua
3. Eurostat. (2025). *Forests, Forestry and Logging – Statistics Explained*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title
4. European Investment Bank. (2025). *Forestry: Investing in Forests to Safeguard Biodiversity and Drive the Green Transition*. https://www.eib.org/en/projects/topics/energy-natural-resources/forestry
5. Kostyakova, A. (2025). Transparency in accounting and auditing of Ukrainian timber: EITI reporting as a factor of sustainable development. In *Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers 2025*.
6. Tsap, V., Tulai, O., & Yatsukh, O. (2025). Ensuring the export potential of Ukraine's forestry sector under conditions of sustainable development. In *Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers 2025* (pp. 145–151).
7. Mazur, H., Shkurat, S., Tsap, V., Samsin, I., & Bukhanevych, O. (2026). Fiscal decentralization and local tax policy: An empirical analysis of community self-sufficiency in Ukraine. *Journal of Applied Economic Sciences, 21*(2(92)), 529–544.

Yatsukh O., doctor of economics 1; Tsap V., PhD 2.Zhuravlova I. doctor of economics 3; Borkovych V. PhD Student 4
1.Head Department of Finance, Accounting and Taxation Dmytro Motornyi Tavria State Agrotechnological University, Ukraine
2.Department of Finance, Accounting and Taxation, Dmytro Motornyi, Tavria State Agrotechnological University
3.Head of Department and Credit Department Simon Kuznets Kharkiv National University of Economic
4. Dmytro Motornyi, Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
Corresponding author: tzapvd@gmail.com

WORKING CAPITAL MANAGEMENT AND PROFITABILITY IN BULGARIAN FOREST-BASED ENTERPRISES: IMPLICATIONS FOR BIOECONOMY DEVELOPMENT

Tsvetomir Manolov

Abstract: This study investigates the relationship between working capital management and firm profitability within the Bulgarian forest-based sector, aiming to identify financial factors relevant to the sustainable development of the bioeconomy.

The research draws on publicly available annual financial statements retrieved from the Bulgarian Commercial Register. The sample covers enterprises engaged in wood processing (NACE 16) and furniture manufacturing (NACE 31) over the period 2020 - 2023, forming a panel dataset of firm-year observations. Working capital management is proxied by Net Working Capital (NWC), Cash Conversion Cycle (CCC), Days Sales Outstanding (DSO), and Days Inventory Outstanding (DIO). Profitability is measured by Return on Assets (ROA). The hypothesized relationships are tested using panel data regression, including pooled OLS and fixed effects specifications.

It is anticipated that a shorter cash conversion cycle will be positively associated with higher asset returns, suggesting that tighter management of receivables and inventories improves financial performance among small and medium-sized enterprises in the sector. The analysis is expected to reveal statistically significant relationships between individual working capital components and profitability.

The study contributes empirical evidence from an underexplored segment of the Central and Eastern European bioeconomy. By relying exclusively on publicly available data from Bulgarian enterprises, it offers a transparent and replicable methodological approach that can be extended to other wood-based industries across the region.

Keywords: working capital management, profitability, forest-based enterprises, bioeconomy, Bulgaria, panel data

1. INTRODUCTION

The forestry sector plays a central role in the European Union's bioeconomy strategy. It links the management of primary forest resources to a range of downstream activities, such as wood processing, furniture manufacturing, and the pulp and paper industry (European Commission, 2018). Small and medium-sized enterprises (SMEs) represent the majority of this sector. The financial viability of these entities is considered a prerequisite for the sector to fulfill its designated role in a sustainable, circular bioeconomy (Lovrić, Lovrić & Mavsar, 2020; Ladu, Imbert, Quitzow & Morone, 2020).

One aspect of financial management that is frequently studied within international financial research is working capital management (WCM). Existing studies of manufacturing firms typically link working capital management to profitability (Deloof, 2003; García-Teruel & Martínez-Solano, 2007; Raheman & Nasr, 2007). The main idea is that a firm that optimise management of its inventory and receivables, shortens its cash conversion cycle, frees up cash, and thereby achieves a higher return on assets. Conversely, the implementation of overly aggressive working capital management policy can reduce sales or strain relationships with

suppliers. All of this means that the relationship between working capital management and profitability is neither strictly linear nor unequivocally negative across all sectors and types of firms (Baños-Caballero, García-Teruel & Martínez-Solano, 2014).

This issue is relevant to wood processing industry and furniture manufacturing sector because these are industries that, by definition, are capital-intensive and have a high proportion of inventory. Despite this significance, empirical research regarding the Bulgarian forestry sector remains limited. Existing studies on Bulgarian and Central European forestry enterprises have focused primarily on a comparative analysis of efficiency through data envelopment analysis (Neykov, Krišťáková, Hajdúchová et al., 2021) and on the determinants of capital structure (Krišťáková, Hajdúchová, Sedliačiková, Antov & Neykov, 2022).

Consequently, this article aims to evaluate whether, and to what extent, working capital management is associated with the profitability of Bulgarian woodworking enterprises and furniture manufacturers, as well as to examine what the empirical findings might imply for the sector's long-term financial sustainability in the broader context of the bioeconomy's development.

2. LITERATURE REVIEW

Much of the researches on working capital are based on the concept of the cash conversion cycle (CCC), proposed by Richards and Laughlin (1980). It examines the time that elapses between the payment of cash for raw materials and the collection of cash from customers. The idea is that the shorter this cycle, the faster a firm recovers its invested funds, which, all else being equal, reduces its dependence on external financing and the associated costs.

This idea has been the subject of a variety of studies. Deloof (2003), examining a sample of large Belgian firms, found that firms with shorter days of receivables and inventory tend to be more profitable, while less profitable firms are more likely to delay payments to their own suppliers. Working with data on Spanish SMEs, García-Teruel and Martínez-Solano (2007) reached a similar conclusion: a shorter cash conversion cycle is associated with higher profitability. Raheman and Nasr (2007), studying listed Pakistani firms, also found a significant negative relationship between CCC and profitability. All of these studies show that effective, relatively aggressive working capital management is generally beneficial for a firm's performance. Baños-Caballero et al. (2014), however, add an important clarification: once financial constraints are taken into account, the relationship is more accurately described as non-monotonic, with firms that adopt a moderate working capital policy tending to achieve the best results.

Financial studies of forestry enterprises in Central and Eastern Europe focus primarily on analyzing capital structure and overall efficiency. Neykov et al. (2022), for example, examine the determinants of the capital structure of forestry enterprises in the Czech Republic, Slovakia, and Bulgaria. They find that liquidity and firm size are significant factors for leverage and conclude that profitability is not a statistically significant factor. Neykov et al. (2021) apply data envelopment analysis to assess the economic efficiency of forestry enterprises. Nicorescu, Hălălișan, Popa, and Neykov (2021) examine how the COVID-19 pandemic has affected FSC forest certification audits, prompting a shift toward remote and hybrid audit procedures in the sector.

Viewed through the perspective of the bioeconomy, the forestry sector is considered one of the pillars of the EU's circular bioeconomy strategy (European Commission, 2018). However, research has focused primarily on Northwestern Europe, leaving Central and Eastern European countries, including Bulgaria, relatively understudied (Lovrić et al., 2020). Ladu et al. (2020) claim that the sector's transition to a circular bioeconomy requires a coordinated set of policies that integrates sustainable forest management with environmental and innovation policies.

Based on these findings, the following working hypothesis is formulated for the purposes of the empirical analysis: firms with shorter cash conversion cycles—and in particular, those with shorter inventory turnover and accounts receivable collection periods—are expected to be more profitable, as measured by return on assets, compared to firms with longer cycles.

3. MATERIALS AND METHODS

The empirical analysis is based on publically available annual financial statements. These were manually extracted from the Bulgarian Commercial Register for companies in Section 16 of NACE classification Rev. 2 (wood processing) and Section 31 (furniture) for the period 2020–2023. A sample of 50 companies and 200 firm-year observations was formed. Six observations with missing values for inventory, accounts receivable, sales revenue, cost of goods sold, or profit were excluded. As a result, the study covers 50 firms, of which 41 are in the woodworking sector and 9 in furniture manufacturing, and includes 194 firm-year observations. All continuous variables were winstorized at the 5th and 95th percentiles.

The analysis of working capital was conducted based on four standard indicators:

• Days in Inventory (DIO) = (Inventory / Cost of Goods Sold) × 365;

• Days Sales Outstanding (DSO) = (Accounts Receivable / Sales Revenue) × 365;

• Cash Conversion Cycle (CCC) = DIO + DSO. Given that data on accounts payable to suppliers are available only for a part of the sample, they are not included in the main specification. For this reason, the CCC values should be interpreted as an upper bound of the operating cycle, rather than as a complete, three-part cash conversion cycle.

• Net Working Capital to Total Assets (NWC/TA) = (Current Assets − Current Liabilities) / Total Assets.

Profitability is examined through return on assets (ROA). The analysis includes two control variables: firm size, measured as the natural logarithm of total assets, and leverage, measured as one minus the ratio of equity to total assets.

The relationship between working capital management and profitability is assessed using the following panel regression:

$$ROA_{it} = \beta_0 + \beta_1\, CCC_{it} + \beta_2\, SIZE_{it} + \beta_3\, LEV_{it} + \varepsilon_{it}$$

ROA_{it}, CCC_{it}, $SIZE_{it}$, LEV_{it} – respectively, return on assets, cash conversion cycle, size, and leverage of firm i in year t; ε_{it} – random error term; β_0–β_3 – estimation coefficients.

The index i refers to the entity, and t refers to the year. A pooled OLS model (heteroscedasticity-resistant standard errors) and a fixed-effects model by entity (clustered standard errors) are applied; an alternative specification decomposes CCC into DIO and DSO separately.

4. RESULTS AND DISCUSSION

Table 1 shows the structure of the sample, which is dominated by woodworking companies.

Table 1. Sample Composition by NACE Rev. 2

Sections NACE	Number of companies	Company-year Observations	Share of the sample (%)
16 – Wood Processing	41	159	82.0
31 – Furniture manufacturing	9	35	18.0
Total	50	194	100.0

Table 2 represents descriptive statistics: an average operating cycle of approximately 114 days and an average ROA of 13.0% (0.2–38.9%).

Table 2. Descriptive statistics for the main variables

Variable	Number	Average	Standard deviation	Min	Max
ROA	194	0.130	0.117	0.002	0.389
CCC (days)	194	114.19	66.28	34.73	274.83
DIO (days)	194	64.36	51.81	1.82	190.72
DSO (days)	194	47.99	40.99	6.60	156.89
NWC / Total assets	194	0.247	0.285	-0.316	0.728
Size (ln total assets)	194	7.455	0.600	6.315	8.454
Leverage	194	0.421	0.262	0.039	0.859

Table 3 shows the correlations: ROA is negatively correlated with CCC (r = -0.211) and DIO (r = -0.266), positively correlated with NWC/TA (r = 0.318), and negatively correlated with firm size (r = -0.380) and leverage (r = -0.208).

Table 3. Matrix of correlations

	ROA	CCC	DIO	DSO	NWC/TA	Size	Leverage
ROA	1.000						
CCC	-0.211	1.000					
DIO	-0.266	0.758	1.000				
DSO	-0.009	0.599	-0.028	1.000			
NWC/TA	0.318	0.200	0.163	0.096	1.000		
Size	-0.380	0.346	0.217	0.278	0.064	1.000	
Leverage	-0.208	0.062	0.027	0.090	-0.645	-0.205	1.000

Table 4 represents the regression results. In the combined model, CCC is negative but not significant (p = 0.500); in the decomposition, DIO is negatively significant (p = 0.030), but DSO is unexpectedly positively significant (p = 0.019).

Table 4. Results of the regression analysis (dependent variable: ROA)

Variable	Combined OLS (1)	Combined OLS (2)	Fixed effects
Constant	0.808***	0.840***	0.259
CCC	-0.0000818		-0.000550***
DIO		-0.000354**	

Variable	Combined OLS (1)	Combined OLS (2)	Fixed effects
DSO		0.000395**	
Size (ln OA)	-0.0823***	-0.0870***	0.0074
Leverage	-0.1299***	-0.1371***	-0.2877***
Observations	194	194	194
Companies	50	50	50
R^2	0.231	0.275	0.194 (within)

Note: *** p<0.01, ** p<0.05. The standard errors for OLS are heteroscedasticity-resistant; for fixed effects, they are clustered by company. The F-test rejects the pooled specification in favor of the firm-specific specifications ($F(49,141) = 4.36$, $p < 0.001$).

The analysis shows that the only variable that is significant in all models is leverage. Unlike the aggregated model, for individual companies, CCC becomes negative and highly significant ($p = 0.001$). This means that changes in an individual company's business cycle over time are systematically linked to changes in its profitability. The F-test strongly supports the model based on individual companies. Improving inventory management (planning, forecasting, shared warehousing) remains a low-capital lever for profitability in the sector, complementing longer-term investments.

5. CONCLUSION

The findings of the analysis show that the operating cycle is systematically linked to profitability in the studied companies. However, this relationship is evident only when differences between individual companies are taken into account, rather than in an aggregated model. The accounts receivable collection period has a positive relationship with profitability. Leverage is the only variable that is negatively correlated with profitability across all companies. All of these results have direct implications for the prospects of the wood products markets within the bioeconomy. This is because achieving financial sustainability is a prerequisite for companies to invest in capacity, certification, and technological modernization, which is necessary for the sector's transition to a circular bioeconomy. Effective inventory management is also an accessible, low-capital leveraging tool for improving performance. It was also found that more flexible terms for customers serve as a tool for market positioning. It should be noted that the study is limited by the sample size and the four-year period affected by COVID-19, and future research could expand the number of included companies and to directly examine the relationship between financial practices and the sector's bioeconomic development.

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REFERENCES (alphabetical order)

1. Baños-Caballero, S.; García-Teruel, P.J.; Martínez-Solano, P. (2014): *Working capital management, corporate performance, and financial constraints*. Journal of Business Research 67 (3): pp. 332-338.
2. Deloof, M. (2003): *Does Working Capital Management Affect Profitability of Belgian Firms?* Journal of Business Finance & Accounting 30 (3-4): pp. 573-587
3. European Commission (2018): *A Sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment*. COM (2018) 673 final. Brussels
4. García-Teruel, P.J.; Martínez-Solano, P. (2007): *Effects of Working Capital Management on SME Profitability*. International Journal of Managerial Finance 3 (2): pp. 164-177
5. Ladu, L.; Imbert, E.; Quitzow, R.; Morone, P. (2020): *The role of the policy mix in the transition toward a circular forest bioeconomy*. Forest Policy and Economics 110: 101937
6. Lovrić, M.; Lovrić, N.; Mavsar, R. (2020): *Mapping forest-based bioeconomy research in Europe*. Forest Policy and Economics 110: 101874
7. Neykov, N.; Krišťáková, S.; Hajdúchová, I.; Sedliačiková, M.; Antov, P.; Giertliová, B. (2021): *Economic Efficiency of Forest Enterprises – Empirical Study Based on Data Envelopment Analysis*. Forests 12 (4): 462
8. Neykov, N.; Krišťáková, S.; Antov, P.; Halalisan, A.-F.; Hajdúchová, I.; Sedliačiková, M.; Sloup, R.; Šišák, L. (2022): *Capital Structure Determinants of Forest Enterprises: Empirical Study Based on Panel Data Analysis from the Czech Republic, Slovakia, and Bulgaria*. Forests 13 (5): 749
9. Nicorescu, A.-I.; Hălălișan, A.-F.; Popa, B.; Neykov, N. (2021): *Challenges for FSC Forest Certification: Audits in the Context of Pandemic COVID-19*. Forests 12 (8): 997
10. Raheman, A.; Nasr, M. (2007): *Working Capital Management and Profitability – Case of Pakistani Firms*. International Review of Business Research Papers 3 (1): pp. 279-300
11. Richards, V.D.; Laughlin, E.J. (1980): *A Cash Conversion Cycle Approach to Liquidity Analysis*. Financial Management 9 (1): pp. 32-38.

Authors address:
Manolov, T.[1]
[1] Accounting Department, Faculty of Finance and Accounting, University of Economics - Varna, Varna, Bulgaria
*Corresponding author: wt_varna@ue-varna.bg

OIL PRICE SHOCKS, MONETARY POLICY, AND BANK FINANCING IN THE WOOD-BASED BIOECONOMY

Deyan Radev

Abstract: This paper provides an overview of the macro-financial channels through which oil price shocks and monetary policy affect the wood-based bioeconomy. Although the wood industry is increasingly positioned as a pillar of the circular and sustainable economy, its firms remain exposed to energy-price volatility, transport and logistics costs, construction-cycle dynamics, and bank-dependent financing. The paper reviews recent work by the IMF, World Bank, ECB, and other central banks, alongside literature on wood product markets and forest-based development. It argues that oil price shocks affect the wood industry through three interrelated channels: a direct cost channel, an indirect inflation and monetary-policy channel, and a financial channel operating through bank credit standards, loan pricing, and investment capacity. Monetary tightening may amplify energy shocks by raising working-capital costs, weakening construction and furniture demand, and increasing lenders' risk aversion towards smaller and more cyclical borrowers. The paper's main contribution is conceptual: it integrates literatures that are usually studied separately and shows that the transition towards a wood-based bioeconomy should be assessed not only through sustainability and innovation, but also through macro-financial resilience. The paper concludes with implications for sustainable finance, industrial policy, and future research.
Keywords: oil price shocks, monetary policy, bank lending, wood industry, bioeconomy, sustainable finance

1. INTRODUCTION

The wood-based bioeconomy has gained strategic importance in recent years. Wood products are increasingly associated with circular production models, lower-carbon construction, renewable materials, and new value-added applications. At the same time, the sector remains embedded in a wider macroeconomic environment shaped by energy costs, inflation, interest rates, credit conditions, and housing cycles. This duality motivates a simple but underexplored question: how resilient is the wood-based bioeconomy to traditional macro-financial shocks?

This paper argues that the wood industry should not be analysed only through the lens of sustainability and technological upgrading. It should also be viewed as a sector exposed to oil price shocks and monetary-policy transmission. The 2026 Strait of Hormuz Crisis confirmed that oil and broader energy shocks affect transport costs, processing costs, kiln drying, resins and chemicals, packaging, and export logistics. They may also raise inflation more broadly and trigger tighter monetary policy. Higher policy rates then affect both the supply and demand for bank credit, especially for small and medium-sized enterprises with limited internal funds and strong reliance on working capital.

An additional perspective follows from the growing role of fintech in the forest-based sector. Earlier work has shown that digital payments, blockchain-based traceability, smart contracts, AI-supported monitoring, and alternative funding platforms can improve transparency, transaction efficiency, and access to finance in forestry and wood-processing activities (Radev, 2024). In the present paper, these instruments are interpreted not only as tools of digital modernization, but also as potential shock absorbers that may soften the effects of tighter monetary policy and higher energy-cost volatility on wood-sector firms.

This perspective is timely for the forest-based sector because recent market conditions have combined high input-price volatility with weaker construction activity and tighter financing

conditions. In other words, the wood-based bioeconomy is being asked to decarbonise, innovate, and expand precisely when macroeconomic conditions have become less supportive. An overview paper is therefore useful not only for identifying the main channels of transmission, but also for clarifying why sector strategy, industrial policy, and financial policy need to be discussed together.

The contribution of this paper is integrative rather than empirical. It synthesises recent work from international financial institutions, central banks, and sector-oriented studies to build a conceptual framework linking oil price shocks, monetary policy, bank financing, and wood product markets.

The paper is structured as follows. Section 2 reviews the main transmission channels. Section 3 discusses implications for the wood-based bioeconomy and outlines a research agenda. Section 4 concludes.

2. RECENT LITERATURE AND TRANSMISSION CHANNELS

2.1. Oil price shocks, inflation, and monetary policy

Recent research confirms that energy shocks remain central to inflation dynamics. Baba and Lee (2022) show that the pass-through from oil price shocks to wages and prices depends on inflation conditions, labour-market institutions, and monetary-policy credibility. Their evidence suggests that second-round effects are not automatic; they vary across countries and are stronger where inflation is already elevated or credibility is weaker. This is particularly relevant for Europe, where imported energy shocks may generate heterogeneous price and wage responses.

Alvarez and Kroen (2025) extend this line of work by analysing sector-level data for more than thirty countries. They find that the inflation pass-through of energy shocks operates through stable sectoral channels and is stronger where energy dependence and price flexibility are higher. For the present topic, this matters because wood processing, wood-based panels, pulp and paper, and furniture manufacturing are not equally exposed. Energy costs, logistics intensity, and the structure of downstream demand all shape how strongly a shock is transmitted.

Other central-bank research underlines the role of the policy regime. Miyamoto, Nguyen, and Sergeyev (2024) show that negative oil supply news shocks are less contractionary when systematic monetary policy is constrained by the zero lower bound than in normal times. Recent ECB analysis also stresses that policy transmission can become stronger after large supply-driven shocks, while the Bank of England and Sveriges Riksbank continue to treat energy-price developments as an important source of uncertainty for the inflation outlook (ECB, 2026; Bank of England, 2024; Sveriges Riksbank, 2024).

IMF work from 2025 adds another layer by showing that oil shocks also affect labour-market adjustment and real incomes, especially in oil-importing economies and in sectors where firms have limited margins to absorb higher costs. For wood-product manufacturers, this means that the energy shock is rarely isolated. It may coincide with softer demand, weaker disposable income, and a more cautious banking sector. The resulting environment is one in which sectoral resilience depends not only on technology and cost efficiency, but also on access to finance and balance-sheet strength.

2.2. Bank lending and financing conditions

The second transmission channel runs through finance. Higher policy rates increase borrowing costs, tighten financial conditions, and can reduce banks' willingness to lend, especially to smaller, riskier, or more opaque borrowers. This mechanism remains particularly

important in Europe, where bank intermediation is still the dominant source of external finance for many firms.

Recent ECB evidence shows that banks tightened credit standards for loans to firms in the fourth quarter of 2025 and expected further tightening in the first quarter of 2026, with perceived risks and lower risk tolerance as the main drivers (European Central Bank, 2025a). This finding is directly relevant for the wood sector, which includes many SMEs and investment projects with medium or long payback periods. Even a moderate deterioration in terms and conditions may postpone capacity expansion, refinancing, or energy-efficiency upgrades.

The Danish evidence provides a particularly useful bridge between energy shocks and firm finance. Moller and Poschl (2025) find that credit growth of energy-intensive firms declined sharply after the 2022 energy shock. Their results point to both demand and supply effects: less risky firms reduced credit demand, while banks tightened the terms of new loans to riskier firms. In parallel, ECB work on housing and consumption highlights that monetary policy affects housing affordability, housing sales, and home-goods consumption, a channel with clear implications for wood products and furniture demand (European Central Bank, 2025b).

2.3. Relevance for wood product markets

The macro-financial perspective is especially relevant for the wood industry. The Forest Products Annual Market Review 2023-2024 by UNECE and FAO explicitly covers housing, wood-based panels, pulp and paper, value-added products, and wood energy, showing that the sector should be analysed across the full chain from roundwood to final demand (UNECE/FAO, 2024). This broad coverage is important because oil shocks and monetary tightening do not affect all segments in the same way.

First, several subsectors are energy-sensitive. Sawmilling, drying, panel production, pulp and paper, and transport-intensive supply chains all rely directly or indirectly on energy. Second, many wood firms are linked to construction and home-related demand. When policy rates rise, mortgage affordability weakens, housing sales slow, and purchases of home goods tend to soften. Third, many firms in the sector remain bank-dependent, which means that tighter credit standards can reinforce the impact of higher input costs.

World Bank research supports this view from both the macro and sectoral side. Recent World Bank work shows that higher electricity prices reduce employment in energy-intensive firms that have not adopted energy-efficiency measures (Aterido, Iootty, and Melecky, 2025). At the same time, the World Bank's forest-related programmes emphasise the need to mobilise private capital and develop forest-based economies, while recognising that long-term financing remains a core bottleneck in sustainable forestry and related value chains (World Bank, 2024a; World Bank, 2024b; World Bank, 2026).

2.4. Housing, inventories, and demand spillovers

A further channel operates through housing and other durable expenditures. Wood demand is closely tied to residential construction, renovation, and furniture purchases, all of which are highly interest-rate sensitive. When monetary policy tightens, mortgage servicing becomes more expensive, housing transactions slow, and households often postpone expenditure on kitchens, flooring, joinery, and durable home goods. Even when sawmills or panel producers are not directly constrained by credit, they may still face weaker downstream demand through this housing channel.

Inventories and working-capital cycles reinforce these effects. Many wood products move through long production and distribution chains, often with sizeable inventory needs and seasonality in orders. Higher interest rates raise the carrying cost of inventories for both

producers and distributors. At the same time, heightened uncertainty can make wholesalers and retailers more cautious, encouraging inventory drawdowns rather than new orders. This mechanism helps explain why macro-financial tightening can affect the sector even before major declines in final demand are fully visible in official production statistics.

Taken together, the literature suggests a layered transmission mechanism: oil and energy shocks raise direct costs; inflationary pressure affects monetary policy; tighter monetary policy shapes credit, housing, and inventories; and these forces ultimately influence production, investment, and resilience in wood product markets. This broader macro-financial framing complements existing sector studies by explaining why periods of stress can produce synchronised pressure on costs, finance, and demand.

3. IMPLICATIONS FOR THE WOOD-BASED BIOECONOMY

3.1. Financing resilience

A first implication is that financing conditions should become a more central part of discussions on wood product markets. Sector performance depends not only on demand trends, carbon policy, and innovation, but also on whether firms can refinance working capital, absorb temporary cost shocks, and continue investing when interest rates rise. This is particularly important for SMEs, which often lack market-based alternatives to bank finance.

A second implication concerns resilience. A sector may be green and strategically desirable, yet still be financially fragile when energy prices surge and credit conditions tighten. Sustainability and resilience should therefore be distinguished analytically. The wood-based bioeconomy may contribute to decarbonisation, but it still requires financial structures capable of smoothing shocks across the cycle.

In practical terms, resilience in wood product markets depends on the interaction between operational flexibility and financial flexibility. Firms that can adjust product mix, pass through part of the cost increase, or rely on more stable customer segments are better positioned when energy prices rise. However, those advantages matter more when firms also have enough liquidity to absorb temporary shocks. The financial side therefore deserves a much more central place in sector analysis than it has typically received in the wood-industry literature.

3.2. Sustainable finance and policy

If the wood-based bioeconomy is treated as strategic, then policy support should also reflect sector-specific financing constraints. Credit guarantees, blended finance, sustainability-linked loans, and public co-financing may help reduce the risk premium attached to long-horizon investments in forestry, processing, efficiency upgrades, and innovation. Such instruments are especially relevant where traditional banks are interested in the sector but constrained by maturity mismatch, collateral issues, or limited expertise in evaluating forestry-related risk.

This line of reasoning also fits the recent policy direction of the World Bank and other development institutions, which increasingly emphasise the mobilisation of private capital for forest-based economies rather than relying only on grants or public budgets. From a European perspective, the policy challenge is to ensure that green transition objectives are not undermined by pro-cyclical tightening in bank credit.

For commercial banks, this also implies a need for better sector-specific risk assessment. Traditional credit models may underweight the long-term strategic value of forestry and wood-processing activities or treat them simply as cyclical manufacturing exposures. Yet the sector contains transition-relevant investments in energy efficiency, circular materials, and low-carbon

construction. More refined risk assessment, combined with public risk-sharing where appropriate, could improve credit allocation without weakening prudential standards.

Fintech can complement these policy instruments. As argued in earlier work on fintech and the forestry industry, digital payments, blockchain traceability, smart contracts, AI-based monitoring, and tokenization can improve the verifiability of transactions, inventories, contracts, and product origin in forest-based value chains (Radev, 2024). In the present context, these technologies matter because they can reduce informational asymmetries between firms and lenders, support more accurate credit-risk assessment, and broaden access to non-traditional funding when bank credit tightens. Fintech should therefore be seen not only as a source of technological innovation, but also as a mechanism that can strengthen financing resilience in wood product markets.

3.3. Future research agenda

The literature reviewed here suggests several directions for future work. First, more sector-specific evidence is needed on how oil and energy shocks affect different wood subsectors across countries. A related question is whether fintech adoption measurably softens the effects of tighter monetary policy on firm funding, working capital, and investment. Second, research should examine whether green and bio-based firms enjoy better financing access during stress periods, or whether they continue to be treated as ordinary cyclical borrowers. Third, more attention should be paid to the interaction between housing-market transmission and wood product demand, especially for furniture and construction materials.

A promising agenda would combine firm-level balance-sheet data, bank-loan information, and sectoral indicators for wood product markets. Even without such data in the present paper, the existing literature is now rich enough to justify a dedicated macro-financial perspective on the wood-based bioeconomy.

3.4. Implications for Central and Eastern Europe

The Central and Eastern European context deserves special attention. Many economies in the region are small and open, relatively bank-based, and exposed to imported energy-price movements. At the same time, several countries host important wood-processing, furniture, and export-oriented manufacturing clusters. These characteristics make the region a relevant laboratory for studying how energy shocks, monetary tightening, and external demand interact in the wood-based bioeconomy.

This regional angle also fits the broader policy debate on convergence, resilience, and strategic autonomy. For firms in smaller open economies, the availability of long-term finance and the stability of banking conditions may shape whether the wood sector moves further up the value chain or remains concentrated in lower-margin activities. A macro-financial overview can therefore help frame not only a research agenda, but also a regional development agenda for higher-value and more resilient wood product markets.

4. Conclusion

This paper has argued that the intersection of oil price shocks, monetary policy, bank lending, and the wood-based bioeconomy deserves greater attention. Recent work by the IMF, World Bank, ECB, and other central banks shows that energy shocks affect inflation, policy transmission, and credit conditions in ways that can materially alter firm financing and investment.

For the wood industry, these mechanisms matter because the sector combines energy exposure, dependence on construction-related demand, and substantial reliance on bank finance. The central conclusion is therefore straightforward: the transition towards a wood-

based bioeconomy is not only a technological and environmental transition, but also a macro-financial one. A resilient wood sector requires not just sustainable materials and growing demand, but also financing arrangements capable of absorbing energy shocks and tighter monetary conditions. The discussion also suggests that fintech may play a constructive role by improving transparency, risk assessment, and access to finance within wood-based value chains.

For the future of wood product markets, the message is clear: market opportunity and sustainability ambition are not enough on their own. The ability of firms to invest and scale up also depends on the macro-financial environment. Recognising this interdependence can help bridge sector studies, monetary economics, banking research, and policy debates on the future of the bioeconomy.

REFERENCES

1. Alvarez, J.; Kroen, T. (2025): The Energy Origins of the Global Inflation Surge. IMF WP 25/91.
2. Aterido, R.; Iootty, M.; Melecky, M. (2025): Energy Prices, Energy Intensity, and Firm Performance. World Bank WPS 11069.
3. Baba, C.; Lee, J. (2022): Second-Round Effects of Oil Price Shocks: Implications for Europe's Inflation Outlook. IMF WP 22/173.
4. Bank of England (2024): Monetary Policy Report, August 2024.
5. European Central Bank (2025a): The euro area bank lending survey: Fourth quarter of 2025.
6. European Central Bank (2025b): The ripple effects of monetary policy on housing and consumption. ECB Blog, 31 July 2025.
7. European Central Bank (2026): Why monetary policy hits harder after big shocks. ECB Blog, 13 April 2026.
8. Miyamoto, W.; Nguyen, T. L.; Sergeyev, D. (2024): How Oil Shocks Propagate: Evidence on the Monetary Policy Channel. FRBSF Working Paper 2024-07.
9. Moller, N. F.; Poschl, J. (2025): The Effects of a Large Energy Price Shock on Firm Credit. Danmarks Nationalbank WP 209.
10. Radev, D. (2024): Fintech and the Forestry Industry. WoodEMA 2024 Proceedings.
11. UNECE/FAO (2024): Forest Products Annual Market Review 2023-2024.
12. World Bank (2024a): Global Challenge Program: Forests for Development, Climate, and Biodiversity.
13. World Bank (2024b): Scaling up Finance for Sustainable Forestry in Paraguay. Project Information Document.
14. World Bank (2026): Global Economic Prospects, June 2026.

Author address:
Department of Statistics and Econometrics, FEBA, Sofia University “St. Kliment Ohridski”, Sofia, Bulgaria. *Corresponding author: d.radev@feb.uni-sofia.bg. The author gratefully acknowledges financial support from Bulgarian National Science Fund’s Scientific Programme “Fundamental Studies” under grant agreement KP-06-N75-9 from December 7, 2023.

INVESTMENT SUPPORT FOR THE DEVELOPMENT OF BIOECONOMY IN THE WOODWORKING INDUSTRY: CHALLENGES AND PROSPECTS

Renata Nováková , Olena Plaksiuk, Oleksandr Yakushev

Abstract: The article examines the theoretical and practical aspects of investment support for the development of the bioeconomy in the woodworking industry. The essence of the bioeconomy is clarified, and its role in ensuring sustainable industrial development, efficient use of natural resources, and environmental protection is substantiated. Particular attention is paid to the importance of the woodworking sector as a key component of the forest-based bioeconomy. The current state of investment activity in the woodworking industry is analyzed, including the identification of major sources of financing, investment trends, and the level of investment attractiveness of the sector. It is determined that despite the growing interest in sustainable industries, investment flows remain insufficient for large-scale technological modernization. Key challenges hindering the development of the bioeconomy are identified, including financial constraints, institutional inefficiencies, technological backwardness, and environmental risks. The study substantiates the impact of investment on enterprise modernization, productivity growth, and increased competitiveness in both domestic and international markets. Prospective directions for intensifying investment processes are proposed, including the development of public-private partnerships, the implementation of innovative and digital technologies, and the adoption of circular economy principles. Practical recommendations aimed at improving the efficiency of investment support and ensuring long-term sustainable development of the woodworking industry are provided.

Keywords: bioeconomy, investments, development, modernization, woodworking industry, forestry sector, sustainable development

1. FIRST GRADE TITLE

The bioeconomy is one of the key concepts of sustainable development of the European Union, which involves the use of renewable biological resources for the production of products, materials and energy in order to replace fossil fuels. According to the EU Bioeconomy Strategy, the bioeconomy covers the production of biomass, its processing into food, materials, industrial goods and bioenergy, ensuring the achievement of climate neutrality and the development of a circular economy by 2050.

The woodworking industry occupies a special place in the structure of the European bioeconomy, since wood is one of the most important renewable resources. Woodworking industry enterprises ensure the production of products with high added value, including sawn timber, furniture, wood-based panels, biocomposites and innovative biomaterials. According to the European Commission's Joint Research Centre (JRC) [3], the wood products and furniture sector generated €61 billion in added value in 2023, making it one of the largest segments of the EU bioeconomy. Figure 1 shows the wood processing sector in the structure of the bioeconomy in recent years.

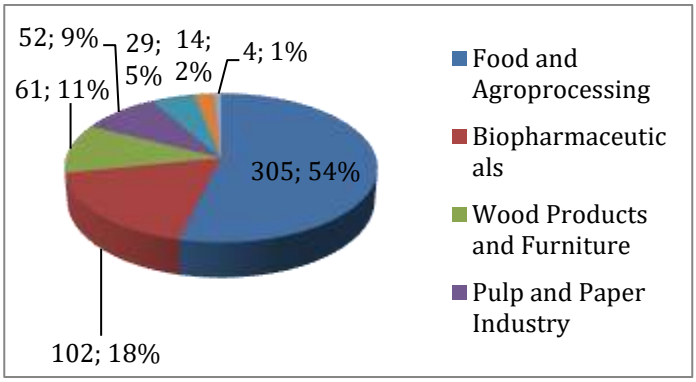

Figure 1. Share of the woodworking industry in the EU bioeconomy structure [3].

The role of the woodworking industry in the EU bioeconomy is to ensure the efficient use of forest resources, reduce dependence on fossil fuels, reduce greenhouse gas emissions, develop circular production models, and create added value in rural and forest regions. Thus, the woodworking industry is one of the basic elements of the implementation of the European Green Deal and the new EU Strategy for a competitive and sustainable bioeconomy. In recent years, investment activity in the woodworking industry of the European Union has been largely determined by the processes of decarbonization, digitalization and the transition to a circular economy. Investments are primarily directed to the modernization of production capacities, the introduction of resource-saving technologies and the development of biomaterials. The European Commission considers the bioeconomy as one of the strategic directions of economic development, which requires the creation of a favorable investment environment and the scaling up of bio-oriented production.

In 2023, the EU bioeconomy sectors provided 17.1 million jobs, €863 billion in gross value added and €17.3 billion in research and development expenditure. At the same time, a characteristic feature of the investment development of the woodworking industry is the high capital intensity of projects, which requires a combination of public and private financing. EU financial instruments aimed at supporting innovative enterprises and the introduction of environmentally friendly technologies play a significant role.

2. MAIN SOURCES AND MECHANISMS OF ATTRACTING INVESTMENTS IN THE BIOECONOMY

The formation of the investment potential of the woodworking industry in the EU is carried out through a multi-level financing system that combines private capital, state support and institutional instruments of the European Union. The main sources of financing are:1. Own funds of enterprises. 2. Bank loans. 3. Foreign direct investment. 4. EU funds. 5. Financing of the European Investment Bank. 6. Venture and innovation capital. 7. Public-private partnerships.

The effective development of the bioeconomy in the European Union largely depends on the availability of a diversified financing system that combines grant mechanisms, bank lending, venture capital and public-private partnership instruments. This is of particular importance for the woodworking industry, where the implementation of projects for deep wood processing,

production of biomaterials and the introduction of circular technologies is characterized by high capital intensity and a long investment cycle. During 2022–2025, the EU policy in the field of bioeconomy was aimed at scaling up innovative solutions and accelerating the transition from scientific developments to industrial production. The main financial support platforms were the Horizon Europe, InvestEU, Circular Bio-based Europe Joint Undertaking (CBE JU), LIFE and credit instruments of the European Investment Bank (EIB) [8].

Table 1. Main mechanisms for investment support for the EU bioeconomy

Mechanism	Main purpose
Horizon Europe	Financing research and innovation
InvestEU	Guarantees and attracting private capital
European Investment Bank (EIB)	Preferential lending for large projects
European Innovation Council	Support for startups and innovations
Cohesion Funds	Regional development and modernization of production
LIFE Programme	Environmental and climate projects

The largest innovation support instrument in the EU remains the Horizon Europe programme, which runs from 2021 to 2027 and provides funding for research and development in the bioeconomy, forestry, biomaterials and circular production systems. Particular attention is paid to Cluster 6 “Food, Bioeconomy, Natural Resources, Agriculture and Environment”, which finances projects on the digitalisation of bioeconomy value chains, the development of biocomposites and resource-efficient wood processing technologies [2].

An important feature of Horizon Europe is the high multiplier effect of investments. According to the European Commission, every euro invested in Horizon programs can generate up to 11 euros of economic impact in the long term.

The most specialized EU bioeconomy financing instrument is the Circular Bio-based Europe Joint Undertaking (CBE JU), established in 2021 as a joint initiative of the European Commission and the Bio-based Industries Consortium. The total budget of the program for 2021–2031 is 2 billion euros. The main objective is to support innovative bio-based industries, including biomaterials, biochemicals, biocomposites and new wood processing technologies [2].

Table 2. CBE JU Program Funding 2022–2025

Year	Budget of competitions, million euros	Nature of support
2022	120	First competitions for the development of bioeconomy technologies
2023	215*	Scaling of innovative projects
2024	213*	Demonstration and flagship projects
2025	172	Commercialization and industrial implementation of technologies
Together	720	Support for innovations in the bioeconomy

**Note: According to the annual programs of CBE JU [2].*

In 2022, 120 million euros were allocated for competitive projects, with applications exceeding 600 million euros, which indicates a high demand for funding among enterprises in the bioeconomy sector. In 2025, the budget of the next CBE JU competition amounted to 172 million euros, which are directed to 13 thematic areas, including the production of biomaterials, biocomposites, digitalization of the bioeconomy and the use of biomass waste.

The European Investment Bank is an important source of long-term financing. In December 2024, the EIB announced the launch of a new €3 billion support programme for the agricultural, forestry and bioeconomy sectors. It is expected that, thanks to the co-financing mechanism, this amount will allow mobilising around €8.4 billion in investments in Europe's bioeconomy.

Particular emphasis is placed on: modernization of wood processing enterprises; − energy-efficient technologies; production of biomaterials; development of circular value chains; support for small and medium-sized enterprises in the forest sector [1].

One of the main mechanisms for attracting private investment is the InvestEU programme. It is based on the EU guarantee system and aims to mobilise over €372 billion in investments over the period 2021-2027. Around 30% of all investments should contribute to the EU's climate goals, including the development of the bioeconomy and circular industry. For the wood-processing sector, this instrument is particularly important because it can attract private capital for large infrastructure and production projects, the risk of which is often too high for traditional bank financing [5].

3. STRUCTURE OF SOURCES OF FINANCING THE EU BIOECONOMY

Analysis of the practice of EU countries allows us to identify the following most effective mechanisms for financing the woodworking industry in the context of the bioeconomy: 1. Grant financing of innovative projects. 2. Preferential lending through the EIB and national development banks. 3. Public-private partnerships. 4. Blended finance. 5. Green bonds and ESG investments. 6. Venture financing of biotechnology startups. 7. EU regional development funds [8].

Table 3. Main sources of investment in the EU bioeconomy in 2022–2025 [8]

Source of funding	Main instrument	Estimated amount of funding
Horizon Europe	R&D Grants	over €95 billion (2021–2027)
CBE JU	Grants for Bioeconomy Projects	€2 billion (2021–2031)
InvestEU	Guarantees and Blended Finance	over €372 billion of investments mobilised
ЄІБ (EIB)	Soft Loans	€3 billion in 2024
LIFE Programme	Environmental Projects	over €5 billion (2021–2027)
Private capital	Direct Investments and Venture Capital	depending on country and sector

Thus, in 2022–2025, a multi-level bioeconomy financing system was formed in the European Union, combining grant, loan and market instruments. The CBE JU, Horizon Europe,

InvestEU and European Investment Bank credit mechanisms are of the greatest importance for the woodworking industry, ensuring the transition from traditional woodworking production to high-tech bioeconomic development models. The EU Bioeconomy Strategy directly defines the need to ensure investment security, scale up innovative solutions and commercialize bioproducts, which creates additional incentives for investors. Despite the significant potential of the industry, investment activity remains below the level required for the full implementation of the goals of the European Green Deal. The main constraining factors include: high capital costs for production modernization; long investment payback periods; instability of energy prices; regulatory complexity of environmental legislation; shortage of highly qualified personnel; uncertainty regarding the future availability of raw materials; competition for investment resources from other sectors of the green economy.

An additional challenge for businesses is the need to comply with new EU requirements for traceability of wood and sustainable forest management, which increases overall administrative costs. Barriers to investment development are summarized in Table 4 [4].

Table 4. Key barriers to investment development in the EU woodworking industry [4]

Group of factors	Manifestations
Economic	High cost of capital, inflation
Technological	Rapid obsolescence of equipment
Regulatory	Environmental and certification requirements
Market	Fluctuations in demand for products
Commodity	Limited access to forest resources
Institutional	Difficulty in accessing financial programs

4. MAIN DIRECTIONS OF INVESTMENT MODERNIZATION

Investments are a determining factor in the modernization of woodworking enterprises and increasing their competitiveness in the context of the development of the bioeconomy of the European Union. The implementation of the EU's strategic goals of decarbonizing the economy, achieving climate neutrality and transitioning to a circular production model requires significant investments in technological renewal of woodworking enterprises. It is investments that ensure the implementation of innovative solutions, contribute to increasing the efficiency of resource use and create conditions for the production of products with high added value [10].

One of the priority areas of investment in EU countries is the automation of production processes. Modern woodworking enterprises are actively implementing automated sawing, sorting and processing lines of wood, robotic complexes for the manufacture of furniture and wooden structures, as well as automatic product quality control systems. Such technologies allow to reduce the share of manual labor, increase the accuracy of production operations and reduce production costs. According to the estimates of the European Federation of the Woodworking Industry, automation of individual production processes can increase labor productivity by 20–30%, as well as significantly reduce the volume of production waste. An important area of modernization is the digitalization of enterprise management. Investments in digital technologies involve the implementation of ERP systems, digital production management platforms, enterprise resource planning systems and electronic document management. The use of digital solutions allows to monitor production processes in real time, optimize logistics chains and increase the efficiency of management decisions. As a result,

enterprises are able to respond more quickly to changes in market conditions and consumer needs [7,9].

Of particular importance is the implementation of the Industry 4.0 concept, which involves the integration of digital technologies, artificial intelligence, big data (Big Data), cloud services and the Internet of Things (IoT) into production processes. At EU woodworking enterprises, such technologies are used to predict the technical condition of equipment, optimize production cycles and improve product quality. The introduction of elements of "smart production" allows you to reduce equipment downtime, reduce operating costs and increase the level of resource efficiency. Another important area of investment modernization is increasing the energy efficiency of production. The growth of energy prices in Europe in 2022–2024 stimulated enterprises to introduce modern energy-saving equipment, heat recovery systems and energy management. Investments in energy-efficient technologies provide a reduction in energy consumption by 15–25%, which has a positive effect on both the economic performance of enterprises and the achievement of EU environmental goals [9].

In general, investment modernization provides a comprehensive positive effect for the woodworking industry [6]. Enterprises get the opportunity to increase labor productivity, reduce material and energy intensity of production, improve product quality and strengthen their own competitiveness. At the same time, environmental effects are achieved, associated with the reduction of greenhouse gas emissions, more rational use of wood raw materials and a decrease in the volume of production waste. Thus, investments are not only an economic factor in the development of the EU woodworking industry, but also an important tool for implementing the principles of a sustainable bioeconomy and the European Green Deal.

REFERENCES

1. €3 billion of EIB Group financing announced for farmers and bioeconomy. www.eib.org/en/press/all/2024-497-eur3-billion-of-eib-group-financing
1. Circular Bio-based Europe Joint Undertaking (CBE JU) https://www.cbe.europa.eu/
1. European Commission. Bioeconomy Strategy. Brussels: European Commission, 2025. Available at: https://environment.ec.europa.eu/strategy/bioeconomy-strategy_en
2. European Commission. Horizon Europe Strategic Plan 2025–2027. Brussels, 2025.
3. European Commission. InvestEU Programme: Sustainable Infrastructure and Innovation Investments. Brussels, 2024. https://commission.europa.eu/funding-and-tenders/find-funding/eu
4. European Commission. The European Green Deal. Brussels, 2019.
5. Kostyakova A. (2025). Transparency in accounting and auditing of Ukrainian timber: EITI reporting as a factor of sustainable development. *Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025.* WoodEMA_2025_proceedings.pdf
6. Knowledge4Policy (K4P) Knowledge for policy
7. Lasarte-López J., M'barek R. The EU Bioeconomy at a Glance: Focus on Economic Value Added, Employment and Innovation. Luxembourg: Publications Office of the European Union, 2025.
8. Plaksiuk, O.; Novakova, R.; Habiňáková, E. (2022).Investment in human capital as a guaranteeof the country's economic development in woodworking industry.*Crisis Management and SafetyForesight in Forest-Based Sector and SMEs Operating in the*

Global Environment .ISBN 978-953-8446-00-9 .https://www.scopus.com/record/display.uri?eid=2-s2.0-85147417058

Authors address:

Nováková, R.[1]; Plaksiuk, O.[2]; Yakushev, O.[3]

1 Department of Economy and Management, Ambis university, Prag, Czech republic
2 Dmytro Motornyi Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
3 Cherkasy State Technological University, Cherkasy, Ukraine

* Corresponding author: re.novakova@gmail.com, plaksyk4@gmail.com

CHAPTER D
MANAGEMENT, INNOVATION AND BUSINESS PERFORMANCE

THE EVOLUTION OF SCIENTIFIC RESEARCH ON CONTROL IN THE FORESTRY SECTOR

Daniela Ventsislavova Georgieva, Emil Asenov, Georgi Ranchev

Abstract: The study examines the evolution of scientific research on control within the forestry sector through a bibliometric analysis of 5,859 publications from the Web of Science database covering the period 2000-2026. Using the VOS (visualization of similarities) method, five primary thematic clusters were identified: institutional, political-economic, ecological-technological, social-labor, and internal organisational control. The findings suggest a shift of control from a periodic administrative process to a system of continuous monitoring of real-time data. Despite technological advancements, several challenges remain, including bureaucratic recentralisation and the limited genuine autonomy of local communities. The study concludes that control in the forestry sector is developing into a multilayered, integrated system where technological innovations and the institutional framework are interdependent to achieve sustainability.
Keywords: control, forestry, thematic clusters, co-occurrence mapping

1. INTRODUCTION

The forestry literature shows a fragmented understanding of "control" across institutional, economic, technological, ecological, and social areas. The authors didn't find a systematic analysis of how these aspects are structured and interconnected over time. This study aims to analyze and visualize the research on control in forestry using bibliometric methods. It is based on mapping the conceptual structure with keyword co-occurrence, identifying key research clusters, tracing the evolution from regulatory to technological and ecological approaches, and evaluating how economic control is integrated into broader forestry research.

The visualisation of information flows through so-called "science maps" and "atlases of knowledge" has been established as a research method within the scientific community since the late twentieth century (Börner, 2010; Small, 2003). Its subsequent development is grounded in the VOS ("visualization of similarities") concept, developed in the early twenty-first century as an analytical tool for examining and graphically representing structural relationships and recurring data patterns (Bukar et al., 2023, p. 2). The methodological toolkit encompasses clustering techniques and co-citation analysis of publications, keywords, and inter-journal linkages, enabling the exploration of the structure, dynamics, and evolution of scientific knowledge. Through these approaches, regularities in the development of scientific fields are identified, leading research themes are highlighted, and interactions among scientific domains and disciplines are analysed (Small, 1973).

The authors adopt this methodological approach because it enables the assessment of the extent to which issues related to economic control in the forestry sector are integrated within the scientific literature, as well as the identification of the principal research directions and the dynamics of the development of the studied problem area. Using the methodological approaches described above, an analysis was conducted of 5,859 scientific publications indexed in the Web of Science database and containing the keywords "control" and "forestry."

The examined time horizon covers the period from January 2000 to February 2026. The analysis was carried out using the VOSviewer software. The selected analytical approach is co-occurrence mapping (i.e., analysis of the co-occurrence of terms control and forestry), with author keywords serving as the unit of analysis. In constructing the maps, the primary data were pre-processed to eliminate potentially redundant or semantically overlapping terms, non-informative words, and terms falling outside the scope of control in its economic sense. Additionally, a cluster-based analysis of publication abstracts was conducted to identify the principal research problems addressed by scholars. The study is limited to publications indexed in the Web of Science database, potentially omitting relevant works from other sources.

2. BIBLIOMETRIC MAPPING AND CLUSTER IDENTIFICATION

Based on the frequency of the keywords “control” and “forestry” and their relationships, as calculated from the analysed publications, five main clusters have been identified (see Figure 1).

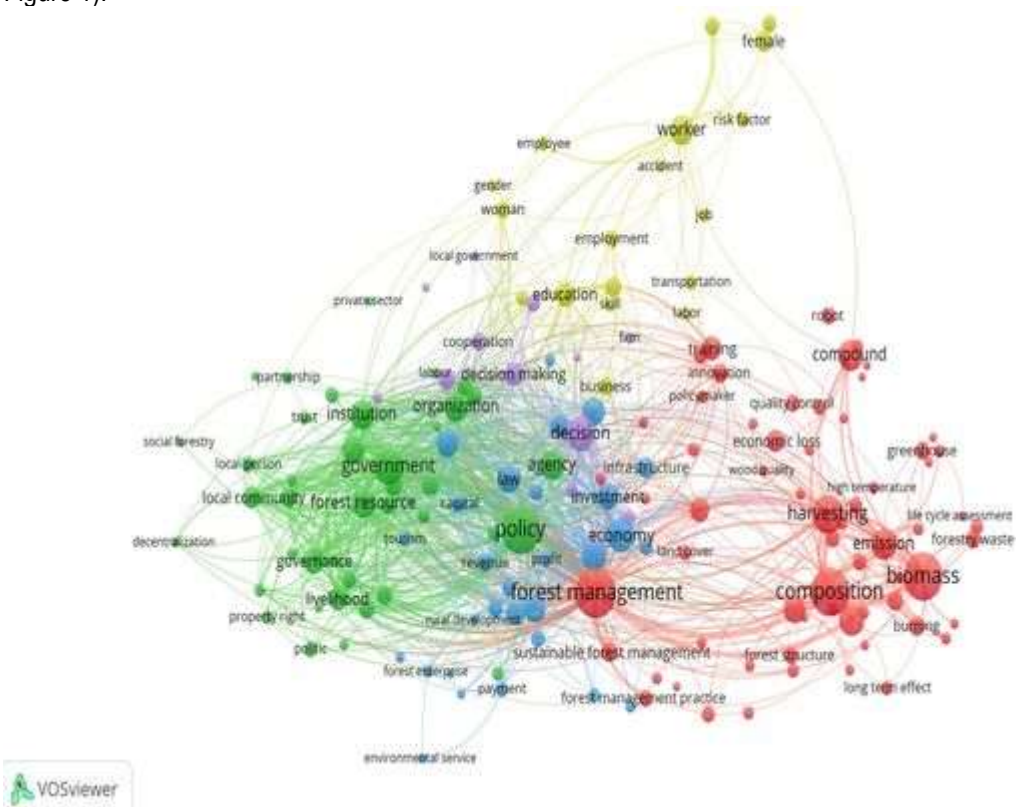

Figure 1. Cluster map of keywords in publications on “control” and “forestry”
Source: Based on data from the Web of Science, processed using VOSviewer, N = 5,859

The closer the keywords are positioned within a cluster, the more frequently they co-occur in the analysed publications, thereby delineating common thematic directions. The identified clusters are as follows:

Cluster 1 (green): "Institutional Control", with primary publication activity during 2000-2012 and 2016-2025

The green cluster encompasses the institutional and governance dimensions of the forestry sector. Key terms include government, governance, institutions, forest resources, local communities, property rights, decentralisation, trust, and social forestry. This cluster reflects macro-level governance, where control is conceptualised as a public regulatory mechanism for managing access to resources and coordinating interactions between the state and local communities. Within this framework, control is predominantly understood as an institutionally embedded process, exercised through both state and transnational governance mechanisms. A more in-depth analysis of the abstracts within this cluster reveals a central research concern regarding the mismatch between the formally established principle of decentralization and the actual concentration of power resources (see Fig. 2). In many countries, the transfer of authority to local communities is accompanied by the phenomenon of "bureaucratic recentralization", whereby state institutions use technical and "scientifically justified" requirements as instruments to reassert administrative control over forest resources. As a result, the formal autonomy of local communities is constrained, and their access to economic benefits is reduced. An additional complication arises from the phenomenon of "elite capture", in which influential local actors monopolise decision-making and resource flows, thereby undermining principles of social equity and democratic participation. In response to the deficiencies of national governance systems, transnational oversight mechanisms have gained prominence, including certification schemes (e.g., FSC) and initiatives such as FLEGT, which function as hybrid forms of regulation and external control.

Cluster 2 (blue): "Political-Economic Control", with primary publication activity during 2002-2015 and 2018-2026

The blue cluster forms the core of the network and encompasses key concepts such as policy, decision, agency, law, economy, investment, infrastructure, and forest management. It serves as a bridge between the other thematic groups. Within this cluster, control takes on a strategic and regulatory dimension, closely linked to decision-making processes, economic planning, and institutional coordination. A transition is observed from a purely normative understanding of control towards a more managerial and economic interpretation (see Fig. 2). At the strategic level, control evolves from a sanctioning mechanism into a system for managing economic efficiency and public accountability. Tax administration in the forestry sector is highlighted as a key instrument for generating revenue and reducing illegal activities. Furthermore, integrated indicator systems link revenues, expenditures, and ecosystem services, whereas transparency deficiencies tend to weaken institutional effectiveness. In many European countries, integrated control systems in forestry, called Integrative Forest Management (IFM), unify financial, environmental, and social indicators. They support sustainable management by measuring forest resources, biodiversity, carbon storage, and socio-economic benefits, balancing economic gains with environmental and social goals.

Cluster 3 (red): "Ecological-Technological Control", with primary publication activity during 2000-2010 and 2016-2026

The red cluster focuses on production and ecological processes, including key terms such as biomass, harvesting, emissions, composition, forest structure, life cycle assessment, quality control, and forestry waste. Within this cluster, control is primarily directed towards managing emissions, product quality, and long-term environmental impacts. It reflects the integration of sustainability and bioeconomy principles into the forestry sector. At the operational level, control

is characterised by advanced technological capabilities and precise monitoring of ecosystem processes. The use of satellite platforms, LiDAR technologies, and unmanned aerial vehicles (UAVs) marks the emergence of "Forestry 4.0", enabling high-resolution spatial inventory and the detection of illegal logging, even in adverse weather conditions. This transformation shifts control from a reactive to a real-time, preventive approach. In the context of climate change, stochastic and hybrid models are being developed to manage risks associated with forest fires, droughts, and floods, while accounting for the interdependencies between forest ecosystems and the hydrological cycle. Consequently, ecological control becomes embedded within a broader framework of climate security governance.

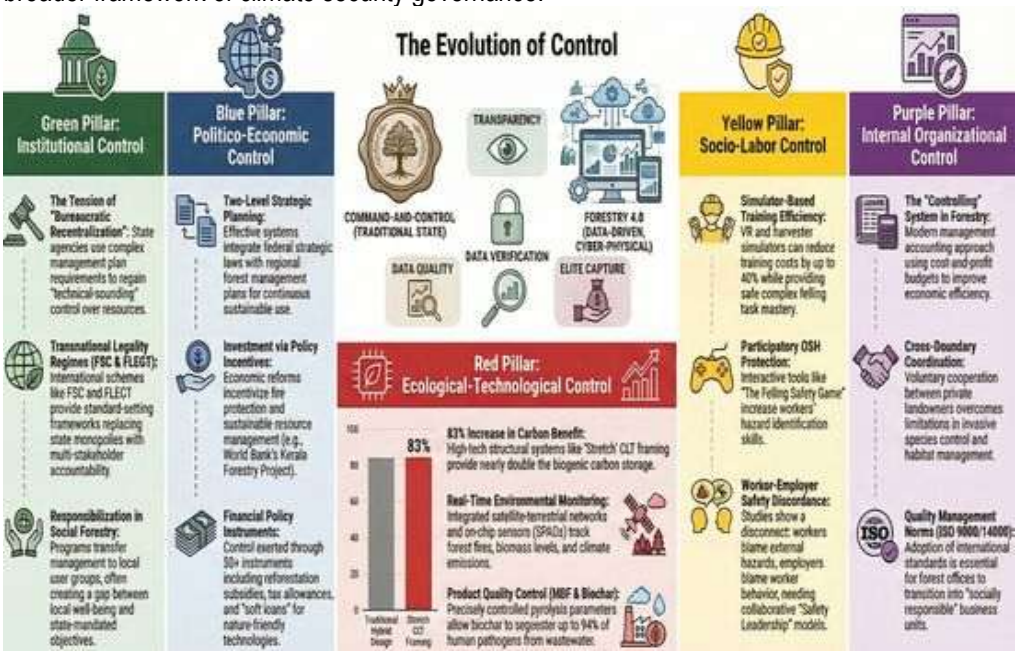

Figure 2. Infographic of the main research issues addressed in publications across clusters
Source: Generated with NotebookLM based on the authors' findings

Cluster 4 (yellow): "Socio-Labour Control", with primary publication activity during 2005-2016 and 2020-2025

The yellow cluster encompasses labour and socio-demographic aspects, including key terms such as worker, employment, risk factor, accident, training, education, gender, and skill. Within this cluster, control is understood as a mechanism for occupational risk management and human resource governance, linking workforce safety, professional qualifications, and the socio-demographic structure of employment. This dimension emphasises both the prevention of occupational hazards and the development of competencies required for increasingly technology-intensive forest operations. Forestry remains one of the most hazardous economic activities, with workers exposed to high levels of noise, vibration, biological agents, and ergonomic strain, frequently leading to musculoskeletal disorders. Recent research highlights innovative solutions such as RFID-based personnel tracking, intelligent machine control systems, and wearable technologies that improve worker safety and operational coordination. Training practices are also evolving through simulation-based and gamified learning tools,

including specialised logging safety applications, which enhance situational awareness and strengthen managerial and supervisory capabilities.

Cluster 5 (purple): "International Organizational Control", with primary publication activity during 2010-2018 and 2019-February 2026

The purple cluster, positioned between the institutional and organisational core, includes key concepts such as organisation, decision-making, business, firm, cooperation, and labour. It represents an intermediate level between macro-institutional control and micro-level management practices, reflecting organisational dynamics and coordination among sectoral actors. Within this cluster, control is exercised through internal managerial mechanisms, inter-organisational interactions, and network-based governance structures. At the firm level, control is expressed through systems of coordination, accountability, and corporate social responsibility (CSR). Empirical studies suggest that enterprises with stronger internal control systems tend to demonstrate better CSR performance, regulatory compliance, and more effective resource management. In addition, the digitalisation of management processes through cloud-based platforms and real-time monitoring systems enables detailed tracking of costs and productivity at the individual machine and operational unit levels.

3. DISCUSSIONS

The analysis underscores trends shaping the future of the scientific research in the forestry sector. Firstly, the rapid advancement of digital technologies is transforming control into an ongoing, data-driven process via sensor networks, satellite tracking, and intelligent algorithms that enable immediate decision-making. However, institutional frameworks frequently lag behind, encountering resistance owing to traditional governance practices, transparency issues, or concerns of corruption. This gap between technological possibilities and real-world use raises important questions about the effectiveness and inclusivity of new control systems. Secondly, the growing hybridization of governance methods (like merging public regulation, market tools, and transnational efforts), indicates a more intricate and interconnected regulatory landscape. Effective management depends on strong coordination, trust, and transparency among stakeholders. Furthermore, climate change is increasingly becoming a critical factor that influences control priorities, emphasizing the management of systemic environmental risks such as wildfires, droughts, and floods. This necessitates the integration of ecological monitoring with predictive models and adaptive strategies. Finally, the increasing significance of organizational and human aspects of control emphasizes the necessity for capacity development, innovation in training methodologies, and the implementation of integrated management systems that harmonize economic efficiency with social and environmental sustainability. Collectively, these trends indicate that the effectiveness of control within the forestry sector would depend on the capacity to integrate technological advancements, institutional reforms, and social participation into a cohesive and adaptable governance framework.

4. CONCLUSION

The cluster map highlights a central theme focused on forest management, policy, government, economy, and decision-making, linking the different research directions. The periphery comprises more specialised domains, such as certification and legality, control and

accountability, fire monitoring, and digitalisation (e.g., robotics and artificial intelligence). Analyzing the temporal progression of research on control within the forestry sector shows a shift towards viewing 'control as a system," integrating regulatory, financial-managerial, ecological, and technological layers. Instead of replacing the classic command-and-control approach, recent research expands it into a digital, adaptive, and predictive framework. Current studies more frequently emphasize technological and ecological control aspects. The analysis identifies several key strategic trends. Firstly, there is a notable technological advancement with control shifting from a periodic administrative task to an ongoing, data-informed process. This is made possible by IoT devices, sensor networks, and smart algorithms that allow for real-time modifications. Secondly, the institutional setting often resists this change, as technological development faces corruption and politically backed violations. Thirdly, successful governance models depend on transparency, trust, and coordination among public and private stakeholders. Fourth, climate change is redirecting control efforts towards managing abiotic factors and systemic risks, emphasizing adaptability as a crucial factor for sectoral sustainability.

In conclusion, control in the forestry sector should be conceptualised as a multi-layered, integrated system in which technological innovation, institutional frameworks, and social mechanisms are interdependent and jointly determine the effectiveness and sustainability of governance.

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REFERENCES

1. Börner, K. (2010): *Atlas of Science: Visualizing what we know*. MIT Press, Cambridge, MA.
2. Bukar, U. A.; Sayeed, M. S.; Abdul Razak, S. F.; Yogarayan, S.; Amodu, O. A.; Raja Mahmood, R. A. (2023): A method for analyzing text using VOSviewer. MethodsX 11: 102339. https://doi.org/10.1016/j.mex.2023.102339.
3. Small, H. (1973): Co-citation in the scientific literature: A new measurement of the relationship between two documents. Journal of the American Society of Information Science and Technology 24 (4): pp. 265-269.
4. Small, H. (2003): Paradigms, citations, and maps of science: A personal history. Journal of the American Society for Information Science and Technology 54 (5): pp. 394-399.

Authors address:
Georgieva, V. D.[1]; Asenov, E.[2]; Ranchev, G.[3]
[1] Economic Research Institute at the Bulgarian Academy of Sciences, Department "Economics of the Firm", Sofia, Bulgaria
[2, 3] Department of Financial Control at the University of National and World Economy (UNWE), Sofia, Bulgaria
The authors contributed equally to the writing of the text and its analysis, with 33.33% each.
*Corresponding author: danielagr999@gmail.com

CONCEPTUAL MODEL FOR THE INTEGRATION OF THE FOREST SECTOR INTO INDUSTRIAL PARKS: STRUCTURE, INTERACTIONS, AND MECHANISMS

Katya Antonova

Abstract: This study aims to develop a conceptual model for the integration of the forest sector into industrial parks within the context of a circular economy. The focus is placed on defining the structural components of the model, the types of interactions among stakeholders, and the mechanisms that ensure their effective functioning. Key elements of integration are identified, including forestry enterprises, related industries, logistics units, and institutional actors, as well as the resource and information flows linking them. Various forms of interaction are analyzed, supporting resource optimization and the reduction of waste and carbon footprint. Special attention is given to mechanisms for coordination and fostering cooperation within industrial parks. The proposed model provides a theoretical foundation for the development of sustainable integration solutions and contributes to more efficient resource management in support of the transition to a circular economy.
Keywords: forestry sector; industrial parks; circular economy; Innovative conceptual model

1. INTRODUCTION

The transition to a circular economy, combined with the development of Industry 4.0 and Industry 5.0, places new demands on the organization of production systems and the interaction between economic actors. Industrial parks are establishing themselves as an environment that creates conditions for industrial symbiosis, resource efficiency, digital transformation and implementation of sustainable production models. In the context of this study, the concept of 'integration of the forest sector into industrial parks' should not be understood as integrating the whole sector, but as building sustainable links between forestry enterprises, enterprises from related industries, logistics structures, research organizations and institutional actors within industrial parks. energy, information and technology, based on the principles of the circular economy, digitalization and industrial symbiosis. Industry 4.0 concepts provide the technological foundation for this integration through the use of the Internet of Things (IoT), artificial intelligence (AI), automation, big data analytics and intelligent systems. For its part, Industry 5.0 expands this approach, placing an emphasis on the role of the human, sustainability, adaptability and increasing the sustainability of industrial ecosystems. In this context, this study aims to develop a conceptual model that systematizes the main structural components, types of interactions and coordination mechanisms between participants, creating prerequisites for increasing resource efficiency, reducing waste and carbon footprint, as well as increasing the competitiveness of forestry enterprises in the digital and circular economy.

2. THEORETICAL FRAMEWORK

The forest sector plays a key role in the development of the circular bioeconomy, as it uses renewable biological resources and creates opportunities to build sustainable value chains. Current trends in the development of forestry industries are related to the transition from linear production models to integrated systems based on resource efficiency, utilization of by-products and the creation of new products with higher added value. The forestry sector is characterized by a complex value chain structure that includes forest resource management, extraction, primary and secondary wood processing, production of wood products, pulp and paper industry and production of organic products. Linking these activities with other industrial sectors within industrial parks creates opportunities for more complete resource utilization and the development of new value models in a circular bioeconomy. In this sense, forestry enterprises can be seen as active participants in industrial ecosystems in which woody biomass, production residues and secondary raw materials are converted into inputs for other production processes. This approach supports the development of industrial symbiosis and contributes to reducing waste, increasing resource efficiency, and limiting the carbon footprint (European Environment Agency, 2022; Schlüter et al., 2023; Rentería Núñez & Perez-Castillo, 2023).

Industrial parks provide an appropriate organizational environment for the realization of such interactions through a concentration of enterprises, shared infrastructure, logistical connections and coordination mechanisms between participants. The modern approach to the development of industrial parks is aimed at building sustainable industrial ecosystems in which economic, environmental and technological objectives are combined (Dai & Day, 2022; Schlüter et al., 2023, UNIDO, World Bank, & GIZ, 2021). Digital transformation creates new opportunities to manage resource flows and optimize interactions between enterprises. The use of technologies such as IoT, AI, Big Data, digital twins, and intelligent manufacturing systems supports traceability, automation, and real-time decision-making (Radev, 2023, Javaid et al., 2022; Nascimento et al., 2023).

The Industry 5.0 concept builds on the digital approach by placing an emphasis on sustainability, human-centricity and resilience to external interactions. This model views technology not only as a means of increasing productivity, but also as a tool to achieve environmental and social goals by balancing human potential and smart technologies (Breque et al., 2021; Ghobakhloo et al., 2023; Narkhede et al., 2023; Xu et al., 2023).

In this context, the integration of enterprises from the forest sector into industrial parks can be seen as a process of building an interconnected industrial ecosystem based on the exchange of resources, knowledge, technologies and a regulatory framework. It is these principles that form the theoretical basis for the development of a conceptual model including structural components, actors, interactions and coordination mechanisms. industrial symbiosis and the digital transformation of production systems, there is still a need for an integrated conceptual model to describe the specific role of forestry enterprises in industrial parks. The complexity of the interactions between production enterprises, logistics structures, technological platforms and institutional actors requires a systematic approach that brings

together the resource, information and management aspects of integration, which implies the development of a conceptual model.

3. CONCEPTUAL MODEL FOR INTEGRATION OF THE FOREST SECTOR IN INDUSTRIAL PARKS

The proposed conceptual model for the integration of the forest sector in industrial parks is based on the understanding of the industrial park as a dynamic industrial ecosystem in which different economic actors interact through the exchange of resources, technology, knowledge and information. Such an approach is in line with modern concepts of circular bioeconomy, industrial symbiosis and sustainable industrial ecosystems, where interaction between enterprises is seen as a prerequisite for increasing resource efficiency, reducing waste and creating added value (UNIDO et al., 2021; European Environment Agency, 2022).

The conceptual model is based on four interrelated principles that determine its structure and functioning. The first principle is **resource integration**, in which material flows from enterprises in the forest sector are managed in order to maximize the use of the resource potential of wood and related biological resources. This includes the utilization of production residues, by-products and by-raw materials as inputs for other production processes within the industrial park, which is in line with the principles of the circular bioeconomy (European Environment Agency, 2022).

The second principle is **technological integration**, which is realized through the application of digital technologies characteristic of Industry 4.0. The use of IoT, AI, Big Data, digital twins and intelligent production systems ensures traceability of resource flows, improves coordination between participants and supports real-time decision-making (Javaid et al., 2022; Nascimento et al., 2023).

The third principle is **sustainable integration**, based on the concept of Industry 5.0, which places emphasis on human-centricity, environmental sustainability and the resilience of industrial systems to external influences. In this context, technological solutions are seen as a means not only to increase productivity, but also to achieve balanced economic, environmental and social development (Breque et al., 2021; Xu et al., 2023).

The fourth principle is **network interaction**, which implies the construction of sustainable links between enterprises in the forest sector, enterprises from related industries, logistics operators, research organizations and public institutions. Such a network organization creates conditions for the exchange of knowledge, the implementation of innovations, the sharing of infrastructure and the development of industrial symbiosis, which increases the competitiveness and adaptability of the industrial ecosystem (UNIDO et al., 2021).

The interaction between these four principles forms the conceptual basis of the proposed model and determines the logic of the interrelationships between its structural components, presented in the next section. The conceptual model includes five main structural elements that form an interconnected industrial ecosystem:

1. Enterprises from the forest sector - central place in the model is occupied by enterprises from the forest sector, which include activities for the extraction and primary processing of wood, production of wood products, furniture industry, pulp and paper industry

and production of biobased products. These enterprises form the main resource flow in the system and provide opportunities for the utilization of wood biomass and production residues.

2. Industrial network (associated manufacturing plants) - includes enterprises from other industrial sectors that can use the resources generated by the forest sector or provide complementary products, services and technologies. These interactions create conditions for industrial symbiosis and expansion of value chains.

3. Infrastructure and logistics environment - includes transport infrastructure, storage facilities, energy systems and facilities for waste management and recovery. Its role is to ensure the efficient movement of material and energy flows between the participants.

4. Digital environment - ensures the connectivity and intelligent management of the system through the use of technologies from Industry 4.0 - IoT, AI, Big Data, digital twins and production management systems. It allows monitoring, forecasting and optimization of processes in real time.

5. Institutional and technological environment - includes universities, research organizations, technology centers and public institutions. Their role is related to knowledge creation, technology transfer, support for innovation and the formation of a regulatory and organizational environment for sustainable development.

The interaction between these components forms an integrated structure in which resource, information and technological flows are managed in a coordinated manner. In this way, the conceptual model creates a basis for the development of sustainable industrial ecosystems based on the principles of the circular bioeconomy, Industry 4.0 and Industry 5.0.

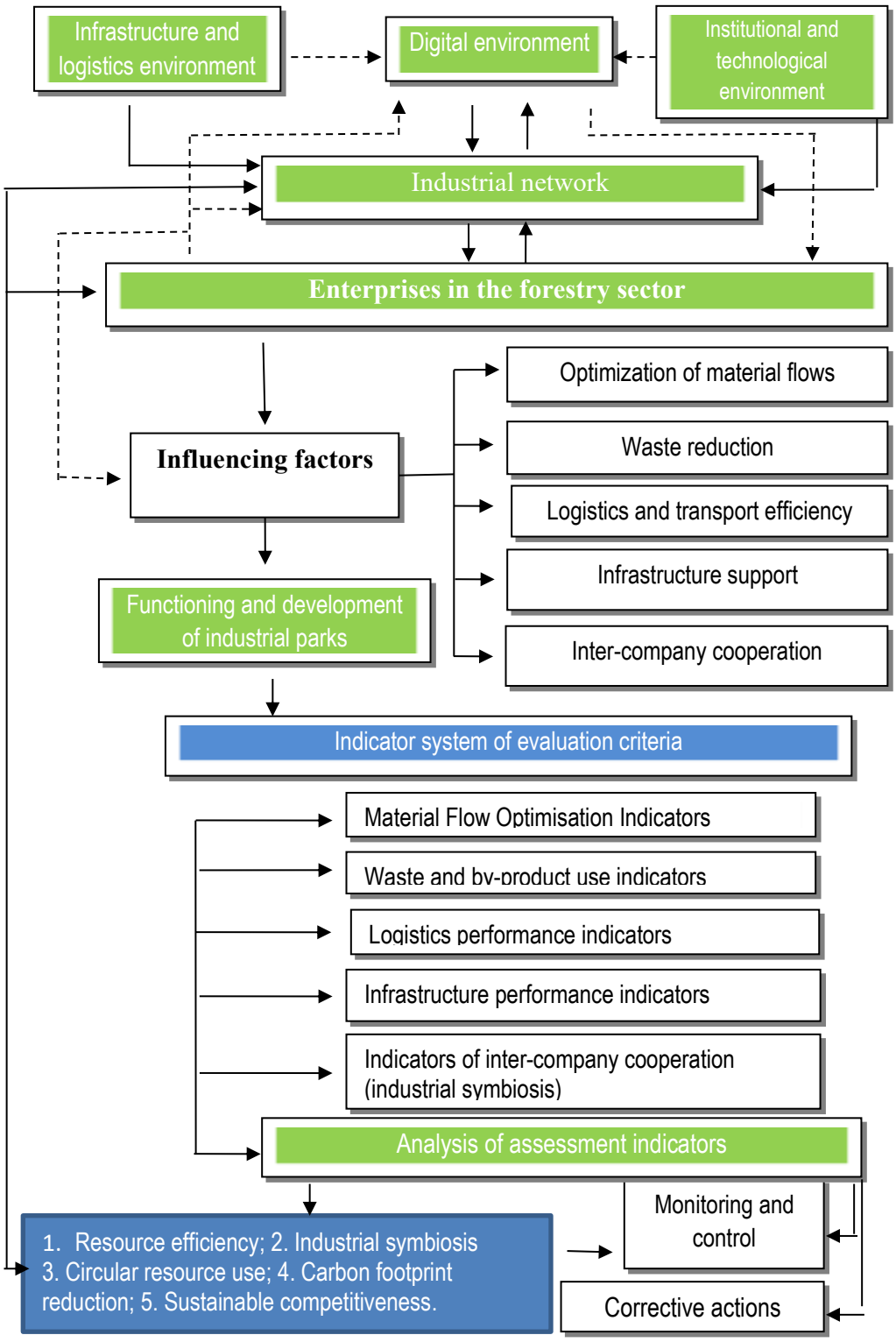

Fig.1 Conceptual model for the integration of forest sector enterprises into industrial parks

The model from Fig. 1 is based on a systems approach, according to which the industrial park functions as an integrated ecosystem where the individual functional elements are interconnected through material, information and management relationships. At the center of the model are **forest sector enterprises**, which constitute the primary source of material resources, production activities and value creation. Their central position reflects the role of the forest sector as the main generator of wood-based raw materials, by-products and biomass that can be utilized within industrial symbiosis networks.

The **industrial network** represents the direct production environment of forest sector enterprises. It enables the exchange of raw materials, by-products and technologies with related industries, thereby extending value chains and supporting the circular use of resources. The interaction between these two elements forms the basis of industrial symbiosis within the industrial park. The **infrastructure and logistics environment** provides the physical conditions necessary for the functioning of the system. Transport infrastructure, warehousing facilities, energy supply and waste management ensure the efficient movement of material and energy flows between enterprises while reducing operational costs and environmental impacts. The **digital environment** performs a horizontal coordinating function within the model. Through Industry 4.0 technologies - including IoT, AI, Big Data and digital twins - it supports monitoring, real-time information exchange, optimization of material flows and performance assessment. Rather than representing a separate production element, the digital environment facilitates the interaction among all functional elements of the model. The **institutional and technological environment** complements the model by supporting knowledge generation, technology transfer, innovation and regulatory coordination. Universities, research organizations, innovation centers and public authorities contribute to the continuous improvement and long-term sustainability of the industrial ecosystem.

The interaction among these functional elements generates several interconnected processes, including optimization of material flows, utilization of waste and by-products, improvement of logistics performance, infrastructure support, monitoring and corrective actions based on performance indicators. These processes create feedback loops that enable continuous improvement of the system and enhance its adaptability to changing technological, environmental and market conditions. As a result, the proposed conceptual model contributes to increased resource efficiency, stronger industrial symbiosis, more effective circular use of resources, reduced carbon footprint and improved inter-company cooperation. These outcomes reflect the combined application of circular bioeconomy principles together with Industry 4.0 and Industry 5.0 concepts within industrial parks.

4. CONCLUSION

The transition towards a circular bioeconomy requires new approaches to organizing production systems and strengthening cooperation among enterprises operating within industrial ecosystems. In this context, the present study proposed a conceptual model for the integration of forest sector enterprises into industrial parks, combining the principles of circular economy, industrial symbiosis, Industry 4.0 and Industry 5.0. The proposed model contributes to the existing body of knowledge by integrating the main functional elements of industrial parks with the mechanisms governing resource exchange, digital coordination and institutional support. Unlike approaches that focus primarily on technological or environmental aspects, the proposed framework considers the integration process from a systemic perspective by combining production, logistics, digital technologies, innovation and governance within a single

conceptual structure. From a practical perspective, the model can support decision-making related to the planning, development and management of industrial parks involving forest sector enterprises. It may also serve as a basis for identifying opportunities for industrial symbiosis, improving resource efficiency, reducing waste generation and enhancing cooperation among stakeholders. The study is conceptual in nature and therefore does not include empirical validation of the proposed framework. Future research should focus on testing the model through case studies of industrial parks, developing quantitative indicators for assessing the effectiveness of integration and examining the application of digital technologies for managing resource flows within circular industrial ecosystems.

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REFERENCES:

Breque, M., De Nul, L., & Petridis, A. (2021). *Industry 5.0: Towards a sustainable, human-centric and resilient European industry*. European Commission.

Dai, Y., & Day, S. (2022). A synthesized framework of eco-industrial park transformation and stakeholder interaction. Business Strategy and the Environment, 31(7), 3122-3151. https://doi.org/10.1002/bse.3067

European Environment Agency. (2022). *Circular economy and bioeconomy: The role of forests and forest-based products in Europe*. Publications Office of the European Union.

Ghobakhloo, M., Iranmanesh, M., Tseng, M.-L., Grybauskas, A., Stefanini, A., & Amran, A. (2023). Behind the definition of Industry 5.0: A systematic review of technologies, principles, components, and values. Journal of Industrial and Production Engineering, 40(6), 432-447. https://doi.org/10.1080/21681015.2023.2216701

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Journal of Industrial Information Integration, 28*, Article 100348. https://doi.org/10.1016/j.susoc.2022.01.008

Korhonen, J., Honkasalo, A., & Seppälä, J. (2021). Circular economy: The concept and its limitations. *Ecological Economics*.

Narkhede, G., Pasi, B., Rajhans, N., & Kulkarni, A. (2023). Industry 5.0 and the future of sustainable manufacturing: A systematic literature review. Business Strategy & Development, 6(4), 704-723. https://doi.org/10.1002/bsd2.272

United Nations Industrial Development Organization, World Bank & Deutsche Gesellschaft für Internationale Zusammenarbeit. (2021). *International framework for eco-industrial parks (Version 2.0)*. UNIDO.

Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2023). Industry 5.0 and smart manufacturing: A systematic review and future research agenda. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2021.10.006

Радев, Е. (2023) Развитие на цифровата икономика в ЕС: нови правила и перспективи, Правото и бизнесът в съвременното общество, Сборник с доклади от 3-та национална научна конференция 13 ноември 2020 г. Изд. „Наука и икономика“, Варна, 13-20.

Authors address:
Antonova, K.
Business, Investments, Real Estate, University of Economics - Varna, Bulgaria
Corresponding author: katia_antonova@ue-varna.bg

COMPARATIVE ANALYSIS OF RESOURCE EFFICIENCY IN PARQUET BLANK PRODUCTION: DEDICATED VS. BY-PRODUCT SAWMILLING STRATEGIES

Ana Marija Stamenkoska, Ivana Antovska, Živka Meloska

Abstract: Efficient raw material utilization is a key component of the circular and sustainable bioeconomy. Sawlogs represent the primary input in sawmilling operations. The sawmilling process is evaluated by measuring how efficiently the raw material is used in terms of quantity, quality, and overall value. Quantitative efficiency refers to the proportion of usable material obtained from the processed logs. Sawlogs are used for a wide range of products, including construction timber, furniture components, and wooden household items. Parquet flooring is a significant wood-based product and occupies an important share of wood utilization in the wood-processing industry. In traditional sawmilling systems, parquet production typically relies on by product generated during primary sawing (wooden slabs obtained from course waste). Hardwood species are predominantly used for parquet manufacturing. The fundamental element of parquet flooring is a parquet lamela, produced in the form of parquet blanks. This study compares two production strategies for parquet blanks: (1) manufacturing directly from logs specifically intended for parquet blank production, and (2) manufacturing from sawmill by-products. Within this framework, the production of parquet blanks represents a relevant segment of hardwood processing, yet the efficiency of different production pathways remains insufficiently examined. The research was conducted under real industrial conditions in a representative sawmilling facility in the Republic of North Macedonia. The objective of the study is to determine the resource efficiency of parquet blank production under both approaches.
Keywords: efficiency, hardwood species, manufacturing, parquet blanks, processing, quantitative yield, sawlogs.

1. INTRODUCTION

The sawmill industry represents a key component of the wood industry. It is the first technological process that predetermines the entire wood processing chain and its utilization. The quality of the sawmilling process is directly related to the quality of the wood products. Although the primary objective of sawmilling is to obtain the highest-quality wood products from sawlogs, an important aspect of the process is the percentage of quantitative yield. This percentage represents the share of the volume of the obtained assortments in the volume of a sawlog, or, in other words, how much usable wood can be obtained from a single sawlog. It is directly related to the economic indicators of the sawmill industry. From a practical point of view, quantitative yield plays an important role. From an economic point of view, the key indicator of a successful sawmilling operation is the quantity of wood products obtained from a single sawlog. Another important indicator of utilization is qualitative utilization. There is a certain dependency between qualitative and quantitative utilization, depending on the type of raw material used in the sawmilling process. This dependency should be logically considered and defined before the sawing process begins in order to obtain the highest possible quality and quantity from a single sawlog.

Sawmilling operations represent one of the most important phases in the wood supply chain because they connect the conversion of raw material into finished products (Borz *et al*., 2021). With the growing demand for wood products and wood-based materials, the importance of efficient wood utilization continues to increase. The utilization of raw material plays an important role in the entire forest biocenosis. Estimating efficiency from an economic point of view is important for establishing an operational framework for a sawmill enterprise (Fotiou & Stamou, 2000). The operational framework and the entire technological flow of materials in a sawmill also depend on the characteristics of the raw material being processed. Because wood is an anisotropic material, the entire mechanical process must follow the anatomical characteristics of the wood in order to obtain the most valuable products. Each wood species is distinguished by different anatomical characteristics. Consequently, these characteristics also include the form of the stem (Stamenkoska *et al*., 2025). Therefore, the percentage of quantitative yield depends on the geometry of the sawlog, which is the primary raw material in the sawmilling process. Consequently, the percentage of quantitative yield varies depending on the wood species being processed. According to Rabajiski (2019), the quantitative yield has a very wide range, from 48.0 to 70.0%. Ištvanić *et al*. (2025) confirmed that the quantitative yield of logs increases with better log quality and larger dimensions.

The main objective of the technological flow in sawmilling is to obtain the primary sawmilling products (boards, planks, and structural lumber intended for construction). During the sawing of these products, a certain amount of waste is generated. Waste occurs as fine and coarse waste. Because this waste is later utilized to produce usable products, the term by-products is commonly accepted. Coarse waste consists of slabs, cut-offs, and cut-outs generated during the sawing of logs, while fine waste consists of sawdust. From the coarse waste, small wooden elements and flooring elements can be produced, as well as wood-based fuels. One of the ways the industry has found to utilize sawing by-products is through the production of flooring elements. Flooring elements are relatively small pieces and generally require a higher quality class. The primary form of a flooring element is the so-called parquet blank. This element is obtained through sawing, mainly in the radial and tangential directions (Stamenkoska *et al*., 2024). For this purpose, both domestic and foreign wood species are used.

This paper investigated the efficiency of the production process of parquet blanks. The main objective was to determine whether the dedicated production of parquet blanks is more efficient than the traditional production of parquet blanks from sawmilling by-products.

2. MATERIALS AND METHODOS

The raw material used in this research consisted of beech (*Fagus sylvatica* L.) sawlogs. The sawlogs originated from domestic forests in North Macedonia. Beech and oak are the most commonly used hardwood species for the production of flooring elements. Their aesthetic and mechanical properties make them suitable for furniture manufacturing and interior applications. The mean diameter of the sawlogs used in this research ranged from 34.0 to 36.0 cm, and all logs had an untrimmed length of 3.0 m. A total of 12 logs were processed for the purposes of this research. The logs were graded as quality classes A, B, and C according to the Macedonian standards MKS EN 1313-2:2010 Round and sawn timber – Permitted deviations and preferred

sizes – Part 2: Hardwood sawn timber and MKS EN 1316-1:2013 Hardwood round timber – Qualitative classification – Part 1: Oak and beech.

The logs were processed using a vertical bandsaw at a representative sawmill in North Macedonia. All logs were measured before processing. The logs were divided into two categories: dedicated logs intended for the production of parquet blanks and logs intended for the production of planks, with parquet blanks produced from the by-products. The two groups consisted of six logs each. The logs were processed using the live uneven sawing method shown in Figure 1. From the dedicated logs, parquet blanks with dimensions of 25 × 50 × 450 mm were sawn (Figure 2). From the logs intended for the production of primary sawmilling products, planks with a thickness of 25 mm and various lengths and widths were produced. From the by-products of these logs (slabs, cut-offs, and cut-outs), parquet blanks with the same dimensions as those produced from the first group of logs were manufactured. After sawing, all obtained wood products were measured accordingly (length, width, and thickness), and their volume was calculated. The quantitative yield was determined as the ratio between the log volume and the volume of the obtained products using standard mathematical formulas.

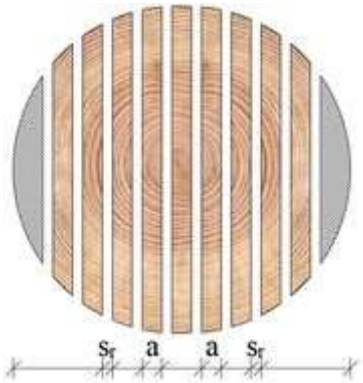

Figure 1. Live uneven sawing method used for the beech sawlog

Figure 2. Parquet blanks obtained from the sawlogs

3. RESULTS AND DISCUSSION

The processed beech logs had a mean diameter ranging from 34.0 to 36.0 cm and a length of 3.0 m. The total volume of the beech logs processed for the dedicated production of parquet blanks was 1.72 m³, while the total volume of the beech logs processed for the production of planks and parquet blanks was 1.78 m³. In total, beech sawlogs with a volume of 3.50 m³ were processed. Table 1 presents the data for the processed beech sawlogs.

Table 1. Quantitative yield of the processed beech sawlogs [%]

Dedicated production of blanks				Production of planks and blanks					
Blanks (yield)	Fine waste	Coarse Waste	Total Waste	Planks	Blanks	Total yield	Coarse waste	Fine waste	Total waste
42.38	24.86	32.76	57.62	41.8	9.34	51.14	27.2	21.66	48.86
41.86	26.58	31.56	58.14	43.6	12.3	55.9	26.32	17.78	44.1
38.25	24.27	37.48	61.75	46.25	10.18	56.43	24.12	19.45	43.57
40.10	24.90	35.00	59.9	48.53	13.25	61.78	23.3	14.92	38.22
32.00	23.85	44.15	68.0	45.2	8.36	56.56	24.12	19.32	43.44
33.12	22.57	44.31	66.88	42.26	9.12	51.38	26.14	22.48	48.62

According to the data presented in Table 1, it can be observed that the mean yield of the logs intended for the dedicated production of parquet blanks was 37.95%, whereas the mean yield of the logs intended for the production of planks and parquet blanks was 55.53%. Regarding the percentage of total waste, the mean value for the dedicated production was 62.05%, while that for the production of planks and parquet blanks was 44.46%. The difference between these percentages is due to the larger number of cuts performed on the primary and secondary machines required to obtain the final products. During the production of parquet blanks directly from the sawlogs, a larger number of cuts is required because of their relatively small dimensions. Furthermore, owing to the high aesthetic requirements for these flooring elements, all anatomical defects, such as knots and discoloration, must be removed. To achieve the required quality, additional cuts are necessary to eliminate these defects. The increased number of cuts results in a higher percentage of sawdust generated by both the primary and secondary machines and also increases the amount of coarse waste that cannot be further utilized because of its small dimensions.

In contrast, the production of planks and parquet blanks results in a higher quantitative yield because fewer cuts are required, thereby reducing the amount of sawdust generated during processing. In this production strategy, the coarse waste generated during plank production is utilized for the manufacture of parquet blanks, which consequently reduces the total amount of waste. It can be observed that the percentage of parquet blanks obtained is considerably lower than that achieved through dedicated production. However, from a manufacturing perspective, the overall efficiency of the process is increased because a smaller amount of waste is generated. This production method also utilizes the machinery more efficiently because it reduces the need for secondary cutting operations, thereby lowering electricity consumption during machine operation, reducing production costs, and improving the overall efficiency of the sawmilling process.

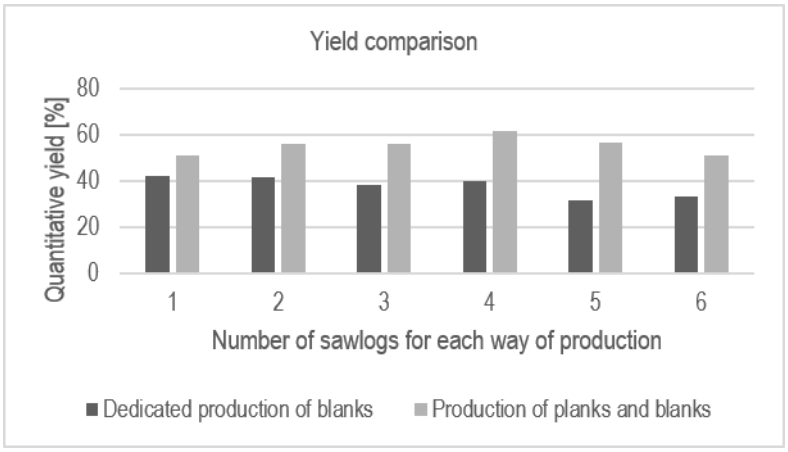

Figure 3. The difference in yield between the dedicated blank production and the production of planks and blanks

Figure 3 illustrates the difference in quantitative yield between the dedicated production of parquet blanks and the production of planks and parquet blanks.To further demonstrate the difference between the two production methods, Figure 4 illustrates the difference in the percentage of total waste generated. A noticeable difference was observed, with an average of 17.58%, a minimum of 8.76%, and a maximum of 24.56%.

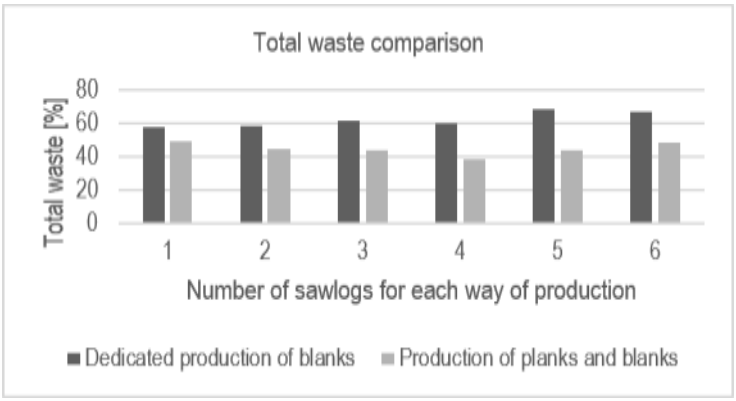

Figure 4. The difference in total waste between the dedicated blank production and the production of planks and blanks

4. CONCLUSIONS

This paper presents an analysis of the efficiency of two sawmilling processes: one intended for the dedicated production of parquet blanks and the other intended for the production of primary sawmilling products (planks), with parquet blanks obtained from coarse waste. A total of 12 beech (*Fagus sylvatica* L.) sawlogs were processed at a representative sawmill in North Macedonia, with six logs assigned to each production method. According to the presented data, it can be concluded that there is a noticeable difference in the quantitative yield between the two production methods. The yield percentage is higher with the traditional sawmilling strategy of producing planks and manufacturing parquet blanks from by-products (coarse waste). These favourable results are due to the fewer technological operations and the smaller number of cuts required for producing the blanks compared with the dedicated production of parquet blanks directly from the sawlogs.In addition, the dedicated production of parquet blanks generates a greater amount of waste, which decreases the economic efficiency of the sawmilling process. Furthermore, the generation of a larger amount of waste also reduces the sustainability of the production process. In conclusion, the dedicated production of small wooden elements is not efficient in terms of raw material utilization.

REFERENCES

1. Borz, S.; Oghnoum, M.; Marcu, M.; Lorincz, A.; Proto, A. (2021): *Performance of Small-Scale Sawmilling Operations: A Case Study on Time Consumption, Productivity and Main Ergonomics for a Manually Driven Bandsaw*. Forests 12 (6).
2. Fotiou, S.; Stamou, N. (2000): *Measuring the Efficiency of the sawmill industry. A frontier production function approach*. In: Proceedings of the International Symposium INFORMATION MANAGEMENT IN FOREST ENTERPRISES. Freising, Germany, April 6-8, 100-108.
3. Ištvanić, J.; Antonović, A.; Jaklić, M.; Pervan, D.; Vukman, K.; Matin, B.; Klarić, M. (2025): *Volume, qualitative and value lumber from linden logs (Tilia spp.).* In: Proceedings of the 7th International Scientific Conference ..Wood Technology & Product Design". Ohrid, North Macedonia, September 17-20, 2025, 86-99.
4. Rabadziski, B. (2019): *Sawmilling processing of wood*. Faculty of Design and Technologies of Furniture and Interior-Skopje.
5. Stamenkoska, A.; Zlateski, G.; Rabadziski, B.; Temelkova, A. (2025): *Yield comparison of beech (Fagus sylvatica L.) and fir/spruce (Abies alba Mill. / Picea abies L.) logs in the sawmill processing industry*. International Journal – Wood, Design & Technology 14 (1): pp. 18-28.
6. ***. MKC EN 1312:2010 Round and sawn timber – Determination of the batch volume of sawn timber
7. ***.MKC EN 1313-2:2010 Round and sawn timber – Permitted deviations and preferred sizes – Part 2: Hardwood sawn timber
8. ***.MKC EN 1316-1:2013 Hardwood round timber – Qualitative classification – Part 1: Oak and beech

Authors address:
Stamenkoska, A.*; Antovska, I.; Meloska, Ž.
Faculty of Design and Technologies of Furniture and Interior-Skopje, Ss. Cyril and Methodius University in Skopje, North Macedonia
*Corresponding author: stamenkoska@fdtme.ukim.edu.mk

FACTORS INFLUENCING FIRM RESPONSES IN WOOD PRODUCT MARKETS: THE ROLE OF BUSINESS AGILITY

Katarína Marcineková, Andrea Janáková Sujová

Abstract: The transition to the bioeconomy continuously increases pressure across all industries, especially in the woodworking industry. The issue of supply chain stability and constant changes in demand is coming to the forefront. The aim of the paper is to map the responses of enterprises to these fundamental changes and to identify the relationships between barriers, adopted measures and innovation opportunities during the COVID-19 crisis. The research was conducted on a sample of 243 Slovak enterprises. To identify relationships, chi-square test analysis and Cramér's V were used. Based on the results, enterprises facing a wider spectrum of barriers also implemented a broader range of organisational and financial measures, while the diversity of adopted measures was associated with a higher diversity of identified innovation opportunities. These findings suggest that agile organisational behaviour plays an important role in strengthening firms' resilience and long-term competitiveness.
Keywords: woodworking industry, business agility, flexibility, digitalization, competitiveness

1. INTRODUCTION

The COVID-19 pandemic placed significant pressure on the business environment by disrupting supply chains, the availability of input resources, and demand stability (Ivanov & Dolgui, 2021). As enterprises faced new barriers, organisational agility emerged as a key capability for rapid adaptation to changing conditions. At the same time, greater emphasis was placed on collaboration, business model adaptation, and the search for new ways to maintain competitiveness (Crick & Crick, 2020). Understanding the factors influencing firms' adaptive capabilities may support more effective managerial decision-making in future crises (Ivanov & Dolgui, 2021). Despite the growing body of research, the relationships between barriers, organisational and financial responses, and identified innovation opportunities remain insufficiently explored.

1.1. Dynamic enterprise environment

The dynamic business environment is characterised by a high degree of uncertainty and rapid changes in demand. Juergensen et al. (2020) found that European manufacturing SMEs simultaneously faced logistics disruptions, labour shortages, supply chain disruptions and declining demand, while the severity of these impacts varied according to firm characteristics and their position within the supply chain. Following the initial survival phase, enterprises increasingly focused on restoring competitiveness through innovation, internationalisation and new business partnerships. Similar findings were reported by Ratnasingam et al. (2020), who identified financial management and supply chain disruptions as the two areas most affected by the COVID-19 pandemic in furniture SMEs. Their results also highlighted the need to combine short-term liquidity measures with longer-term strategic changes aimed at strengthening firms' resilience to future external shocks. These findings indicate that firms'

adaptive capabilities are shaped by several interrelated factors, the importance of which varies across industries and external conditions.

1.2. Business Agility and Adaptive Capabilities in the Woodworking Industry

The importance of organisational agility and adaptive capabilities is particularly evident in the woodworking and furniture industries, which are highly dependent on supply chain stability, the availability of raw materials and changes in market demand. During the COVID-19 pandemic, the most significant challenges faced by enterprises operating in these industries included declining orders, supply chain disruptions, shortages of raw materials and deteriorating financial conditions (Ratnasingam et al., 2020). Teece (2018) argues that firms' competitive advantage is primarily based on their ability to continuously adapt organisational resources to changing environmental conditions through opportunity identification, decision-making and the transformation of internal business processes. Clauß et al. (2019) examined the relationship between strategic agility, business model innovation and firm performance. They found that strategic agility directly supports business model innovation, while its effect on firm performance is realised indirectly through the successful implementation of these innovations. Lokuge et al. (2019) identified digital readiness as one of the prerequisites for successful digital innovation. Their findings emphasise the importance of organisational, technological and managerial capabilities that enable firms to respond more effectively to changing environmental conditions. At the same time, the authors concluded that the implementation of innovations alone does not automatically improve firm performance, but depends on their successful market acceptance and the ability to create customer value (Clauß et al., 2019). Long-term competitiveness in the woodworking industry is conditioned by firms' ability to respond to uncertainty associated with raw material availability, changing market conditions and increasing sustainability requirements (Ma et al., 2025). It may therefore be assumed that organisational agility and adaptive capabilities represent important prerequisites for firms to operate successfully in a dynamic business environment.

2. MATERIALS AND METHODS

The research was conducted using a questionnaire survey aimed at identifying barriers, adopted measures, decision-making criteria and innovations related to managing the COVID-19 crisis in Slovak enterprises. Data collection was carried out between December 2023 and May 2024. Only questionnaires containing complete responses to all analysed questions were included in the statistical analysis, resulting in a final sample of 243 enterprises. The sample comprised enterprises operating across various industries, with particular attention paid to firms from the woodworking and furniture industries, which formed a subsample for additional descriptive analysis. The basic characteristics of the sample are presented in Table 1.

Table 1. Basic characteristics of the study sample

Characteristic	Category	n	Share (%)
Firm size	Micro (0–9 employees)	109	44.9
	Small (10–49 employees)	70	28.8
	Medium-sized (50–249 employees)	38	15.6
	Large (250 or more employees)	26	10.7
Business activity	Manufacturing	122	50.2

	Services	121	49.8
Industry	Woodworking and furniture industry	34	14.0
	Other industries	209	86.0
ROE	Below 2%	63	25.9
	2–7%	119	49.0
	Above 7%	61	25.1

2.1. Research Methods

The questionnaire allowed respondents to select multiple responses simultaneously. The responses were grouped into related categories and transformed into binary variables, which were subsequently used to construct four composite indicators (BDS, RDS, FRDS and IDS) (Table 2). Each indicator represented the sum of the corresponding binary variables, with higher values indicating a greater diversity of identified barriers, adopted measures or innovation opportunities.

Table 2. Composite indicators

Indicator	Number of categories	Range	Categories
BDS	6	0–6	Resource, Human, Organisational, Financial & Market, Information, Governmental
RDS	4	0–4	Organisational, Strategic & Market, Cost Reduction, Restrictive
FRDS	5	0–5	Liquidity, Cost, Investment, Transformation, Government Support
IDS	6	0–6	Market, Product, Process, Digital, Adaptive, Social

Relationships between the categorised variables were analysed using Pearson's chi-square test of independence. The strength of the identified relationships was assessed using Cramér's V. The composite indicators were further analysed using descriptive statistics.

3. RESULTS AND DISCUSSION

The analysis (Table 3) showed that enterprises generally faced multiple types of barriers simultaneously during the COVID-19 crisis. The mean value of the BDS indicator was 1.97, indicating that most enterprises were exposed to more than one group of barriers. The mean value of the RDS indicator was 1.52, while the FRDS indicator reached a mean value of 1.98. These results indicate that enterprises responded to the consequences of the COVID-19 crisis by adopting a combination of organisational, strategic and financial measures, with the diversity of adopted measures generally exceeding a single isolated response.

Table 3. Descriptive statistics of the composite indicators

Indicator	N	Min	Max	Mean	Median	Standard deviation
BDS	243	0	5	1.97	2	1.09
RDS	242	0	4	1.52	1	0.92
FRDS	241	0	5	1.98	2	1.09
IDS	240	0	5	1.35	1	1.12

3.1. Relationships among barriers, responses and innovation

To identify the relationships between the diversity of barriers, organisational and financial responses, identified innovation opportunities and firms' financial performance, six research hypotheses were formulated. The hypotheses were tested using Pearson's chi-square test of independence, while the strength of the identified relationships was assessed using Cramér's V. The results of hypothesis testing are presented in Table 4.

Table 4. Results of hypothesis testing

Hypothesis	Variables	χ^2	df	p	Cramér's V
H1	BDS × RDS	59.264	4	< 0.001	0.35
H2	BDS × FRDS	55.254	4	< 0.001	0.339
H3	BDS × IDS	23.798	4	< 0.001	0.223
H4	RDS × IDS	37.418	4	< 0.001	0.28
H5	FRDS × IDS	32.632	4	< 0.001	0.261
H6	ROE × IDS	2.486	4	0.647	0.072

Table 4 presents the results of Pearson's chi-square test. Statistically significant relationships were confirmed between all analysed indicators, except for the relationship between return on equity and the diversity of identified innovation opportunities. It may therefore be concluded that the identification of innovation opportunities alone does not necessarily lead to higher financial performance, as its effect also depends on successful implementation (Crossan & Apaydin, 2010) and other business-related factors, such as firm size, industry, business environment and the type of innovation (Rosenbusch et al., 2011). The highest value of Cramér's V was identified between the diversity of barriers and the diversity of organisational responses (V = 0.350). A statistically significant relationship was also confirmed between the diversity of identified barriers and the diversity of financial responses (V = 0.339). Teece (2018) argues that firms achieve competitive advantage not only through their resources, but primarily through their ability to continuously adapt those resources to changing environmental conditions. The relationships between the diversity of organisational responses and identified innovation opportunities (V = 0.280), the diversity of financial responses and identified innovation opportunities (V = 0.261), and the diversity of barriers and identified innovation opportunities (V = 0.223) were weak. It may therefore be assumed that the identification of innovation opportunities was influenced by additional factors. Similar conclusions regarding the importance of organisational agility, digital readiness and managerial capabilities for identifying and exploiting new opportunities were reported by Teece (2018), Clauß et al. (2019) and Lokuge et al. (2019).

3.2. Woodworking industry

Particular attention was paid to enterprises operating in the woodworking and furniture industries. Their results were compared with those of the remaining enterprises included in the study sample using the basic descriptive statistics of the composite indicators BDS, RDS, FRDS and IDS.

Table 5. Comparison of composite indicators by industry

Statistic	Woodworking industry (N = 19)	Furniture industry (N = 13)	Other industries*
BDS – Mean (SD)	1.63 (0.60)	2.85 (0.90)	1.94 (1.12)
BDS – Median	2	3	2
RDS – Mean (SD)	1.58 (0.77)	1.62 (1.04)	1.51 (0.92)
RDS – Median	2	1	2
FRDS – Mean (SD)	2.11 (0.74)	2.54 (1.13)	1.93 (1.11)
FRDS – Median	2	3	2
IDS – Mean (SD)	1.17 (1.29)	1.69 (0.85)	1.34 (1.12)
IDS – Median	1	2	1

* Note: Sample size varies across indicators because of missing responses.

The results presented in Table 5 indicate differences among the analysed industries. The highest values of both the BDS and FRDS indicators were recorded for enterprises operating in the furniture industry, suggesting that they faced a broader range of barriers during the COVID-19 crisis while simultaneously adopting a broader range of financial responses. This trend is also reflected in the median values of both indicators, which reached 3, compared with a median of 2 in the remaining groups of enterprises. Greater sensitivity of the furniture industry to changes in demand, supply chain disruptions and shifts in consumer behaviour has also been reported in previous studies (Ratnasingam et al., 2020, UNECE, FAO, 2022). In contrast, enterprises operating in the woodworking industry recorded the lowest mean value of the BDS indicator and identified the lowest number of innovation opportunities (IDS). The RDS indicator reached comparable mean values across all three groups of enterprises, although the median indicated a slightly lower diversity of organisational responses in furniture enterprises. Given the small number of enterprises included in the woodworking and, in particular, the furniture industry, these results should be interpreted only as a descriptive comparison and do not allow for general conclusions.

4. CONCLUSION

The aim of the paper was to analyse the relationships between barriers, organisational and financial responses, and identified innovation opportunities during the COVID-19 crisis. The results confirmed that enterprises facing a broader range of barriers generally adopted a broader range of organisational and financial responses, while greater diversity of adopted responses was also associated with greater diversity of identified innovation opportunities. In contrast, no statistically significant association was found between identified innovation opportunities and financial performance measured by return on equity (ROE). The descriptive comparison also indicated differences between enterprises operating in the woodworking and furniture industries and those from the remaining analysed industries.

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REFERENCES (alphabetical order)

1. Clauß, T.; Abebe, M.; Tangpong, C.; Hock-Döpgen, M. (2019): Strategic Agility, Business Model Innovation, and Firm Performance: An Empirical Investigation. IEEE Transactions on Engineering Management. pp. 1–18.
2. Crick, J. M.; Crick, D. (2020): Coopetition and COVID-19: Collaborative Business-to-Business Marketing Strategies in a Pandemic Crisis. Industrial Marketing Management 88: pp. 206–213.
3. Crossan, M. M.; Apaydin, M. (2010): A Multi-Dimensional Framework of Organizational Innovation: A Systematic Review of the Literature. Journal of Management Studies 47 (6): pp. 1154–1191.
4. Ivanov, D.; Dolgui, A. (2021): OR-methods for Coping with the Ripple Effect in Supply Chains during COVID-19 Pandemic: Managerial Insights and Research Implications. International Journal of Production Economics 232: 107921.
5. Juergensen, J.; Guimón, J.; Narula, R. (2020): European SMEs amidst the COVID-19 Crisis: Assessing Impact and Policy Responses. Journal of Industrial and Business Economics 47 (3): pp. 499–510.
6. Lokuge, S.; Sedera, D.; Grover, V.; Dongming, X. (2019): Organizational Readiness for Digital Innovation: Development and Empirical Calibration of a Construct. Information & Management 56 (3): pp. 445–461.
7. Ma, C.; Zhang, L.; Gao, X.; Liu, C. (2025): Modelling and Evaluating Wood Supply Chain Resilience Factors Based on System Dynamics. Scientific Reports 15: 16207.
8. Ratnasingam, J.; Khoo, A.; Jegathesan, N.; Wei, L.; Latib, H.; Thanasegaran, G.; Liat, L.; Yi, L.; Othman, K.; Amir, M. (2020): How are Small and Medium Enterprises in Malaysia's Furniture Industry Coping with COVID-19 Pandemic? Early Evidences from a Survey and Recommendations for Policymakers. BioResources 15 (3): pp. 5951–5964.
9. Rosenbusch, N.; Brinckmann, J.; Bausch, A. (2011): Is Innovation Always Beneficial? A Meta-analysis of the Relationship between Innovation and Performance in SMEs. Journal of Business Venturing 26 (4): pp. 441–457.
10. Teece, D. J. (2018): Business Models and Dynamic Capabilities. Long Range Planning 51 (1): pp. 40–49.
11. ***: UNECE; FAO (2022): Forest Products Annual Market Review 2021–2022. United Nations Economic Commission for Europe (UNECE) and Food and Agriculture Organization of the United Nations (FAO). URL: https://unece.org/forests/publications/forest-products-annual-market-review-2021-2022

Authors address:
Marcineková, K.[1*]; Janáková Sujová, A[1];
[1] Department of Economics, Management and Business, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia
[*]Corresponding author: XmarcinekovaK@tuzvo.sk

INNOVATION EFFICIENCY IN THE EUROPEAN WOOD-PROCESSING AND PRODUCTION OF FURNITURE SECTORS: A DEA APPROACH WITH UNDESIRABLE OUTPUTS

Nikolay Neykov, Vesela Dimchova, Radostina Popova-Terziyska

Abstract: This study evaluates the efficiency of innovation activity in the European forestry and wood-processing sector by applying a radial directional distance function (DDF) within a Data Envelopment Analysis (DEA) framework. The analysis is based on Community Innovation Survey (CIS) data for the periods 2018, 2020, and 2022 and considers European Union member states as decision-making units. The proposed model distinguishes between innovation inputs, desirable outputs, and undesirable outputs. Innovation efforts are captured through the share of enterprises engaged in innovation activities, while desirable outputs reflect successfully implemented product and process innovations. Importantly, the study introduces the share of enterprises that undertake innovation activities without achieving innovation outcomes as an undesirable output, capturing inefficiencies in the innovation process. The results reveal significant disparities in innovation efficiency across EU countries, indicating that higher levels of innovation activity do not necessarily translate into better innovation performance. The study contributes to the literature by extending DEA applications to innovation analysis in low- and medium-tech industries and by explicitly incorporating unsuccessful innovation attempts as undesirable outputs. The findings provide important policy implications, emphasizing the need to improve the effectiveness of innovation support mechanisms rather than merely increasing innovation activity levels.
Keywords: innovation efficiency; Data Envelopment Analysis (DEA); Directional Distance Function (DDF)

1. INTRODUCTION

Innovation management has become one of the key determinants of industrial competitiveness, productivity and long-term economic development. Within the European Union, innovation is recognized as an essential driver of industrial resilience, sustainable growth and the green transition. Nevertheless, the existence of a large enterprise base or a high level of innovation activity does not necessarily result in successful innovation outcomes, making the assessment of innovation efficiency increasingly important (Durana et al., 2020; Wang et al., 2022). The wood-processing (C16) and furniture manufacturing (C31) industries constitute an important component of the European bioeconomy, generating employment, regional development and value added while supporting sustainable forest-based value chains (Trigkas et al., 2012). At the same time, these sectors face increasing challenges requiring enterprises to improve not only their innovation capacity but also the effectiveness of innovation processes (Cervený et al., 2022; Sedliačiková et al., 2026). Data Envelopment Analysis (DEA) has become one of the most widely applied non-parametric methods for evaluating innovation efficiency because it simultaneously considers multiple inputs and outputs without requiring an explicit production function. Previous studies have successfully applied DEA to assess technological innovation, innovation management and R&D efficiency at regional, industrial and

national levels (Cruz-Cázares et al., 2013; Durana et al., 2020; Wang et al., 2022). However, most studies focus on successful innovation outcomes, while enterprises that abandon or suspend innovation activities are usually ignored, despite representing an important source of inefficiency within innovation systems. To address this research gap, the present study applies a radial Directional Distance Function (DDF) within the DEA framework. Unlike conventional innovation efficiency models, the proposed approach considers the total number of enterprises as the production input, enterprises with completed innovation activities as the desirable output, and enterprises with abandoned or suspended innovation activities as the undesirable output. Consequently, innovation efficiency is evaluated according to the ability of countries to transform their enterprise base into completed innovation activities while simultaneously minimizing unsuccessful innovation processes (Chambers et al., 1996; Färe & Grosskopf, 2004). Using Community Innovation Survey (CIS) data for 2018, 2020 and 2022, the study evaluates innovation efficiency in the European wood-processing and furniture manufacturing sectors. By explicitly incorporating undesirable innovation outputs, the proposed framework extends previous DEA applications in innovation research and provides a more comprehensive assessment of innovation performance, offering evidence that may support the design of more effective innovation policies.

2. MATERIALS AND METHODS

The efficiency of innovation activities was evaluated using a radial Directional Distance Function (DDF) within the Data Envelopment Analysis (DEA) framework. The DDF approach enables the simultaneous expansion of desirable outputs and contraction of undesirable outputs, making it particularly suitable for assessing innovation systems where unsuccessful innovation efforts represent inefficiencies (Chambers et al., 1996; Färe & Grosskopf, 2004). Using DEA framework is well established in the scientific papers when estimate innovations' efficiency of technological (Cruz-Cázares et al., resource; Wang et al., 2022 and Wang S. et al., 2024) and managerial (Wang et al., 2022, Liu et al., 2024) development of particular economic system. Implementation of the DEA DDF methodology is commonly used in innovation focused research. Li et al. (2023) estimated the innovation activity efficiency of the cultural industry in China's selected regions. In similar way Li et al. (2024) estimated through DDF the R&D efficiency of China regions. European Union member states were considered as Decision-Making Units (DMUs). The analysis in the current study is based on Community Innovation Survey (CIS) data for 2018, 2020, and 2022. The model includes one innovation input (number of enterprises engaged in innovation activities), one desirable output (number of enterprises introducing selected by the Eurostat innovations), and one undesirable output (number of enterprises with abandoned or suspended innovations). Innovation efficiency was estimated under the assumption that efficient countries have bigger number of successfully innovated enterprises while simultaneously reduce number of enterprises with unsuccessful innovations. The empirical analysis was made with Stata 17. The analysis utilized data from the Eurostat Community Innovation Survey (CIS), covering three consecutive survey waves: CIS 2018 (reference period 2016–2018), CIS 2020 (reference period 2018–2020), and CIS 2022 (reference period 2020–2022). Two Eurostat datasets were used. The first, Innovation-active enterprises by type of innovation activities (inn_cis11_inact, inn_cis12_inact, and inn_cis13_inact. The second, Enterprises, employed persons and turnover by type of enterprise, NACE Rev. 2 activity and size class (inn_cis11_bas, inn_cis12_bas, and inn_cis13_bas), was used for the input variable in the DDF model. The analysis covers the

available European countries with harmonized CIS data, ensuring methodological comparability across survey waves. The number of units are EU21 countries with available data for the inputs and outputs and Norway as additional DMU due to only available in the database country with full set of information.

3. RESULTS AND DISCUSSION

The results reveal substantial differences in innovation performance across the European wood processing sector (C16). Germany remained the clear leader throughout the observation period, increasing the number of enterprises with completed innovation activities from 1,128 in 2018 to 3,668 in 2022, followed by Italy (1,036 to 1,952), Poland (269 to 631), Spain (251 to 401) and Czechia (191 to 335). In contrast, smaller innovation systems such as Cyprus, Hungary, Bulgaria and Romania recorded considerably lower numbers of completed innovation activities, although Bulgaria showed a gradual increase from 89 to 116 enterprises while reducing the number of abandoned or suspended innovation activities from 9 in 2018 to zero in 2022. Overall, the results suggest that the leading European wood processing industries not only expanded the scale of completed innovation activities but also maintained relatively moderate levels of unsuccessful innovation projects, whereas smaller economies exhibited slower innovation dynamics and greater variability, revealing the differences in the capacity to complete innovation processes and ventures. Manufacture of furniture (C31) also revealed increase in completed innovation activities between the 2018 and 2022 surveys, although with greater variation across countries than observed in the wood-processing. Germany and Italy remained the innovation leaders, increasing the number of enterprises with completed innovation activities from 1,524 to 3,184 and from 1,846 to 3,374. Among the smaller innovation systems, Bulgaria improved its innovation performance from 154 to 197 enterprises with completed innovation activities while reducing abandoned or suspended innovation activities from 138 in 2018 to zero in 2022, whereas Romania experienced a marked decline in completed innovation activities from 210 to 61 enterprises. Overall, the results indicate stronger innovation dynamics in the leading furniture-producing countries, while the considerable heterogeneity observed among smaller economies suggests substantial differences in their capacity to successfully complete innovation projects. The DDF results are presented in the Table 1.

Table 1. DDF results for the two analyzed sectors

	NACE Rev. 2: C16			NACE Rev. 2: C31		
Country	2016-2018	2018-2020	2020-2022	2016-2018	2018-2020	2020-2022
Belgium	0.96	0.97	0.56	0.00	0.00	0.27
Bulgaria	0.84	0.15	0.00	0.54	0.00	0.00
Croatia	0.00	0.00	0.21	0.85	0.54	0.20
Cyprus	0.96	0.43	0.14	0.24	0.00	0.00
Czechia	0.53	0.60	0.53	0.10	0.29	0.51
Denmark	0.92	0.06	0.00	0.87	0.00	0.00
Finland	0.90	0.07	0.39	0.75	0.36	0.00
France	0.00	0.00	0.96	0.17	0.31	0.94
Germany	0.00	0.00	0.00	0.02	0.00	0.00

Greece	0.94	0.36	0.35	0.78	0.25	0.34
Hungary	0.00	0.36	0.60	0.00	0.63	0.45
Ireland	0.94	0.63	0.64			
Italy	0.00	0.01	0.00	0.00	0.00	0.00
Latvia	0.76	0.22	0.72	0.62	0.60	0.23
Luxembourg	0.98	0.00	0.00			
Norway	0.98	0.00	0.35	0.37	0.52	0.18
Poland	0.28	0.26	0.00	0.27	0.01	0.21
Portugal	0.77	0.23	0.18	0.32	0.26	0.00
Romania	0.00	0.00	0.82	0.32	0.00	0.73
Slovakia	0.88	0.00	0.72	0.38	0.53	0.00
Spain	0.14	0.14	0.25	0.21	0.04	0.04
Sweden	0.00	0.00	0.00	0.00	0.03	0.00
Efficient	27.27%	36.36%	31.82%	20.00%	35.00%	45.00%

Table 1 presents the radial Directional Distance Function (DDF) efficiency scores for the wood manufacturing (NACE C16) and furniture manufacturing (NACE C31) sectors. A score of zero indicates that a country lies on the efficiency frontier, while higher values indicate greater potential to simultaneously increase completed innovation activities and reduce abandoned or suspended innovation activities relative to the existing enterprise base. The analysis was performed under the assumption of variable returns to scale (VRS), allowing countries of different sizes to be compared according to their innovation efficiency rather than their absolute innovation capacity. For the wood manufacturing sector (C16), the proportion of efficient countries increased from 27.27% during 2016–2018 to 36.36% during 2018–2020 before slightly decreasing to 31.82% in 2020–2022. Germany and Italy consistently remained on the efficiency frontier together with considerably smaller economies such as Sweden and, in the final period, Bulgaria. The furniture manufacturing sector (C31) exhibits an even stronger improvement over time, with the proportion of efficient countries increasing from 20.00% to 35.00% and 45.00%, respectively. Germany and Italy again remained on the efficiency frontier despite their substantially larger innovation systems, while Bulgaria, Denmark, Finland, Portugal and Sweden also achieved full efficiency in the final survey wave. At the same time, countries such as Czechia, Hungary, Greece and Belgium continued to display relatively large efficiency gaps, indicating that further improvements could be achieved by increasing completed innovation activities and reducing unsuccessful innovation projects without necessarily expanding the enterprise base. It should be noted that the number of analysed countries differs between the two sectors because only countries with complete observations for all variables were included in the respective models. Therefore, the reported shares of efficient countries are directly comparable only within each sector. Overall, the results demonstrate that innovation efficiency is determined primarily by the ability of national innovation systems to utilize their existing enterprise base effectively rather than by the absolute scale of innovation activity.

4. CONCLUSSION

The study confirms that innovation efficiency in the European wood-processing and furniture sectors depends not only on the scale of innovation activity, but on the ability to transform the existing enterprise base into completed innovation outcomes while minimizing abandoned or suspended activities. The radial DDF results show that smaller countries can achieve the efficiency frontier together with larger innovation leaders when variable returns to scale are considered. The findings support the need for innovation policies focused on improving the effectiveness of innovation processes rather than only increasing the number of innovation activities.

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REFERENCES (alphabetical order)

1. Chambers, R. G.; Chung, Y.; Färe, R. (1996): Benefit and distance functions. *Journal of Economic Theory* 70 (2): pp. 407–419. https://doi.org/10.1006/jeth.1996.0096

1. Červený, L.; Sloup, R.; Červená, T. (2022): The Potential of Smart Factories and Innovative Industry 4.0 Technologies—A Case Study of Different-Sized Companies in the Furniture Industry in Central Europe. *Forests* 13 (12): 2171. https://doi.org/10.3390/f13122171
2. Cruz-Cázares, C.; Bayona-Sáez, C.; García-Marco, T. (2013): You can't manage right what you can't measure well: Technological innovation efficiency. *Research Policy* 42 (6–7): pp. 1239–1250. https://doi.org/10.1016/j.respol.2013.03.012
3. Durana, P.; Zauskova, A.; Vagner, L.; Zadnanova, S. (2020): Earnings Drivers of Slovak Manufacturers: Efficiency Assessment of Innovation Management. *Applied Sciences* 10 (12): 4251. https://doi.org/10.3390/app10124251
4. European Commission, Eurostat (n.d.): *Enterprises, employed persons and turnover by type of enterprise, NACE Rev. 2 activity and size class* (Dataset **inn_cis11_bas**). URL: https://ec.europa.eu/eurostat/databrowser/view/inn_cis11_bas/default/table?lang=en
5. European Commission, Eurostat (n.d.): *Enterprises, employed persons and turnover by type of enterprise, NACE Rev. 2 activity and size class* (Dataset **inn_cis12_bas**). URL: https://ec.europa.eu/eurostat/databrowser/view/inn_cis12_bas/default/table?lang=en
6. European Commission, Eurostat (n.d.): *Enterprises, employed persons and turnover by innovation status, NACE Rev. 2 activity and size class* (Dataset **inn_cis13_bas**). URL: https://ec.europa.eu/eurostat/databrowser/view/inn_cis13_bas/default/table?lang=en

7. European Commission, Eurostat (n.d.): *Innovation-active enterprises by type of innovation activities* (Dataset **inn_cis11_inact**). URL: https://ec.europa.eu/eurostat/databrowser/view/inn_cis11_inact/default/table?lang=en
8. European Commission, Eurostat (n.d.): *Innovation-active enterprises by type of innovation activities* (Dataset **inn_cis12_inact**). URL: https://ec.europa.eu/eurostat/databrowser/view/inn_cis12_inact/default/table?lang=en
9. European Commission, Eurostat (n.d.): *Innovation-active enterprises by type of innovation activities* (Dataset **inn_cis13_inact**). URL: https://ec.europa.eu/eurostat/databrowser/view/inn_cis13_inact/default/table?lang=en
10. Färe, R.; Grosskopf, S. (2004): *New Directions: Efficiency and Productivity*. Boston, MA: Kluwer Academic Publishers.
11. Li, X.; Hung, H. W.; Lin, I. F.; Lu, C. C. (2024): Application of parallel dynamic two-stage directional distance function for R&D efficiency evaluation in China. *Decision Support Systems* 177: 114081. https://doi.org/10.1016/j.dss.2023.114081
12. Li, X.; Zhang, J.; Chen, X.; Lu, C. C. (2023): Evaluation of innovation efficiency in China's cultural industry: A meta-frontier with non-radial directional distance function approach. *Sustainable Development* 31 (5): pp. 3709–3720. https://doi.org/10.1002/sd.2605
13. Liu, Y.; Alnafrah, I.; Zhou, Y. (2024): A systemic efficiency measurement of resource management and sustainable practices: A network bias-corrected DEA assessment of OECD countries. *Resources Policy* 90: 104771. https://doi.org/10.1016/j.resourpol.2024.104771
14. Sedliačiková, M.; Kostúr, M.; Osvaldová, M. (2026): Family Businesses in the Wood-Processing and Furniture Industry and Their Role in Sustainable Forest-Based Development. *Forests* 17 (5): 589. https://doi.org/10.3390/f17050589
15. Trigkas, M.; Papadopoulos, I.; Karagouni, G. (2012): Economic efficiency of wood and furniture innovation system. *European Journal of Innovation Management* 15 (2): pp. 150–176. https://doi.org/10.1108/14601061211220973
16. Wang, Q.; Chen, Y.; Guan, H.; Lyulyov, O.; Pimonenko, T. (2022): Technological innovation efficiency in China: Dynamic evaluation and driving factors. *Sustainability* 14 (14): 8321. https://doi.org/10.3390/su14148321
17. Wang, S.; Xing, L.; Chen, X.; Song, M. (2024): Evaluating and enhancing natural resource asset management efficiency in China: A data envelopment analysis study. *Resources Policy* 92: 105000. https://doi.org/10.1016/j.resourpol.2024.105000

Authors address:
Neykov, N[1]; Dimchova, V[2]; Popova-Terziyska, R[3]
[1,3] Alternative Tourism, Ecology and landscape Architecture, University of Forestry, Sofia, Bulgaria
[2] Forest Management, Forestry, University of Forestry, Sofia, Bulgaria
*Corresponding author: nkneykov@gmail.com

INTEGRATING GREEN ECONOMY ASPECTS INTO PROJECT MANAGEMENT TEACHING

Erika Loučanová, Martina Nosáľová, Miriam Olšiaková

Abstract: The paper deals with the transformation of traditional project management in the context of the emerging green economy. The aim of the paper is to present a shift from the conventional "iron triangle" (time, budget, scope) to a modern methodological framework based on the 5P sustainability standards in project management. In the conditions of the forestry and wood processing complex, this integration is of paramount strategic importance, as the industry directly works with renewable natural resources. The application of the 5P standards in this sector involves linking project management procedures with the principles of the circular economy. The transition from short-term savings to long-term economic sustainability takes into account ecological externalities. Therefore, to ensure the competitiveness and sustainability of the industry in the 21st century, it is necessary to educate future project managers in the field of natural resources, reflecting these the paradigm shifts.
Keywords: Project management, Green economy, Iron Triangle, 5P standards, Forestry and timber complex, Sustainability, Circular economy.

1. INTRODUCTION

Project management is considered one of the successful and widespread methods of managing large-scale and demanding actions, requiring the combination of resources and forces of several work teams and people of various specializations. Project management is a method used to plan and implement complex, especially one-time actions, which are characterized by a unique course, a set start and end date, tasks and goals, participation of several or more people, working groups, complexity.

The most important element of project management is a project, which represents a controlled process, has its beginning and end, as well as precise rules of management and regulation. Projects are very diverse. A project can be the development of a new product or service, but also the implementation of changes in the organization of a company or management style, and others. Projects can be classified according to several criteria, e.g. content, subject, scope, risk, complexity and many others. The definitions show the main characteristics by which a project is characterized and defined. Authors (Wysocki, 2009; Mariáš and Čimo, 1998; Sabol and Macej, 2001; Svozilová, 2006) as well as organizations (Loučanová and Kalamárová, 2015) agree on the main characteristics of a project, namely that the project is unique, goal-oriented, limited by time and resources. Mariáš and Čimo (1998), Sabol and Macej (2001) add to the above characteristics that the project is characterized by risk and uncertainty, involvement and efforts of experts from different fields. Loučanová and Kalamárová (2015) indicates the progressiveness of project processing as a feature of projects, which results from uniqueness and temporariness. Wysocki (2009) also mentions characteristics such as sequence and connection of activities, complexity and specification of projects.

According to Kadukova (2003), project management can be defined as “the application of knowledge, experience, tools and techniques to project activities in order to satisfy the needs of the recipient and the expectations of the project”. The set of activities that are necessary to realize the project objectives is often called the project framework. It forms one of the three basic elements that it is ideal to keep in balance (Figure 1).

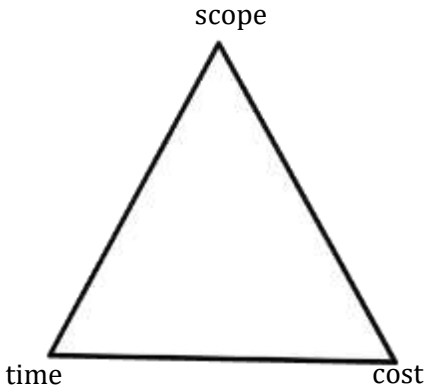

Figure 1. Basic elements for maintaining project balance, the so-called "iron triangle"

Resources are needed to implement each project, but they create costs and are therefore dependent on the budget. The work schedule determines the time and sequence of individual steps, as well as the overall duration of the project, while the timing and sequence of individual steps can be modified within the project according to needs. All these elements are interconnected. For example, if a specific task is not implemented within the planned period, either additional personnel resources need to be added, or another task cannot be implemented. This will, of course, result in a narrowing of the project scope (Kaduková, 2003).

Project management is considered a set of activities consisting of planning, organizing, managing and controlling company resources with a relatively short-term goal that was set for the implementation of specific goals and objectives

Project management is the application of knowledge, skills, tools and technologies to project activities so that they meet customer requirements (Svozilová, 2006; Loučanová, Kalamárová, 2015).

The Iron Triangle is a model for project management. The three vertices of the triangle are cost, time, and scope. Scope is often replaced by quality in the literature. Some view quality as the result of the other three vertices of the Iron Triangle (Pollack et al, 2018; Rudder and Main, 2023). Therefore, project managers may make trade-offs between these three factors to achieve sufficient quality of the project output - the product, or its sub-outputs, figure 2 - Tetrahedron. The triangle is called “iron” because the factors determine hard and tightly integrated project constraints, any change in which will affect the entire project, or the other vertices of the Iron Triangle (Wright and Lawlor-Wright, 2019; Bronte-Stewart, 2015).

Modern approaches to project management incorporate sustainability principles into the iron triangle. This approach represents a star model that includes economic, environmental, time, quality and social aspects, figure 2 - pentahedron (Devopedia, 2023; Vahidi and Greenwood. 2009).

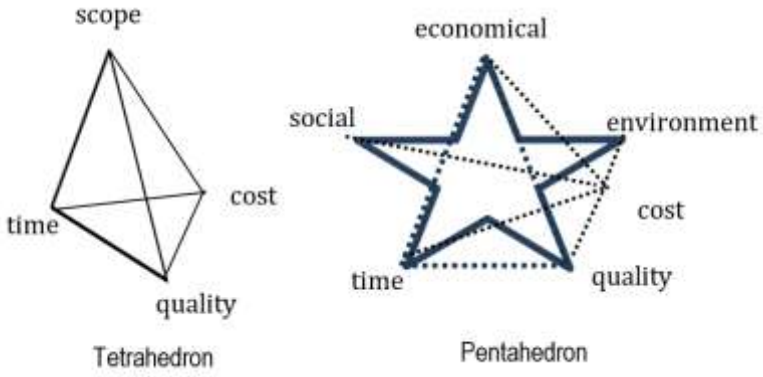

Figure 2. Tetrahedron and Star model - pentahedron

When agile methodologies began to be introduced in project management from the beginning of the 21st century, it was found that the Iron Triangle had its limitations. Therefore, many variations began to be proposed in the literature to suit modern project management practices (Highsmith, 2023). Project constraints began to be discussed, which needed to be incorporated into the original Iron Triangle. The Iron Triangle therefore also began to be called the Triple Constraint Model (Pollack et al, 2018; Dovepedia, 2023). Triple constraints determine the project deadline, the allocated budget/resources and what features the product should contain - the framework (Pollack et al, 2018; Devopedia, 2023; Campbell, 2026). These constraints are captured by PMI's six-point star model, adding to the traditional triple constraints of risk, schedule, and resources, figure 3 - hexahedron (Devopedia, 2023; Vahidi and Greenwood. 2009).

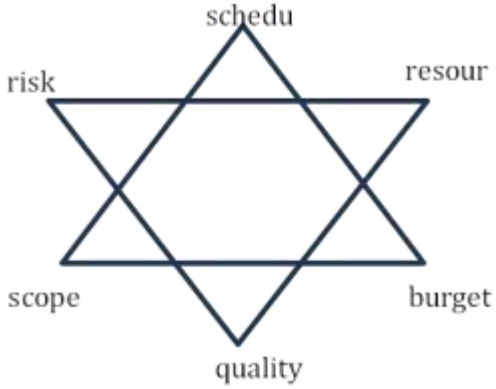

Figure 3. Hexahedron

2. INTEGRATING GREEN ECONOMY ASPECTS INTO PROJECT MANAGEMENT EDUCATION

The traditional concept of project management, which for decades was defined by the so-called "Iron Triangle" (time, budget and scope), is currently undergoing a fundamental transformation. In the era of the climate crisis and pressure to decarbonize industry, a project

manager can no longer be evaluated solely on the basis of timely delivery and financial efficiency. Projects are becoming a key tool for implementing corporate sustainability strategies.

The education of future project managers must therefore reflect this paradigm shift and integrate the principles of the green economy directly into the work methodology.

For the successful integration of the green economy into project management, it is essential to expand traditional management competencies with the so-called 5P standards:

1. Planet – From measurement to minimization – Environmental dimension of ESG

Education must lead students to master the tools for measuring carbon footprint. The project manager must also think about the impacts of the project from the perspective of carbon footprint, assess the entire life cycle of the delivered project outputs – LCA analyses. Ultimately, it must mean real optimization of logistics, selection of materials and energy intensity of individual project activities.

2. People – Social dimension of ESG

Sustainability is not only about the environment, but also about the impact of projects on communities and employees. The green economy requires that projects respect human rights throughout the supply chain and support an inclusive environment. The project manager becomes a mediator between the interests of investors and the needs of affected parties - stakeholders.

3. Process impact – Lean and circularity – Governance dimension ESG

Efficient processes are the basis of a green economy, and therefore, from a project management perspective, the connection of lean management with the principles of the circular economy allows project management to manage activities at each stage of the project life cycle in such a way as to eliminate negative impacts, whether economic, social or environmental. Teaching should emphasize agile approaches that enable rapid adaptation to environmental requirements.

4. Profit – Converting costs into value – Economic dimension

The green economy in projects changes the perception of costs. Investment in energy-efficient technologies or circular solutions may have higher initial costs (CAPEX), but significantly lower operating costs (OPEX). Students must learn to work with a modified business plan that also includes environmental externalities.

5. Product impact

Each project should be assessed according to how it contributes to the fulfillment of the organization's sustainability strategy. The project manager must be able to defend why we are doing the project not only from a financial but also from a sustainability perspective. A project without a clear environmental or social purpose risks losing credibility (so-called greenwashing) (Global, 2019; Johan and Turan, 2016).

This approach helps project managers to comprehensively grasp the impact of their activities not only on business, but also on society as a whole.

3. APPLICATION OF THE PROJECT TRIANGLE AND 5P STANDARDS IN THE FORESTRY AND TIMBER COMPLEX

The forestry and timber complex represents a specific environment in which natural processes intersect with industrial production, which places increased demands on effective project management. The application of the principles of the iron triangle of project

management (time, cost, scope) allows for systematic optimization of planning and implementation of activities in this sector.

In forestry conditions, the dimension of time is determined by the biological cycles of tree growth and the seasonality of logging. Costs are influenced not only by technological inputs and labor, but also by environmental regulations and transport accessibility. The scope of the project includes the entire chain from forest cultivation, through logging, to wood processing and distribution of final products. Balancing these three parameters is key to achieving both economic and ecological sustainability.

By supplementing this perspective with the concept of 5P standards, a more comprehensive view of project management is achieved:

- Planet - project – individual forestry and woodworking activities can be understood as projects with clearly defined goals, schedules and resources, which are directly related to the natural resources of the planet and therefore it is important to take this fact into account.
- People – the qualification of forestry and woodworking workers, their safety and professional preparation are essential for the effective implementation of processes.
- Processes and governance – include technological procedures for harvesting, handling and processing wood, while their optimization leads to a reduction in losses and environmental impacts.
- Profit – measured by economic indicators, productivity, but also environmental and social aspects.
- Product – the result is various forms of wood products, the quality of which depends on the correct management of the previous phases.

By integrating the Iron Triangle and the 5P standards, better coordination between the individual links of the forest-timber complex value chain can be achieved. This approach supports not only the efficiency and competitiveness of the sector, but also its long-term sustainability in the context of environmental challenges.

CONCLUSION

Integrating the green economy into project management education is no longer an optional add-on, but a prerequisite for the competitiveness of organizations in the 21st century. The transition from short-term savings to long-term sustainability, especially in sectors such as the forestry and timber complex, will prepare a new generation of leaders capable of creating lasting positive benefits for society and the planet. A new look at the basic elements for maintaining project balance and using the 5P standards within management practices will prepare a new generation of leaders who understand that the success of a project is measured not only by economic indicators and meeting deadlines, but also by its lasting positive benefits for the world, nature, the space in which they do business and the entire society.

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REFERENCES

1. Bronte-Stewart, M. (2015): Beyond the Iron Triangle: Evaluating Aspects of Success and Failure using a Project Status Model. In: *Computing and Infor. Sys. J.* 19 (2): pp. 19–36.
2. Johan, K.; Turan, F. M. (2016): Industrial training approach using GPM P5 Standard for Sustainability in Project Management: a framework for sustainability competencies in the 21st century. In: *IOP Conference Series: Materials Science and Engineering* 160 (1): p. 012075. IOP Publishing.
3. Kaduková, E. (2003): *Projektový manažment v kocke*. Metodicko-pedagogické centrum v Prešov.
4. Loučanová, E., Olšiaková, M., & Štofková, J. (2022): Ecological innovation: Sustainable development in Slovakia. *Sustainability*, *14*(19), 12620.
5. Mariáš, M.; Čimo, J. (1998): *Inovácie vo firemnej stratégii*. Bratislava: Sprint.
6. Pollack, J.; Helm, J.; Adler, D. (2018): What Is the Iron Triangle, and How Has It Changed? *International Journal of Managing Projects in Business* 11 (2): pp. 527–547.
7. Rudder, A.; Main, K. (2023): What Is The Project Management Triangle? *Forbes*, July 20.
8. Sabol, T.; Macej, P. (2001): *Projektový manažment*. Košice: Technická univerzita v Košiciach, 289 s.
9. Svozilová, A. (2006): *Projektový manažment*. Praha: Grada Publishing, 356 s.
10. Štofková, J. et al. (2017): Possibilities of using e-learning system of education at universities. In: *INTED2017 proceedings*. IATED: Pp. 6965-6972.
11. Vahidi, R., & Greenwood, D.: (2009). Triangles, tradeoffs and success: A critical examination of some traditional project management paradigms. In *Construction Facing Worldwide Challenges: CIB Joint International Symposium:* pp. 27-30.
12. Wright, A.; Lawlor-Wright, T. (2019): *Project success and quality: balancing the iron triangle*. Routledge, Taylor & Francis, Abingdon, UK.
13. Wysocki, R. K. (2009): *Effective Project Management. Indianapolis*: Willey Publishing.
14. ***: Devopedia (2023): *Iron Triangle. Devopedia*.
URL: https://devopedia.org/iron-triangle#Highsmith-2023
15. ***: Campbell, M.: *The Iron Triangle: Is it Time to Improve the Triple Constraint*? URL: https://onlinepmcourses.com/the-iron-triangle-is-it-time-to-improve-the-triple-constraint-update/
16. ***: Global G. P. M. (2019): *The GPM® P5™ Standard for Sustainability in Project Management. GPM Global.*
URL:www.gpm.org/images/PDF/P5/The_GPM_P5_Standard_for_Sustainability_in_Project_Management_v3.1_6.pdf
17. ***: Highsmith, J. (2023): The ghosts of project management's Iron Triangle still haunt agile teams.
URL:https://www.linkedin.com/pulse/ghosts-project-managements-iron-triangle-still-haunt-highsmith-/

Authors address:
Erika Loučanová, E.L.[1]; Martina Nosáľová, M.N.[1]; Miriam Olšiaková, M.O.[1]
[1] Department of Marketing, Trade and World Forestry, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia
*Corresponding author: loucanova@tuzvo.sk

THE POTENTIAL OF QUALITY MANAGEMENT IN WOOD PROCESSING INDUSTRY ENTERPRISES IN SLOVAKIA IN THE CONTEXT OF ENHANCING THEIR COMPETITIVENESS

Pavol Gejdoš

Abstract: The aim of the article is to analyse the potential of quality management in wood-processing industry enterprises in Slovakia and to assess its impact on enhancing their competitiveness. The article focuses on the identification of fundamental principles and tools of quality management, as well as on the evaluation of their current application in practice. The empirical part of the article is based on the results of a questionnaire survey and an analysis of selected quality indicators in wood-processing enterprises. The findings indicate that the systematic implementation of quality management contributes to increased efficiency of production processes, higher customer satisfaction, and overall competitiveness of enterprises. The conclusion presents recommendations for managerial practice aimed at the more effective use of quality management as a strategic tool for the development of wood-processing industry enterprises.

Keywords: quality management, competitiveness, wood processing industry

1. INTRODUCTION

Quality represents one of the decisive factors of business competitiveness in the current business environment. Increasing customer demands, pressure on process efficiency, and the need to achieve stable results lead companies to implement systematic quality management approaches. Quality management systems enable companies to optimize processes, reduce error rates, and improve overall performance.

Among the most important approaches are systems based on the ISO 9000 standards, as well as advanced methods such as Total Quality Management (TQM) and Six Sigma. These approaches provide companies with tools to improve processes and enhance the quality of outputs, with their benefits being particularly evident in the long term. Despite their importance, however, there are differences among companies in the extent to which they are applied, which may influence their performance and process quality.

Authors Gorondutse (2021), as well as Olaleye et al. (2021) and Potjanajaruwit (2021), highlight the importance of implementing quality management systems in enhancing the overall performance and competitiveness of enterprises. Kumar et al. (2018) emphasize that the implementation of quality management systems leads to improvements in operational efficiency and financial performance. Similarly, Cai et al. (2023) demonstrated that the concept of Quality 4.0 significantly contributes to increasing the innovation performance of Chinese manufacturing enterprises. O'Neill et al. (2016) identified a positive impact of a strategic orientation toward quality on the financial performance of Australian manufacturing firms.

Lamine and Lakhal (2018) confirm that the implementation of Six Sigma methodologies and Total Quality Management principles has a beneficial effect on business performance, especially in terms of efficiency and customer satisfaction. Cződörová and Gnap (2023) showed that the implementation of ISO 9001 has a statistically significant positive impact on return on assets (ROA) and return on sales (ROS). Similarly, Bakator and Ćoćkalo (2018) report that ISO 9001 certification leads to improvements in both financial and operational performance of enterprises.

Interesting findings are also presented by Basu and Bhola (2016), who identified three TQM dimensions with a direct impact on quality and performance growth of enterprises. These results are consistent with the conclusions of Parvadavardini et al. (2016), who confirmed a positive relationship between TQM, output quality, and the financial performance of enterprises.

The aim of this paper is to analyze the use of quality management systems in industrial enterprises in Slovakia and to evaluate their impact on business performance and competitiveness.

2. METHODOLOGY

For the purposes of the empirical research, a standardized questionnaire survey was used, conducted from November 2025 to February 2026 via the online platform Google Forms. The questionnaire was distributed to selected enterprises through electronic communication and was supplemented by personal communication with managers of selected companies. The research sample consisted of industrial enterprises operating in the Slovak Republic, classified under SK NACE Section C – Manufacturing. To assess the representativeness of the research sample, the minimum required sample size was determined according to the following formula (Lind., 2020):

$$n = \frac{N}{1+N \cdot E^2} \quad (1)$$

The data obtained from the questionnaire survey were processed using statistical methods in Microsoft Excel and the statistical software Statistica. To verify the statistical significance of relationships, Pearson's chi-square test of independence was applied. This test makes it possible to assess whether a statistically significant relationship exists between two categorical variables. The test results were evaluated based on the p-value at a significance level of α = 0.05. To assess the strength of the relationship between variables, the measure of association – Cramer's V – was used, which allows quantifying the intensity of the relationship between the examined variables.

3. RESULTS AND DISCUSION

The population consisted of industrial enterprises operating in the Slovak Republic according to data from the Statistical Office of the Slovak Republic, with a total size of N = 3,152 enterprises. Given the selected maximum permissible estimation error of E = 0.05, the minimum required sample size was calculated as follows:

$$n = \frac{3152}{1 + 3152 \cdot 0.05^2} = 355 \qquad (2)$$

A total of 402 respondents participated in the research, representing approximately a 12.7% response rate. The representation of individual industrial sectors in the research sample is shown in Figure 1.

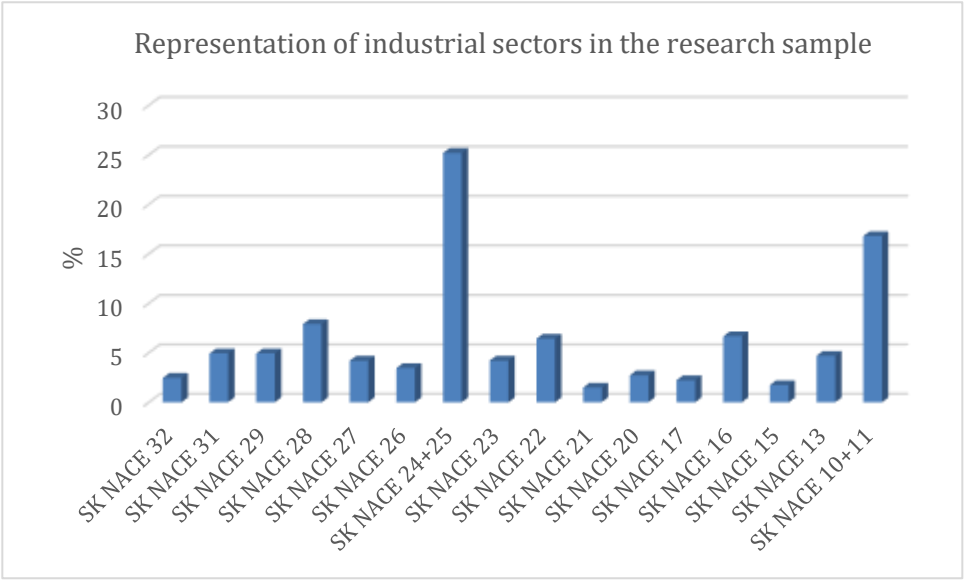

Figure 1 Representation of industrial sectors in the research sample

Figure 2 shows the quality management methods and tools used in wood – processing enterprises in the Slovak Republic. The survey results indicate significant differences in the use of individual quality management methods and tools among the analyzed enterprises. The most frequently used approach is the ISO 9000 standard, reported by as many as 25.9% of respondents. This result confirms the dominant position of standardized quality management systems in practice.

Basic quality tools also have a significant representation, cited by 17.4% of respondents, including, for example, the Pareto diagram, Ishikawa diagram, control charts, and histograms. These tools are mainly used by companies for problem analysis and process improvement. Process management also plays an important role (13.5% of respondents), focusing on managing the enterprise through processes and their continuous improvement.

The implementation of a process approach enables companies to increase efficiency, reduce error rates, and better respond to customer requirements. An interesting finding is that as many as 13.3% of respondents reported that they do not use any quality management tools or methods. This result indicates the existence of a group of enterprises that likely manage quality in an informal manner or do not devote sufficient attention to it, which may negatively affect their performance and competitiveness.

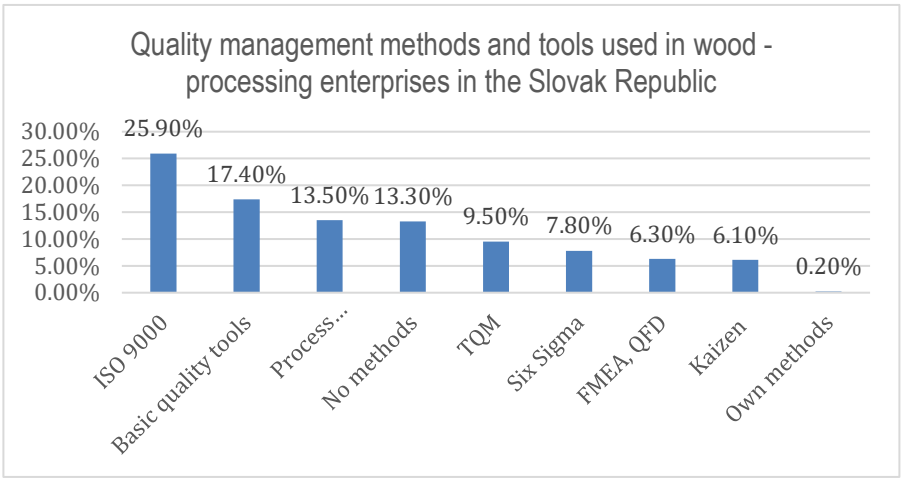

Figure 2 Quality management methods and tools used in wood – processing enterprises in the Slovak Republic

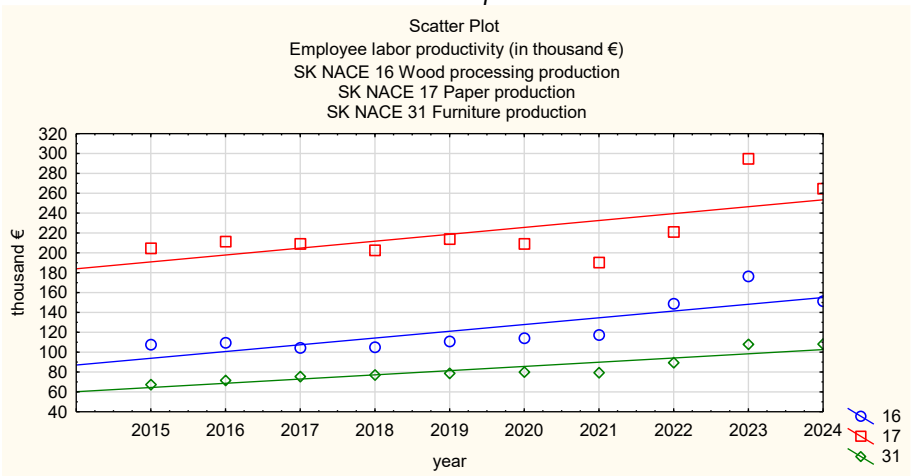

Figure 3 Linear trend model of development for SK NACE 16, 17, and 31 for the indicator "Employees labor productivity."

Based on the values of the regression coefficient b1 and their graphical visualization in Figure 3, it can be stated that in the wood processing industry, employee labor productivity shows an average year-on-year increase of €6,803. In paper production, the average increase is €6,937, and in furniture manufacturing, it is €4,240 per year. These values represent the slopes of the trend lines, which quantify the rate of productivity growth in the respective industries.

H1 We assume that companies with an implemented quality management system achieve a higher level of performance.

The test results are presented in Table 1. The resulting p-value reaches 0.000. Based on this, it can be concluded that there is a statistically significant relationship between the examined variables. The value of the test statistic $\chi^2 = 109.5$, with 3 degrees of freedom, indicates a substantial difference between the individual categories. The strength of the

relationship, expressed by Cramér's V coefficient, reaches a value of 0.524, which can be interpreted as a moderate to strong association.

Table 1 Results of Pearson chi-square test of contingency – the use of QMS versus performance of wood - processing enterprises.

Using of QMS vs. Performance	Chi-square test	Degree of freedom	p-level	Cramer's V
	109,5	3	0,000	0,524

Based on the conducted analysis (Table 2) , it can be concluded that there is a statistically significant relationship between the implementation of a quality management system and the level of profit achieved by enterprises. The results indicate that companies with an implemented quality management system generally achieve a higher level of economic performance compared to those that have not implemented this system.

Table 2 Contingency table of residual frequencies – the implementation of QMS versus achieved profit of wood - processing enterprises.

Implementation of QMS	Profit in thousand €			
	< 0	0-100	100-500	> 500
no	**24,15**	**10,79**	-28,95	-5,99
yes	-24,15	-10,79	**28,95**	**5,99**

4. CONCLUSION

The research results confirm that quality management tools play a significant role in enhancing business performance. The implementation of a quality management system (QMS) is particularly reflected in the reduction of non-productive costs and losses, as well as in increased profit and overall customer satisfaction.

Very similar results were achieved across all sectors of the national economy; therefore, it can be concluded that this is not a factor that significantly influences the outcome. A more significant factor is the size of the enterprise. In particular, small and medium-sized enterprises implement quality management methods and tools to a much lesser extent than large enterprises.

Another important factor is the capital structure, where enterprises with domestic capital implement quality management methods and tools to a much lesser extent compared to those with foreign capital. Since a large number of small and medium-sized enterprises with domestic capital operate in the wood processing and furniture manufacturing sectors in Slovakia, it can be concluded that enterprises in the wood processing sector implement quality management systems to a lesser extent than those in other sectors of the national economy. This statement does not apply to the pulp and paper industry in Slovakia.

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REFERENCES

1. Bakator, M., Ćoćkalo, D. 2018. Improving business performance with ISO 9001: A review of literature and business practice. The European Journal of Applied Economics, 15(1), 83–93, https://doi.org/10.5937/ejae15-16145
2. Basu, R., Bhola, P. 2016. Impact of quality management practices on performance stimulating growth: Empirical evidence from Indian IT enabled service SMEs. International Journal of Quality & Reliability Management, 33(8), 1179–1201, https://doi.org/10.1108/IJQRM-10-2015-0153
3. Cai, W., Liu, H.-C., Liu, R., Gu, X., Yang, M. 2023. From total quality management to Quality 4.0: A systematic literature review and future research agenda. Frontiers of Engineering Management, 10(2), 191–205s, https://doi.org/10.1007/s42524-022-0243-z
4. Cződörová, R., Gnap, J. 2023. Investigation of the Effectiveness of the Introduction of the Quality Management System According to the ISO 9001 Standard in Transport Companies: Slovakia Case Study. Sustainability, 15(3), 2401, https://doi.org/10.3390/su15032401
5. Gorondutse, A.H., Ali, G.A., Hilman, H, 2021. Developing rightly culture on TQM - evidence from SMEs in the context of emerging economy. *RAUSP Management Journal,* 56(4), 465 – 481, https://doi.org/10.1108/RAUSP-11-2020-0264
1. Kumar P, Maiti J, Gunasekaran A. 2018. Impact of quality management systems on firm performance, International Journal of Quality & Reliability Management, 35(5), 1034-1059, https://doi.org/10.1108/IJQRM-02-2017-0030
2. Lamine K, Lakhal L. 2018. Impact of TQM/Six Sigma practices on company's performance: Tunisian context, International Journal of Quality & Reliability Management, 35(9), 1881-1906, https://doi.org/10.1108/IJQRM-05-2017-0097
3. Lind, D. A., 2020. *Statistical Techniques in Business and Economics*. McGraw-Hill. 880.
4. Olaleye, B.R., Ali-Momoh, B.O., Herzallah, A., Sibanda, N., Ahmed, A.F. 2021. Dimensional Context of Total Quality Management Practices and Organizational Performance of SMEs in Nigeria: Evidence from Mediating Role of Entrepreneurial Orientation. International Journal of Operations and Quantitative Management, 27(4), 399 – 415, https://doi.org/10.46970/2021.27.4.6
5. O'Neill, P. J., Sohal, A. S., Teng, C. W. 2016. Quality management approaches and their impact on firms' financial performance – an Australian study. International Journal of Production Economics, 171 (3), 381–393, https://doi.org/10.1016/j.ijpe.2015.07.015
6. Potjanajaruwit P. 2021. TQM knowledge management and analysis of smes in Thailand. Polish Journal of Management Studies, 24(2), 386 – 397, https://doi.org/10.17512/pjms.2021.24.2.24

Authors address:
Gejdoš, P[1];
[1] Department of Economics, Management and Business, Faculty of Wood Science and Technology, Technical University in Zvolen, Zvolen, Slovakia
*Corresponding author: gejdosp@tuzvo.sk

IMPLEMENTATION OF INNOVATION MANAGEMENT IN THE PRODUCTION OF WOODEN COMPONENTS AND PARTS IN THE AUTOMOTIVE INDUSTRY

Alena Pauliková, Henrieta Hrablik Chovanová

Abstract: The presented contribution examines the strategic implementation of innovation management systems according to the new certifiable standard ISO 56001:2024 within the wood-processing industry. In the context of global bioeconomy, wood and bio-composites are being transformed from decorative elements into functional engineering materials for structural components. The aim of the contribution is to define specific requirements for the management of innovation processes within forestry and wood-sector organizations that enable the safe introduction of variable natural materials into demanding engineering chains, such as the automotive industry. The analysis focuses on selected technical parameters in the project decision-making framework (stage-gates) specifically adapted for the research and development of wood-based products. The emphasis is placed on an auditing methodology according to ISO 19011, where objective evidence of innovation capability must be sought, including the validation of bio-based prototypes and systematic learning from unsuccessful models. The results indicate that the innovation management system increases the competitiveness of producers in the forest-based industry and ensures traceability in accordance with EUDR regulations, providing practical recommendations for wood-processing enterprises to successfully integrate into advanced industrial clusters.
Keywords: bioeconomy, ISO 56001:2024, automotive industry, wood composites, innovation audit, EUDR compliance.

1. INTRODUCTION

The contemporary global industrial ecosystem is undergoing a fundamental shift toward a circular bioeconomy to mitigate carbon emissions and reduce reliance on non-renewable fossil resources (Baumann et al., 2020; Baumann et al., 2021). In this transition, the forest-based sector is emerging as a critical provider of high-value renewable materials (Kurzböck et al., 2018; Müller et al., 2020). While wood has traditionally been used in building construction and packaging, its role is expanding into highly demanding technological sectors such as the automotive industry (Müller et al., 2020; European Parliament and Council, 2023). Every year, the European automotive industry utilizes approximately 80,000 tonnes of wood and plant fibres to reinforce composite materials, displacing conventional fossil-derived polymers and energy-intensive glass or carbon fibres (Müller et al., 2020).

Historically, the connection between automotive engineering and organic raw materials is not new; in 1941, Henry Ford unveiled the "Soybean Car" prototype, which used a natural fibre-reinforced bioplastic body panel assembly (Müller et al., 2020). Today, wood-based panels, veneers, and wood-plastic composites (WPCs) are widely utilized in passenger cars as substrates for interior door panels, roof headliners, seat backs, rear decks, and trunk liners (Müller et al., 2020). However, introducing variable natural raw materials into highly standardized, zero-defect engineering chains presents a profound quality and managerial challenge. This article explores how the systematic implementation of the newly released ISO 56001:2024 standard can guide this transition (ISO 56001, 2024).

1.1. Bioeconomy Moves Forward: Wooden Components in Mobility

Wood and engineered wood products (EWPs) exhibit excellent mechanical properties, high fatigue resistance, exceptional acoustic damping, and a very low density, combined with low raw material costs (Kurzböck et al., 2018). These characteristics position wood-based composites as ideal candidates for lightweighting, which is a major driver for fuel-efficiency in combustion engines and range-extension in electric vehicles (EVs) (Müller et al., 2020).

1.1.1. Advanced Lightweighting and Structural Performance

Over the last decade, large-scale research initiatives such as the "Wood C.A.R." (Wood - Computer Aided Research) project have demonstrated that modern wood composites can be successfully simulated under complex static and dynamic loads, including dynamic crash situations, using finite element method (FEM) software like LS-DYNA (Kurzböck et al., 2018; Müller et al., 2020). By deploying advanced material cards such as MAT58 and MAT143, engineers can model linear elasticity, strain-hardening, and the typical step-wise brittle failure of solid birch or beech wood under high impact energy (Baumann et al., 2019-2021).

MAT58 (Material: LAMINATED COMPOSITE FABRIC): Originally developed for woven composite fabric materials. In wood mechanics, it is applied as an orthotropic material model, allowing for the independent definition of mechanical properties, yield curves, and failure criteria in three principal anatomical directions: longitudinal/radial/tangential. This capability is highly effective for describing the non-symmetric tension, compression, and shear behaviours of laminated wood veneers, plywoods, and hybrid composites (Baumann et al., 2019).

MAT143 (Material: WOOD): A specialized material model developed in LS-DYNA specifically for wood. Unlike MAT58, it is transversally isotropic, meaning it does not distinguish between the radial and tangential directions of the material, which requires a trade-off parameter entry for perpendicular-to-grain behaviour. Its principal advantage, however, is its built-in capability to consider environmental and physical parameters such as moisture content, temperature, and the quality sorting degree of the wood, significantly increasing simulation accuracy under varying real-world climate conditions (Baumann et al., 2019).

Concurrently, the Fraunhofer Institute for Wood Research (WKI) has pioneered "wood foam" – a lightweight porous material (density 45 to 200 kg/m³) compiled without synthetic adhesives by utilizing the wood's inherent self-bonding forces. These foams open new horizons for ecological sandwich panels and hybrid mouldings (e.g., combining beech veneer with thin metal sheets) to reinforce car doors (Bunzel and Ritter, 2017; Müller et al., 2020), see Table 1.

Table 1. Physical and mechanical properties of selected engineered wood and bio-composite materials

Material	Density [kg/m³]	Tensile Strength [MPa]	Key Application
Wood Foam	45 - 200	0.62	Core material, acoustic/thermal insulation
Densified Birch Veneer	920 - 1190	Up to 400	Structural load-bearing components, car doors
Hemp & Kenaf Composite	700 - 900	Up to 50	Sunroof frames (Mercedes-Benz E/A-Class)

2. SYSTEMATIC INNOVATION MANAGEMENT: ISO 56001:2024

In September 2024, the International Organization for Standardization published ISO 56001:2024, the first certifiable requirements standard for an Innovation Management System (IMS). Previously, organizations relied on non-certifiable guidelines (ISO 56002), but the transition to ISO 56001 establishes binding "shall" requirements. An IMS under ISO 56001 ensures that innovation is treated not as an ad-hoc or purely creative process, but as a repeatable, systemic discipline that reduces uncertainty, optimizes return on investment (ROI), and manages strategic risks (ISO 56001, 2024).

2.1. Common and Specific Requirements for Automotive Suppliers

Most Tier 1 and Tier 2 automotive suppliers are certified under the stringent IATF 16949 quality standard. Because ISO 56001 follows the Harmonized Structure (HS) for management system standards, organizations can easily integrate the common (common) requirements of both standards, such as leadership commitment (Clause 5), support structures (Clause 7), and performance evaluation (Clause 9), (ISO 56001, 2024).

However, specific (specific) requirements must remain separate due to a fundamental philosophical conflict: while IATF 16949 is strictly designed to eliminate variation and achieve a zero-defect rate in mass production, ISO 56001 is designed to navigate and exploit uncertainty, promote safe experimentation, and utilize failures as essential learning loops, see Table 2.

A critical technical and R&D parameter for wood-based components under variable climatic conditions (ranging from -30 °C to +90 °C) is moisture content stability (Baumann et al., 2020-2021). For instance, during the validation phase of natural veneer-based composites, the rate of water absorption W_A is mathematically calculated according to the following formula (1):

$$W_A = \frac{m_2 - m_1}{m_1} \cdot 100 \qquad (1)$$

where W_A is the water absorption in %, m_1 is the mass of the dry wood specimen, and m_2 is the mass of the specimen after exposure to high humidity or immersion.

Table 2. Integration matrix of ISO 56001:2024 and IATF 16949 requirements

Clause	Common Area (HS/HLS)	IATF 16949 (Specific)	ISO 56001 (Specific)
4	Context & Interested Parties	Automotive Tier customer requirements	EUDR compliance, raw material geolocation
5	Leadership & Policy	Zero-defect target, PPAP approval	Supportive culture, risk-taking allocation
8	Operation & Processes	Mass production control, APQP	Exploratory R&D, Phase-Gated Validation
9	Performance Evaluation	PPM defects, warranty rates	KPIs on value realized, learning indicators

2.1.1. Stage-Gate Product Development Framework for Wood-Based R&D

Clause 8.3 of ISO 56001:2024 requires a structured, multi-phase innovation process. When developing novel wood-based composites, organizations must adapt the traditional Stage-Gate model, see Figure 1, to balance structural rigidity with natural material variability (Cooper, 2017).

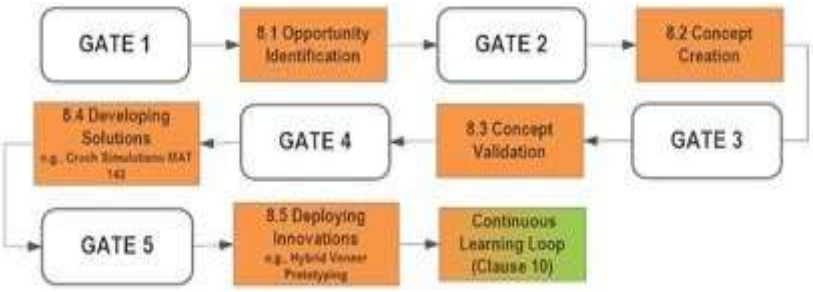

Figure 1. The Stage-Gate model integrated with ISO 56001:2024 operational requirements.

The validation gate (8.3) is highly technical in automotive R&D; for example, wood parts must undergo extensive physical impact pendulum testing and finite element crash simulations to prove they can substitute metals or fiber-reinforced plastics before they enter the formal product development phase (Baumann et al., 2019-2020). Additionally, Safe and Sustainable by Design (SSbD) frameworks can be integrated into the stage-gate format to assess environmental safety and toxicity early in the material development cycle (Cooper, 2017).

2.1.2. Auditing Methodology Aligned with ISO 19011

Auditing an IMS according to ISO 19011 (ISO 19011, 2018) requires a major shift in auditor competency. Rather than auditing purely for conformity to static procedures, auditors must search for objective evidence of innovation capability. This includes:

- Documented proof of concept (PoC) and pilot project results, even those that were discontinued, as they represent vital sources of learning (ISO 56001, 2024);
- Evidence of senior management's commitment to providing dedicated resources, time, and training for innovation activities (ISO 56001, 2024);
- Clear mechanisms for managing intellectual property (IP) and exploiting internal and external knowledge streams (ISO 56001, 2024).

3. REGULATORY COMPLIANCE AND SUPPLY CHAIN TRACEABILITY (EUDR)

The European Union Deforestation Regulation (EUDR, Regulation (EU) 2023/1115) represents one of the most operationally demanding supply chain regulations ever enacted. The regulation prohibits placing wood, rubber, leather, and soy-based components on the EU market unless they are verifiably deforestation-free (not sourced from land deforested after December 31, 2020) and legally produced (European Parliament and Council, 2023).

For automotive OEMs, this is not a regulation targeting the vehicle as a finished product, but rather its individual component inputs. Typical affected parts include wooden interior trim inserts, tires containing natural rubber, leather steering wheels, and soy-based bioplastics (European Parliament and Council, 2023), see Table 3.

Table 3. EUDR requirements and due diligence workflows for automotive operators

EUDR Step	Requirement Details	Automotive Application
1. Data Gathering (Art. 9)	Plot geolocation coordinates (polygons) & species identification	Tracing veneer wood or natural rubber back to the specific forest parcel
2. Risk Assessment (Art. 10)	Evaluation of country risk levels, governance, and traceability data	Continuous mapping of Tier 1-3 suppliers on deforestation risk
3. Risk Mitigation (Art. 11)	Implementing corrective measures where risk is non-negligible	Deploying RFID tags on logs or deep-learning image-based tracking

The German Association of the Automotive Industry (VDA) has highlighted the immense complexity of tracing minimal quantities of wood powder or wood pulp integrated into complex polymer parts. To overcome these challenges, advanced traceability innovations must be integrated into the organization's IMS. Modern systems employ cost-effective deep learning models (such as YOLOv8) to track alphabetic codes on logs or use RFID-based forestry tags linked to mobile tablets to maintain an unbroken chain of custody from the forest parcel directly to the sawmill and the finished component (European Parliament and Council, 2023).

4. CONCLUSION

The implementation of a certifiable Innovation Management System according to ISO 56001:2024 (ISO 56001, 2024), in combination with the requirements of IATF 16949 and the EUDR (European Parliament and Council, 2023), represents a strategic shift from reactive, ad-hoc solutions to a proactive and highly resilient engineering value chain. This research demonstrates that for the successful introduction of variable natural materials (such as birch and beech) into demanding automotive applications, the systematic division and integration of management requirements is key (Kurzböck et al., 2018; Müller et al., 2020):

Common Processes: Areas such as context of the organization, leadership, and documented information management can be efficiently integrated into a single Integrated Management System, eliminating administrative duplication, particularly for small and medium-sized enterprises (SMEs), (ISO 56001, 2024).

Specific Processes: Areas focusing on the management of risks and uncertainties (ISO 56001) and the strict management of zero defects (IATF 16949) must remain methodologically separated. The innovation environment requires a phased Stage-Gate approach (Cooper, 2017) with clearly defined technical gates (e.g., FEM simulations using MAT58 and MAT143 (Baumann et al., 2019), moisture absorption W_A calculation, and physical impact testing) before initiating the formal Product Part Approval Process (PPAP) for mass production.

From the perspective of market competitiveness and regulatory compliance, traceability under the EUDR (European Parliament and Council, 2023) is not merely an administrative hurdle but an innovation opportunity. The deployment of modern technologies, such as deep learning visual detection systems (YOLOv8) or RFID-based forestry tags, enables absolute transparency of the material flow from the specific forest plot directly to the structural component of the vehicle. For the Slovak automotive and wood-processing sector, which possesses a strong research foundation (such as the Slovak University of Technology in

Bratislava) and innovative companies, the synergy of these standards offers a unique pathway to produce high-tech bio-components for the mobility of the future.

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REFERENCES

1. Baumann, G.;F Brandner, R.; Müller, U.; Kumpenza, C.; Stadlmann, A.; Feist, F. (2020): *Temperature-related properties of solid birch wood under quasi-static and dynamic bending*. Materials 13 (23): pp. 5518-5518.
2. Baumann, G.; Brandner, R.; Müller, U.; Stadlmann, A.; Feist, F. (2021): *A comparative study on the temperature effect of solid birch wood and solid beech wood under impact loading*. Materials 14 (24): pp. 7616-7616.
3. Baumann, G.; Feist, F.; Kurzböck, C.; Müller, U.; Hartmann, S. (2019): *Comparison of the two material models 58, 143 in LS Dyna for modelling solid birch wood.* In: Proceedings of the 12th European LS-DYNA Conference, Koblenz, Germany, May 2019.
4. Bunzel, F.; Ritter, N. (2017): *Wood Foam. In: Cultivated Building Materials*: Industrialized Natural Resources. Birkhäuser, pp. 100-107.
5. Cooper, R.G. (2017): Robert G. *Cooper's Stage-Gate Agile idea-to-launch system*. Product Development Institute.
6. ISO Standard 56001 (2024): Innovation management system — Requirements. ISO, Geneva.
7. ISO Standard 19011 (2018): Guidelines for Auditing Management Systems. ISO, Geneva.
8. Kurzböck, C.; Jost, T.; Müller, U.; Feist, F.; Hartmann, S. (2018): *Wood C.A.R. – Wood-based materials for functional vehicle structures.* Virtual Vehicle & University of Natural Resources and Life Sciences (BOKU), Vienna.
9. Müller, U.; Jost, T.; Kurzböck, C.; Stadlmann, A.; Wagner, W.; Kirschbichler, S.; Baumann, G.; Feist, F. (2020): *Crash simulation of wood and composite wood for future automotive engineering*. Wood Material Science & Engineering 15 (5): pp. 312-324.
10. Regulation (EU) 2023/1115 on *the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation*. European Parliament and Council (2023). Official Journal of the European Union.

Authors address:
Pauliková, A.[1]; Hrablik Chovanová, H.[1]
[1] Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology, Slovak University of Technology in Bratislava, Trnava, the Slovak Republic
Corresponding author: alena.paulikova@stuba.sk

NEW ASPECTS OF UPDATING QUALITY MANAGEMENT ACCORDING TO ISO 9001 IN THE CONTEXT OF INTERNATIONAL WOOD PRODUCTS MARKETS

Alena Pauliková, Renata Nováková, Olena Plaksiuk

Abstract: The presented contribution analyses the key changes in the upcoming revision of the world's most widely adopted quality management standard, ISO 9001:2026, and their strategic impact on the forestry and wood-processing sector. Primary focus is placed on the mandatory integration of climate change aspects into the context of the organization (Clauses 4.1 and 4.2), which serves as a critical tool for organizations facing the implementation of the EUDR regulation and requirements for transparent biogenic carbon auditing. The paper identifies new requirements for quality culture and ethical behaviour (Clauses 5.1.1 and 7.3), which are becoming the foundation for building trust in international bio-product markets. The aim of this contribution is to compare the 2015 and 2026 versions, emphasizing a clearer separation of risk management and opportunity management under Clause 6.1 in the context of digital transformation and Industry 4.0. The results indicate that the revised quality management system is transitioning from a mere procedural tool to a strategic framework for resilience and sustainability within the circular bioeconomy. The paper provides timely recommendations for quality managers in the wood sector to successfully navigate the three-year transition period.
Keywords: ISO 9001:2026, quality management, wood product markets, climate change, EUDR, supply chain resilience.

1. INTRODUCTION

The global transition to a circular bioeconomy has placed the forestry and wood-processing sector at the centre of international sustainability policies. Wood and engineered wood products (EWPs) represent crucial biogenic resources for carbon sequestration and the substitution of fossil-based materials. However, wood-processing enterprises operating in international markets face unprecedented challenges, including raw material price volatility, supply chain disruptions, and stringent trade regulations. Chief among these is the European Union Deforestation Regulation (EUDR, Regulation (EU) 2023/1115), which prohibits placing non-compliant timber and derived products on the EU market (European Parliament and Council, 2023).

To remain competitive and demonstrate compliance, enterprises must rely on structured management systems. The ISO 9001 standard represents the global benchmark for Quality Management Systems (QMS), with over one million certified organizations worldwide. However, the currently active version, ISO 9001:2015, was developed more than a decade ago and does not fully reflect modern operational realities, such as rapid digital transformation, sustainability expectations, and the necessity of supply chain resilience (ISO 9001, 2026).

To bridge this gap, the ISO Technical Committee ISO/TC 176 is finalizing the revised edition, ISO 9001:2026, scheduled for official publication in late 2026. This article examines the key changes introduced in ISO 9001:2026 and explores how wood-processing enterprises can leverage the updated standard as a strategic governance framework to navigate international markets and regulatory mandates.

2. KEY REVISIONS IN ISO 9001:2026 AND IMPACT ON WOOD ENTERPRISES

The 2026 revision represents an evolutionary update rather than a complete overhaul, preserving the core process approach, risk-based thinking, and the ten-clause Harmonized Structure (HS) (ISO 9001, 2026). However, the standard introduces profound conceptual shifts that elevate quality management from a procedural level to a strategic business alignment.

2.1. Climate Change Integration into QMS Context (Clauses 4.1 & 4.2)

One of the most immediate changes is the formal integration of climate change considerations into the standard text. Following the 2024 climate amendment (ISO 9001:2015/Amd 1:2024), organizations are required to determine whether climate change is a relevant issue within their operational context (Clause 4.1) and whether key interested parties have climate-related requirements (Clause 4.2) (ISO 9001, 2026).

For the wood-processing sector, this requirement is highly material:

Physical Risks: Climate change directly impacts forest health (e.g., bark beetle infestations, droughts, extreme weather events), leading to disruptions in timber supply, quality degradation, and raw material volatility (ISO 9001, 2026).

Regulatory and Market Demands: Customers and regulatory bodies increasingly demand verifiable data regarding a product's carbon footprint and proof of sustainable forest management (ISO 9001, 2026).

Under ISO 9001:2026, climate change is not treated as a separate environmental topic (as in ISO 14001) but as an issue affecting the QMS's capability to deliver conforming products (ISO 9001, 2026). Wood enterprises must assess how climate-related resource scarcity or logistics disruptions affect process stability and moisture content stability under changing environmental conditions (ISO 14067, 2018).

2.2. Explicit Separation of Risks and Opportunities (Clause 6.1)

In the 2015 edition, risk-based thinking was formulated in an open-ended manner, which often led organizations to focus heavily on risk mitigation while under-representing the systematic identification of business opportunities (ISO 9001, 2026). ISO 9001:2026 addresses this by restructuring Clause 6.1 (Actions to address risks and opportunities) into separate sub-clauses: Clause 6.1.2 explicitly covers "Actions to address risks," while Clause 6.1.3 covers "Actions to address opportunities" (ISO 9001, 2026).

Table 1. Separation of risks and opportunities for international wood product manufacturers

Category	QMS Focus Area	Specific Application in Wood-Processing Sector	Source
Risks (6.1.2)	Supply Chain & Compliance	Geopolitical trade barriers, EUDR non-compliance fines, raw material price volatility.	(ISO 9001, 2026; European Parliament and Council, 2023)
Opportunities (6.1.3)	Product Innovation & Growth	High-value product diversification (e.g., wood foam, transparent wood), circular economy utilization of post-production wood waste.	(osapiens, 2026; Richnák, 2022)

By cleanly decoupling these two areas, organizations can seamlessly apply the classic SWOT analysis to their QMS. Specifically, *Clause 4* focuses on analysing the internal and external context of the organization, which directly defines the Strengths (S) and Weaknesses (W) of the enterprise. In turn, the newly separated sub-clauses of *Clause 6* provide a structured framework to map out and systematically execute actions targeting Opportunities (O) and mitigating Threats or risks (T) (ISO 9001, 2026). This structural mapping prevents a purely bureaucratic approach to risk management, transforming the QMS into an active tool for corporate strategy, see Table 1.

2.3. Fostering Quality Culture and Ethical Behaviour (Clauses 5.1.1 & 7.3)

The 2026 revision places a strong emphasis on organizational culture and integrity. Clause 5.1.1 (Leadership and commitment) is expanded to require top management to explicitly promote and demonstrate a "quality culture" and "ethical behaviour". Furthermore, Clause 7.3 (Awareness) now requires all personnel working under the organization's control to be aware of the defined quality culture and ethical conduct expectations (ISO 9001, 2026).

From an auditing perspective aligned with ISO 19011, quality culture and ethical behaviour represent the most difficult items to verify and prove within the entire QMS (ISO 19011, 2018; ISO Standard 9001, 2026). These concepts are highly subjective and culturally dependent: what is perceived as a standard corporate culture in one region or business environment may be viewed as non-cultural or inadequate in another. Similarly, ethical norms are non-universal and vary significantly across global social landscapes (ISO 9001, 2026). Consequently, external auditors will look beyond signed policies, demanding objective evidence of actual leadership behaviours, transparent internal communication, and employee values in daily decision-making (Stoyanova et al., 2019; Drljača, 2003).

3. SUPPLY CHAIN RESILIENCE AND REGULATORY COMPLIANCE (EUDR)

The European Union Deforestation Regulation (EUDR) mandates complete supply chain traceability, requiring operators to collect the precise geolocation coordinates of the forest plots where the timber was harvested (European Parliament and Council, 2023).

3.1. Quality Management as a Foundation for Traceability

Under the EUDR, incomplete or unverifiable supplier data results in immediate market exclusion and severe financial penalties (European Parliament and Council, 2023). Wood-processing enterprises must integrate EUDR due diligence workflows directly into their QMS.

However, long-term strategic planning must account for the dynamic nature of geopolitics. Trade blocks and political communities like the EU are not permanent and may weaken, dissolve, or be superseded by other rising economic coalitions (such as the BRICS group). To build genuine resilience, wood enterprises must decouple their operational compliance from specific political entities (ISO 9001, 2026). By utilizing international, block-neutral standards like *ISO 38200:2018* (Chain of custody of wood and wood-based products) as the core of their QMS, organizations establish a universal, robust traceability model that remains valuable and marketable regardless of shifts in global trade alliances.

Furthermore, the QMS must handle Product Carbon Footprint (PCF) data, as carbon accounting under *ISO 14067:2018* becomes a key customer requirement in international wood

markets. Wood-processing organizations must accurately track biogenic carbon content (stored carbon), which can be calculated using the dry mass of wood and the chemical conversion factor, where:

$$\text{Biogenic } CO_2 \text{ eq.} = -1 \cdot (\text{dry wood mass} \cdot 0.5 \cdot 3.67) \quad (1)$$

Equation (1) reflects that 1 kg of stored biogenic carbon is equivalent to 3.67 kg of atmospheric CO_2 removed during tree growth (Stora Enso, 2024). Under ISO 14067, this biogenic carbon must be reported separately from fossil-based CO_2 emissions, ensuring complete transparency for international buyers and auditors (ISO 14067, 2018).

Additionally, wood-processing enterprises can implement automated, digitalized due diligence platforms (such as the osapiens HUB for EUDR) to automate geolocation data collection, perform deforestation risk analysis, and compile the mandatory Due Diligence Statements (DDS) for direct submission to the EU TRACES system, integrating legal compliance seamlessly into their existing QMS (osapiens, 2026), see Table 2.

Table 2. Integration of EUDR and ISO 14067 requirements into ISO 9001:2026 QMS processes

QMS Process	ISO 9001:2026 Clause	Integrated Compliance Action
Purchasing & Supplier Evaluation	8.4 (External providers)	Mandatory collection of GeoJSON plot polygons and harvesting permits.
Product Design & Development	8.3 (Design & development)	Calculation of biogenic carbon footprint per functional product unit.
Traceability & Operations	8.5.2 (Identification & traceability)	Batch-level linking of due diligence statements (DDS) to customer shipments.

4. TRANSITION ROADMAP AND CHALLENGES FOR WOOD SMEs

Following the official release of ISO 9001:2026 (expected in the second half of 2026), certified organizations will have a standard *three-year transition period*—until approximately September 2029—to align their QMS and maintain certification validity (ISO 9001, 2026).

Only after the full migration in 2029 will industry practice reveal whether these new revisions were designed appropriately and effectively, serving as a basis for the subsequent revision cycle. In standardization theory, the longevity and stability of a standard are directly proportional to the complexity and depth of its integration with the era's technical and economic realities; a deep, well-planned revision "survives" much longer without needing sudden intermediate patches or corrections (ISO 9001, 2026).

In Fig.1 there are illustrated the quantitative comparison of core requirements and documented information between ISO 9001:2015 and ISO 9001:2026. (Note: Evaluated based on the research work of Oboril (2026). The 100 documented information items in ISO 9001:2026 comprise 61 "Maintain" and 39 "Retain" items).

4.1. The Role of Quality 4.0 in Slovak Wood-Processing Enterprises

The Slovak wood-processing enterprises, primarily represented by small and medium-

sized enterprises (SMEs), frequently struggle with a high technological debt and administrative fragmentation (Richnák, 2022). The transition to ISO 9001:2026 should not be viewed as an increase in paperwork, but as an opportunity to adopt the Quality 4.0 paradigm (Richnák, 2022).

Quality 4.0 refers to the digitalization of quality management systems through Industry 4.0 SMTs (smart manufacturing technologies), including the Internet of Things (IoT), big data analytics, and cloud computing (Richnák, 2022). For wood SMEs, implementing digital solutions—such as RFID-based timber tracking, AI-powered defect detection, and automated DDS generation platforms—significantly reduces the manual compliance burden (osapiens, 2026).

Figure 1. Quantitative comparison of core requirements and documented information between versions.

5. CONCLUSIONS

The upcoming revision of ISO 9001:2026 represents a critical milestone in the modernization of quality management. By formally integrating climate change, business ethics, and supply chain resilience into the core QMS requirements, the standard evolves into a true strategic governance framework compatible with the circular bioeconomy.

This evolutionary shift gains immense urgency in light of the United Nations and Eurostat initiative for *Natural Capital Accounting* (SEEA EA), where *2027* stands as the mandatory milestone for EU member states to submit completed ecosystem conversion matrices (United Nations, 2021; Eurostat, 2024). This milestone concludes the initial valuation of the Earth's natural capital, making it transparent which nations possess the richest ecological assets. Once advanced wood-extraction and cascading-use technologies are fully deployed, countries well-endowed with sustainable forest resources will be positioned as major resource-independent powerhouses in the global bioeconomy.

For forestry and wood-processing enterprises, the systematic implementation of ISO 9001:2026 provides a robust methodology to manage the inherent variability of natural raw materials under changing climate conditions, while ensuring strict compliance with demanding international trade regulations like the EUDR. Furthermore, by linking quality management with Quality 4.0 technologies and established supply chain standards (ISO 38200, ISO 14067), wood-processing enterprises can turn regulatory compliance into a lasting competitive advantage on the international market.

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"Novel Trends and Sustainability in Logistics").

REFERENCES

1. Drljača, M. (2003): *Utjecaj sustava upravljanja kvalitetom na poslovnu uspješnost*. Kvaliteta 11 (3): pp. 45-52.
2. European Parliament and Council (2023): Regulation (EU) 2023/1115 *on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation*. Official Journal of the European Union.
3. Eurostat (2024): *European environmental economic accounts — Ecosystem accounts regulation guidelines*. European Commission, Luxembourg.
4. ISO Standard 9001 (2026): *Quality management systems — Requirements*. ISO, Geneva.
5. ISO Standard 14067 (2018): G*reenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.* ISO, Geneva.
6. ISO Standard 19011 (2018): *Guidelines for Auditing Management Systems*. ISO, Geneva.
7. ISO Standard 38200 (2018): *Chain of custody of wood and wood-based products*. ISO, Geneva.
8. Oboril, I. (2026): R*esearch work for evaluation requirement for ISO 9001:2026 & ISO 56001:2024*. STU MTF, Trnava, Slovak Republic, 16th April 2026, 3 Excel sheets.
9. osapiens. (2026): osapiens HUB for EUDR: *Automated Software Solution for Compliance with the EU Deforestation Regulation*. osapiens Services GmbH, Mannheim, Germany. Available online: https://osapiens.com/solutions/eudr/ (accessed on 9th July 2026).
10. Richnák, P. (2022): *Quality 4.0: New Concept for Quality Management in Wood Processing Industry*. In: Proceedings of the International Scientific Conference WoodEMA 2022, pp. 115-122.
11. Stora Enso. (2024): *Environmental Product Declaration: KVH Solid Timber*. Stora Enso Wood Products, Zdírec, Czech Republic. Available online: https://www.storaenso.com (accessed on 9th July 2026).
12. Stoyanova, A.; Stefanova, M.; Kirechev, D. (2019): *Risk Assessment of Timber Wood Fumigation by Applying the Requirements of ISO 9001:2015*. In: Proceedings of the 12th International Scientific Conference WoodEMA 2019, pp. 231-236.
13. United Nations (2021): *System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA)*. United Nations Statistical Commission, New York.

Authors address:
Pauliková, A.[1*]; Nováková, R.[2], Plaksiuk, O.[3]
[1] Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology, Slovak University of Technology in Bratislava, Trnava, the Slovak Republic
[2] Ambis University, Prague, the Czech Republic
[3] The Slovak Association for Quality, Trnava, the Slovak Republic
*Corresponding author: alena.paulikova@stuba.sk

THE ROLE OF INDUSTRIAL PROPERTIES IN THE DEVELOPMENT OF BIOECONOMIC CLUSTERS IN BULGARIA

Bozhidar Chaparov

Summary: The development of bioeconomy clusters represents a strategic priority for forest-rich countries seeking to transition towards more sustainable and circular economic models. While the theoretical foundations of cluster formation are well established, the specific role of industrial real estate as a physical and institutional enabler of bioeconomy cluster development remains underexplored in the academic literature. This paper addresses that gap by developing a conceptual framework that integrates industrial real estate market dynamics into the broader model of bioeconomy cluster formation.

The study adopts a qualitative-analytical approach, drawing on cluster theory, bioeconomy policy frameworks, and secondary data sources including national statistics, market reports on the Bulgarian industrial property sector, and comparative evidence from European bioeconomy cluster models. Bulgaria serves as the primary empirical context, given its combination of significant forest resources and a dynamically developing industrial real estate market.

The findings suggest that while Bulgaria's industrial real estate sector has experienced considerable growth driven primarily by logistics and light manufacturing demand дх its potential to anchor bioeconomy cluster development, particularly in regions with high concentrations of forest-based enterprises, remains largely unrealised. Key barriers include fragmented ownership structures, limited policy coordination, and insufficient linkages between industrial park operators and forest-based sector enterprises.

The paper concludes that targeted industrial real estate development, supported by appropriate policy instruments, could serve as a strategic enabler for bioeconomy cluster formation in Bulgaria. Recommendations are offered for policymakers, regional development agencies, and private investors.

Keywords: bioeconomy clusters, industrial real estate, forest-based sector, Bulgaria, cluster theory, regional development, sustainable economy

INTRODUCTION

The transition to a bioeconomy has become one of the top priorities of the European Union's economic and environmental policy. The updated EU Bioeconomy Strategy (European Commission, 2018) sees the bioeconomy as a means of reconciling economic growth, environmental sustainability and rural development through biological resources. The forestry and wood-processing sector is particularly important in countries such as Bulgaria, where forests cover over one third of the territory (Executive Forest Agency, 2023). It is here that two processes that are rarely considered together intersect: the development of biological resources and the development of the real estate market.

The formation of bioeconomic clusters is being established as a key strategy for realizing the potential of biological resources at the regional level (Porter, 1990). However, clusters do not arise by themselves. One dimension of their formation remains relatively poorly studied and that is the role of physical infrastructure and in particular industrial properties. Without suitable and accessible industrial areas, even resource-rich regions fail to attract and retain the enterprises necessary to build a functioning bioeconomic cluster, as a result of which the potential of the raw material base remains unexploited.

Bulgaria is a particularly suitable subject for research in this regard. On the one hand, it has significant forest resources, and on the other hand, a dynamically developing industrial

property market. These two areas are usually not studied together, and their intersection has not received sufficient attention in the studies of Bulgarian authors. This study attempts to partially fill this gap by developing a conceptual framework linking industrial properties with the development of bioeconomic clusters.

The report is structured in an introduction, four thematic sections including a literature review, a conceptual framework, the current state of the industrial property sector and market, barriers and enabling conditions, and a conclusion with recommendations for policies that can be implemented.

1. Literature review and theoretical framework

The theoretical basis of this report is built on Porter's cluster theory (Porter, 1990, 1998). It identifies the geographical concentration of interconnected firms and institutions as a key driver of competitive advantage, and was later supplemented by contributions from economic geography and bioeconomic. All of these are summarized in a tabular form for the purposes of this paper (Table 1).

Table 1. Key theoretical contributions

Author(s), year	Key contribution
Marshall, 1890	Agglomeration economies from industrial areas
Porter, 1990, 1998	Clusters and three mechanisms of competitive advantage
Krugman, 1991	New economic geography, scale and transport
Cooke, 2002	Clusters and regional innovation systems
Boschma & Martin, 2010	Evolutionary dynamics of regions
Piplani & Smith-Hall, 2021	Five schools of thought in the forest bioeconomy
Mihova & Nikolova-Alexieva, 2020	Business communities and bioeconomy in Bulgaria
Ivanov, 2019	230+ clusters in Bulgaria; low internationalization

What these contributions have in common is the emphasis on geographical proximity. It reduces transaction costs, facilitates knowledge exchange and creates a competitive environment that stimulates innovation. However, to achieve this, adequate physical infrastructure is required. This aspect often remains implicit in the cluster literature, although it is rarely treated as a stand-alone research variable. At the European level, bioeconomic clusters are usually seen as a tool for achieving the objectives of the EU Strategy, focusing on connecting biomass, processing industries and end markets in regional value chains.

For the purposes of the study, it is important to distinguish between the concepts of "industrial cluster" and "industrial park". The first is a functional economic concentration of interconnected enterprises; while the second concept denotes a physical, planned unit with certain boundaries and a management regime. In practice, the two structures are often intertwined. The park can serve as a physical place around which a functioning cluster can be formed over time, especially when its management purposefully attracts enterprises from related industries. For bioeconomy industries, proximity to raw material sources is an additional, specific location factor. It does not always coincide with the traditional criteria for the

development of industrial and logistics parks, oriented towards transport corridors and urban agglomerations.

2. Conceptual framework

Based on the literature review, this study proposes a conceptual framework that integrates three interrelated elements: (1) the availability and quality of the biological resource - in this case, forests and raw materials from wood processing; (2) the availability of suitable industrial properties in close proximity to the resource base or to key transport nodes; and (3) the institutional and policy conditions that facilitate the connection of the first two elements into a sustainable cluster structure.

The framework is based on the premise that in order to realize the bioeconomic potential of a region, the mere availability of raw materials is not enough. There is always a connecting link between the raw material base and the functioning cluster, which is the availability of physical infrastructure. When industrial properties in a given region are insufficient or fragmented, potential investors are forced to turn to alternative locations. Usually these are the logistics areas around city centres, which, however, lose the locational advantage of proximity to the resource. In this framework, industrial property performs two functions simultaneously: a physical location that makes the siting of a company technically possible, and a “catalyst” that, with targeted management, actively attracts complementary companies, such as suppliers, processors and logistics operators. In this way, the formation of a dense network of interconnections characteristic of mature clusters in Porter's sense is accelerated.

The institutional element of the framework encompasses the existence of a regional bioeconomy strategy, coordination between industrial park operators and sector associations, and access to financial instruments under the Recovery and Resilience Plan (RRP) or EU operational programmes. Without this third element, even a good match between resource and property remains a purely theoretical possibility.

3. Industrial properties and the potential for bioeconomic clusters in Bulgaria

Forest areas in Bulgaria cover over one third of the country's territory. For this reason, the forestry and wood-processing sector is traditional and has a significant place in regional economies, especially in the central and southern parts of the country, where the concentration of wood processing and furniture manufacturing enterprises is relatively high. Studies by Gateva et al. (Gateva et al., 2022; Georgieva & Georgieva, 2025) on the innovation potential of the furniture industry value chain show that the leading regions in terms of economic activity and innovation development are Ruse, Gabrovo, Dobrich and Yambol, with none of them being among the four largest cities in the country. However, the sector as a whole is characterized by low investment in innovation and limited digitalization.

The regions with the highest bioeconomic potential in terms of available raw materials do not always coincide with the regions with the most developed industrial property market. According to market consultants (Colliers International Bulgaria, 2025), it remains highly concentrated around Sofia and the main logistics corridors of the country.

The industrial and logistics property market in Bulgaria has seen significant growth in recent years, driven primarily by the demand for properties for logistics and light industry (Colliers International Bulgaria, 2025). The development of road infrastructure and proximity to

European transport corridors make the country an attractive destination for investments in warehousing and manufacturing facilities. However, a significant share of the new supply is concentrated around the capital, while areas with a concentration of forestry and wood-processing enterprises remain relatively less covered in terms of modern industrial infrastructure.

Industrial areas inherited from the period of the centrally planned economy still constitute a significant part of the supply in smaller cities. However, they often require substantial reconstruction and renovation. The comparison between the geographical distribution of forest resources and the location of modern industrial parks reveals a partial mismatch, which is both a challenge and an opportunity. Regions with a high concentration of forestry and wood-processing enterprises could benefit from targeted development of industrial properties tailored to their specific needs: wood storage spaces, biomass installations, areas for processing by-products. Such development could serve as a physical basis for the gradual formation of functioning bioeconomic clusters.

4. Barriers and enabling conditions

The analysis of the researched literature and the current state of industrial properties in Bulgaria outlines three key barriers to the development of bioeconomic clusters, but at the same time also identifies a corresponding set of favourable conditions (Table 2).

Table 2. Barriers and enabling conditions for bioeconomic cluster development

Barriers	Favourable conditions
Fragmented ownership, making it difficult to plan industrial zones	EU Strategy and Sector Strategy for the Agricultural Sector in the Bioeconomy (MAFF, 2021) - framework for targeted funding
Lack of coordination between parks, clusters and authorities - a factor also related to the low international activity of clusters (Ivanov, 2019)	Access to European funding (RRP, EU operational programmes)
Limited funding for modernization in peripheral regions compared to investments around the capital	Experience from Finland and Austria: public investments + active role of cluster organizations

It is significant that almost every barrier is reflected in a specific, already existing policy or financial instrument. The issue is therefore not so much in the lack of solutions as in their targeted and coordinated implementation precisely where the raw material base is rich and the industrial infrastructure is still underdeveloped.

5. Conclusion and policy recommendations

This report develops a conceptual framework linking industrial properties to the formation of bioeconomic clusters, applied to the Bulgarian context with a focus on the forestry and wood-processing sector. The analysis shows that despite the significant growth of the industrial property market in the country in recent years, its potential to serve as a location for

bioeconomic cluster development remains largely unrealized. The reason is primarily the spatial mismatch between regions with a rich resource base and regions with developed industrial infrastructure, as well as the limited institutional coordination between them.

From a policy perspective, the report suggests three lines of action. First, regional and national authorities can integrate criteria for proximity to a forest-biological resource in the planning and financing of new industrial zones, instead of relying solely on traditional logistical criteria. In addition, industrial park operators and cluster organizations can develop joint mechanisms for targeted attraction of companies from bioeconomic value chains, building on the initiatives for innovative development of the furniture industry (Georgieva & Georgieva, 2025). Last but not least, access to financing under European funds for regions with high bioeconomic potential but limited industrial infrastructure should be facilitated and targeted.

This report is conceptual in nature and is based on secondary sources and qualitative analysis. This is its main limitation. Future research could deepen the empirical basis of the proposed framework through quantitative analysis of the spatial correspondence between specific industrial zones and raw material sources, as well as through comparative case studies of successfully formed bioeconomic clusters in Central and Eastern European countries.

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REFERENCES:

1. Boschma, R., Martin, R. (Eds.) (2010): *The Handbook of Evolutionary Economic Geography*. Cheltenham: Edward Elgar Publishing. https://doi.org/10.4337/9781849806497
2. Colliers International Bulgaria (2025): *Real Estate Market Overview H1 2025: Bulgaria*. Sofia: Colliers International.
3. Cooke, P. (2002): *Knowledge Economies: Clusters, Learning and Cooperative Advantage*. London: Routledge. https://doi.org/10.4324/9780203445402
4. European Commission (2018): *A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment*. Updated Bioeconomy Strategy. Brussels: European Commission. https://doi.org/10.2777/792130
5. Gateva, N., Georgieva, D.V., Georgieva, T., Tsakova, I., Juknevičienė, V. (2022): *Assessing the innovation potential of the furniture industry value chain in Bulgaria*. 15th International Scientific Conference WoodEMA 2022 Proceedings, pp. 85–91.
6. Georgieva, T., Georgieva, D.V. (2025): *Cluster analysis of the furniture industry and agribusiness in Bulgaria: Innovation potential, challenges, and development opportunities*. 18th International Scientific Conference WoodEMA 2025 Proceedings "Wood for the Future: Integrating Sustainability across Industries", p. 163.
7. Ivanov, C. (2019): *Internationalization of Bulgarian Clusters*. Management of Organizations: Systematic Research, 82(1), 25–35. https://doi.org/10.1515/mosr-2019-0011
8. Krugman, P. (1991): *Geography and Trade*. Cambridge, MA: MIT Press.
9. Marshall, A. (1890): *Principles of Economics*. London: Macmillan.

10. Mihova, T.B., Nikolova-Alexieva, V.N. (2020): *Business communities — a factor of industry and bioeconomy development*. IOP Conference Series: Materials Science and Engineering, 878, 012070. https://doi.org/10.1088/1757-899X/878/1/012070
11. Piplani, M., Smith-Hall, C. (2021): *Towards a Global Framework for Analysing the Forest-Based Bioeconomy*. Forests, 12(12), 1673. https://doi.org/10.3390/f12121673
12. Porter, M.E. (1990): *The Competitive Advantage of Nations*. New York: Free Press.
13. Porter, M.E. (1998): *Clusters and the New Economics of Competition*. Harvard Business Review, 76(6), 77–90.
14. Executive Forest Agency (2023): *Annual Report of the Executive Forest Agency for 2023.* Sofia: IAG.
15. Ministry of Agriculture, Food and Forestry (2021): *Strategy for Strengthening the Role of the Agricultural Sector in the Bioeconomy.* Sofia: Ministry of Agriculture, Food and Forestry.

Author's address:
Chaparov, B.
Business, Investments, Real Estate, University of Economics - Varna, Bulgaria
Corresponding author: bchaparov@ue-varna.bg

TOWARDS SUSTAINABLE FORESTRY: A SYSTEMATIC REVIEW OF MANAGEMENT CONTROL INSTRUMENTS

Antoaneta Angelova-Stanimirova

Abstract: The forestry sector is increasingly challenged to balance economic profitability with the imperative to preserve environmental resources. To address these challenges, management control systems (MCS) help managers align financial targets with ecological sustainability by guiding decision-making, systematically monitoring operations, and providing and collecting data. Specifically, MCS integrate real-time data and structured feedback mechanisms. By doing so, MCS enables organisations to identify inefficiencies, assess regulatory compliance, and proactively address emerging environmental concerns while maintaining productivity. This paper systematically reviews the scientific literature on the instruments used in MCS within the forestry sector. This systematic review of the Scopus database from 2020 to March 2026 identified 14 relevant documents. Based on the analysis of these documents, five key categories of MCS instruments were identified: monitoring systems, performance measurement tools, predictive analytics, process and operational control tools, and sustainability-oriented tools. The review revealed that MCS in the forestry sector are evolving toward an integrated, data-driven, and sustainability-oriented approach. This paper contributes to the literature by offering a systematic classification of these instruments. Additionally, it systematised MCS instruments which can be used in the management practice of the forestry sector.
Keywords: control, management control systems, forestry sector

1. INTRODUCTION

Today, sustainability has become a key component in the strategies and policies of all economic sectors and organisations (Todorova & Gergova, 2025). It is particularly important for those involved in forestry, timber (Kostova, 2025), and transport (Todorova, 2012). The forestry sector is increasingly challenged to balance economic profitability with the imperative to preserve environmental resources (Krainovic et al., 2025). To address these challenges, management control systems (MCS) help managers align financial targets with ecological sustainability. MCS guides decision-making (Tian et al., 2024), systematically monitors operations (Henriques et al., 2024), and facilitates data provision and collection (Dombashov, 2025). These systems integrate real-time data (Gomes et al., 2026) and structured feedback mechanisms (Lambovska, 2018). By doing so, MCS enables organisations to identify inefficiencies, assess regulatory compliance, and proactively address emerging environmental concerns (Florêncio et al., 2023) while maintaining effectiveness (Dombashov, 2024) and productivity.

This paper provides a systematic review of the scientific literature indexed in the Scopus database concerning instruments used in MCS within the forestry sector.

Data collection followed the systematic approach outlined by Lambovska (2023). Data analysis was conducted by inductive and deductive reasoning.

2. METHODOLOGY

This study adopts the approach outlined by Lambovska (2023), which consists of three stages: planning, conducting, and reporting (Figure 1).

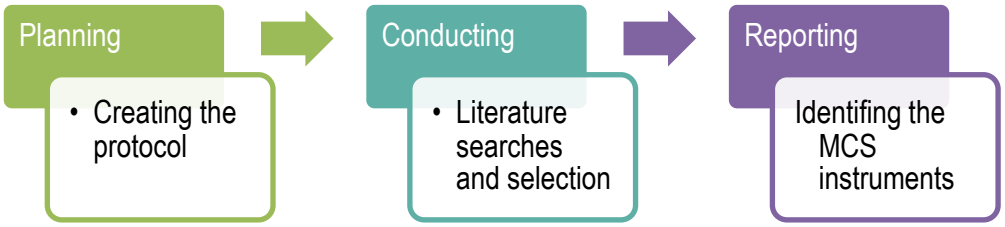

Figure 1. Research approach, adopted by Lambovska (2023)

During the planning stage, the protocol was created. The defined search source was the Scopus database. The search strategy included the field “Title, abstract and keywords”, and the period of 2020 to March 2026. The used search term was (("management control system" OR "management control") AND ("forest" OR "forestry" OR "wood")). Only open-access or available from the author in English records were included in the sample. 14 outcomes were identified within the required timeframe and constraints during the second stage. These results constute the sample in section Results. Stage three involved doing the analysis of the sample, systematising and summarising the results, and drawing conclusions. This stage combined analytical and synthetic reasoning to ensure a comprehensive understanding of the identified MCS instruments.

3. RESULTS

The study’s results are organised in Table 1. The columns of Table 1 contain the following information: document references and recognised MCS indications.

Table 1. A sample of the research

References	MCS indications
13	Monitoring, measure systems: ERT (electrical resistivity tomography), and TDR (time-domain reflectometry), data calibration
18	FSC certification, sustainability KPIs, reporting systems, stakeholder transparency
10	Operational control (effort tracking), resource allocation (time/person-hours), adaptive control
19	Monitoring & control of invasive species, field survey systems, density indicators
1	Remote sensing monitoring, forecasting models (ARIMA - Autoregressive Integrated Moving-Average), early warning indicators

20	Mass balance control models, resource allocation control (water), environmental monitoring
21	Predictive analytics (machine learning), early warning systems, data-driven control
9	Internal control systems, risk prediction models (PCA (Principal component analysis), Random Forest), control indicators (Z-score, ROA, ROE, etc.)
2	Environmental monitoring systems, pollution indicators, risk assessment tools
3	Process control (pyrolysis parameters), temperature control, resource efficiency metrics
26	Adaptive management, systemic vs symptomatic controls, preventive vs restorative controls
12	Simulation models, energy management control strategy, performance indicators (fuel consumption)
11	Optimisation models, control variables, dynamic programming (control optimisation)
22	Surveillance systems, performance monitoring, control programs (transferable MCS logic)

The reviewed literature indicated that MCS instruments in the forestry sector rely on a combination of management tools, with different authors emphasising specific instruments depending on their research focus.

Based on the analysis, five key categories of MCS instruments were identified: monitoring systems, performance measurement tools, predictive analytics, process and operational control tools, and sustainability-oriented tools (Table 2).

Table 2. Key categories of MCS instruments

№	Key categories of MCS instruments	References
1	Monitoring systems (ERT, remote sensing, sensors)	1, 2, 13, 19, 20, 22
2	Performance measurement (KPIs) (fuel, efficiency, emissions)	1, 2, 3, 9, 10, 11, 12, 18, 20
3	Predictive analytics (ML, ARIMA, simulation)	1, 9, 12, 21, 26
4	Process & operational control (optimisation, resource allocation)	3, 9, 10, 11, 12, 19, 20
5	Sustainability control tools (FSC, ESG indicators)	2, 3, 18, 26

Monitoring systems provide the data foundation for control processes through remote sensing and environmental measurement systems. Performance measurement tools focus on efficiency and resource optimisation through different indicators such as fuel consumption and emissions. Predictive analytics tools further enhance decision-making by enabling forecasting and risk assessment. Process and operational control tools improve resource allocation and production efficiency. Sustainability-oriented tools, such as FSC certification, support transparency, stakeholder engagement, and alignment with environmental objectives.

4. CONCLUSION AND DISCUSSION

This paper examined instruments used in management control systems (MCS) within the forestry sector in the scientific literature in the Scopus databases from 2020 to March 2026. The research sample comprised 14 documents. The systematic review revealed that MCS in the forestry sector are evolving toward an integrated, data-driven, and sustainability-oriented approach. The results indicated that MCS in this sector extend beyond traditional control mechanisms and incorporates a wide range of interdisciplinary tools.

The present research yields main insights and conclusions, as follows:

1) The results reveal that, over the period from 2020 to March 2026, there is a paucity of publications on the research topic (Table 1).

2) Five key categories of MCS instruments were identified: monitoring systems, performance measurement tools, predictive analytics, process and operational control tools, and sustainability-oriented tools.

3) The following conclusions can be drawn from this study:

- Some of the studies in the sample emphasise technical and monitoring-oriented tools, such as measurement systems, remote sensing, and simulation models. This indicates that MCS in this sector are grounded in engineering and environmental measurement approaches rather than traditional management tools.
- Performance measurement tools are based on operational and environmental indicators such as fuel consumption, emissions, and efficiency.
- The increasing use of predictive tools like machine learning, forecasting models, and simulations suggests a shift toward more proactive and data-driven control tools.
- Process and operational control tools are closely linked to optimisation and resource allocation. The studies in the sample highlight the importance of controlling production processes and resource flows. Hence, there is a strong connection between MCS and operations management.

This paper contributes to the literature by offering a systematic classification of the MCS instruments within the forestry sector. Additionally, these instruments can be used in the management practice of the forestry sector. Future research should further examine the interaction between different MCS instruments and their impact on organisational performance and sustainability outcomes.

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REFERENCES

1. Alkan, E., Aydin, A. (2024). Machine learning-based prediction of insect damage spread using auto-ARIMA model. *Croatian Journal of Forest Engineering*, 45 (2). https://doi.org/10.5552/crojfe.2024.2299
2. An, X., Li, W., Lan, J., Di, X., & Adnan, M. (2022). Seasonal co-pollution characteristics of parent-PAHs and alkylated-PAHs in karst mining area soil of Guizhou, Southwest

China. *Frontiers in Environment Science*, 10, 990471. https://doi.org/10.3389/fenvs.2022.990471

3. Charvet, F., Silva, F., Ruivo, L., Tarelho, L., Matos, A., Figueiredo da Silva, J., & Neves, D. (2021). Pyrolysis Characteristics of Undervalued Wood Varieties in the Portuguese Charcoal Sector. *Energies*, 14(9), 2537. https://doi.org/10.3390/en14092537
4. Dombashov, R. (2024). *Criteria for management control of forest sector enterprises*. In Proceedings of the WoodEMA 2024 - Green Deal Initiatives, Sustainable Management, Market Demands, and New Production Perspectives in the Forestry-Based Sector; 325–330.
5. Dombashov, R. (2025). *Challenges and opportunities in managing forestry industry enterprises with artificial intelligence*. In Proceedings of the WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers, 333-338.
6. Florêncio, M., Oliveira, L., & Oliveira, H. C. (2023). Management control systems and the integration of the Sustainable Development Goals into business models. *Sustainability*, 15(3), 2246. https://doi.org/10.3390/su15032246
7. Gomes, R., Chidozie, B. C., Matias, J. C. O., & Silva, R. G. (2026). Real-time IOT-enabled decision support for forest supply chains: an optimization-simulation approach to mitigating wildfire risk. *Forests*, 17(2), 279. https://doi.org/10.3390/f17020279
8. Henriques, N.S., Russo, T., Erzini, K., & Gonçalves, J.M.S. (2025). Improving monitoring, control and surveillance efforts through vessel tracking and fishery-dependent data. *Ocean & Coastal Management*, 269, 107789. https://doi.org/10.1016/j.ocecoaman.2025.107789
9. Huang, Z. (2022). A Hybrid Approach for Identification of Deficiencies in Enterprise Internal Control. *Wireless Communications and Mobile Computing*, 3022726. https://doi.org/10.1155/2022/3022726
10. Jenkins, D. M., Mecaskey, J.M., Knisely, C., Swab, R. M., & Stuble, K. L. (2025). Effort required for sustained management of non-native shrubs drops dramatically over time in a deciduous forest. *Ecological Solutions and Evidence*, 6, e70033. https://doi.org/10.1002/2688-8319.70033
11. Karlušić, J., Cipek, M., Pavković, D., Benić, J., Šitum, Ž., Pandur, Z., & Šušnjar, M. (2020). Simulation Models of Skidder Conventional and Hybrid Drive. *Forests*, 11(9), 921. https://doi.org/10.3390/f11090921
12. Karlušić, J., Cipek, M., Pavković, D., Šitum, Ž., Benić, J., & Šušnjar, M. (2020). Benefit Assessment of Skidder Powertrain Hybridization Utilizing a Novel Cascade Optimization Algorithm. *Sustainability*, 12(24), 10396. https://doi.org/10.3390/su122410396
13. Kašiar, M., Židó, J. & Homolák, M. (2025). Tree species and management controls on the water storage in forest soil and underlying slope deposits revealed by electrical resistivity tomography. *Central European Forestry Journal*, 71(2), 145-158. https://doi.org/10.2478/forj-2024-0027
14. Kostova, S. (2025). Key Indicators for Assessing Double Materiality in the Wood Industry. *WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers*, 477–482.
15. Krainovic, P.M., Brandão, D.O., Resende, A.F. et al. (2025). Current constraints to reconcile tropical forest restoration and bioeconomy. *Sustainability Science,* 20, 219–229. https://doi.org/10.1007/s11625-024-01573-8

16. Lambovska, M. (2018). A fuzzy model for team control and its application. *Management and Production Engineering Review*, 9(3), 108–119. https://doi.org/10.24425/119540
17. Lambovska, M. (2023). What is Behind the Shine? The Dark Side of Research Evaluation: A Conceptual Framework. *TEM Journal*, 12(4), 2552–2563. https://doi.org/10.18421/TEM124-67
18. Leite, J., Ribeiro, V., & Carmo, C. (2025). FSC certification in the sustainability management control systems: a case study of four wood trading companies. *IBIMA Business Review*, 419807. https://doi.org/10.5171/2025.419807
19. Lopez, L., Warren, A., Rhoades, S., Neely, S., Melvin, T., Moreno, A., Cook, D., Sparks, S., Sharp, P., & Collins, T. (2025). Distribution and densities of the invasive New Guinea flatworm (Tricladida: Geoplanidae) in forest conservation areas of the Miami Rock Ridge in Southeast Florida. *Florida Entomologist*, 108(s1), 20240021. https://doi.org/10.1515/flaent-2024-0021
20. Murphy, S. F., Runkel, R. L., Stets, E. G., Nolan, A. J., & Repert, D. A. (2024). Urbanization and water management control stream water quality along a mountain to plains transition. *Water Resources Research*, 60, e2023WR035633. https://doi.org/10.1029/2023WR035633
21. Puspasari, R.L., Yoon, D., Kim, H., Kim, K. (2023). Machine Learning for Flood Prediction in Indonesia: Providing Online Access for Disaster Management Control. *Economic and Environmental Geology*, 56 (1), 65-73. https://doi.org/10.9719/EEG.2023.56.1.65
22. Rajvanshi, H., Bharti, P.K., Nisar, S. et al. (2020). Study design and operational framework for a community-based Malaria Elimination Demonstration Project (MEDP) in 1233 villages of district Mandla, Madhya Pradesh. *Malaria Journal*, 19, 410. https://doi.org/10.1186/s12936-020-03458-4
23. Tian, Z., Xu, F., Nie, R. rt al. (2024). An adaptive consensus model for multi-criteria sorting under linguistic distribution group decision making considering decision-makers' attitudes. *Information Fusion*, 108 (C), 102406, https://doi.org/10.1016/j.inffus.2024.102406
24. Todorova, D. (2012). Competitiveness and sustainable development of ground transport. *Ikonomicheski Izsledvania*, *21*(3).
25. Todorova, D., & Gergova, N. (2025). Impact of Transport on Forests: A Concept for Sustainable Development. *WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers*, 111–116.
26. Wilman, E.A. (2021). Kelp Forests: Catastrophes, Resilience, and Management. *Frontiers in Ecology and Evolution*, 9, 674792. https://doi.org/10.3389/fevo.2021.674792

Authors address:
Angelova-Stanimirova, A.1
1 Chief Assist. prof. PhD at Department "Financial Control", University of National and World Economy, Sofia, Bulgaria
*Corresponding author: a.angelova@unwe.bg

INTRODUCING AN INNOVATIVE MODEL IN FORESTRY: INTEGRATING RISK, ECONOMICS, AND DIGITALIZATION FOR SUSTAINABLE FOREST MANAGEMENT

Todor Stoyanov, Nikolay Neykov

Abstract: The forestry sector is undergoing an unprecedented transformation driven by climate change, increasing wildfire occurrence, biodiversity decline, and the transition toward a circular bioeconomy. Traditional forest management approaches, primarily focused on timber production and post-disturbance recovery, are no longer sufficient to address complex ecological, economic, and social challenges. This paper proposes an innovative integrated framework – the Wildfire Risk & Economics Laboratory (WREL)—which combines wildfire risk assessment, economic valuation of forest ecosystem services and damages, and digital decision-support technologies in a unified management model. The framework integrates hazard, exposure, vulnerability, risk assessment, economic loss estimation, governance mechanisms, and prevention optimization, supported by GIS, remote sensing, UAV observations, and decision-support systems. Unlike conventional approaches, the proposed model shifts forest management from reactive fire suppression to proactive, adaptive, and economically optimized prevention. The study analyzes the conceptual architecture of the model and discusses its applicability under current European forest policies, including the EU Forest Strategy, the Green Deal, the Climate Adaptation Strategy, and the Circular Bioeconomy Strategy. The results show that integrating economic indicators with spatial risk modeling significantly improves the prioritization of preventive measures, resource allocation, and the long-term sustainability of forest ecosystems. The proposed framework contributes to the digital transformation of forestry and provides a basis for future AI-supported decision systems applicable at local, regional, and national governance levels.
Keywords: forestry innovation; wildfire risk; forest economics; decision-support systems; GIS; bioeconomy; sustainable forest management.

1. INTRODUCTION

European forests are increasingly exposed to multiple interacting disturbances associated with climate change, prolonged drought, insect outbreaks, and, in particular, extreme wildfire events. Over the past decade, the frequency, intensity, and spatial extent of wildfires have increased substantially, causing considerable economic losses, ecosystem degradation, and social impacts across Southern and Central Europe.

Traditionally, forest management has focused on timber production, silvicultural planning, and post-fire restoration. Although these approaches remain essential, they no longer adequately address the growing complexity of forest disturbances. Contemporary forestry requires the integration of ecological resilience, economic efficiency, technological innovation, and adaptive governance.

At the same time, European forest policy increasingly emphasizes prevention rather than suppression, ecosystem resilience rather than recovery, and evidence-based decision-making supported by digital technologies. These policy developments create a need for integrated

scientific models capable of linking forest risk assessment with economic valuation and decision-support tools.

The objective of this study is to propose a conceptual framework that integrates wildfire risk assessment, economic analysis, and digital technologies into a unified model for sustainable forest management.2. Literature Review

2. LITERATURE REVIEW

2.1. From Traditional Forestry to Integrated Forest Management

For decades, forest management primarily focused on sustained timber production, forest regeneration, and silvicultural practices. Although these principles remain fundamental, increasing climate-related disturbances have significantly broadened management objectives. Modern forestry now requires the simultaneous consideration of ecological resilience, economic efficiency, biodiversity conservation, and social well-being.

Among the various disturbance factors affecting European forests, wildfires represent one of the fastest-growing threats. The frequency and intensity of extreme wildfire events have increased considerably due to prolonged droughts, higher temperatures, and changes in land use. Consequently, forest management has gradually shifted from suppression-oriented approaches toward integrated risk management and prevention planning.

This transition is also reflected in recent European policy documents, including the EU Forest Strategy for 2030, the European Green Deal, the Climate Adaptation Strategy, and the Bioeconomy Strategy, all of which emphasize resilience, prevention, and digital transformation.

2.2. Risk Assessment in Forestry

Risk assessment has become one of the central components of contemporary forest management. Most existing methodologies evaluate wildfire risk through the interaction of three principal components: hazard, exposure, and vulnerability.

Hazard describes the probability of fire occurrence and fire behavior under given environmental conditions. It is influenced by climatic variables, fuel characteristics, topography, and ignition sources.

Exposure represents the presence of forest resources, infrastructure, human settlements, and ecosystem services that are potentially affected by wildfire.

Vulnerability reflects the susceptibility of exposed elements to damage and their capacity to recover after disturbance.

Although numerous wildfire risk assessment methodologies have been developed worldwide, many remain focused exclusively on biophysical indicators and do not adequately integrate economic consequences into the assessment process.

2.3. Economic Assessment of Forest Disturbances

The economic consequences of wildfires extend far beyond direct timber losses. Recent studies show that wildfire impacts include destruction of timber resources, damage to infrastructure, interruption of forest-based industries, loss of recreational opportunities, degradation of ecosystem services, reduction of carbon storage capacity, and long-term socioeconomic impacts on rural communities.

Traditional economic assessments often concentrate only on marketable timber. However, forests generate multiple ecosystem services whose value frequently exceeds the commercial value of harvested wood.

Consequently, comprehensive wildfire damage assessments should include direct economic losses, indirect economic losses, environmental damage, ecosystem service valuation, carbon emissions, biodiversity impacts, and social costs.

Such an integrated assessment enables better prioritization of preventive investments and more efficient allocation of financial resources.

2.4. Digital Transformation of Forestry

Digital technologies have become a key driver of innovation in forestry. Recent advances include Geographic Information Systems (GIS), remote sensing, LiDAR, UAV-based monitoring, artificial intelligence, machine learning, the Internet of Things (IoT), digital twins, and decision support systems (DSS).

These technologies provide continuous monitoring of forest conditions, improve spatial accuracy, and enable real-time assessment of wildfire hazards. Nevertheless, existing digital platforms often operate independently of economic analyses and policy frameworks, limiting their practical applicability in strategic forest management.

2.5. Research Gap

Despite substantial scientific progress in wildfire modeling, forest economics, and digital forestry, relatively few studies integrate these components into a single operational framework. Most existing approaches address only individual aspects such as wildfire hazard modeling, economic valuation, remote sensing, and forest governance.

The lack of integration among these disciplines limits the ability of decision-makers to optimize prevention strategies and efficiently allocate resources. This study addresses this gap by proposing an integrated conceptual model that combines wildfire risk assessment, economic valuation, digital technologies, and governance mechanisms in a unified decision-support framework.3. Materials and Methods

3. MATERIALS AND METHODS

3.1. Conceptual Framework

The proposed framework, called the Wildfire Risk & Economics Laboratory (WREL), is an integrated conceptual model that links ecological risk assessment with economic analysis and digital decision support.

Unlike traditional forestry approaches, the WREL model treats wildfire management as a continuous decision-making process rather than a set of isolated activities.

The model consists of eight interconnected modules: Hazard Assessment, Exposure Assessment, Vulnerability Assessment, Integrated Risk Assessment, Economic Loss Assessment, Governance and Organization, Digital Decision Support, and Prevention Optimization.

These modules are linked through continuous feedback loops that support adaptive forest management.

3.2. Hazard Assessment

The hazard component evaluates the probability of wildfire occurrence and potential fire behavior.

Key variables include climatic conditions, fuel characteristics, vegetation type, topography, historical wildfire occurrence, and ignition probability.

Spatial analyses are conducted using GIS-based modeling supported by remote sensing products.

3.3. Exposure Assessment

Exposure includes all forest resources that may be affected by wildfire.

These include forest stands, timber resources, infrastructure, settlements, protected areas, ecosystem services, industrial facilities, and cultural heritage.

Each component is assigned a spatially explicit value to enable subsequent economic analysis.

3.4. Vulnerability Assessment

Vulnerability is evaluated using both ecological and socioeconomic indicators.

Ecological indicators include stand structure, species composition, regeneration capacity, and forest health.

Socioeconomic indicators include economic dependence, management capacity, institutional preparedness, and emergency response capability.

3.5. Integrated Risk Assessment

Risk is calculated as Risk = Hazard × Exposure × Vulnerability.

The resulting risk values are classified into categories ranging from very low to very high, supporting the prioritization of preventive measures and investment planning.

3.6. Economic Loss Assessment

Unlike traditional forest management models, which primarily evaluate direct timber losses, the WREL framework provides a comprehensive economic assessment of wildfire impacts by integrating market and non-market values of forest ecosystems.

The methodology distinguishes among direct, indirect, environmental, and social losses, providing a holistic representation of wildfire consequences.

Direct economic losses include timber and biomass destruction, damage to forest infrastructure, losses of machinery and equipment, damage to nurseries and plantations, and suppression costs.

Indirect economic losses include interruption of forest production, reduced timber supply, disruption of forest-based industries, tourism losses, reduced recreational income, and increased management costs.

Environmental losses include ecosystem service degradation, biodiversity loss, soil degradation, carbon stock reduction, deterioration of watershed protection, and landscape fragmentation.

Social losses include health impacts, reduced employment, demographic decline in rural areas, reduced quality of life, and impacts on cultural heritage.

An innovative component of the framework is the application of the perpetual rent approach to estimate the long-term economic value of destroyed forest ecosystems. Unlike conventional valuation methods that focus solely on timber market prices, the perpetual rent

approach estimates the present value of future ecosystem benefits that are permanently lost due to catastrophic wildfire.

This enables forest managers to quantify the long-term economic consequences of wildfire events and justify increased investment in prevention.

3.7. Governance and Decision Support

Effective wildfire management extends beyond ecological assessment and requires coordinated governance involving multiple stakeholders and institutional levels. The proposed WREL framework incorporates governance as an independent analytical component that links scientific knowledge to policy implementation. The governance module includes national forest administrations, regional forest enterprises, municipalities, civil protection authorities, research institutions, forest owners, local communities, and policymakers. Decision-making is supported through continuous information exchange between scientific assessment and policy implementation. The framework therefore adopts the principles of multilevel governance, in which strategic decisions are based on scientific evidence rather than reactive emergency responses.

3.8. Digital Decision Support

Digitalization is one of the main innovations of the proposed framework. The Decision Support System integrates GIS databases, satellite observations, UAV monitoring, meteorological information, fuel maps, forest inventory data, economic databases, and policy indicators. These data are processed within an integrated analytical environment that produces real-time spatial risk maps and economic prioritization scenarios. The system enables dynamic updating of risk indicators and supports adaptive forest management under changing climatic conditions. Future developments will incorporate artificial intelligence algorithms for automatic wildfire prediction and optimization of preventive investments.

3.9. Prevention Optimization

The final module of the framework focuses on optimizing preventive investments. Traditional wildfire management allocates substantial financial resources to suppression after wildfire occurrence. The proposed approach reverses this logic by evaluating prevention as an investment rather than an expenditure. Cost-benefit analysis is applied to compare expected wildfire losses, prevention costs, avoided damages, ecosystem resilience gains, and long-term economic benefits. The optimization procedure identifies the level of preventive investment at which total societal costs are minimized. This approach supports evidence-based allocation of limited public resources and contributes to more sustainable forest governance.

4. RESULTS

The proposed WREL framework shows that integrating ecological risk assessment with economic valuation substantially improves forest management efficiency. The model establishes a continuous analytical chain:

Hazard → Exposure → Vulnerability → Risk → Economic Loss → Governance → Decision Support → Prevention Optimization

Unlike conventional wildfire management models, the proposed framework explicitly incorporates economic indicators at every stage of the decision-making process. This enables

forest managers to identify not only areas with the highest wildfire probability but also those where preventive measures yield the greatest economic return. Consequently, prevention priorities become economically justified rather than solely hazard-based.

4.1. Scientific Innovation

The principal innovation of the proposed model lies in the integration of disciplines that have traditionally evolved independently. The framework combines wildfire science, forest economics, ecosystem service valuation, digital forestry, governance, policy analysis, and decision-support systems. This interdisciplinary integration provides a significantly broader analytical capacity than existing wildfire assessment methodologies.

4.2. Practical Applicability

The WREL framework can support decision-making at multiple governance levels.

Forest enterprise level: prioritization of preventive measures; optimization of harvest planning; economic justification of investments.

Regional level: spatial risk mapping; resource allocation; coordination among forest administrations.

National level: development of prevention policies; budgeting; strategic planning; climate adaptation.

European level: harmonization of wildfire risk methodologies; support for the EU Forest Strategy; implementation of Green Deal objectives; bioeconomy planning.

Table 1. Comparison between conventional and WREL-based forest management

Conventional forestry	**WREL integrated model**
Timber-oriented	Risk-oriented
Reactive	Preventive
Separate ecological assessment	Integrated ecological-economic assessment
Static planning	Adaptive management
Manual analysis	Digital decision support
Post-fire recovery	Prevention optimisation
Local information	Multi-level governance
Limited economic analysis	Full economic valuation of ecosystem services

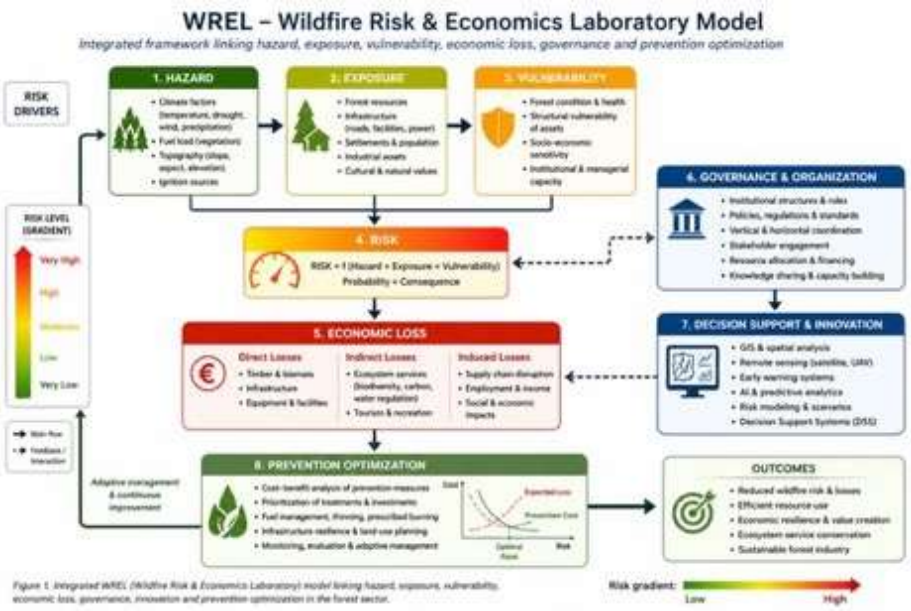

Figure 1. Conceptual architecture of the Wildfire Risk & Economics Laboratory (WREL)

5. DISCUSSION

5.1. Towards a New Paradigm in Forest Management

The growing complexity of forest disturbances requires a fundamental transformation of conventional forest management. Climate change, extreme wildfires, biodiversity decline, and growing socioeconomic pressures show that traditional systems focused on timber production and post-disturbance recovery are no longer sufficient.

The proposed Wildfire Risk & Economics Laboratory (WREL) represents a conceptual shift from reactive management to adaptive, knowledge-based, economically optimized forest governance. Unlike existing approaches, which typically analyze wildfire hazard, economic losses, or governance separately, WREL integrates these components into a single analytical framework that supports strategic decision-making. This integration enables forest managers not only to estimate wildfire probability but also to evaluate the economic consequences of alternative management scenarios before disturbances occur.

5.2. Integration of Economics into Wildfire Risk Assessment

One of the principal scientific contributions of the proposed framework is the direct incorporation of economic valuation into wildfire risk assessment. Most existing wildfire models conclude with the calculation of hazard or risk indices, leaving decision-makers to determine priorities largely based on expert judgment.

The WREL framework introduces an additional analytical layer by translating ecological risk into measurable economic consequences. This enables the prioritization of prevention investments, optimization of limited financial resources, comparison of management alternatives, estimation of avoided losses, and support for evidence-based policymaking. The

proposed methodology thus transforms wildfire risk assessment from a descriptive instrument into a strategic economic planning tool.

5.3. Digital Transformation of Forest Governance

Digitalization is rapidly becoming one of the most influential drivers of innovation in forestry. The integration of Geographic Information Systems, remote sensing, UAV technologies, artificial intelligence, digital twins, cloud computing, and decision support systems is creating entirely new opportunities for forest management. However, technological innovation alone does not guarantee better decisions.

The WREL framework shows that digital technologies become significantly more valuable when combined with ecological indicators, economic valuation, and governance mechanisms. Instead of producing isolated datasets, digital tools become part of an integrated decision-making environment that supports adaptive management.

5.4. Contribution to Circular Bioeconomy

The proposed framework also contributes to the development of the circular forest bioeconomy. Wildfires cause substantial losses of biomass resources that could otherwise support sustainable wood-based industries, renewable energy production, and bio-based products.

Reducing wildfire impacts therefore increases biomass availability, resource efficiency, carbon storage, ecosystem resilience, and the long-term economic competitiveness of the forest sector. Consequently, wildfire prevention should be regarded not only as an environmental activity but also as an investment that supports the transition to a circular bioeconomy.5.5. Policy Implications

Recent European policy documents increasingly emphasize resilience, climate adaptation, and integrated forest governance.

The proposed framework directly supports implementation of the EU Forest Strategy for 2030, the European Green Deal, the EU Climate Adaptation Strategy, the EU Biodiversity Strategy, the Circular Bioeconomy Strategy, and the Fire-Adapted Europe initiative.

By integrating scientific assessment with economic optimization, WREL provides practical support for evidence-based policymaking at local, regional, national, and European levels of governance.

6. SCIENTIFIC CONTRIBUTIONS

The proposed framework advances forestry research in several ways.

Theoretical contributions: Development of a novel conceptual framework that integrates wildfire science, economics, and digital forestry; expansion of wildfire risk assessment through the incorporation of economic valuation; integration of ecosystem service economics into strategic forest management; and introduction of adaptive governance principles into wildfire decision making.

Methodological contributions: Development of an integrated risk–economics assessment model; combination of GIS, remote sensing, and economic analysis; introduction of prevention optimization based on cost-benefit analysis; and integration of multilevel governance into wildfire management.

Practical contributions: A decision-support framework applicable to forest enterprises; prioritization of preventive investments; support for national wildfire strategies; improved

allocation of public resources; and a foundation for future AI-driven forest management systems.

7. CONCLUSIONS

The forestry sector is entering a period of unprecedented transformation driven by climate change, increasingly frequent disturbance regimes, and rapid technological development.

Traditional forest management approaches are increasingly insufficient for addressing the complex interactions among ecological, economic, and social processes.

This study proposes an innovative conceptual framework – the Wildfire Risk & Economics Laboratory (WREL)—that integrates wildfire risk assessment, economic valuation, digital technologies, and governance into a unified decision-support model.

The framework introduces several important innovations.

First, it extends conventional wildfire risk assessment by incorporating comprehensive economic evaluation, including direct, indirect, and ecosystem service losses.

Second, it integrates advanced digital technologies with economic indicators, creating an adaptive analytical platform capable of supporting evidence-based decision making.

Third, it introduces prevention optimization as a core management principle, demonstrating that investments in prevention can substantially reduce long-term economic losses while increasing ecosystem resilience.

The proposed framework contributes simultaneously to forest science, forest economics, and digital forestry, providing a basis for future interdisciplinary research and practical implementation.

Future research should focus on developing operational software platforms, artificial intelligence applications, digital twins of forest ecosystems, and real-time decision-support systems capable of assisting forest managers under rapidly changing environmental conditions.

The WREL framework represents a significant step toward a new generation of integrated forest management models, supporting the transition from reactive wildfire suppression to proactive, economically justified, climate-resilient forest governance.

Future Research

The next stage of the WREL concept will include artificial intelligence for wildfire prediction; digital twins of forest ecosystems; real-time monitoring through UAVs and satellites; economic optimization algorithms; integration with European Copernicus services; carbon accounting; climate adaptation indicators; multihazard risk assessment; forest resilience indicators; and cloud-based decision-support systems.

REFERENCES

1. Bowman, D. M. J. S., et al. (2020). Vegetation fires in the Anthropocene. Nature Reviews Earth & Environment, 1(10), 500–515.

2. Jones, M. W., et al. (2022). Global and regional trends and drivers of fire under climate change. Reviews of Geophysics, 60(3).

3. JRC. (2024). Forest Fires in Europe, Middle East and North Africa 2023. European Commission.

4. San-Miguel-Ayanz, J., et al. (2023). European Forest Fire Information System (EFFIS): Annual Report. European Commission.
5. Pearce, D. (2001). The Economic Value of Forest Ecosystems.
6. Costanza, R., et al. (2014). Changes in the global value of ecosystem services. Global Environmental Change, 26, 152–158.
7. TEEB. (2010). The Economics of Ecosystems and Biodiversity.
8. Daily, G. C. (Ed.). (1997). Nature's Services: Societal Dependence on Natural Ecosystems.
9. Millennium Ecosystem Assessment. (2005).
10. IPBES. (2019). Global Assessment Report.
11. de Groot, R., et al. (2012). Global estimates of ecosystem services. Ecosystem Services, 1.
12. IPCC. (2023). AR6 Synthesis Report.
13. IPCC. (2022). Impacts, Adaptation and Vulnerability.
14. FAO. (2022). The State of the World's Forests.
15. FAO. (2024). Global Forest Resources Assessment.
16. Forest Europe. (2020). State of Europe's Forests.
17. European Commission. (2021). EU Forest Strategy for 2030.
18. European Commission. (2019). European Green Deal.
19. European Commission. (2021). EU Adaptation Strategy.
20. European Commission. (2020). EU Biodiversity Strategy 2030.
21. European Commission. (2018). Bioeconomy Strategy.
22. White, J. C., et al. (2016). Remote sensing technologies for enhancing forest inventories.
23. Puliti, S., et al. (2020). UAV applications in forest inventories.
24. Torresan, C., et al. (2017). Forestry applications of UAVs.
25. Liang, X., et al. (2018). Forest remote sensing using UAVs.
26. Eastman, J. R. (2020). TerrSet Manual.
27. Burrough, P., & McDonnell, R. (2015). Principles of GIS.
28. Power, D. J. (2002). Decision Support Systems.
29. Shim, J., et al. (2002). Past, present and future of DSS.
30. Turban, E., et al. (2021). Decision Support and Intelligent Systems.
31. Goodfellow, I., et al. (2016). Deep Learning.
32. Russell, S., & Norvig, P. (2021). Artificial Intelligence: A Modern Approach.
33. Holzinger, A. (2022). Explainable AI.
34. European Commission. (2018). Sustainable Bioeconomy.
35. Hetemäki, L., et al. (2017). Leading the way to a European Circular Bioeconomy Strategy.Seidl, R., et al. (2017). Forest disturbances under climate change.
36. Johnstone, J. F., et al. (2016). Changing disturbance regimes.
37. Stephens, S. L., et al. (2013). Managing forests and fire.
38. Moritz, M. A., et al. (2014). Learning to coexist with wildfire.
39. Moreira, F., et al. (2020). Wildfire management in Europe.
40. Stoyanov, T. (2024). Preliminary Assessment of the Wildfire Risks as a Tool for Their Management – The Case of Bulgarian Forests. Springer. (Това трябва да е основният методологичен източник за раздела по оценка на риска.)

41. Stoyanov, T. (2025). Пожари в горските територии – законодателство, управление и превенция.
42. Stoyanov, T., Neykov, N. (2026). Economics, Organization and Management of the Forest Industry under Increasing Wildfire Risk.
43. Stoyanov, T. Integrated Wildfire Risk Assessment Methodology.
44. Stoyanov, T. Wildfire Damage Assessment Methodology.
45. Copernicus Emergency Management Service;
46. European Forest Fire Information System (EFFIS);
47. Sendai Framework for Disaster Risk Reduction 2015–2030;
48. UNDRR Global Assessment Report 2023;
49. OECD (2023). Building Climate Resilience.

OPERATIONAL RESEARCH METHODS FOR HYBRID GOVERNANCE OF INNOVATION PROJECTS IN WOOD PRODUCT MARKETS

Henrieta Hrablik Chovanová, Martin Hirtl, Alena Pauliková

Abstract: Innovation in wood product markets increasingly depends on the quality of managerial decisions concerning project selection, resource allocation, production changes, logistics and time-to-market. This paper explores how operational research methods can strengthen hybrid project management in the forest- and wood-based sector by connecting analytical rigor with adaptive project execution. It argues that hybrid governance becomes substantially more robust when classical planning and agile implementation are supported by network analysis, multi-criteria decision-making, optimization, simulation, resource analysis and selected quality-oriented methods. These approaches can support portfolio prioritization, evaluation of innovation alternatives, capacity balancing, supplier and technology selection, distribution design, and risk-informed decision-making under market uncertainty. The paper does not treat operational research as a purely technical add-on; rather, it frames it as a managerial architecture for evidence-based decisions across the wood product value chain. Drawing on long-term research in project maturity, managerial decision-making, quantitative methods and industrial applications of operational research, the paper proposes an integrative framework for wood-sector enterprises seeking to combine flexibility, transparency and market responsiveness. The main contribution lies in showing how hybrid project management and operational research can jointly improve project success, innovation outcomes and competitiveness in bioeconomy-oriented wood product markets.
Keywords: operational research, hybrid project management, innovation projects, wood product markets, bioeconomy, decision support

1. INTRODUCTION

Wood product markets are undergoing structural change as forest-based industries are expected to contribute to a competitive and sustainable bioeconomy, climate neutrality and circular substitution of fossil-based materials. These pressures create opportunities for engineered wood products, wood-based construction, biocomposites, packaging and circular business models, but they also increase the complexity of managerial decisions across product development and market introduction (European Commission, 2018; European Commission, 2021; FAO, 2024; Verkerk et al., 2022).

Innovation projects in the forest- and wood-based sector rarely follow a stable, linear path. They are exposed to uncertainty in raw material supply, certification and regulation, energy prices, customer requirements and production technology. Enterprises must simultaneously protect investment discipline, maintain product quality and coordinate several value-chain actors. This tension requires governance models that combine structured planning with adaptive execution.

Hybrid project management responds to this need by combining classical planning and decision gates with iterative learning and short feedback cycles. Hybrid logic is particularly useful when the project's technical core requires careful planning while market requirements and product features remain open to learning during implementation (Cooper, 2014; Cooper and Sommer, 2016a; Cooper and Sommer, 2016b; Conforto et al., 2016).

Hybrid governance needs analytical decision support, which operational research provides through optimization, network analysis, scheduling, simulation, multi-criteria decision-making and risk analysis (Hillier and Lieberman, 2021; Taha, 2017).

The objective of this paper is to propose an integrative framework showing how operational research methods can strengthen hybrid governance of innovation projects in wood product markets. The paper addresses three research questions: (1) which decision problems in wood product innovation are most suitable for operational research support, (2) how can these methods be integrated into hybrid project governance, and (3) what managerial benefits and implementation conditions can be expected. The contribution is conceptual and managerial: it positions operational research not as an isolated technical toolkit, but as a decision architecture that links strategy, project execution and market responsiveness.

2. CONCEPTUAL BACKGROUND

2.1. Hybrid governance of innovation projects

Hybrid project governance combines plan-driven and agile principles in one system. Plan-driven elements provide milestones, documentation and accountability. Agile elements increase responsiveness through iterative refinement, stakeholder feedback and team-based learning. This combination reflects the shift towards value delivery, adaptability and outcome orientation (Project Management Institute, 2021; Project Management Institute and Agile Alliance, 2017).

In product innovation, the hybrid form commonly appears as Agile-Stage-Gate models. Stage-Gate contributes discipline in screening, business-case assessment, resource approval and launch readiness, while agile practices support experimentation and adaptation inside stages (Cooper and Sommer, 2016a; Cooper and Sommer, 2016b).

The weakness of many hybrid approaches is that the link between governance meetings and analytical evidence remains underdeveloped. A project board may approve a portfolio, select suppliers or allocate capacity mainly through experience and negotiation. Experience is valuable but can be biased when alternatives are numerous, trade-offs conflict and uncertainty is high. Operational research can therefore strengthen hybrid governance by converting project questions into explicit decision models.

2.2. Operational research as managerial decision architecture

Operational research is the systematic modelling and analysis of decision problems. It supports managers by defining alternatives, constraints, criteria and uncertainty assumptions. For innovation projects, the most relevant methods include network analysis, linear and integer programming, scheduling, simulation, decision trees, multi-criteria decision analysis and sensitivity analysis (Belton and Stewart, 2002; Hillier and Lieberman, 2021; Hwang and Yoon, 1981; Saaty, 1980; Taha, 2017).

Multi-criteria methods such as AHP, TOPSIS and scoring models evaluate alternatives against technical, market, financial, sustainability and strategic criteria, while optimization supports resource allocation, capacity balancing, supplier assignment, procurement and distribution design. CPM and PERT reveal critical tasks and improve schedule transparency, and simulation tests production bottlenecks, lead-time variability and demand scenarios (Law, 2015; Pinedo, 2016).

The managerial value of operational research lies not only in optimal numerical results but also in structuring dialogue, revealing trade-offs and documenting the rationale for

decisions. Operational research thus complements hybrid project management by providing analytical content for gates, sprint reviews, portfolio meetings and risk reviews.

2.3. Specific decision context of wood product markets

The wood product value chain makes analytical decision support particularly relevant. Forest-based supply chains connect biological resources, harvesting, sawmilling, engineered wood products, construction and recycling. Planning horizons range from short-term dispatching and production sequencing to long-term forest and investment planning (D'Amours et al., 2008; Rönnqvist, 2003).

Optimization and decision support tools have already been used in forestry and forest products for wood-flow planning, supply chain coordination, transportation, production planning and tactical-operational decision-making (Carlsson and Rönnqvist, 2005; D'Amours et al., 2008; Rönnqvist, 2003).

Innovation in wood product markets therefore requires a governance logic that connects market opportunity, technological feasibility, supply-chain capability, sustainability performance and time-to-market. Operational research helps managers integrate these dimensions.

3. PROPOSED INTEGRATIVE FRAMEWORK

The framework assumes that hybrid governance requires both a process layer and an analytical layer. The process layer defines project stages, agile iterations, decision gates and responsibilities. The analytical layer defines the decision models used wherever managers must select, prioritize, allocate or adapt. Figure 1 illustrates this framework.

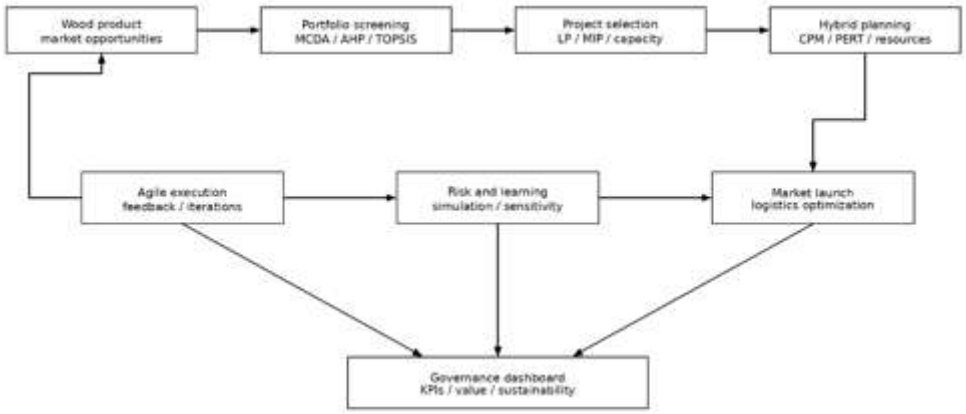

Figure 1. Integrative framework for OR-supported hybrid governance of innovation projects in wood product markets

The framework begins with market opportunities generated by customer demand, regulation, material substitution and digital technologies. Multi-criteria decision-making screens these opportunities, because early alternatives differ in expected profitability, technical risk, sustainability value, production compatibility and strategic fit. The result is a transparent argument for why certain ideas enter the portfolio, not simply a ranked list.

After screening, project selection and capacity allocation can be supported by optimization models. For example, an enterprise may need to decide which projects to approve under

budget, labour, machine-hour and supplier constraints. A linear or mixed-integer programming model can support the portfolio gate by showing feasible combinations of projects and the opportunity costs of resource constraints. This is particularly valuable when several product innovations compete for the same kiln capacity, engineering staff, testing facilities or marketing budget.

During planning, network analysis and scheduling translate the approved project into tasks, precedence relationships and resource requirements. CPM identifies critical activities, while PERT or simulation represents uncertainty in task durations. During execution, agile iterations provide learning, while the analytical layer updates priorities, resources, risk exposure and launch options.

4. OPERATIONAL RESEARCH METHODS ACROSS THE PROJECT LIFE CYCLE

Operational research methods can be linked to the project life cycle to support both formal governance and agile learning. Table 1 summarizes the major decision problems, suitable methods and governance use across the innovation project life cycle. Their selection should depend on project scale, data availability and uncertainty, not mechanical application.

Table 1. Operational research methods supporting hybrid governance across the innovation project life cycle

Project phase	Typical decision problem	Suitable OR methods	Governance use
Opportunity identification	Which market or technology opportunity to explore?	Trend analysis, scenario analysis, MCDA	Pre-screening and strategic fit discussion
Idea evaluation	Most attractive concept under several criteria?	AHP, TOPSIS, weighted scoring, QFD	Transparent ranking of alternatives
Portfolio selection	Which projects to fund with limited resources?	Linear and integer programming, knapsack models	Investment gate and resource approval
Feasibility analysis	Expected value and risk of the innovation?	Decision trees, sensitivity analysis, Monte Carlo simulation	Business-case validation
Project planning	Feasible activity sequence and durations?	CPM, PERT, network analysis	Baseline schedule and critical path control
Resource planning	How to allocate labour, machines and materials?	Resource-constrained scheduling, LP/MIP, queuing models	Capacity balancing and bottleneck reduction
Supplier and technology selection	Which suppliers, equipment or technologies to select?	MCDA, assignment models, total-cost optimization	Procurement gate and partner selection
Production and logistics design	How to configure production and distribution?	Simulation, transportation	Launch readiness and operational robustness

		models, facility-location models	
Monitoring and adaptation	When to adapt, accelerate or stop the project?	KPI dashboards, earned value, control charts, risk matrices	Sprint review, gate review, corrective action

Operational research is most valuable when embedded in governance routines: a portfolio committee may use MCDA to justify why a cross-laminated timber product line receives priority over a lower-risk packaging project and a project board may use simulation to test whether a new production concept meets launch volumes.

In a hybrid system, these methods are used iteratively: early models may be simple because information is incomplete and are later refined with production data, pilot tests and market feedback. The model evolves with the project, preserving agility and decision discipline.

5. MANAGERIAL IMPLICATIONS FOR WOOD PRODUCT MARKETS

The framework has several implications for wood-sector managers. First, it encourages portfolio transparency. Innovation opportunities in furniture, engineered wood or packaging often compete for capital, production capacity and managerial attention. MCDA and optimization help clarify how each project contributes to market growth and operational feasibility.

Second, it improves resource allocation. Wood product innovation often depends on shared resources such as testing laboratories, drying capacity or press lines. A resource model can reveal overloads and show whether the portfolio is realistic. This is particularly important in small and medium-sized enterprises, where informal planning can hide bottlenecks.

Third, MCDA can structure supplier and technology selection for new adhesives, machinery or recycling partners. Optimization can estimate total cost and capacity implications. Simulation and sensitivity analysis help managers understand market uncertainty before full-scale launch.

Table 2. Examples of operational research support in wood product innovation contexts

Innovation context	Managerial decision	OR support
Engineered wood products	Balancing structural performance, certification, capacity and launch timing	AHP for concept selection; CPM/PERT for certification and testing; simulation for capacity ramp-up
Furniture and interior products	Selecting variants and customization options under cost and lead-time constraints	MCDA for design alternatives; scheduling for prototype cycles; optimization for batch and material planning
Wood-based panels and composites	Choosing technology, raw material mix and production parameters	Optimization for input mix; simulation for line performance; sensitivity analysis for energy and raw-material prices

Packaging and fibre-based products	Prioritizing sustainable product concepts and distribution channels	Scoring models for sustainability-market fit; transportation models for distribution design
Circular and recycled wood products	Integrating recycled inputs, suppliers and reverse logistics	Network models, supplier selection MCDA and scenario analysis

Project governance must also be connected with data governance, because OR models require reliable information on costs, capacities, task durations, supplier performance, market assumptions and sustainability indicators. Digitalization can improve data availability, but managers must define data ownership, model updates and interpretation of results (Molinaro and Orzes, 2022; Müller et al., 2019). A common decision model also supports communication between technical, production, marketing and financial actors because it makes criteria, constraints and trade-offs explicit, which matters where agile teams emphasize learning while senior management emphasizes budget control and investment justification.

6. DISCUSSION

The proposed framework extends existing research in three ways. First, it links hybrid project management with operational research more explicitly than traditional project governance models. OR methods can provide the decision spine of hybrid governance.

Second, the framework adapts operational research to the specific context of wood product markets. Previous OR research in forestry and forest products emphasized supply-chain planning, optimization and wood-flow coordination (Carlsson and Rönnqvist, 2005; D'Amours et al., 2008; Rönnqvist, 2003). The framework extends this foundation towards innovation project governance, adding portfolio prioritization, product design, supplier and technology selection, and market launch.

Third, the framework positions OR as a managerial architecture rather than a purely technical add-on. Enterprises without advanced analytics departments can still benefit from structured scoring models, simple optimization, risk matrices, scenario analysis and visual dashboards. Method sophistication should match organizational maturity and the value at stake.

Table 3. Expected managerial effects and implementation conditions

Governance capability	Expected managerial effect	Required conditions
Decision transparency	Criteria, assumptions and trade-offs are explicit	Clear criteria, documented data sources and participative review
Portfolio discipline	Projects are selected according to strategic value and constraints	Defined portfolio rules and comparable project information
Resource realism	Hidden bottlenecks are detected earlier	Reliable capacity data and updated resource calendars
Market responsiveness	Learning from customers can be translated into revised priorities	Short feedback cycles and model updates
Risk-informed launch	Uncertainty is tested before irreversible commitments	Scenario analysis, simulation and sensitivity review

The main limitation is that the framework is conceptual and requires empirical validation in wood-sector enterprises such as sawmills, furniture, panel and engineered wood producers. Future research should test the framework through case studies, action research and simulation-based experiments. A further limitation is data availability, since smaller enterprises may lack accurate data on durations, capacities or market scenarios.

Another practical challenge is the risk of false precision, because a model may appear objective even when its inputs are uncertain or politically influenced. OR-supported governance should therefore include sensitivity analysis and managerial discussion, improving the transparency and robustness of judgment rather than replacing it.

7. CONCLUSIONS

This paper proposed an integrative framework using operational research to strengthen hybrid governance of innovation projects in wood product markets. Bioeconomy-oriented wood markets require more than flexible execution and formal control: enterprises need an analytical decision architecture supporting project selection, resource allocation and market launch.

The first research question asked which decision problems are most suitable for OR support. The paper identified portfolio prioritization, project selection, feasibility assessment, scheduling, resource planning, supplier selection, production design, logistics and monitoring as key areas. The second question asked how these methods can be integrated into hybrid governance. The proposed answer is to embed OR methods into stage gates, agile reviews, portfolio meetings and dashboards, with models updated as the project learns. The third question concerned managerial benefits and implementation conditions. The framework suggests benefits in decision transparency, resource realism, market responsiveness and risk-informed launch, provided that data quality, stakeholder participation and managerial interpretation are ensured.

The main contribution is to show that operational research and hybrid project management are complementary: hybrid management provides the governance rhythm and operational research the analytical content of decisions. In competitive and sustainable bioeconomy markets, this combination supports better project success and competitiveness.

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REFERENCES

1. Agile Alliance (2001): Manifesto for Agile Software Development. Agile Alliance.
2. Belton, V.; Stewart, T.J. (2002): Multiple Criteria Decision Analysis: An Integrated Approach. Kluwer Academic Publishers, Boston.
3. Boehm, B.; Turner, R. (2005): Management challenges to implementing agile processes in traditional development organizations. IEEE Software 22 (5): pp. 30-39. DOI: 10.1109/MS.2005.129.
4. Carlsson, D.; Rönnqvist, M. (2005): Supply chain management in forestry - case studies at Södra Cell AB. European Journal of Operational Research 163 (3): pp. 589-616. DOI: 10.1016/j.ejor.2004.02.001.

5. Conforto, E.C.; Salum, F.; Amaral, D.C.; da Silva, S.L.; de Almeida, L.F.M. (2014): Can agile project management be adopted by industries other than software development? Project Management Journal 45 (3): pp. 21-34. DOI: 10.1002/pmj.21410.
6. Conforto, E.C.; Amaral, D.C.; da Silva, S.L.; Di Felippo, A.; Kamikawachi, D.S.L. (2016): The agility construct on project management theory. International Journal of Project Management 34 (4): pp. 660-674. DOI: 10.1016/j.ijproman.2016.01.007.
7. Cooper, R.G. (2014): What's next? After Stage-Gate. Research-Technology Management 57 (1): pp. 20-31. DOI: 10.5437/08956308X5606963.
8. Cooper, R.G.; Sommer, A.F. (2016a): The Agile-Stage-Gate hybrid model: a promising new approach and a new research opportunity. Journal of Product Innovation Management 33 (5): pp. 513-526. DOI: 10.1111/jpim.12314.
9. Cooper, R.G.; Sommer, A.F. (2016b): Agile-Stage-Gate: new idea-to-launch method for manufactured new products is faster, more responsive. Industrial Marketing Management 59: pp. 167-180. DOI: 10.1016/j.indmarman.2016.10.006.
10. D'Amours, S.; Rönnqvist, M.; Weintraub, A. (2008): Using operational research for supply chain planning in the forest products industry. INFOR 46 (4): pp. 265-282. DOI: 10.3138/infor.46.4.265.
11. European Commission (2018): A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy. European Commission, Brussels.
12. European Commission (2021): New EU Forest Strategy for 2030. COM(2021) 572 final. European Commission, Brussels.
13. European Commission (2022): EU Bioeconomy Strategy Progress Report. COM(2022) 283 final. European Commission, Brussels.
14. FAO (2024): The State of the World's Forests 2024 - Forest-sector innovations towards a more sustainable future. Food and Agriculture Organization of the United Nations, Rome. DOI: 10.4060/cd1211en.
15. Geraldi, J.; Lechler, T. (2012): Gantt charts revisited: a critical analysis of its roots and implications to the management of projects today. International Journal of Managing Projects in Business 5 (4): pp. 578-594. DOI: 10.1108/17538371211268889.
16. Hassegawa, M.; Karlberg, A.; Hertzberg, M.; Verkerk, P.J. (2022): Innovative forest products in the circular bioeconomy. Open Research Europe 2: 19. DOI: 10.12688/openreseurope.14413.2.
17. Hillier, F.S.; Lieberman, G.J. (2021): Introduction to Operations Research. 11th ed. McGraw-Hill Education, New York.
18. Hurmekoski, E.; Jonsson, R.; Korhonen, J.; Jänis, J.; Mäkinen, M.; Leskinen, P.; Hetemäki, L. (2018): Diversification of the forest industries: role of new wood-based products. Canadian Journal of Forest Research 48 (12): pp. 1417-1432. DOI: 10.1139/cjfr-2018-0116.
19. Hwang, C.L.; Yoon, K. (1981): Multiple Attribute Decision Making: Methods and Applications. Lecture Notes in Economics and Mathematical Systems 186. Springer, Berlin. DOI: 10.1007/978-3-642-48318-9.
20. Law, A.M. (2015): Simulation Modeling and Analysis. 5th ed. McGraw-Hill Education, New York.

21. Molinaro, M.; Orzes, G. (2022): From forest to finished products: the contribution of Industry 4.0 technologies to the wood sector. Computers in Industry 138: 103637. DOI: 10.1016/j.compind.2022.103637.
22. Müller, F.; Jaeger, D.; Hanewinkel, M. (2019): Digitization in wood supply - a review on how Industry 4.0 will change the forest value chain. Computers and Electronics in Agriculture 162: pp. 206-218. DOI: 10.1016/j.compag.2019.04.002.
23. Pinedo, M.L. (2016): Scheduling: Theory, Algorithms, and Systems. 5th ed. Springer, Cham. DOI: 10.1007/978-3-319-26580-3.
24. Project Management Institute (2021): A Guide to the Project Management Body of Knowledge (PMBOK Guide) - Seventh Edition and The Standard for Project Management. Project Management Institute, Newtown Square.
25. Project Management Institute; Agile Alliance (2017): Agile Practice Guide. Project Management Institute, Newtown Square.
26. Rönnqvist, M. (2003): Optimization in forestry. Mathematical Programming 97: pp. 267-284. DOI: 10.1007/s10107-003-0444-0.
27. Saaty, T.L. (1980): The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York.
28. Taha, H.A. (2017): Operations Research: An Introduction. 10th ed. Pearson, Boston.
29. Triantaphyllou, E. (2000): Multi-Criteria Decision Making Methods: A Comparative Study. Kluwer Academic Publishers, Dordrecht. DOI: 10.1007/978-1-4757-3157-6.
30. UNECE/FAO (2024): Forest Products Annual Market Review 2023-2024. United Nations Economic Commission for Europe and Food and Agriculture Organization of the United Nations, Geneva.
31. Verkerk, P.J.; Hassegawa, M.; Van Brusselen, J.; Cramm, M.; Chen, X.; Maximo, Y.I.; Koç, M.; Lovrić, M.; Tegegne, Y.T. (2022): The role of forest products in the global bioeconomy - Enabling substitution by wood-based products and contributing to the Sustainable Development Goals. Food and Agriculture Organization of the United Nations, Rome. DOI: 10.4060/cb7274en.

Authors address:
Henrieta Hrablik Chovanová, HHCH[1]*; Martin Hirtl, MH[2]; Alena Pauliková, AP[3]
[1, 2, 3] Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Trnava, Slovakia
*Corresponding author: henrieta.chovanova@stuba.sk

LATENT EMPLOYEE RESISTANCE TO CHANGE IN SMES: BEHAVIOURAL INDICATORS AND ECONOMIC IMPLICATIONS IN THE WOOD PROCESSING AND FURNITURE INDUSTRIES

Emilia Kirecheva

Abstract: Organizational change in small and medium-sized enterprises (SMEs) operating in the wood processing and furniture industries is frequently accompanied by employee resistance that remains latent and therefore difficult to detect through conventional managerial practices. Rather than manifesting itself through explicit opposition, latent resistance often emerges as subtle behavioural changes that gradually affect operational performance before becoming visible as organizational problems. This study examines behavioural indicators that lead to measurable operational deviations, including reduced productivity, quality defects, delayed orders, inefficient use of working time and increased absenteeism. The paper emphases on the sector vulnerability due to centralized management structures, limited functional specialization and dependence on key employees. The empirical part is based on a questionnaire survey conducted among employees in SMEs from the Bulgarian wood processing and furniture industries. It identifies behavioural patterns associated with latent resistance and to examine their relationship with operational and economic outcomes. The findings support the proposition that behavioural indicators can serve as an early diagnostic mechanism, enabling managers to recognize emerging resistance before substantial organizational and financial losses occur. The study links the behavioural manifestations of resistance with measurable economic implications and provides practical guidance for improving change management in manufacturing SMEs.
Keywords: latent resistance to change; SMEs; behavioural indicators; organizational change; wood processing industry; furniture industry; economic implications.

1. INTRODUCTION AND THEORETICAL BACKGROUND

Organizational change has become a continuous managerial requirement driven by technological development, digitalization, increasing quality standards and changing customer expectations. The success of change depends not only on technical implementation but also on employees' cognitive, emotional and behavioural responses (Khaw et al., 2023). These challenges are particularly important for SMEs in the wood processing and furniture industries. Compared with large organizations, SMEs possess fewer financial and managerial reserves, rely on a limited number of key employees and operate with centralized decision-making (European Commission, 2023; North & Varvakis, 2016). Consequently, even minor behavioural changes may rapidly affect production continuity, quality, coordination and customer satisfaction. In manufacturing environments, operational inefficiencies are directly reflected in defective products, rework, delays and inefficient resource utilization (Červený et al., 2022; Ince et al., 2023).

Contemporary research demonstrates that resistance extends beyond explicit opposition and includes cognitive, emotional and behavioural dimensions (Piderit, 2000; Oreg, 2006). Employees may formally comply with organizational decisions while simultaneously reducing initiative, withholding information, limiting cooperation or disengaging from organizational goals. Organizational silence, passive compliance and withdrawal of discretionary effort may conceal disagreement until operational problems become visible (Van Dyne et al., 2003; Nechanska et al., 2020). Recent studies further demonstrate that silence can function as an

active behavioural strategy capable of delaying organizational change without violating formal organizational rules.

For manufacturing SMEs these behavioural manifestations are particularly important because they may precede measurable operational deviations, including lower productivity, reduced work quality, inefficient use of working time, defective production and delayed customer orders. Although such outcomes are not exclusively caused by resistance, their repeated occurrence during organizational change may indicate emerging behavioural risks requiring managerial attention.

Despite extensive research on resistance to change, relatively little attention has been devoted to the relationship between latent behavioural indicators and their operational and economic implications in manufacturing SMEs. This study addresses this gap by examining behavioural indicators of latent employee resistance and their association with operational outcomes in Bulgarian SMEs operating in the wood processing and furniture industries.

2. VULNERABILITY OF SMES IN THE WOOD PROCESSING AND FURNITURE INDUSTRIES

The effects of latent resistance depend on the organizational context in which it develops. SMEs frequently combine centralized authority, informal communication, limited functional specialization and dependence on key employees. These characteristics may facilitate rapid decision-making, but they also increase exposure to local behavioural disturbances. Where critical knowledge is concentrated in a small number of people, reduced cooperation or knowledge withholding by one employee may affect an entire production stage.

The absence of specialized human-resource, analytical or quality-management functions may further limit the systematic observation of employee responses. Managers often perform strategic, administrative and operational roles simultaneously, which restricts the time available for analysing weak behavioural signals. As a result, management may react only after the signals have been translated into visible production problems.

In the wood processing and furniture industries, this vulnerability is reinforced by the interdependence of operations and the importance of workmanship, process discipline and quality control. Sector research demonstrates that quality-management systems, process standardization and continuous improvement are closely connected with operational efficiency and competitiveness (Červený et al., 2022; Ince et al., 2023). A mistake, omission or delay at one production stage may require rework, cause material waste, interrupt subsequent operations or delay final delivery.

The economic implications of latent resistance may therefore arise through several channels: additional labour time for correction and rework; increased material consumption and defective production; underutilized working time; production delays; absenteeism; managerial time devoted to monitoring and conflict resolution; and potential damage to customer relationships. Some of these costs are directly measurable, while others appear indirectly through reduced productivity, lost orders or weakened organizational capacity.

3. BEHAVIOURAL INDICATORS OF LATENT RESISTANCE

Behavioural indicators are observable changes in employee conduct that may precede explicit resistance or measurable operational deterioration. They do not constitute direct proof of intentional opposition. Their role is diagnostic: they indicate where additional managerial attention, communication and analysis may be required.

One important indicator is organizational silence, expressed through reduced feedback, avoidance of critical discussions and reluctance to report emerging problems. Silence limits the information available to management and increases the probability that operational weaknesses will remain unidentified. When employees do not communicate production problems, unrealistic requirements or implementation difficulties, managers may retain an overly positive assessment of the change process (Van Dyne et al., 2003; Nechanska et al., 2020).

A second indicator is formal compliance without substantive engagement. Employees may publicly accept new procedures while applying them selectively, mechanically or only under direct supervision. Such behaviour differs from open refusal because formal requirements appear to be satisfied. Nevertheless, the intended objectives of the change are not fully achieved. The difference between compliance and genuine commitment is particularly important in small production firms, where managers often rely on direct observation and informal communication instead of specialized monitoring systems.

A third indicator is the withdrawal of discretionary effort. This involves a reduction in initiative, voluntary cooperation, problem solving and willingness to perform tasks beyond minimum formal requirements. The employee may continue to fulfil the job description while no longer contributing additional effort that previously supported coordination and production continuity. Although such behaviour does not necessarily constitute misconduct, a collective decline in discretionary effort can significantly affect SMEs because fewer employees are available to compensate for production interruptions, absences or unexpected orders.

Other indicators include avoidance of responsibility, slower task completion, weaker cooperation, selective sharing of knowledge and a gradual decline in attention to quality. These manifestations may initially appear as separate and minor deviations. Their diagnostic significance increases when several indicators occur together, persist over time or emerge after the announcement or implementation of organizational change.

4. RESEARCH METHODOLOGY AND RESULTS

The empirical study was conducted through a structured questionnaire designed to examine employees' sensitivity to organizational change, the management practices that increase or reduce resistance, and the behavioural reactions that may arise when a change is perceived as harmful. The questionnaire included ordinal five-point response scales, ranking questions and a multiple-response item describing potential behavioural reactions to an unfavourable change. The empirical instrument covered 4 areas: sensitivity to different types of workplace change; managerial actions that reduce employee motivation; latent and overt behavioural reactions; and management measures capable of restoring motivation and reducing resistance. Higher scale values indicated stronger sensitivity, stronger agreement with a statement or greater support for the relevant action. Descriptive statistics included frequencies, percentages, arithmetic means and standard deviations. Because most variables were ordinal, relationships between composite scores were examined primarily through Spearman's rank correlations.

The sample consisted of 101 respondents, of whom 65.3% were women and 34.7% were men. The mean age was 32.73 years (SD = 11.90), with a median of 26 and a range from 19 to 59 years. The relatively broad age range allowed the survey to capture both early-career employees and respondents with longer employment experience.

The study is exploratory and is based on a relatively small convenience sample of employees from wood-processing and furniture industries in Bulgaria. The data are self-reported and may be affected by social desirability, particularly in questions involving sabotage or intentionally harmful behaviour.

The strongest negative reaction was associated with an increase in workload without a corresponding increase in remuneration (M = 4.01, SD = 1.06)[11]. A total of 75.2% of respondents reported that they would accept such a change with difficulty or would not accept it. This result indicates that resistance is particularly likely when employees perceive an imbalance between the additional contribution required from them and the return provided by the organization.

The second most sensitive area was a change that would place the organization's product or business practices in conflict with employees' moral values (M = 3.87, SD = 1.10). Resistance was also relatively high when the change threatened status, prestige or established social relationships (M = 3.55, SD = 1.23), deteriorated the workplace climate (M = 3.50, SD = 1.14), or altered an established team (M = 3.32, SD = 1.07).

In contrast, stricter quality control generated comparatively low resistance (M = 2.62, SD = 0.96). This finding is important for the wood-processing and furniture industries because it suggests that quality-oriented change is not inherently rejected. Resistance is more likely to arise from the manner in which the change redistributes effort, rewards, security and social relations than from the technical requirement to improve quality.

Exploratory factor analysis supported a two-factor structure of sensitivity to change (KMO = 0.776; Bartlett's $\chi^2(91) = 437.69$, $p < 0.001$). The first factor combined threats to individual interests and organizational relationships, including remuneration, career opportunities, status, moral values and workplace climate. The second factor reflected operational and structural change, including quality control, managerial style, ownership and work organization. The reliability of the complete sensitivity scale was good (Cronbach's $\alpha = 0.823$).

The absence of an explanation of why change was necessary was identified as the most demotivating managerial behaviour. Similarly high ratings were observed when employees did not know what would be required of them, when the change was imposed through explicit or implicit threats), and when its short- and long-term effects on employees were not explained.

The result suggests that employees do not perceive communication, timing, rumours and coercion as unrelated managerial mistakes. Instead, these elements form a broader pattern of deficient implementation that increases uncertainty and weakens motivation.

4.1. Behavioural indicators and operational implications

The most common behavioural response to a harmful change was the withdrawal of discretionary effort. More than half of the respondents (50.5%) stated that they would perform their explicitly assigned duties conscientiously but would not contribute additional effort. A further 45.5% reported that they would continue working but with reluctance and low morale, while 31.7% indicated that the firm's interests would no longer be a personal priority. These manifestations correspond to latent resistance because formal job performance may continue while voluntary cooperation, initiative and organizational commitment decline. Such behaviour is difficult to identify through conventional disciplinary or performance-control mechanisms.

11 SD- Standard deviation, Mean – average

Nevertheless, in a small production enterprise it may reduce flexibility and the ability of employees to compensate for production interruptions, urgent orders or absent colleagues.

The findings also reveal behavioural manifestations with more direct operational and economic implications. Unintentional deterioration in work quality was reported by 32.7% of respondents; 18.8% indicated that they might become less careful in avoiding waste of materials, energy or other company resources; 17.8% would conceal poor-quality work; and 9.9% expected to produce more defective output because of reduced motivation. Selective reporting of information to managers was reported by 14.9%, while 15.8% indicated that their behaviour toward customers and business partners could be reduced to the min required level.

These results do not establish the actual monetary cost of resistance. They identify plausible behavioural channels through which resistance may affect costs: additional material consumption, rework, defective production, weaker quality control, inefficient use of working time, incomplete managerial information and deterioration of customer service. The economic implications are therefore indirect but operationally observable.

Not all reactions were negative. Approximately 37.6% stated that they would respond to the firm's difficulties with additional effort. This coexistence of supportive and resistant behaviours confirms that employee responses to change are heterogeneous and that resistance should not be treated as an automatic or universal reaction.

Table 1. Behavioural manifestations when the change is expected to be harmful

Behavioural manifestation	%
Performing only explicitly assigned duties without additional effort	50,5 %
Openly expressing disagreement	46,5 %
Continuing to work, but with reluctance and low morale	45,5 %
Providing additional effort because of understanding the firm's difficulties	37,6 %
Reduced loyalty to the employer	33,7 %
Unintentional deterioration in work quality	32,7 %
The firm's interests are no longer treated as a priority	31,7 %
Demonstrating loyalty strategically to gain managerial recognition	28,7 %
Wasteful use of materials, energy or other company resources	18,8 %
Forming a group to oppose the employer	17,8 %
Concealing poor-quality work	17,8 %
Minimal courtesy toward customers and business partners	15,8 %
Selective or partial reporting of information to managers	14,9 %
Producing more defective output because of lower motivation	9,9 %
Simulating engagement and effort	10,9 %
Neglecting the employer's reputation	10,9 %
Sharing company information with competitors	5 %

4.2. Measures to reduce resistance

Free training in the required skills received the highest support, followed by linking additional effort to remuneration or bonuses. Respondents also strongly supported explanations of how the change would affect employees and what management would do to reduce adverse effects, periodic collection of employee feedback, and an adaptation period without immediate sanctions. The positive measures formed a reliable common construct. The threat of job or pay loss received substantially lower support and did not belong to the same

underlying factor. This distinction indicates that coercion is not perceived as another version of change support but as a qualitatively different managerial approach.

Spearman's analysis showed that stronger support for constructive managerial actions was associated with lower declared willingness to participate directly in covert sabotage ($\rho = -0.313$, $p = 0.001$). An exploratory regression model remained statistically significant after the inclusion of age, gender, negative attitudes and perceptions of deficient management ($R^2 = 0.110$, $p = 0.022$). Supportive managerial action was the only individually significant predictor of lower sabotage propensity ($B = -0.241$, $p = 0.049$).

5. CONCLUSION

The findings suggest that latent resistance is expressed primarily through a gradual withdrawal from active organizational participation rather than through open opposition. Employees may continue to perform their formal duties while reducing discretionary effort, initiative, loyalty and commitment to organizational objectives. Consequently, managers may observe normal attendance and task completion despite declining employee engagement.

These findings are particularly relevant for Bulgarian SMEs, where limited functional specialization, dependence on key employees and low workforce interchangeability increase organizational vulnerability. In such settings, reduced effort by a single experienced employee may disrupt interconnected production activities and increase managerial intervention.

The results also indicate that resistance is driven less by technical changes than by perceived unfairness and poor change management. Unpaid additional workload, threats to status, moral conflict and deterioration of the workplace climate generated stronger resistance than stricter quality control. This suggests that employees do not reject higher performance standards themselves but rather changes perceived as unfair or insufficiently communicated.

The identified behavioural indicators, such as withdrawal of discretionary effort, reduced motivation, information withholding and declining work quality, represent potential ways through which latent resistance may generate operational and economic consequences. In wood-processing and furniture SMEs, these behaviours may contribute to defective production, inefficient resource utilization, production delays and weaker customer service.

The findings do not imply that every operational problem results from resistance. However, the repeated occurrence of several behavioural indicators during organizational change provides managers with valuable early warning signals that justify timely intervention.

Overall, the results support the proposed analytical sequence:

Organizational change → Latent behavioural response → Operational deviation → Economic implications

Rather than representing a deterministic causal model, this sequence offers a practical diagnostic framework that enables managers to identify behavioural risks before they become visible through production, quality or financial performance indicators.

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REFERENCES

1. Červený, V., Dudík, R., Paluš, H. and Parobek, J. (2022) 'Competitiveness and sustainability challenges in the European wood-processing sector', *Forests*, 13(5), 730. https://doi.org/10.3390/f13050730
2. European Commission (2023) *Annual Report on European SMEs 2022/2023*. Luxembourg: Publications Office of the European Union.
3. Ince, H., Kaya, A. and Yildiz, S. (2023) 'Operational performance and sustainability in furniture manufacturing enterprises', *Sustainability*, 15(18), 13244. https://doi.org/10.3390/su151813244
4. Khaw, K.W., Yap, C.S., Tan, F.Y. and Ali, A. (2023) 'Employee reactions to organizational change: A systematic literature review', *Behavioral Sciences*, 13(7), 540. Lewin, K. (1951) *Field Theory in Social Science*. New York: Harper & Row.
5. Nechanska, E., Hughes, D.J. and Dundon, T. (2020) 'Towards an integration of employee voice and silence', *Human Resource Management Review*, 30(1), 100674. North, K. and Varvakis, G. (2016) *Competitive Strategies for Small and Medium Enterprises*. Cham: Springer.
6. Oreg, S. (2006) 'Personality, context, and resistance to organizational change', *European Journal of Work and Organizational Psychology*, 15(1), pp. 73–101. Piderit, S.K. (2000) 'Rethinking resistance and recognizing ambivalence: A multidimensional view of attitudes toward an organizational change', *Academy of Management Review*, 25(4), pp. 783–794.
7. Van Dyne, L., Ang, S. and Botero, I.C. (2003) 'Conceptualizing employee silence and employee voice as multidimensional constructs', *Journal of Management Studies*, 40(6), pp. 1359–1392.

Authors address:
1 Department of Management, University of Economics – Varna, Bulgaria

A CONCEPTUAL METHODOLOGICAL FRAMEWORK FOR OPTIMISING FOREST BIOMASS SUPPLY CHAINS IN DISTURBANCE-AFFECTED AREAS: ILLUSTRATIVE REGIONAL CONTEXT OF HOREHRONIE

Lucia Kružlicová, Daniel Halaj

Abstract: This paper develops a conceptual and methodological framework for analysing and optimising forest biomass supply chains in disturbance-affected areas. The Horehronie region in central Slovakia is used as an illustrative application context. The contribution is not an empirical optimisation model, but a structured basis for future data-driven applications. Disturbances such as wind damage, drought and bark beetle outbreaks change biomass availability, quality, logistical relationships and market balance. The proposed framework integrates actor and flow mapping, supply and demand analysis, cost and spatial logistics, and digital decision-support tools, including artificial intelligence. It supports the assessment of biomass flows, cost drivers, absorption capacity and alternative scenarios under uncertainty, thereby strengthening links between forestry and the energy biomass market and contributing to regional bioeconomy development.
Keywords: forest biomass; biomass supply chain; supply chain optimisation; disturbance-affected areas; bioeconomy; Horehronie region

1. INTRODUCTION

The forest-based sector is increasingly affected by climate change, market instability and demand for renewable resources. In Central Europe, windstorms, drought and bark beetle outbreaks have become important drivers of timber-market and forest-management change, influencing ecological stability as well as the economic and organisational functioning of forest supply chains (Hlásny et al., 2010; Kunca et al., 2019; Pirtskhalava-Karpova et al., 2024; Hartmann et al., 2025). Disturbance-related harvesting also affects the supply curve of wood raw material and forest biomass (Gejdoš and Potkány, 2017; Sikora, 2017).

The Horehronie region illustrates these challenges. Extreme weather and bark beetle outbreaks can generate sudden volumes of damaged timber and biomass that exceed harvesting, transport or processing capacities. Forest owners must process damaged wood quickly to prevent quality losses, while contractors and energy companies face higher logistical pressure, price volatility and temporary market imbalance (Kot and Ślusarczyk, 2013; Acuna et al., 2019; Nunes et al., 2020; Roos, 2023; Březina et al., 2024). Demand for energy biomass is also shaped by substitute fuel prices, buyer capacity, investment policy and European Union renewable-energy regulation (Faaij, 2008; Wieruszewski and Mydlarz, 2022; Langholtz et al., 2022).

Although forest biomass supply-chain optimisation has been widely addressed through logistics, routing, storage, procurement and cost minimisation, disturbance-affected regions create a specific methodological problem: biomass availability changes suddenly, quality deteriorates over time and demand is often relatively rigid. Recent reviews confirm that the literature remains fragmented in this respect and that uncertainty, collaborative planning and cross-chain coordination are insufficiently integrated (Acuna et al., 2019; Nunes et al., 2020; Roos, 2023). Therefore, this paper develops a conceptual and methodological framework for analysing and optimising forest biomass supply chains in disturbance-affected areas, using Horehronie as an illustrative regional context.

2. THEORETICAL BACKGROUND

2.1. Forest biomass supply chains

A supply chain is a system of interconnected actors, activities and flows enabling the movement of raw material from its source to final use (Rehman Khan and Yu, 2019). Forest biomass supply chains include harvesting, extraction, manipulation, transport, chipping, storage, processing and final energy utilisation, as well as information, financial and contractual flows among forest owners, harvesting companies, transport providers, biomass processors, energy producers and institutions.

Compared with standard industrial supply chains, forest biomass chains are biologically, spatially and seasonally conditioned. Biomass is heterogeneous in quality, moisture content, energy value and accessibility; availability depends on silviculture, weather, terrain, road infrastructure and market demand (Rentizelas, 2013; Wolfsmayr and Rauch, 2014). A supply-chain perspective is therefore useful because biomass value is determined not only by volume but also by transport distance, handling, storage, moisture, market access and information exchange.

2.2. Disturbance-induced disruption and decision support

In disturbance-affected areas, natural events create large, unexpected and time-sensitive volumes of damaged wood. This should be treated as a specific supply-chain disruption rather than a simple increase in available biomass. It combines spatially uneven supply, quality degradation, limited harvesting and transport capacities, market pressure and constrained absorption by buyers (Roos, 2023). The biomass chain may be described at three levels: primary production, logistics and processing, and final use (Van Belle et al., 2003; Nunes et al., 2020).

Optimisation requires a multidisciplinary approach. Economic analysis clarifies supply, demand, costs and prices; spatial analysis assesses resource distribution, routes and processing capacities; managerial analysis identifies actors, bottlenecks and coordination gaps; and digital tools support prediction, optimisation and scenario modelling (Windisch et al., 2013; Zhang et al., 2020; Nunes and Silva, 2023). Methods such as GIS, optimisation models, MCDA, simulation and machine learning should be combined as complementary components of a single methodological framework.

3. ILLUSTRATIVE REGIONAL CONTEXT: HOREHRONIE, SLOVAKIA

Horehronie is located in central Slovakia and is characterised by a high share of forested land, mountainous terrain and close links among forestry, wood processing, energy use and regional development. Its natural conditions make it vulnerable to wind damage, drought stress and bark beetle outbreaks, corresponding with wider Central European trends in forest disturbance (Hlásny et al., 2010; Kunca et al., 2019; Pirtskhalava-Karpova et al., 2024).

For the proposed framework, Horehronie is not used to provide empirical optimisation results, but to define conditions for future application. Disturbances change the structure of the regional biomass market: forest owners must decide when to harvest and sell damaged biomass, contractors must allocate machinery and transport capacity, and energy producers must assess whether increased volumes can be absorbed within storage, technology and demand limits. These conditions make the region a suitable context for developing and testing a framework that can later be adapted to other disturbance-affected regions.

4. METHODOLOGICAL FRAMEWORK

The framework integrates economic, managerial, spatial and digital approaches. It assumes that the biomass market is shaped by the interaction of supply, demand and price, but that disturbance conditions modify this mechanism through sudden supply shocks, time pressure and limited demand flexibility (Varian, 1995; Šálka et al., 2009). The framework consists of five stages: actor and flow mapping; biomass supply analysis; biomass demand analysis; cost and logistics analysis; and optimisation with decision support.

Table 1. Methodological components of forest biomass supply-chain analysis in disturbance-affected regions

Component	Purpose	Methods	Expected output
Actor and flow mapping	Identify actors, roles, dependencies and coordination gaps.	Stakeholder, process and material-flow mapping; semi-structured interviews.	Actor-flow matrix; material, information and financial-flow diagram.
Supply and demand analysis	Define biomass availability, buyer absorption capacity and market constraints.	Inventory, market and capacity data; interviews; conceptual supply and demand functions.	Variables for supply, demand, price sensitivity and capacity constraints.
Cost and spatial logistics	Identify cost drivers, accessibility limits, routes and storage or chipping options.	Cost accounting; GIS and network analysis; logistics records.	Cost structure, route structure and spatial bottleneck map.
Scenario and decision support	Compare alternatives under uncertainty and support coordination.	MCDA, simulation, optimisation and AI-based prediction.	Scenario ranking and decision-support model.

Source: Own elaboration based on Acuna et al. (2019), Wolfsmayr and Rauch (2014), Nunes et al. (2020), Roos (2023) and Zhang et al. (2020).

4.1. Actor and flow mapping

The first stage identifies forest owners and managers, harvesting companies, transport providers, processors, chip producers, energy companies and public or regulatory institutions. It maps material flows from damaged stands to final utilisation, information flows on volume, quality, prices, routes and delivery schedules, and financial flows including costs, revenues, contracts and payment mechanisms. The output is an actor-flow matrix and a representation of critical links, bottlenecks and coordination failures (Hakkila, 2003; Van Belle et al., 2003; Wolfsmayr and Rauch, 2014).

4.2. Supply and demand analysis

Supply analysis specifies the available quantity of disturbance-related biomass as a function of biomass price, production costs, technology and terrain or natural-resource conditions: $Qp = f(C, N, T, Z)$. In a simplified form, $Qp = a + bC$, where $b > 0$ indicates supply sensitivity to price. Under disturbance conditions, the function is modified by the urgent need to process damaged wood, environmental restrictions and time-sensitive quality loss. Primary data should include biomass volumes, harvesting capacities, cost structures, accessibility and technological limits.

Demand analysis focuses on energy companies, heat producers, biomass processors and other users. Demand depends on biomass or substitute-fuel prices, buyer financial capacity, substitution possibilities and technological capacity: $Qd = f(C, R, S, K)$. In a simplified form, $Qd = a - dC$, where $d > 0$ indicates price sensitivity. The key disturbance-specific constraint is absorption capacity: the maximum biomass volume that buyers can receive and use within a defined period, given storage, moisture, technology, contracts, seasonal demand and substitute-fuel availability. Demand elasticity may be used in scenario modelling to estimate the market effect of sudden supply increases (Šálka et al., 2009).

4.3. Cost, spatial logistics and decision-support modelling

Cost and logistics analysis identifies the main cost drivers: harvesting, forwarding, chipping, loading, transport, storage and handling. A simplified total-cost identity is $TC = Charv + Cforw + Cchip + Cload + Ctrans + Cstor + Chand$. Transport is particularly important because biomass has low energy density and often high moisture content, increasing cost per energy unit (Kot and Ślusarczyk, 2013; Acuna et al., 2019). GIS and network analysis should be used to assess stands, forest roads, storage sites, chipping points, processing capacities and end users.

Decision-support modelling integrates four layers. The prediction layer estimates biomass availability, demand, prices, moisture and transport variables. The optimisation layer addresses routing, allocation, scheduling and capacity use. The decision layer compares scenarios using criteria such as cost, transport distance, reliability, biomass quality, environmental impact and market stability. The uncertainty layer applies sensitivity analysis or simulation to assess variation in supply, demand, costs and constraints. Depending on data availability, suitable methods include regression, random forests, gradient boosting, neural networks, MCDA, genetic algorithms, ant colony optimisation, simulated

annealing and Monte Carlo simulation (Kühmaier and Stampfer, 2012; Zhang et al., 2020; Almeida et al., 2022; Esmaeili et al., 2023; Wang, 2024).

5. ANTICIPATED OUTPUTS AND DISCUSSION

The proposed framework should enable the identification of critical supply-chain links, the quantification of biomass flows, assessment of supply and demand conditions, calculation of cost drivers and evaluation of alternative logistical and market scenarios (Acuna et al., 2019; Nunes et al., 2020; Zhang et al., 2020). Managerially, it can improve coordination among forest owners, contractors, processors and energy companies. Economically, it can support cost reduction, pricing stability and better utilisation of disturbance-generated biomass. Spatially, it can improve transport planning and allocation of storage or processing capacities. Technologically, it illustrates how AI and data analytics can be integrated into biomass supply-chain management (Bucha, 2019; Wang, 2024; Wesolowska et al., 2025).

The main methodological contribution is the integration of disturbance-specific supply shocks, market absorption capacity, spatial logistics and digital decision support into one analytical structure. Unlike standard approaches focused mainly on procurement, routing or cost minimisation, the framework emphasises situations where biomass availability increases suddenly while harvesting, transport, storage and demand capacities remain constrained. Its implementation depends on regional data quality and cooperation among supply-chain actors, whose objectives, information systems and planning horizons often differ. The principal limitation is that the framework has not yet been empirically validated. Future research should apply it in Horehronie through parameter estimation, GIS-based route modelling, cost calculation, scenario analysis and stakeholder validation.

6. CONCLUSION

This paper proposed a conceptual and methodological framework for analysing and optimising forest biomass supply chains in disturbance-affected areas. The framework combines actor mapping, supply and demand analysis, cost and logistics assessment, spatial analysis and decision-support modelling. Horehronie was used as an illustrative regional context reflecting disturbance pressure, sudden biomass availability and constrained market absorption capacity. The paper contributes a structured methodological basis for future data-driven applications rather than empirical optimisation results. Future research should validate the framework using regional data and stakeholder input, with attention to trade-offs among economic recovery, biomass utilisation, ecological impacts and subsequent risk management (Cambero and Sowlati, 2014; Leverkus et al., 2018; Dashtpeyma et al., 2021).

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REFERENCES

1. Acuna, M.; Sessions, J.; Zamora, R.; Boston, K.; Brown, M.; Ghaffariyan, M. R. (2019): Methods to Manage and Optimize Forest Biomass Supply Chains: A Review. Current Forestry Reports 5 (3): pp. 124-141. DOI: https://doi.org/10.1007/s40725-019-00093-4.
2. Almeida, R. O.; Munis, R. A.; Camargo, D. A.; Da Silva, T.; Sasso Júnior, V. A.; Simões, D. (2022): Prediction of Road Transport of Wood in Uruguay: Approach with Machine Learning. Forests 13 (10): 1737. DOI: https://doi.org/10.3390/f13101737.
3. Březina, D.; Michal, J.; Hlaváčková, P. (2024): The Impact of Natural Disturbances on the Central European Timber Market—An Analytical Study. Forests 15 (4): 592. DOI: https://doi.org/10.3390/f15040592.
4. Bucha, T. (2019): Modelling in Forestry Sciences, High Technologies and Decision-Support Systems in Forestry and Wood-Processing. Central European Forestry Journal 65 (3-4): pp. 145-146. DOI: https://doi.org/10.2478/forj-2019-0024.

5. Cambero, C.; Sowlati, T. (2014): Assessment and Optimization of Forest Biomass Supply Chains from Economic, Social and Environmental Perspectives—A Review of Literature. Renewable and Sustainable Energy Reviews 36: pp. 62-73. DOI: https://doi.org/10.1016/j.rser.2014.04.041.
6. Dashtpeyma, M.; Ghodsypour, S. H.; Ahmadi, A. (2021): Forest Biomass and Bioenergy Supply Chain Resilience: A Systematic Literature Review on the Barriers and Enablers. Sustainability 13 (12): 6964. DOI: https://doi.org/10.3390/su13126964.
7. Esmaeili, F.; Mafakheri, F.; Nasiri, F. (2023): Biomass Supply Chain Resilience: Integrating Demand and Availability Predictions into Routing Decisions Using Machine Learning. Smart Science 11 (2): pp. 293-317. DOI: https://doi.org/10.1080/23080477.2023.2176749.
8. Faaij, A. (2008): Developments in International Bio-Energy Markets and Trade. Biomass and Bioenergy 32 (8): pp. 657-659. DOI: https://doi.org/10.1016/j.biombioe.2008.02.008.
9. Gejdoš, M.; Potkány, M. (2017): Prediction and Analysis of Slovakian Timber Trade on Global Market Conditions. Serbian Journal of Management 12 (2): pp. 281-289. DOI: https://doi.org/10.5937/sjm12-11228.
10. Hartmann, H.; Battisti, A.; Brockerhoff, E. G.; et al. (2025): European Forests Are under Increasing Pressure from Global Change-Driven Invasions and Accelerating Epidemics by Insects and Diseases. Journal of Cultivated Plants 77 (2): pp. 6-24. DOI: https://doi.org/10.5073/JFK.2025.02.02.
11. Hlásny, T.; Kulla, L.; Barka, I.; Turčáni, M.; Sitková, Z.; Koreň, M. (2010): The Proposal of Biotic Hazard Zones in Selected Spruce Dominated Regions in Slovakia. Journal of Forest Science 56 (5): pp. 236-242. DOI: https://doi.org/10.17221/56/2009-JFS.
12. Kunca, A.; Zúbrik, M.; Galko, J.; et al. (2019): Salvage Felling in the Slovak Republic's Forests during the Last Twenty Years (1998-2017). Central European Forestry Journal 65: pp. 3-11. DOI: https://doi.org/10.1515/forj-2017-0055.
13. Kot, S.; Ślusarczyk, B. (2013): Aspects of Logistics in Biomass Supply for Energy Production. Applied Mechanics and Materials 309: pp. 206-212. DOI: https://doi.org/10.4028/www.scientific.net/AMM.309.206.
14. Kühmaier, M.; Stampfer, K. (2012): Development of a Multi-Criteria Decision Support Tool for Energy Wood Supply Management. Croatian Journal of Forest Engineering 33 (2): pp. 181-198. URL: https://hrcak.srce.hr/file/172706.
15. Langholtz, M.; Ebersole, D.; Schroeder, R.; Milbrandt, A. (2022): Price Response of Waste Resources under Demand Shocks: Four Case Studies. ORNL/TM-2022/2356. DOI: https://doi.org/10.2172/1869090.
16. Leverkus, A. B.; Rey Benayas, J. M.; Castro, J.; et al. (2018): Salvage Logging Effects on Regulating and Supporting Ecosystem Services—A Systematic Map. Canadian Journal of Forest Research 48 (9): pp. 983-1000. DOI: https://doi.org/10.1139/cjfr-2018-0114.
17. Nunes, L. J. R.; Causer, T. P.; Ciolkosz, D. (2020): Biomass for Energy: A Review on Supply Chain Management Models. Renewable and Sustainable Energy Reviews 120: 109658. DOI: https://doi.org/10.1016/j.rser.2019.109658.
18. Nunes, L. J. R.; Silva, S. (2023): Optimization of the Residual Biomass Supply Chain: Process Characterization and Cost Analysis. Logistics 7 (3): 48. DOI: https://doi.org/10.3390/logistics7030048.
19. Pirtskhalava-Karpova, N.; Trubin, A.; Karpov, A.; Jakuš, R. (2024): Drought Initialised Bark Beetle Outbreak in Central Europe: Meteorological Factors and Infestation Dynamic. Forest Ecology and Management 554: 121666. DOI: https://doi.org/10.1016/j.foreco.2023.121666.
20. Rehman Khan, S. A.; Yu, Z. (2019): Introduction to Supply Chain Management. In: Strategic Supply Chain Management. Springer International Publishing. DOI: https://doi.org/10.1007/978-3-030-15058-7_1.
21. Rentizelas, A. A. (2013): Biomass Supply Chains. In: Biomass Combustion Science, Technology and Engineering. Elsevier. DOI: https://doi.org/10.1533/9780857097439.1.9.
22. Roos, A. (2023): Forest Damage and Forest Supply Chains: A Literature Review and Reflections. International Journal of Forest Engineering 34 (3): pp. 330-339. DOI: https://doi.org/10.1080/14942119.2023.2240607.
23. Sikora, A. T. (2017): Wpływ klęsk żywiołowych na rynek drzewny. Instytut Badawczy Leśnictwa, Sękocin Stary. DOI: https://doi.org/10.48538/FRP-2017-0031.
24. Šálka, J.; Holková, V.; Balážová, E.; Sujová, A. (2009): Mikroekonómia. Technická univerzita vo Zvolene, Zvolen. ISBN 978-80-228-2069-1.
25. Van Belle, J.-F.; Temmerman, M.; Schenkel, Y. (2003): Three Level Procurement of Forest Residues for Power Plant. Biomass and Bioenergy 24 (4-5): pp. 401-409. DOI: https://doi.org/10.1016/S0961-9534(02)00161-7.
26. Varian, H. R. (1995): Mikroekonomie: Moderní přístup. Victoria Publishing, Praha. ISBN 80-85865-25-4.
27. Wang, J. (2024): Machine Learning Applications in Biomass Supply Chain Management and Optimization. BioResources 19 (4): pp. 6961-6963. DOI: https://doi.org/10.15376/biores.19.4.6961-6963.

28. Wesolowska, M.; Żelazna-Jochim, D.; Wisniewski, K.; et al. (2025): Optimization of Biomass Delivery through Artificial Intelligence Techniques. Energies 18 (18): 5028. DOI: https://doi.org/10.3390/en18185028.
29. Wieruszewski, M.; Mydlarz, K. (2022): The Potential of the Bioenergy Market in the European Union—An Overview of Energy Biomass Resources. Energies 15 (24): 9601. DOI: https://doi.org/10.3390/en15249601.
30. Windisch, J.; Röser, D.; Mola-Yudego, B.; Sikanen, L.; Asikainen, A. (2013): Business Process Mapping and Discrete-Event Simulation of Two Forest Biomass Supply Chains. Biomass and Bioenergy 56: pp. 370-381. DOI: https://doi.org/10.1016/j.biombioe.2013.05.022.
31. Wolfsmayr, U. J.; Rauch, P. (2014): The Primary Forest Fuel Supply Chain: A Literature Review. Biomass and Bioenergy 60: pp. 203-221. DOI: https://doi.org/10.1016/j.biombioe.2013.10.025.
32. Zhang, X.; Wang, J.; Vance, J.; Wang, Y.; Wu, J.; Hartley, D. (2020): Data Analytics for Enhancement of Forest and Biomass Supply Chain Management. Current Forestry Reports 6 (2): pp. 129-142. DOI: https://doi.org/10.1007/s40725-020-00111-w.

Authors address:
Kružlicová, L.1; Halaj, D.1*
1 Technical University in Zvolen, Faculty of Forestry, Department of Forest Economics and Policy, T. G. Masaryka 24, SK-96001 Zvolen, Slovakia
*Corresponding author: daniel.halaj@tuzvo.sk

ELECTROMOBILITY IN THE INTERNAL LOGISTICS OF WOOD PROCESSING COMPANIES: CHALLENGES, OPPORTUNITIES AND IMPLEMENTATION PERSPECTIVES

Patrik Richnák, Nikol Valachovičová

Abstract: Growing pressure to reduce greenhouse gas emissions, increase energy efficiency and implement the principles of sustainable development is leading industrial companies to seek innovative solutions in the field of internal logistics. Wood processing companies, characterised by a high intensity of material handling and the energy demands of logistics processes, represent a suitable environment for the implementation of electromobility. This paper focuses on analysing the possibilities for introducing electromobility in the internal logistics of 54 wood processing companies in Slovakia, taking into account technological, economic and environmental aspects. The aim of the paper is to identify the main challenges, opportunities and perspectives for implementing electromobility within the internal logistics of the wood processing industry. The research is based on a synthesis of knowledge from the scientific literature and a questionnaire survey examining the current state of the use of electric logistics solutions. The findings indicate the potential of electromobility in reducing emissions, lowering workplace noise levels, optimising operational costs and improving the safety of work operations. At the same time, the main barriers to implementation are identified, particularly high initial investment costs, requirements for charging infrastructure and the need to adapt existing logistics processes.
Keywords: electromobility, internal logistics, wood processing companies, electric material handling equipment

1. INTRODUCTION

Growing pressure to reduce greenhouse gas emissions, improve energy efficiency, and promote sustainable development is driving companies to seek new logistics solutions. Consequently, electromobility is gaining increasing importance due to its potential to reduce energy consumption, emissions, and other environmental impacts associated with transport and logistics activities. Fernández Gil et al. (2022) emphasise that road freight transport is among the most fuel-intensive logistics segments and that more efficient route management can significantly reduce greenhouse gas emissions. Similarly, Li et al. (2024) identify electric vehicles as an important means of mitigating carbon emissions in the logistics sector. In addition, the digital transformation of logistics, supported by data-driven technologies, enhances the efficiency, resilience, and sustainability of logistics systems (Meier et al., 2023), reflecting the broader transition towards intelligent and sustainable mobility (Kalašová et al., 2026). Therefore, electromobility should be regarded not merely as the replacement of internal combustion engine vehicles, but as an integral component of green logistics that combines environmental sustainability with operational optimisation and efficient energy use. As Fan (2023) notes, electric vehicles also offer lower energy consumption, reduced noise, and lower emissions than conventional fossil-fuel-powered vehicles.

In the field of internal logistics, electromobility is particularly relevant because material flows within production facilities are typically repetitive, spatially confined, and closely

integrated with the continuous operation of production processes. Boysen et al. (2026) point out that electrically powered material-handling equipment, such as forklifts, tractor-trailer combinations, automated guided vehicles, and autonomous mobile robots, represents a significant component of logistics in manufacturing and warehousing operations. Their effective utilisation depends on decisions regarding charging strategies, energy consumption, fleet size, and route planning. More broadly, the efficiency of internal logistics can be further enhanced through the integration of advanced technologies such as RFID and the Internet of Things, which improve material traceability, optimise warehouse operations, and eliminate process inefficiencies (Fidlerova et al., 2025). This perspective is particularly relevant to wood processing companies, where internal logistics requires the efficient and reliable movement of raw materials, semi-finished products, and finished goods between storage areas, production facilities, and dispatch zones.

However, implementing electromobility in logistics involves considerably more than simply replacing internal-combustion-powered material-handling equipment with electric alternatives. As noted by Küçükoğlu et al. (2021), electric vehicles can reduce both the costs and environmental impacts of logistics operations; however, their deployment remains constrained by limited operating range, longer charging times, and the availability of charging infrastructure. Similar limitations are highlighted by Li et al. (2024), who observe that although electric vehicles offer lower emissions, reduced noise, and lower operating costs, their practical application is restricted by battery capacity, charging duration, and access to charging facilities. In the context of internal logistics, this implies that the integration of electric material-handling equipment into existing material flows is just as important as the selection of the equipment itself.

Energy and battery management therefore require particular attention. Challoob et al. (2024) emphasise that effective energy and battery management systems are essential for increasing operating range, controlling rapid battery discharge, extending battery life, and improving the overall efficiency of electric vehicles. Within a manufacturing environment, this issue has considerable practical significance, as poorly scheduled charging, insufficient battery capacity, or inadequately sized charging infrastructure may result in equipment downtime, the need for additional material-handling equipment, or disruptions to the smooth flow of internal logistics operations. Diefenbach et al. (2023) demonstrate that logistics systems within manufacturing facilities must take account of limited battery capacity, charging interruptions, the location of charging stations, and the influence of these factors on the required fleet size.

2. METHODOLOGY

The primary aim of this paper was to evaluate the current state of electromobility adoption in the internal logistics of wood processing companies in Slovakia and to identify the key technological, economic, and organisational factors influencing its implementation. The research sample consisted of 54 wood processing companies in Slovakia representing different company sizes, legal forms, geographical regions, and wood-processing segments.

The first phase of the research involved a comprehensive review of relevant international scientific literature to establish the theoretical background of the paper. The second phase comprised quantitative empirical research conducted using a structured questionnaire survey. The questionnaire consisted of questions examining the dominant type of handling equipment used in companies' internal logistics, the current level of electric equipment utilisation, the principal barriers limiting the implementation of electromobility, the most significant

technological constraints associated with electric equipment, and the environmental and operational benefits perceived by the respondents. The questionnaire was distributed to managers within the participating companies.

3. FINDINGS AND DISCUSSION

The research sample comprised 54 wood processing companies in Slovakia. With regard to company size, small companies constituted the largest proportion of the sample, accounting for 19 companies (35.19 %), followed closely by medium-sized companies with 18 companies (33.33 %). Large companies accounted for 11 respondents (20.37 %), whereas micro-companies represented the smallest group, comprising 6 companies (11.11 %).

The geographical distribution of the participating companies covered all regions of Slovakia, although the representation varied considerably. The highest proportion of companies was located in the Nitra Region (15 companies; 27.78 %), followed by the Banská Bystrica Region (13; 24.07 %) and the Žilina Region (10; 18.52 %). Lower representation was observed in the Prešov Region (5; 9.26 %), the Trnava Region (4; 7.41 %), and the Trenčín Region (4; 7.41 %), while only two companies (3.70 %) were headquartered in the Bratislava Region and one company (1.85 %) in the Košice Region.

Regarding legal form, the sample was dominated by limited liability companies, with 41 companies (75.93 %), whereas joint-stock companies accounted for 13 companies (24.07 %).

With respect to the principal business activity, the largest group comprised companies engaged in combined or other wood-processing activities, representing 22 companies (40.74 %). Secondary wood processing, including furniture manufacturing and joinery products, was reported by 17 companies (31.48 %), while primary wood processing, such as sawmilling and timber cutting, accounted for 9 companies (16.67 %). The smallest segment consisted of companies specialising in the production of wood-based panels and materials, including plywood, particleboard, and medium-density fibreboard, representing 6 companies (11.11 %).

The findings indicate that combustion-engine handling equipment continues to dominate the internal logistics of wood processing companies in Slovakia. The largest proportion of respondents (42.59 %) reported using predominantly combustion-engine equipment supplemented by a limited number of electric vehicles. A further 29.63 % indicated that electric equipment had become the dominant technology within their fleets, although combustion-engine equipment remained in use to some extent. Exclusive reliance on combustion-engine equipment was reported by 16.67 % of the surveyed companies, whereas only 11.11 % operated exclusively electric handling equipment.

The results demonstrate that the adoption of electric equipment has become an established practice among many wood processing companies in Slovakia. Routine utilisation of electric handling equipment was reported by 35.19 % of the surveyed companies, representing the most frequently selected response. In addition, 27.78 % of respondents indicated that electric equipment was used on a limited scale, suggesting that many companies are currently in the early stages of technological transition. Among companies that had not yet implemented electric equipment, 24.07 % were considering future acquisition, whereas only 12.96 % reported having neither adopted nor planned to introduce such technologies. Collectively, these findings indicate that nearly two-thirds of the surveyed companies (62.97 %) have already incorporated electric equipment into their internal logistics operations, while a further proportion is actively considering future investment in electromobility.

High initial investment costs were identified as the most significant barrier to the implementation of electromobility in the internal logistics of wood processing companies in Slovakia. Nearly half of the respondents (46.30 %) identified high initial investment costs as the most significant barrier, substantially exceeding all other response categories. Concerns related to insufficient or unsuitable charging infrastructure were reported by 22.22 % of companies, making this the second most frequently identified challenge. The need to adapt existing logistics processes and facility layouts was perceived as the primary barrier by 18.52 % of respondents, whereas a lack of information or practical experience with electromobility technologies was considered the most significant obstacle by only 12.96 % of companies.

Battery-related issues emerged as the most frequently perceived technological limitation associated with the deployment of electric handling equipment. More than one-third of the surveyed companies (37.04 %) considered insufficient battery capacity or operating range during a full working shift to be the most significant constraint. Long charging or battery replacement times represented the second most common concern, being reported by 27.78 % of respondents. Environmental and operational suitability, including operation in dusty environments, outdoor storage areas, or on uneven surfaces, was identified as the principal limitation by 20.37 % of companies. In contrast, only 14.81 % regarded the lower load capacity or operational performance of electric equipment compared with combustion-engine alternatives as the most important technological challenge.

The perceived environmental benefits of electromobility were relatively evenly distributed across several response categories, although strategic sustainability considerations were identified most frequently. Specifically, 31.48 % of respondents regarded support for the company's overall sustainability and environmental strategy as the principal environmental benefit of adopting electric handling equipment. A further 29.63 % considered the reduction of greenhouse gas emissions to be the most significant advantage, while 25.93 % emphasised improvements in indoor air quality through reduced dust generation. The reduction of workplace noise was selected least frequently, accounting for 12.96 % of responses.

Operational cost reduction was identified as the most important operational benefit of electromobility by 40.74 % of the surveyed companies, making it the dominant response category. Increased reliability and reduced equipment downtime were considered the primary advantage by 24.07 % of respondents, indicating that operational continuity also represents an important motivation for adopting electric equipment. Improvements in occupational safety and working conditions were prioritised by 18.52 % of companies, whereas the simplification and optimisation of internal material flow was selected by 16.67 % of respondents.

4. CONSLUSION

The relevance of electromobility in internal logistics is reflected in the rapid growth of automation in warehouse and material-handling processes. According to Statista data, the global logistics automation market increased from $39.29 billion in 2018 and is projected to reach $121.34 billion by 2027 (The Insight Partners, 2020). Similarly, the warehouse automation market was valued at $23.44 billion in 2023 and is expected to reach $41 billion by 2027, driven primarily by the automation of repetitive and labour-intensive tasks (Statista, 2023). This trend is particularly relevant for wood processing companies, where internal logistics depends on the continuous movement of raw materials, semi-finished products, and finished goods. Moreover, AGV and AMR technologies are projected to account for 14.7 % of

the global warehouse automation market by 2025 (Messe Frankfurt, 2019), highlighting the growing importance of electrically powered and autonomous material-handling systems in industrial logistics. The broader development of electromobility further supports this trend. In 2024, approximately 58.1 million electric vehicles were in operation worldwide, while global sales of plug-in electric vehicles reached 17.51 million units (IEA, 2025a; IEA, 2025b). Although these figures relate primarily to road transport, they demonstrate the technological maturity of electric propulsion, battery systems, and charging infrastructure. In addition, the global weighted average price of battery cells declined from $290/kWh in 2014 to $78/kWh in 2024 (Statista, 2025), potentially reducing the economic barriers to investing in electric material-handling equipment. Nevertheless, challenges related to charging infrastructure, battery costs, and the environmental impact of electricity generation continue to influence the wider adoption of electromobility.

The findings of this paper indicate that although combustion-engine handling equipment continues to dominate the internal logistics of wood processing companies in Slovakia, the use of electric material-handling technologies has become increasingly common across the sector. The majority of the surveyed companies indicated that both combustion-engine and electric handling equipment were used within their internal logistics operations. High initial investment costs, charging infrastructure, and battery-related limitations were identified as the principal barriers to wider implementation, whereas reduced operating costs, support for corporate sustainability strategies, and lower greenhouse gas emissions were perceived as the most significant benefits.

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REFERENCES

1. Boysen, N.; Schneider, M.; Žulj, I. (2026): Energy management for electric vehicles in facility logistics: A survey from an operational research perspective. *European Journal of Operational Research* 333: pp. 321-336. DOI: 10.1016/j.ejor.2025.12.031.
2. Challoob, A.F.; Rahmat, N.A.B.; Ramachandaramurthy, V.K.A.L.; Humaidi, A.J. (2024): Energy and battery management systems for electrical vehicles: A comprehensive review & recommendations. *Energy Exploration & Exploitation* 42 (1): pp. 341-372.
3. Diefenbach, H.; Emde, S.; Glock, C.H. (2023): Multi-depot electric vehicle scheduling in in-plant production logistics considering non-linear charging models. *European Journal of Operational Research* 306 (2): pp. 828-848. DOI: 10.1016/j.ejor.2022.06.050.
4. Fan, L. (2023): A hybrid adaptive large neighborhood search for time-dependent open electric vehicle routing problem with hybrid energy replenishment strategies. *PLOS ONE* 18 (9): e0291473. DOI: 10.1371/journal.pone.0291473.

5. Fernández Gil, A.; Lalla-Ruiz, E.; Gómez Sánchez, M.; Castro, C. (2022): A Review of Heuristics and Hybrid Methods for Green Vehicle Routing Problems considering Emissions. *Journal of Advanced Transportation* 2022: Article ID 5714991. DOI: 10.1155/2022/5714991.
6. Fidlerova, H.; Kuka, M.; Adamczak, M. (2025): Innovative solutions for warehouse logistics: Improving efficiency with RFID and IoT integration. *Acta Logistica* 12 (1): pp. 135-145. DOI: 10.22306/al.v12i1.603.
7. IEA (2025a): *Estimated number of electric vehicles in use worldwide between 2010 and 2024, by type*. Statista. Statista Inc. URL: https://www.statista.com/statistics/1101415/number-of-electric-vehicles-by-type/
8. IEA (2025b): *Estimated plug-in electric car sales worldwide from 2015 to 2024 (in million units)*. Statista. Statista Inc. URL: https://www.statista.com/statistics/665774/global-sales-of-plug-in-light-vehicles/
9. Kalašová, A.; Poliak, M.; Fabian, P.; Čulík, K. (2026): Assessing the Effect of Hypothetical Urban Air Mobility Demand Redistribution on Signalized Intersection Performance: A Microsimulation Study of Threshold Effects. *Urban Science* 10 (7): p. 353. DOI: 10.3390/urbansci10070353.
10. Küçükoğlu, İ.; Dewil, R.; Cattrysse, D. (2021): The electric vehicle routing problem and its variations: A literature review. *Computers & Industrial Engineering* 161: 107650. DOI: 10.1016/j.cie.2021.107650.
11. Li, Y.; Lim, M.K.; Xiong, W.; Huang, X.; Shi, Y.; Wang, S. (2024): An electric vehicle routing model with charging stations consideration for sustainable logistics. *Industrial Management & Data Systems* 124 (3): pp. 1076-1106.
12. Meier, T.; Makyšová, H.; Pauliková, A. (2023): Evaluation of the Economic, Ecological and Ethical Potential of Big Data Solutions for a Digital Utopia in Logistics. *Sustainability* 15 (6): p. 5088. DOI: 10.3390/su15065088.
13. Messe Frankfurt (2019): *Forecasted global warehouse automation market share in 2025, by technology*. Statista. Statista Inc. URL: https://www.statista.com/statistics/1147839/global-warehouse-automation-market-share-technology/
14. Statista (2023): *Size of the warehouse automation market worldwide from 2023 to 2027 (in billion U.S. dollars)*. Statista. Statista Inc. URL: https://www.statista.com/statistics/1094202/global-warehouse-automation-market-size/
15. Statista (2025): *Electric vehicles: A global overview*. Overview report. Statista. 48 p. Report ID: 134904.
16. The Insight Partners (2020): *Logistics automation market size worldwide from 2018 to 2027 (in billion U.S. dollars)*. Statista. Statista Inc. URL: https://www.statista.com/statistics/1099087/logistics-automation-market-size-worldwide/

Authors address:
Richnák, P.[1]; Valachovičová, N.[2]
[1 2]Department of Business Economy, Faculty of Business Management, Bratislava University of Economics and Business, Bratislava, Slovak Republic
[*]Corresponding author: patrik.richnak@euba.sk

KNOWLEDGE TRANSFER AS A STRATEGIC FACTOR FOR INNOVATION AND SUSTAINABLE GROWTH IN THE FORESTRY SECTOR

Teodora Marinova Georgieva

Abstract: In the context of global environmental change and the transition to a circular bioeconomy, effective technology and expertise exchange is becoming a key pillar for the development of the forestry sector. This report examines the role of knowledge transfer as a key driver for innovation in forest management and the processing industry. The subject of analysis is the knowledge and innovation systems in forestry, with the aim of accelerating the implementation of scientific achievements in forestry practice. Emphasis is placed on the digitalisation of forest inventories, precision forestry, and the implementation of sustainable logging technologies that minimise the ecological footprint. The study is based on primary data on the innovation potential of Bulgarian enterprises in the sector and their interaction models with research institutes. The report identifies specific barriers to knowledge transfer in the sector, such as the remoteness of forest territories and the need for specialised personnel qualifications. The conclusion proposes specific mechanisms to support cooperation with state forestry enterprises, the private sector, and the academic community by establishing demonstration centres and compatible platforms for the exchange of innovative forestry practices.
Keywords: knowledge transfer, forestry, innovation

1. INTRODUCTION

In recent decades, knowledge exchange has become a fundamental factor in the development of a competitive information-based economy. Providing access to cutting-edge research is crucial for addressing the contemporary economic, social and environmental challenges facing countries (Santos, 2024). Through this process, public research organisations can maximise the impact of their activities, bringing real benefits to society. (Guimón, 2014). At the micro level, knowledge transfer helps individual enterprises improve their productivity, optimise their results and secure access to new resources and world-leading expertise, while at the macro level it stimulates national economic growth (Popa, 2020). On a global scale, significant successes have already been achieved in building partnerships between business, academia and government structures. However, serious challenges remain, especially in assessing the impact of these initiatives, a necessary condition for improving future policies and practices (Advanced Technology Program, 2022).

The forestry sector is a particularly suitable research context for analysing knowledge transfer, as it coexists with high-tech solutions, traditional production practices, formal and tacit knowledge, large enterprises and small firms, publicly funded research, and market-oriented innovations. This heterogeneity allows knowledge transfer to be studied not only as a process

of technology implementation but also as an interaction among different types of actors, different levels of absorptive capacity, and different institutional settings.

The present report presents the findings of a nationally representative study conducted between April and May 2025. The sample size comprises 522 enterprises distributed across the country. The respondents interviewed include owners, managers, and executive personnel from the agricultural sector.

2. KNOWLEDGE TRANSFER

In the context of global climate change, geopolitical instability, and increasing demands for sustainability, knowledge and technology transfer have become a critical pillar for the survival and development of the forestry sector and the processing industry. Forestry is no longer an isolated, traditional industry but a high-tech ecosystem that directly contributes to gross added value and employment at the national and European levels. The effective diffusion of innovations – such as automated video surveillance and sensor systems, satellite and remote sensing, registries and GIS platforms – allows companies to become data-driven decision-makers. Reducing the footprint and valorisation of biomass are the basis of modern circular economy strategies (ShapingBio, 2024). In the context of the entire value chain, technologies are qualitatively changing logistics and transparency. IoT-based cold chain monitoring and digital traceability systems guarantee product authenticity and safety, reduce waste, and facilitate market access for small farmers. In Bulgaria, strengthening the so-called Agricultural Knowledge and Innovation System (AKIS) through joint initiatives among ministries, universities, and advisory services is a key priority to accelerate this transfer and improve employees' skills (European Commission, 2022).

The theoretical understanding of knowledge transfer is rooted in the evolution of economic and management theories that redefine knowledge from a public good into a strategic economic resource. At the heart of this transition is the Resource-Based View and its offshoot, the Knowledge-Based View. According to these theories, the sustainable competitive advantage of organisations does not simply stem from their physical or financial assets, but from their ability to generate, codify, and integrate unique knowledge (Popa, 2020). To understand the dynamics of transfer, the classic distinction between two types of knowledge is fundamental: 1) explicit (codified) knowledge, which includes information that can be easily recorded, structured, and transmitted in the form of patents, publications, software, and technical specifications; and 2) tacit (hidden) knowledge, embodied in personal experience, intuition, contextual skills and "know-how", which are acquired through practice and are extremely difficult to transfer without direct human interaction and mobility of researchers. In modern literature, the paradigm is shifting from linear information transfer to "knowledge valorisation" (European Commission, 2022). This concept views transfer not as a one-time act of selling technology but as a complex process of co-creating value, in which scientific research is transformed into social and economic innovations. The modern "knowledge economy" requires an understanding of the processes of the so-called "knowledge spillovers", in which investments in science in one sector generate unplanned, positive externalities for the entire economy, stimulating regional development and long-term macroeconomic growth (Santos, 2024). The evolution in the practice of scientific-industrial cooperation requires the transition from elementary, one-way models to complex ecosystem frameworks.

3. RESULTS AND DISCUSSION

Despite the developed theoretical basis and the desire to build partnerships, knowledge transfer faces critical barriers of various kinds every day. Knowledge and technology transfer is a particularly difficult form of communication because it often requires collaboration among two or more individuals or functional units separated by structural, cultural, and organisational boundaries (Devine, 1987). The widening chasm between theoretical awareness of advanced technologies and their practical deployment on the ground is one of the most prominent structural features of the contemporary Bulgarian forestry and wood-processing sector. Empirical evidence derived from the nationally representative survey indicates that the domestic forest-based bioeconomy resides in a phase of passive digital observation. While sectoral entrepreneurs exhibit a high degree of cognitive familiarity with existing technocentric solutions, entrenched economic and operational risk aversion impedes the large-scale integration of these innovations into daily forest management and harvesting workflows.

Within the domain of forest management and logging, this discrepancy is most visible in the adoption rates of precision forestry solutions. The dataset reveals that while a striking 43.3% of surveyed executives report explicit familiarity with precision principles, only 4.8% of enterprises have deployed or are currently integrating precision forestry tools. A mirrored paradox is observable regarding Internet of Things (IoT) architectures, ambient sensors, and unmanned aerial vehicles (drones) utilised for canopy monitoring and biomass inventorying. Although more than half of the sampled respondents (52.0%) possess theoretical knowledge of IoT capabilities, actual diffusion within field operations is limited to a modest 3.0%. These figures substantiate the premise that the visibility of digital applications in public and professional discourses has generated high awareness, yet fails to automatically trigger a techno-economic transformation within corporate structures.

When analysing automation processes, business entities are significantly more inclined to adopt innovations that yield immediate, quantifiable economic returns by optimising material inputs and mitigating labour shortages. Automated timber-processing lines have been integrated by 3.3% of operators, while automation within forest nurseries and silvicultural care stands at 2.5%. These higher rates of practical execution, compared with more complex systems, are driven by the urgent need to reduce prime costs amid volatile inflationary pressures and aggressive market competition. Conversely, highly sophisticated cyber-physical systems, such as autonomous forest machinery (heavy harvesters and forwarders), register a deployment rate of 3.5%, while the application of artificial intelligence (AI) and machine learning for algorithmic log grading or wildfire predictive modelling languishes at a critical low of 1.4%. Indeed, AI has the highest rate of absolute unfamiliarity, with 41.8% of managers admitting a complete lack of knowledge. Advanced cryptographic frameworks, such as blockchain for verifying the legal provenance of timber and preventing illicit logging, remain entirely unknown to 53.0% of sectoral executives.

In terms of organisational back-office infrastructure, digitisation is noticeably more advanced due to stringent domestic and European regulatory mandates. Enterprise accounting and financial software is utilised by half of the surveyed population (50.4%), primarily forced by strict compliance and complex reporting regimes. Dedicated warehouse and timber-yard management systems are deployed by 18.4%, and business process automation tools are adopted by 19.5%. However, a deeply alarming 43.5% of enterprises explicitly state that they do not use any software utilities in their operations. This substantial pocket of administrative

stagnation signals an acute digital divide that fragments the structural cohesion of the domestic forestry sector.

The fundamental justification for these depressed innovation indicators lies in the macroeconomic pressures and structural constraints of the sector's financial subsystem. Bulgarian forestry enterprises rely on a deeply conservative funding mix. The primary engines of capital accumulation are strictly internal, dominated by revenues from ongoing operations (93.1%) and personal or family equity (81.3%). This behaviour demonstrates that technological upgrades are funded almost exclusively from realised financial surpluses rather than from calculated risk-taking. Commercial bank credit is utilised by 56.6% of firms, whereas institutional public funds, such as the Rural Development Programme (RDP), support only 37.8% of the entities. Crucially, the use of dedicated innovation tools, such as the National Innovation Fund (1.6%) or venture capital (1.6%), is statistically negligible, indicating that available financial instruments are fundamentally misaligned with the risk profiles inherent in forestry innovations.

These barriers are further aggravated by severe external vulnerabilities. Corporate leaders identify the chronic shortage of manual and technical labour as their primary operational obstacle (25.6%), which logically necessitates automation, yet leaves firms without the investment margins to pursue it. This is compounded by an oppressive administrative burden (20.8%) and the escalating impacts of climate change, including severe droughts and pest infestations (20.4%). Because the vast majority of small-scale logging firms operate in asymmetric dependence on large downstream wood processors and wholesalers, they fail to retain the added value generated within the supply chain. Coupled with an apparent deficit in targeted state aid for technological conversion (6.7%), the modernisation of the Bulgarian forestry sector remains largely confined to conceptual aspirations and unfulfilled theoretical capacity.

Table 1. Established practices and main channels for knowledge transfer in the forestry sector in Bulgaria

Technological Upgrades / Innovative Business Practices	Share (%)	Related Academic Collaboration / Knowledge Transfer	Share (%)	Key Structural Innovation System Insight
Investments in machinery & equipment *(Upgrades implemented over the last 3 years)*	56.8	Contacts with research organizations *(Partnerships planned for the current year)*	7.8	Forestry enterprises opt for "off-the-shelf" commercial machinery rather than investing in collaborative, tailor-made R&D projects.
Precision forestry & inventory software *(Deployed or in the process of deployment)*	4.8	Contacts with specialised academic experts *(Maintaining close institutional ties)*	14.0	Higher education institutions train qualified personnel but lack the operational capacity to provide scaled, on-site consultation for smart technologies.

Digital diffusion (IoT devices & drones) *(Theoretical knowledge of IoT in the market)*	52.0	Information exchange with Inno Hubs *(Channels for digital and technological transfer)*	14.6	European digital innovation hubs are gaining traction but currently cover only a narrow segment of the commercial forestry sector.
Innovative collective projects *(Planned applications for innovative funding)*	21.1	Membership in EIP Operational Groups *(European Innovation Partnerships)*	3.7	Collective innovation remains obstructed; business entities apply for funding individually, failing to distribute technological risk.

The primary barrier to technological diffusion is not a lack of interest, but a fragmented innovation ecosystem. Academic institutions and research centres operate in silos, largely detached from the immediate needs of commercial forest enterprises. Furthermore, asymmetric supply-chain relationships leave small-scale operators dependent on middlemen and large processors, capturing minimal added value and draining the capital reserves necessary for technological risk-taking. Financed almost exclusively through internal revenue and constrained by acute labour shortages, the sector cannot modernise "on its own".

4. CONCLUSION

The empirical findings of the present study demonstrate that the Bulgarian forestry and wood processing sector is caught in a "low-innovation equilibrium". While cognitive awareness of advanced technologies (such as precision forestry, IoT, and automated logging) is remarkably high, it remains functionally passive. A deep structural polarisation divides the sector: back-office administration is moderately digitised to comply with state regulations, yet field operations remain largely insulated from modern cyber-physical systems.

Overcoming the abovementioned bottlenecks requires a deliberate, structurally engineered state intervention to transform the traditional Agricultural/Forestry Knowledge and Innovation System into a dynamic, collaborative network, including policy actions such as: 1) Introduction of a state-funded Forestry Innovation Voucher Scheme. These vouchers should allow commercial forestry companies to directly procure R&D, structural diagnostics, or digitalisation blueprints from universities and tech hubs. This will bridge the gap between academic theory and industry reality, providing researchers with market-driven funding and offering enterprises affordable access to high-level tech expertise. 2) Execution of a state-led modernisation of public forest monitoring infrastructure. The government should build a publicly accessible, high-resolution spatial data infrastructure featuring open-access satellite imagery, drone-mapping corridors, and predictive AI dashboards for early wildfire detection and tracking pest migrations. Providing this foundational data as a public utility lowers the technological entry barrier, enabling commercial firms to deploy localised precision forestry applications on top of the national infrastructure.3) The Ministry of Agriculture and Food should launch targeted financial incentives to double corporate membership in EIP groups. State-backed programs

should prioritise and offer higher co-financing rates to horizontal clusters, consisting of logging companies, private forest owners, and software developers, that jointly deploy shared digital tracking systems or automated equipment, thereby effectively distributing capital risk.

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REFERENCES

1. Advanced Technology Program. (2022). Evaluating Knowledge Transfer Policies and Practices: Conceptual Framework and Metrics. In: Harnessing Public Research for Innovation in the 21st Century. Cambridge University Press
2. Devine, M. D., T. E. James и T. I. Adams. Government Innovation Policy: Design, Implementation, and Evaluation. Policy Studies Organization Series. New York: Palgrave Macmillan, 1987. ISBN 978-0312341152.
3. European Commission. Boosting knowledge circulation: new study on the economic impact of possible measures. Brussels: European Commission, 30 April 2026.
4. EUROPEAN COMMISSION. Factsheet on 2014-2020 Rural Development Programme for Bulgaria. Brussels: European Commission, 2022.
5. Guimón, J. (2014). Public Policies to Foster Knowledge Transfer from Public Research Organizations. In: Innovation Policy: A Guide for Developing Countries. Washington, DC: World Bank.
6. Popa, A., & Radu, C. (2020). The impact of knowledge transfer on the Organizational Performance. Proceedings of the International Conference on Business Excellence, 14(1), 577-588.
7. Santos, R. и M. Castro. The Impact of Knowledge Spillovers on Economic Growth from a Literature Review Perspective. Sustainability, 2024, vol. 16, no. 15, art. no. 6537, pp. 1–22. DOI: 10.3390/su16156537.
8. SHAPINGBIO. Bulgaria: Country file on biomass production and circular bioeconomy valorisation. Heidelberg: ShapingBio Project Consortium, 2024.

Authors address:
Georgieva, T. M.
Department of Industrial Economics and Management, Faculty of Economics and Business Administration, Sofia University "St. Kliment Ohridski", 1113 Sofia, Bulgaria
tmgeorgieva@feb.uni-sofia.bg

"FOREST-AS-A-SERVICE" - THE INNOVATIVE ALTERNATIVE FOR EXPLOITING NATURAL RESOURCES

Teodora Marinova Georgieva

Abstract: The report explores the conceptual framework of "Forest as a Service" (FaaS) as an innovative model for sustainable forest resource management, shifting the focus from raw material extraction to the provision of ecosystem benefits. In the context of the growing climate crisis and the need to transition to a circular economy, the opportunities for monetising non-timber forest functions – such as carbon sequestration, biodiversity conservation, and water purification – are analysed. The technological and economic prerequisites for implementing this model are examined, including the roles of digitalisation and precise monitoring in assessing the value of natural capital. The role of Internet of Things (IoT) and artificial intelligence (AI) technologies in the automated collection and processing of carbon footprint and biodiversity data is analysed. These digital tools create the necessary transparency and traceability, turning ecosystem functions into measurable and tradable assets independent of traditional logging. The report explores the dynamic interaction l between the concepts of Forest-as-a-Service and Farming-as-a-Service as paradigms for innovative natural resource management. The study focuses on the challenges and opportunities of implementing Forest/Farming-as-a-Service (FaaS) as an alternative to traditional industrial approaches. The conclusion highlights the need to update the regulatory framework and create new financial instruments to incentivise forest owners to invest in maintaining viable ecosystems. Through a comparative analysis, the model's potential to generate long-term economic value while ensuring environmental sustainability and social benefits for local communities is demonstrated. The report offers guidelines for integrating the innovative paradigm into national resource management strategies, charting the path towards a more balanced interaction between the economy and nature.
Keywords: Forest as a Service, innovation

1. INTRODUCTION

In the context of escalating climate change and intensifying anthropogenic pressures on ecosystems, traditional linear models of natural resource exploitation are proving economically and environmentally unsustainable (UNECE, 2025). Historically, the forestry and agricultural sectors have been seen primarily as sources of raw materials (wood, biomass, food crops). However, this approach has significant negative consequences, including soil degradation, biodiversity loss, and destabilisation of the carbon balance (MDPI, 2022).

The global transition to a circular economy and the goals of carbon neutrality require a fundamental transformation (EEA, 2025). The scientific discussion is directed towards a reassessment of the so-called "natural capital" and the commercialisation of ecosystem services, both renewable and non-renewable (ScienceDirect, 2024). The present paper explores the conceptual framework of Forest as a Service as an innovative model for moving from resource extraction to the monetisation of environmental benefits. It also analyses the dynamic interaction between the forestry model and its agricultural counterpart, Farming as a Service.

2. CONCEPTUAL FRAMEWORK OF THE FOREST AS A SERVICE MODEL

The Forest as a Service concept interprets forests not as a physical warehouse for wood but as a dynamic infrastructure platform that provides continuous, measurable, and tradable ecosystem services. In modern ecological economics, these functions are classified into three main areas:

- Regulating services: carbon dioxide capture and long-term storage, thermoregulation and microclimatic control.
- Supporting services: surface and groundwater filtration, soil erosion prevention and habitat maintenance for endangered species.
- Cultural services: recreation, ecotourism and aesthetic value.

Full transparency and traceability within carbon and biodiversity markets are provided through three interconnected layers of the FaaS technology architecture (PatSnap, 2025):

- Hardware layer (Internet of Things, IoT): Deploying sensor networks in forest stands that measure moisture, temperature, soil composition and biomass levels in real time. The data is complemented by satellite imagery and LiDAR scanning for precise 3D forest taxonomy.
- Analytical layer (Artificial Intelligence and Machine Learning): Artificial Intelligence (AI) algorithms process terabytes of unstructured information. They predict carbon sequestration rates, identify early outbreaks of pests or fires, and perform automated biodiversity audits (via audio analysis of bioacoustic data).
- Transactional layer (DLT / Blockchain): The transformation of captured carbon or stored biodiversity into measurable assets is done through tokenisation. Smart contracts automate payments to forest owners based on verified sensor data (Monitoring, Reporting and Verification - MRV systems).

The main obstacle to implementing this model is the difficulty of valuing the intangible assets created. The FaaS model overcomes this limitation by leveraging deep technologies (BFH, 2025).

3. FAAS IMPLEMENTATION: STATE OF PLAY AND TRANSITION REQUIREMENTS

The implementation of FaaS models is in line with the European Union's current regulatory framework. The new EU Forest Strategy to 2030 and the EU Biodiversity Strategy to 2030 explicitly envisage the creation of financial incentives and compensation schemes for owners who maintain the ecosystem functions of their forests instead of relying on logging (European Commission, 2021).

Table 1. Aspects of the transition to FaaS

Aspect	European Union	Bulgaria
Forest cover	About 39% of the EU's land area is covered by forests (EEA, 2025).	Forests cover over 3.9 million hectares (~35% of the country's territory) (EFA, 2021).

Carbon potential	EU forests absorb about 10% of the EU's total greenhouse gas emissions annually (European Commission, 2021).	Bulgarian forests are characterised by a high average age and significant unrealised capacity for carbon credits (DBR, 2025).
Regulatory maturity	EU Carbon Removal Certification Framework (ScienceDirect, 2024).	As of 2025, Bulgaria reports early fulfilment of the goals for strict protection of forests (over 12% under strict protection) (DBR, 2025).
Financial instruments	LIFE funding, recovery funds and private ESG markets (BFH, 2025).	Strategic plan for the development of agriculture and rural areas; increased pressure for digitisation (EFA, 2021).

A major challenge for Bulgaria remains the highly fragmented ownership of forests (especially in the private sector) and the lack of a functioning national carbon trading platform outside the common EU Emissions Trading Scheme (EU ETS). The implementation of FaaS platforms would allow for the aggregation of data from smallholders and direct access to international voluntary carbon credit markets.

4. FOREST-AS-A-SERVICE VS. FARMING-AS-A-SERVICE: TWO COMPLEMENTARY MODELS

Although both concepts are based on the Product-as-a-Service business model, they differ significantly in their operational cycles, end products and market dynamics.

Table 2. Comparison of the Forest-as-a-Service and Farming-as-a-Service models

Benchmark	Forest-as-a-Service	Farming-as-a-Service
Main focus	Biodiversity conservation, carbon sequestration and resource protection (UNECE, 2025).	Increasing crop yields and optimising resource costs (ResearchGate, 2022).
Time horizon	Long-term (decades, centuries-long ecosystem life cycles) (ScienceDirect, 2024).	Short-term (seasonal, annual cropping cycle and harvest) (ScienceDirect, 2023).
Business model	Payment for ecosystem services (PES), carbon credits, ESG certificates (BFH, 2025).	Shared inventory subscription (mechanisation), precision farming, agronomic software (MarkNtel, 2026).
Core technologies	Drones, LiDAR, bioacoustic IoT sensors, decentralised ledgers (Blockchain) (PatSnap, 2025).	GPS-guided tractors, smart irrigation, satellite-based vegetation index (NDVI) (Qamcom, 2021).
Revenue source	External corporate investors seeking carbon neutrality (Extension Journal, 2024).	Direct sales of agricultural produce, savings on operating costs (fertilisers, fuels) (MRFR, 2026).

Despite existing challenges, there are successful practices and pilot projects that illustrate how the Forest-as-a-Service and Farming-as-a-Service models are applied globally and in Eastern Europe and Bulgaria, and demonstrate the transition from theoretical frameworks to the real economic valuation of natural resources through digital technologies.

Pilot schemes for PES in Western Stara Planina (WWF Bulgaria Initiatives)

In Bulgaria, the concept of FaaS is developing mainly in two directions: through Payments for Ecosystem Services (PES) mechanisms and through the certification of forest areas as providers of added ecological value. One of the most striking examples of the valuation of "intangible" forest services was developed by WWF Bulgaria. The project focuses on the Danube River Basin and mountainous areas, where forest owners and farmers receive financial compensation for maintaining watersheds, water filtration, and biodiversity. This is a classic form of FaaS, where businesses (e.g. distilleries, water supply companies or ecotourism) pay for the “service” of clean water and preserved nature (WWF Bulgaria, 2025).

Digitalisation and expansion of the FSC network

In 2025, Bulgaria officially joined the global network for sustainable forest management with a new national FSC (Forest Stewardship Council) standard. Bulgarian foresters are implementing digital registers for biodiversity monitoring (by marking trees with bird nests and bats) and leaving deadwood to capture carbon, which prepares the sector for future digital tokenisation of these assets (FSC, 2025).

Historical agroforestry practices

The Dobrudzha Shelterbelt plantations (established in the last century) are being modernised through satellite monitoring. They function as a joint FaaS/FaaS platform – protecting crops from erosion (a service for agriculture) while accumulating biomass and carbon.

5. CONCLUSION AND STRATEGIC RECOMMENDATIONS

The transition from traditional resource extraction to digitally managed ecosystem services is a key step towards achieving economic sustainability. The Forest-as-a-Service and Farming-as-a-Service models demonstrate how digitalisation (IoT, AI, Blockchain) can transform natural capital into a measurable, traceable and convertible economic asset. The following measures are recommended for the successful integration of these innovations into national resource management strategies in Bulgaria: 1) Updating the legal framework: It is necessary to legally recognize carbon credits generated by forests as legitimate financial instruments and define clear property rights over captured emissions; 2) Public-private partnerships for IoT infrastructure: The state should stimulate the construction of national digital forest monitoring networks (jointly with the Executive Forestry Agency and scientific institutes) in order to create reliable databases for carbon taxation; 3) Financial support for smallholders: Develop mechanisms in the Strategic Plan for Agriculture and Forestry to subsidize the costs of software platforms and IoT sensors for small and medium-sized foresters, facilitating their inclusion in global ESG markets; 4) Integration of resource markets: Promote hybrid models in

which farmers and foresters exchange data and resources (e.g. using forest biomass to improve soil fertility in adjacent agricultural areas or joint management of watersheds).

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REFERENCES

1. Abdullah, S., et al. (2024). Unleashing the power of farming as a service (FaaS) in global supply chains. Extension Journal of Agricultural Sciences, 7(4), 84-96. Extension Journal Archive.
2. Drottberger, A., et al. (2023). Farming-as-a-service initiative in the making: Insights from digitally augmented agriculture. Journal of Rural Studies, 102, 103-114. ScienceDirect Database
3. European Commission. (2021). Questions and Answers: New EU Forest Strategy for 2030. EU Press Corner.
4. European Environment Agency (EEA). (2025). Forest ecosystem services and soil regulation metrics in Europe. EEA Knowledge Base.
5. EU ECSEL Joint Undertaking. (2021). AFarCloud (Aggregate Farming in the Cloud): White Paper on Farming-as-a-service through AI and Cloud Computing. Qamcom Research.
6. FSC, 2025, https://fsc.org
7. Kumar, A., & Gujarat Tech Consortium. (2022). Farming-as-a-Service (FAAS) for a Sustainable Agricultural Ecosystem: Design of an Innovative Farm Management System 4.0. ResearchGate Publication.
8. Li, W. (2022). Review of the Integrated Development of Ecological and Cultural Forestry Industries. Sustainability, 14(11), 6818. MDPI Open Access.
9. Market Research Future. (2026). Farming as a Service Market Size, Share & Forecast Till 2035. MRFR Reports.
10. MarkNtel Advisors. (2026). Global Farming as a Service Market Industry Outlook (2026–2032). MarkNtel Market Intelligence.
11. PatSnap Tech Reports. (2025). Exploring the Role of 5G UC and IoT in Advancing Smart Forest Management Solutions. PatSnap Intelligence.
12. Potschin-Young, M., et al. (2024). Mapping the research of Forest ecosystem Services in Europe. Forest Policy and Economics, 160, 103-115. ScienceDirect Database.
13. Rauter, R. (2025). Circular-oriented and Collaborative Business Models in Silviculture. Business School Research Output. BFH Publication Repository.
14. United Nations Economic Commission for Europe (UNECE). (2025). Forests 5.0: Service-driven economic and governance models for ecosystem monitoring. UNECE Official Publication.
15. Executive Forest Agency (EFA). (2021). The European Commission adopted the new EU Forest Strategy to 2030 – opportunities for Bulgaria. Official website of the EFA.

16. WWF Bulgaria. (2025). Payments for ecosystem services - the Bulgarian experience from Western Stara Planina. Official WWF blog, https://www.wwf.bg
1. ***, https://europeanagroforestry.eu.

Authors address:
Georgieva, T. M.
Department of Industrial Economics and Management, Faculty of Economics and Business Administration, Sofia University “St. Kliment Ohridski”, 1113 Sofia, Bulgaria
tmgeorgieva@feb.uni-sofia.bg

CURRENT TRENDS AND COMPARATIVE ANALYSIS OF INNOVATION ACTIVITY IN FORESTRY AND AGRICULTURE

Teodora Marinova Georgieva, Daniela Ventsislavova Georgieva

Abstract: The report examines the dynamics and priority areas of innovation activity in the forestry and agriculture sectors in the context of global climate change and the European framework for sustainable development. The main objective is to identify and compare the key technological and management transformations that determine the competitiveness of both sectors.
The study analyses three main pillars of innovation: digitalisation (integration of Precision Forestry and Precision Agriculture through IoT, LiDAR, and AI systems), circular bioeconomy (biomass utilisation and the development of bio-based materials), and ecosystem services (mechanisms for carbon agriculture and biodiversity). Special attention is paid to the comparative analysis of the speed of innovation diffusion, taking into account the specific production cycles – the long-term horizon in the forestry sector versus the seasonal dynamics in the agricultural sector.
The analysis is based on both secondary quantitative data and empirical data from a nationally representative survey and interviews with experts from both sectors. The results show that while agriculture demonstrates greater adaptability to market-oriented technological solutions, the forestry sector is a strategic hub for innovations in low-carbon materials and environmental sustainability. The report concludes with recommendations for improving knowledge transfer between scientific institutions and business, as well as for optimising financial instruments to stimulate cross-sectoral cooperation.
Keywords: innovation, innovation activity, forestry, agriculture

1. INTRODUCTION

Global climate change, soil degradation, and biodiversity loss require a radical transformation of sectors that depend directly on natural resources. Agriculture and forestry play a strategic role in this process. They are among the most vulnerable to climate instability, but they also have the largest potential to capture and store carbon in biomass and soils. Within the European Union (EU), this transformation is guided by the European Green Deal and the New EU Forest Strategy for 2030, which make environmental sustainability a core requirement for economic competitiveness.

In economic theory, both sectors are classified as "low-tech" or traditional industries. This classification is based on their low spending on Research and Development (R&D) compared to their total turnover. However, this creates a "low-tech paradox." In reality, innovations in these sectors are highly important but mostly embedded. This means that technologies are developed in high-tech industries, such as Information Technology (IT), Artificial Intelligence (AI), biotechnology, and mechanical engineering, and then transferred to agriculture and forestry. Therefore, the success of these businesses depends on their absorptive capacity - their ability to recognise, adopt, and adapt external technological solutions.

The main objective of this report is to identify and compare the key technological and management transformations in agriculture and forestry, with a primary focus on the forestry sector. The central research question is how specific production cycles, the long-term horizon

in forestry (often between 40 and 100 years), versus the fast, seasonal dynamics of agriculture, affect the speed and character of innovation diffusion. The analysis uses secondary data from international databases (Eurostat, FAO, EFI) as well as empirical data from a nationally representative survey and expert interviews in Bulgaria. The surveys and the interviews were done in 2025. The main target groups were company management in the two sectors. Both surveys included shared questions for validation purposes. The current paper presents aggregated analyses from the surveys and interviews.

2. PRIORITY AREAS OF INNOVATION AND DIGITAL TRANSFORMATION

Innovation in both sectors develops across several main pillars of sustainable development. However, practical application currently faces significant digital deficits. **Digital transformation** connects traditional practices with the technologies of the Fourth Industrial Revolution (Industry 4.0).

- Precision Agriculture: This involves integrating the Internet of Things (IoT), soil sensors, and satellite data from the EU Copernicus program to optimise the application of fertilisers and pesticides.
- Precision Forestry: Due to the fact that forest areas are large and difficult to access, innovation relies heavily on LiDAR (Light Detection and Ranging) technologies- laser scanning from aeroplanes or drones. LiDAR creates three-dimensional models of forests to measure wood volume, tree height, and biomass. Additionally, Artificial Intelligence (AI) helps with the early detection of forest fires and the prediction of pest outbreaks.

Despite the potential of these technologies, empirical data from the national survey in Bulgaria reveal a large digital gap and low adoption rates among managers and operators:

Table 1: Level of Awareness and Adoption of Digital Technologies (in %)

Digital Technology	Do Not Know	Know but Do Not Use	In the Process of Adoption	Use Partially	Use in Full Capacity
Precision Management	15.9%	43.3%	4.8%	16.7%	17.2%
Internet of Things (IoT, Drones)	25.1%	52.0%	3.0%	11.6%	6.7%
Process Automation	23.5%	41.8%	2.5%	19.1%	12.6%
Artificial Intelligence & ML	41.8%	50.3%	1.4%	3.0%	0.3%
Blockchain Technologies	53.0%	40.8%	0.8%	1.1%	1.1%

The data in Table 1 clearly illustrate the "low-tech trap". Almost half of the respondents (41.8%) are unaware of the capabilities of AI and machine learning, and only 0.3% use them fully. Similarly, only 6.7% of businesses fully use IoT sensors and drones. This lack of application slows down the transition to data-driven resource management.

Circular bioeconomy and biomass utilisation shift the focus from a linear economy ("take-make-waste") to closed loops in which waste products become new resources.

- In Agriculture: The focus is on using crop residues and animal manure to produce biogas and organic fertilisers like biochar.
- In Forestry: The sector needs to move away from producing raw, low-value materials (like firewood) and transition to innovative engineered wood products, such as CLT (Cross-Laminated Timber). These materials can replace steel and concrete in construction, turning buildings into long-term carbon storage units.

However, survey results show that on-site processing is very low. Only 3.2% of companies providing agricultural and forestry services have established a closed-loop processing cycle for raw materials within their own holdings.

The third pillar - **Ecosystem Services and Environmental Sustainability** - creates economic value from the benefits that nature provides for free, which have historically been unpriced.

- Carbon Farming and Forestry: This is a new management and technological innovation supported by European Commission regulations. Farmers and foresters use practices like no-till farming and close-to-nature forestry to maximise carbon storage. This requires Measurement, Reporting, and Verification (MRV) systems to certify carbon credits.
- Agroforestry: Integrating trees into agricultural lands is an important tool to increase biodiversity and prevent soil erosion. However, the survey shows a major knowledge gap in Bulgaria: 35.8% of practitioners are unaware of agroforestry, and 57.0% are aware of it but do not use it. Only 0.8% use it fully, proving that environmental innovations face strong informational barriers.

Technological modernisation cannot succeed without **Data-Driven Management**. Traditional management in these sectors often relies on intuition and history rather than software simulations. The survey shows a major imbalance in software use. While financial and accounting software is common (50.4%), Enterprise Resource Planning (ERP) systems, which are critical for long-term planning in forestry, are used by only 5.0% of entities. Furthermore, 43.5% of all surveyed companies do not use software to automate their business processes, reinforcing their traditional character.

Understanding innovation in Bulgarian forestry requires comparison with the wider European context. Studies by the European Forest Research and Innovation Ecosystem (EUFORE, 2025) show that regional and institutional factors strongly influence the speed at which innovations are adopted.

The main similarity between Bulgaria and other European countries (such as Germany, Austria, and Romania) is the increasing pressure from climate risks. Research by the European Forest Institute (EFI) shows that extreme ecological events, such as bark beetle outbreaks in

Central Europe, forest fires in the Mediterranean, and droughts, act as a primary driver for forced innovation.

Across Europe, climate change is shifting the focus from maximising short-term timber profits to using digital technologies for early warning and adaptation. Additionally, all European countries face challenges in creating stable market systems for carbon credits due to the lack of a single, unified EU methodology for pricing ecosystem services.

Differences become clear when analysing technological maturity and funding structures across three European models:

- The Nordic Model (Finland and Sweden): These countries lead in *Precision Forestry*. Innovation is fast due to large-scale forest ownership and strong public-private partnerships. Finland has achieved 100% forest digitalisation using LiDAR scanning. Data from harvesting machines is processed in real-time using cloud computing to manage timber supply chains.
- The Central European Model (Germany and Austria): This model focuses on high R&D investments in *Close-to-Nature Forestry*. Complex computer simulations are used to model forest ecosystems under different climate scenarios. The goal is to replace vulnerable monocultures (like spruce) with resilient mixed forests.
- The Eastern European Model (Bulgaria and Romania): This region has high natural potential but very low investments in innovation. Innovation is usually limited to "basic mechanisation", buying modern tractors or trucks, without installing digital systems for data analysis, inventory, or forecasting. As a result, the sector remains stuck in low-value production.

3. FACTORS FOR INNOVATION AND DIFFUSION

The adoption of innovations in Bulgaria is limited by specific market, demographic, and institutional barriers. The length of the production cycle explains why agriculture adopts technologies much faster than forestry. In agriculture, the seasonal cycle (within 1 year) allows farmers to test a new technology (like precision fertiliser software), measure its economic benefit, and see a return on investment within 1 to 3 seasons. In forestry, the timeline is often longer than a human lifespan (40 to 120 years). Investing in digitalisation does not bring immediate market profits, and the benefits are often realised by the next generation. Therefore, forestry cannot rely only on private market investments and requires public financial support. The survey data identify the main problems that slow down business growth and innovation:

Table 2: The Most Serious Systemic Barriers to Business Development (in %)

Specific Barrier / Difficulty	Percentage Share (Col %)
Lack of labour / qualified workers	25.6%
Administrative burden and bureaucracy	20.8%
Global warming and climate change	20.4%
Poor price conditions for import and export	17.1%

High costs, inflation of raw materials	16.1%
Lack of state support and long-term strategy	10.3%
Lack of subsidies/funds for innovation	6.7%

Table 2 shows that the most critical barrier is the lack of qualified labour (25.6%). The ageing population in rural areas lacks the skills to operate complex digital platforms, AI, or LiDAR systems. The second major obstacle is the administrative burden and complex regulations (20.8%), which force managers to spend their time on bureaucracy rather than on innovation planning. The survey reveals that the business sector is heavily isolated from scientific organisations:

- Only 3.5% of companies maintain close contact with specialists from the Bulgarian Academy of Sciences.
- Only 8.4% cooperate with the Agricultural Academy.
- Just above 94% of operators do not participate in Operational Groups under the European Partnership for Innovation (EIP-AGRI).

This means that scientific discoveries remain inside universities, while businesses rely on traditional methods. The main sources of information for new developments are colleagues (84.9%) and the internet/media (71.1%). This reproduces the existing low-tech level instead of introducing new technologies. Financing structures also show a lack of a long-term focus on innovation. Venture capital is almost non-existent (1.6%), and the National Innovation Fund is used by only 1.6% of businesses. Companies rely almost entirely on their own revenues (93.1%) and short-term bank loans (56.6%), which do not fit the long timelines of the forest sector.

4. CONCLUSION

Innovation in both sectors develops across three main pillars of sustainable development. The analysis shows that although forestry and agriculture are traditionally defined as low-tech sectors, they are changing under the pressure of climate change (20.4% barrier). Digitalisation, the circular bioeconomy, and ecosystem services are turning these industries into key players in the green economy. The main conclusion is that agriculture shows a much faster speed of technology adoption due to its short, seasonal production cycle. In contrast, forestry is a strategic but slower hub for innovation in low-carbon materials and long-term environmental sustainability. In Bulgaria, this process is blocked by a large digital gap (only 0.3% use AI fully), a severe labour shortage (25.6%), and a deep separation between scientific institutes and businesses (only 3.5% contact with the Academy of Sciences).

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REFERENCES (alphabetical order)

1. European Commission. (2021). *Communication on Sustainable Carbon Cycles*. Brussels.
2. European Forest Institute (EFI). (2023). *The Role of Bioeconomy in Transforming the European Forestry Sector*. EFI Policy Brief No. 12, Helsinki.
3. Hetemäki, L., et al. (2022). *Forest bioeconomy: a new paradigm for sustainability*. Current Forestry Reports, 8(2), 143-157.
4. Maltamo, M., Næsset, E., & Vauhkonen, J. (2014). *Forestry Applications of Airborne Laser Scanning: Concepts and Case Studies*. Springer Science & Business Media.
5. OECD. (2021). *Innovation, Productivity and Sustainability in Ecological Sectors: Main Findings from Country Policy Reviews*. OECD Publishing, Paris.
6. Popa, I., & Nichiforel, L. (2022). *Comparative analysis of forest governance and innovation patterns in Eastern Europe*. Forest Policy and Economics, 141, 102760.
7. Pucher, J., Huber, P., & Stern, T. (2026). *Comparative evaluation of the forestry sector of the bioeconomy: A harmonized data assessment across EU member states*. Forest Science and Technology, 22(2), 89-104.
8. Seidl, R., & Rammer, W. (2023). *Climate change disturbances as drivers of socio-technical transitions in forest management*. Global Environmental Change, 78, 102622.
9. Senf, C., & Seidl, R. (2021). *Mapping the pathways of forest disturbance regimes in Europe using remote sensing*. Global Change Biology, 27(19), 4732-4743.
10. Weiss, G., Ludvig, A., & Živojinović, I. (2026). *Mapping Forestry and Agroforestry Innovations in Europe: Challenges, competence gaps, and value chains*. Environmental Science & Policy, 164, 103612.

Authors address:
Georgieva, T. M. [1]; Georgieva, V. D.[2]
[1] Department of Industrial Economics and Management, Faculty of Economics and Business Administration, Sofia University “St. Kliment Ohridski", Bulgaria
[2] Economic Research Institute at the Bulgarian Academy of Sciences, Department "Economics of the Firm", Sofia, Bulgaria
*Corresponding author: tmgeorgieva@feb.uni-sofia.bg

ENTREPRENEURSHIP UNDER ENVIRONMENTAL PROTECTION: A MINDFUL LOCAL APPROACH AS A PATH TO MUTUAL UNDERSTANDING?

Vladislav Kaputa, Agnieszka Pieniążek, Mateusz Stopa

Abstract: The paper focuses on assessing the entrepreneurial environment in the protected areas of the Carpathians from the perspective of the entrepreneurs themselves. The aim of the study was to identify the main barriers and development opportunities for entrepreneurial activities in protected areas, as well as to assess the impact of environmental protection on economic activities in these regions. Data were collected through an anonymous questionnaire survey. We evaluate the sectoral structure of business, the business environment, perceptions of the success of individual economic sectors, as well as the importance of supporting factors such as financial assistance, cooperation with local authorities, and legislative and advisory support. It is obvious that entrepreneurial activities in the area of the bioeconomy play a significant role in this region. The survey results are intended to serve as a basis for developing recommendations in the areas of public policy and support for sustainable entrepreneurship in the protected areas of the Carpathians. We also analyse findings from other regions regarding man's embeddedness to the environment in which he lives and carries out economic activities by utilizing local natural resources. The aim is to emphasize the possibilities of a conscious and mutually beneficial coexistence between man and his environment.
Keywords: local entrepreneurship, protected areas, Slovak Carpathians

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1. METHODOLOGY

This study builds on extensive research by a team of authors (Kaputa et al., 2026) focused on business conditions in protected areas of the Carpathian countries. In this paper, we analyze and evaluate unpublished data collected as part of that research—in this case, exclusively from Slovak respondents[12]. To provide readers with a broader conceptual and geographical perspective, we refer them to the aforementioned study. This article focuses exclusively on the specific characteristics of entrepreneurship in protected areas within the Slovak part of the Carpathians. The survey examining the specific conditions for entrepreneurial activities in the protected areas of the Slovak Carpathians was conducted in 2023. The questionnaire was developed by the Association for the Development and Promotion of Podkarpacie „Pro Carpathia", based in Poland, and was designed with a broader focus encompassing the entire Carpathian mountain region. Based exclusively on responses provided by Slovak entrepreneurs operating within this region, we assessed the impact of environmental protection measures on their economic activities. The survey involved entrepreneurs from across Slovakia who had business experience in various protected mountain areas of the Carpathians.

The study cited (Kaputa et al., 2026) analyses data from expert interviews – Focus Group Interviews – in which different respondents participated compared to those whose attitudes are analysed in this paper.

Data collection was carried out by means of an electronic questionnaire distributed via e-mail. The questionnaire included demographic identification questions as well as items through which respondents evaluated business opportunities in the protected areas according to various criteria. Respondents expressed their perceptions of business opportunities using a five-point Likert scale. The questionnaire also included open-ended questions that allowed participants to provide their own views and opinions. Responses to the principal research premise – the evaluation of entrepreneurial opportunities in the protected areas of the Carpathians – were tested against respondents' demographic characteristics. Prior to hypothesis testing, response categories were merged into three groups (e.g., positive–neutral–negative or barrier–neutral–opportunity) in order to comply with the validity assumptions of Pearson's χ^2 test. After excluding incomplete questionnaires, the final sample consisted of 49 respondents. In addition, Fisher's exact test (appropriate for small sample sizes) was performed. The null hypothesis tested the dependence of respondents' answers on demographic characteristics. H_0: The examined demographic characteristics (gender, age, and educational attainment) do not influence respondents' evaluations of entrepreneurial opportunities. As the Fisher's exact test is analytically defined only for 2×2 contingency tables, a Monte Carlo permutation version was employed for larger contingency tables. Responses to the remaining questions were evaluated using frequency analysis and are presented just verbally due to space limitations. The question sets focused on: (i) barriers to entrepreneurial development or development opportunities (i.e. specific activities identified as opportunities); (ii) the degree of success or failure of particular entrepreneurial activity; and (iii) the perceived importance of supporting factors for entrepreneurial development in protected areas. For all these thematic categories, respondents provided their answers using a five-point scale.

2. RESULTS

In the sample of 49 respondents, men make up a larger proportion (68%), which can be explained in part by the type of industry in which most respondents are engaged. This industry is forestry and wood processing (35%), which, together with agriculture (15%), accounts for as much as 50 percent of the sample. The remaining 50 percent of the respondents' activities are in the service sector – specifically, 25 percent in tourism and the remaining 25 percent in services such as education/consulting, IT, and retail. Based on a combination of gender, age, education, and sector, the following groups of respondents can be identified: 1) Experienced entrepreneurs in forestry: men aged 36–55, mostly with university degrees, operating in forest-based sector (including the energy sector/biofuels and the wood processing industry); 2) Entrepreneurs in tourism (Tatras, Liptov, Spiš): men and women aged 26–55, mostly with university degrees, from the districts of Liptovský Mikuláš, Poprad, and Kežmarok, focused on tourism, culture, recreation, hospitality, and related services (e.g., mountain guiding); 3) Farmers and food producers: men and women, more commonly active in the districts of Levice and Bardejov; focused on agriculture and food production (often combined with forestry activities); 4) Education, science, and professional services: more women (including those with doctoral degrees), but also men, in the districts of Zvolen, Banská Bystrica, Liptovský Mikuláš, and Dolný Kubín; they are engaged in education, professional, scientific, and technical activities, as well as regional development; 5) "Other" or specialized services: IT, financial and insurance activities, sports (rock climbing), translation, beekeeping, and property management.

Table 1. Comparison of the χ^2 Test and Fisher's MC (Monte Carlo) Test

Combination	Contingency Table	χ^2 Observed	p (Chi-square Test)	p (Fisher's Exact Test, MC)	Conclusion (α = 0.05)
Gender × Evaluation (2×3)	2×3	1.957	0.3760	0.4249	Independent
Age × Evaluation (2×3)	2×3	2.299	0.3168	0.3271	Independent
Education × Evaluation (3×3)	3×3	2.997	0.5584	0.5822	Independent

Fisher's exact test with Monte Carlo simulation confirmed the results of the chi-square test of independence, as the null hypothesis of independence was not rejected for any combination of variables. For the variable gender (pFisher = 0.425), Fisher's test yielded a more conservative result than the chi-square test, as reflected by the higher p-value. For the variable age (pFisher = 0.327), the p-values obtained from both tests were nearly identical (difference = 0.010). Similarly, for education level (pFisher = 0.582), the results were fully consistent across both methods. Also, educational attainment does not exhibit a statistically significant association with the evaluation of the entrepreneurial environment in the Carpathian region. Based on the results presented above, we confirm the validity of the null hypothesis.

Additional findings from the responses analysis can be summarized (Table 2) as follows: 1) Respondents' assessment of business opportunities in protected areas tends to be negative or indifferent; 2) Tourism potential is perceived as an opportunity. Regarding forestry activities, there is a combination of opportunity and barrier (e.g., due to the zoning of protected areas); 3) - Access to loans and co-financing is mostly perceived as a barrier. Respondents also see a problem in securing the necessary equity capital to start a business; 4) Local natural resources – for forestry, agriculture, and tourism – are mostly perceived as an opportunity. Respondents distinguish between the natural values of protected areas and the formal framework of environmental protection. While local natural resources and tourism potential are widely perceived as assets, the legal status of protected areas is less frequently regarded as a source of entrepreneurial opportunities; 5) Support from local governments and agencies is frequently perceived as a "barrier." Responses also point to bureaucracy, a lack of transparency in subsidies, and a lack of interest on the part of state and public organizations; 6) Knowledge and traditions are viewed as opportunities. Residents' incomes and capital are seen more as barriers.

Table 2. Respondents' Perceptions of Factors

Area / Factor	Opportunities (Positive Perception)	Barriers (Negative Perception)
Overall Entrepreneurial Opportunities	–	*Predominantly negative or indifferent perception*
Tourism Attractiveness	*Significant opportunity, particularly for tourism and service-related activities*	–
Forestry Activities	*Partially perceived as an opportunity, but simultaneously perceived as a barrier (e.g., due to zoning restrictions)*	
Access to Financing (Loans, Co-financing)	–	*Major barrier – limited access to credit and difficulties in securing co-financing*
Local Natural Resources	*Opportunity for forestry, agriculture, and tourism development*	–

Support from Local Governments and Public Authorities	–	*Barrier – bureaucracy, lack of transparency in subsidy allocation, and insufficient institutional support*
Knowledge and Traditions	*Opportunity – positively perceived factor*	–
Residents' Income Levels	–	*Rather a barrier – limited financial capacity of local residents*

The most strongly represented sectors in the sample are forestry and wood processing, as well as tourism. Perceptions of entrepreneurial activities within protected areas differ across these sectors. Respondents engaged in tourism-related activities generally expressed an optimistic view of entrepreneurial opportunities, whereas those involved in forestry and wood processing tended to perceive the business environment more pessimistically. The factors identified as creating opportunities for entrepreneurship development in protected areas include tourist attractiveness, natural resources, local traditions, and entrepreneurial initiative. These findings indicate a strong orientation toward tourism and the utilization of local resources. The most frequently perceived barriers were access to finance (loans and investment capital), support from public authorities, legislation related to nature conservation, and the income level of local residents. Within the open-ended responses, recurring barriers included bureaucracy, subsidy systems, nature conservation regulations, non-governmental organizations, and legislative constraints.

When evaluating the success or failure of business activities in protected areas, respondents identified the following sectors as the most successful: tourism, agriculture, education, and services. These sectors received the most favourable assessments. In contrast, industry, energy production, construction, and financial services were evaluated as the least successful sectors. Respondents identified several forms of support that they consider essential for entrepreneurship development in protected areas. These include financial assistance, legal support (particularly in relation to environmental permits), cooperation with public authorities, access to knowledge and training, promotion of protected areas, and support in acquiring new technologies. A high degree of consensus regarding the importance of these factors was observed across the sample. Certain advisory and consulting services were considered less important when they were not directly linked to tangible opportunities for obtaining permits, capital, or market access The open-ended responses repeatedly emphasized several recommendations for improving the entrepreneurial environment in protected areas. These include the development of sustainable tourism, support for local products, the establishment of clusters, associations, and cooperative networks, improved communication between state authorities, local governments, conservation organizations, and entrepreneurs, and the digitalization of administrative processes.

3. DISCUSSION

The view that mindful human activity is not detrimental but, on the contrary, beneficial to biodiversity and ecosystem functioning is supported by a range of studies conducted within the Carpathian region. These studies highlight the positive effects of traditionally practiced land-use activities, particularly low-intensity agriculture. Janišová et al. (2020), in their study from the Romanian Carpathians, demonstrated that low-intensity management practices (including mowing, grazing, manuring, and ploughing) support the persistence of species-rich grasslands.

The authors also emphasize the preservation of "deep local ecological knowledge and experience" among rural communities in the Carpathian region. Notably, this concept of a profound "knowledge of one's own landscape" has likewise been discussed in some foreign studies (Hernández-Morcillo et al., 2014; Vlasov, 2021). Interestingly, even earlier studies from the Slovak Carpathians (Hadač et al., 1969; Kliment, 1994) identified the abandonment of traditional agricultural practices and the subsequent conversion of grasslands into fallow land or their overgrowth of trees as the principal threats to mountain meadows. Based on these findings, it can be concluded that small-scale, ecologically mindful land management has considerable potential to maintain and enhance biodiversity in Carpathian landscapes.

Respondents highlighted the great potential of tourism as well as the use of natural resources. On the negative side, they pointed to barriers such as bureaucracy, legislation, weak government support, and funding. In other words, the development of entrepreneurial activities in the Slovak Carpathians protected areas has potential, but it is significantly constrained by institutional and legislative barriers. Consistent with the geographically extensive study of entrepreneurship in protected areas across all countries of the Carpathian arc conducted by Kaputa et al. (2026), it can be argued that nature conservation should not rely exclusively on the prohibition and restriction of economic activities but should also actively support entrepreneurship. Therefore, protected areas themselves do not constitute the core problem; rather, the issue lies in the absence of systematic compensation mechanisms addressing the restrictions and disadvantages arising from the existence of regulatory framework.

It is essential that the competent authorities create an environment in which policy mechanisms are designed through active engagement with the needs of the people living in these regions – individuals who understand the broader societal responsibility to protect and enhance valuable ecosystems. Frequently, these stakeholders are proactive individuals, families, or local interest groups whose mindful actions contribute to the preservation of not only natural heritage but also the wider cultural landscape. Through their activities, they interact with the environment in a sensitive manner. Respecting people's need to pursue their work and entrepreneurial activities in order to achieve a dignified standard of living should therefore be reflected in regulatory and legislative frameworks that promote the coexistence of nature conservation objectives with socially and economically favourable conditions. Such an approach acknowledges that environmental protection and local economic development should be viewed not as competing priorities but as complementary goals within sustainability framework. In this context, the statement by Benedict XVI (2009) is particularly relevant: "When 'human ecology' is respected within society, environmental ecology also benefits."

This local situation also gives rise to an important discourse – even in a global context – on achieving the SDGs in practice, where there is no balanced integration of the pillars such as People (a dignified life for all), Planet (environmental protection), Prosperity (sustainable economic growth), but also Partnership (partnerships between governments, enterprises and civil society). Creating an environment where the fulfilment of one pillar dominates at the expense of others is not the path to achieving the set goals. A similar line of reasoning applies in the context of the EU, where nature conservation interests conflict, for example, with the interests of rural development or methods of managing natural resources. This may require more subsidiarity or flexibility in establishing legislative frameworks to reflect local specificities, but above all, it certainly requires well-considered political decisions across all levels – from the international to the regional.

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REFERENCES

1. Kaputa, V., Nizioł, A., Nycz, E., Pieniążek, A., Stopa, M., & Szpara, K. (2026). Local entrepreneurship in protected areas of the Carpathians: cross-border insights from stakeholder dialogues. *Agricultural and Resource Economics: International Scientific E-Journal*, *12*(1), 57–91. https://doi.org/10.51599/are.2026.12.01.03
2. Benedict XVI. (2009). Caritas in veritate. Available at: https://www.vatican.va/content/benedict-xvi/en/encyclicals/documents/hf_ben-xvi_enc_20090629_caritas-in-veritate.html
3. Hadač, E., Březina, P., Ježek, V., Kubička, J., Hadačová, V., & Vondráček, M. (1969). *Die Pflanzengesellschaften des Tales "Dolina Siedmich prameňov" in der Belaer Tatra*. Veda, Bratislava
4. Hernández-Morcillo, M., Hoberg, J., Oteros-Rozas, E., Plieninger, T., Gómez-Baggethun, E., & Reyes-García, V. (2014). Traditional ecological knowledge in Europe: status quo and insights for the environmental policy agenda. *Environment: Science and Policy for Sustainable Development*, 56(1), 3-17. https://doi.org/10.1080/00139157.2014.861673
5. Vlasov, M. (2021). In transition toward the ecocentric entrepreneurship nexus: how nature helps entrepreneurs make ventures more regenerative over time. *Organization & Environment*, 34(4), 559–580. https://doi.org/10.1177/1086026619831448
6. Janišová, M., Biro, A., Iuga, A., Širka, P., & Škodová, I. (2020). Species-rich grasslands of the Apuseni Mts (Romania): role of traditional farming and local ecological knowledge. *Tuexenia*, 40, 409-427. https://doi.org/10.14471/2020.40.017
7. Kliment, J. (1994). *Die polygono-trisetion-gesellschaften in der Slowakei* [The Polygono-Trisetion communities in Slovakia]. *Preslia*, 66(2), 133-149. Available at: https://www.preslia.cz/article/pdf?id=11461

Authors address:
Kaputa, V.[1*]; Pieniążek, A.[2], Stopa, M.[3]
[1] Department of Marketing, Trade and World Forestry, Technical University in Zvolen, Slovakia
[2] State University of Applied Sciences in Przemyśl & The Association for the Development and Promotion of Podkarpacie „Pro Carpathia", Poland
[3] Solidata (analytical and research company), Poland
[*]Corresponding author: kaputa@tuzvo.sk

PROJECT MANAGEMENT IN THE CARPATHIAN REGION: ISSUES AND CHALLENGES AFFECTING LOCALLY ACTIVE COMMUNITIES

Attila Rácz, Vladislav Kaputa, Agnieszka Pieniążek

Abstract: The article explores the concept of the active citizen who makes conscious decisions in the economic sphere and acts in a pro-social and pro-environmental manner. It describes the activities of such individuals and local groups based on facts arising from focus group discussions. Representatives of Carpathian non-profit organizations participated in the discussion, which focused on the role of the civic sector in regional development, the protection of cultural and natural heritage, youth work, and the promotion of tourism in the Slovak Carpathians region. The core of their activities involves implementing development strategies, organizing cultural and educational events, preserving traditional crafts, and engaging young people in border regions. They identified the most important areas as the development of tourism linked to the preservation of cultural and natural heritage, support for local products, and systematic network cooperation between NGOs, local governments, and other stakeholders. In the area of cross-border cooperation, positive aspects have been identified, but also barriers such as bureaucracy, co-financing, and complicated communication with institutions. Personal leadership, connecting people, and long-term relationships were cited as key success factors, with NGOs relying primarily on social media, websites, local media, and media coverage of thematic events to communicate with the public. They emphasized the need to strengthen civic society's capacity, including through special grant schemes, community foundations, and the coordination of activities. The panellists viewed NGOs as a complement to the activities of national parks, capable of introducing new forms of public engagement and improving the quality of life in the region.
Keywords: project management, local communities, Slovak Carpathians

1. INTRODUCTION

The idea behind this article arises from an understanding of the work of dedicated (and, in their own way, exceptional) people in the Carpathian mountain regions of Slovakia. They direct their efforts toward benefiting specific regions where they are physically, but above all mentally, embedded due to their perception of the values they wish to highlight, enhance, or simply preserve for themselves and future generations. The relationship between individuals and the environment/region in which they live has attracted considerable scholarly interest. Højrup (2003) discusses the concept of value embeddedness, emphasizing the connection between individuals, their work, and a specific socio-spatial context. Velvin et al. (2016) highlight the link between such embeddedness and the entrepreneurial skills and capabilities of farmers. Nordic studies focusing on the role of embeddedness (Korsgaard et al., 2022; Vlasov et al., 2018) further underscore the importance of this factor and call for additional research aimed at gaining a deeper understanding of entrepreneurs' proactive engagement with their local environment (Wigren-Kristoferson et al., 2022).

In this paper, we build on previous studies (Kaputa et al., 2026, Kaputa et al., 2024, Maťová et al., 2024, Rácz et al., 2023, Kaputa et al., 2020) analysing the role of the individual – an active citizen who makes mindful decisions in economic matters and acts in a pro-social and pro-environmental manner. In sustainability research, such individuals are conceptualised

as change agents: actors whose personal commitment and value-driven action catalyse broader social-ecological transformations (Pringle et al., 2026). Such individuals behave in this authentic manner primarily within smaller, local communities. In both their consumption and economic activities, they prefer natural materials with a strong emphasis on resource reuse. When engaging in economic activities in the service sector, they prioritize education focused on sustainability and emphasize intangible needs (cultural, spiritual).

2. METHODOLOGY

The study reflects on previous activities carried out as part of cross-border (Polish-Slovak) cooperation, as well as on the overall activities of actors in the nonprofit sector to date. Information was collected from these actors through their participation in a Focus Group Interview (FGI). It took place online in 2023 with representatives from a total of nine organizations – including six civic associations, two representatives from Local Action Groups (LAGs), and one representative from the Poloniny National Park. The moderator led the discussion in the form of a structured interview, during which participants responded to given questions.

The methodology is based on the FGI conducted with Carpathian non-governmental organizations engaged in the protection and promotion of cultural and natural heritage, the development of tourism, and the support of local products. The discussion is structured into four thematic blocks. The first block addresses the significance and role of non-governmental organizations in activities carried out for the benefit of the Carpathians. It examines the core mission of individual organizations, the motivations underlying their establishment, and the extent to which these founding assumptions have been reflected in the outcomes achieved. It further verifies the continued relevance of the four key areas identified in 2020 (cultural heritage, natural heritage, tourism and related entrepreneurship, and local and regional products). The second block addresses good practices in Carpathian-related activities, covering implemented projects, forms of cooperation – including their benefits and limitations - and specific approaches to leveraging cultural and natural heritage. The third block focuses on cross-border cooperation for the benefit of the Carpathians, examining concrete cross-border projects, their objectives, key challenges encountered, and the results achieved. The fourth block concerns external communication and image-building, addressing the methods used to promote organizational activities, their perceived effectiveness, and the objectives pursued through such promotion.

We approached this paper as a sociological and managerial study, in which we selectively focused on interesting aspects emerging from the research. The subsequent analysis of the results is based on a verbatim transcript of the FGI. The quotations in the text are direct paraphrases from the discussion transcript, with no changes to the content. The abbreviation “OZ” (in the following text) means NGO.

2. RESULTS

2.1. The project manager between values and profession

The FGI with representatives of Carpathian non-governmental organizations reveals an intriguing picture of professional identity within the regional development sector. Respondents do not perceive their work primarily through a formal position or administrative competencies,

but rather through personal conviction and commitment to the community. Within the Carpathian context, the project manager simultaneously fulfils multiple roles – serving as a community leader, a mediator of cultural values, and a guardian of local heritage.

A representative of the OZ Košiar in Topoľa captures this attitude aptly: in his view, the fundamental precondition for successful work is "doing things with heart," as personal dedication naturally builds trust and the organization's good reputation. This value orientation is closely linked to the theme of conscious consumption – these individuals' decisions stem not from economic interest but from a sense of responsibility toward cultural and natural heritage.

At the same time, the discussion reveals an inherent tension within this approach. While the voluntary character of the work is a source of authenticity, it also constitutes a long-term vulnerability of the entire sector. A representative of TAKE NAŠE, o. z. states this plainly: "for the work of NGOs to be sustainable in the long run, we need money for salaries." This reflects a fundamental paradox of the non-profit sector – it rests on strong personal dedication yet lacks adequate conditions for its long-term reproduction.

2.2. Social capital: between networking and fragmentation

The functioning of the organizations under study rests on two mutually reinforcing forms of social capital. The internal cohesion of communities and organizations (bonding capital) intertwines with the capacity to build relationships among diverse partners – local governments, national parks, the non-governmental sector, and entrepreneurs (bridging capital) (Putnam, 2000). This networking capacity ranks among the decisive preconditions for regional development. Respondents' experiences in this regard vary considerably. TAKE NAŠE, o. z. notes that organizations in the region often carry out similar activities without mutual coordination – "many times they are not even aware of each other." From a sociological perspective, this represents a manifestation of the fragmentation of social capital, which weakens the capacity for joint action. A different trajectory is described by a representative of MAS Terchovská dolina, where cooperation develops organically through a good reputation and long-cultivated personal contacts. "The advertising takes care of itself" – here, community trust is the result of the organization's activity rather than its precondition. The crowdfunding campaign of the OZ Bašta Bardejov further illustrates how a concrete initiative can simultaneously test and reinforce community trust. Respondents emphasized that cooperation between organizations develops not only through formal project partnerships but also through everyday contacts, the exchange of experience, and informal mutual support. In their opinion, relationships built in this way facilitate the establishment of new partnerships and enhance the capacity of organizations to respond jointly to local needs. Cross-border cooperation constitutes a distinct area of concern. Respondents value their experience with Polish partners (Pro Carpathia, the Bieszczady Foundation) but point to marked disparities in institutional capacity on either side of the border. A representative of MAS Terchovská dolina formulates this with undisguised irony: "In front of our Polish friends, I sometimes feel ashamed of our competent authorities." This statement reflects a deeper sense of structural disadvantage, which affects organizations' willingness to enter into international partnerships.

2.3. Cultural heritage as a living social practice

Respondents converge on one point: the protection of cultural heritage is not a matter for museums. It is an everyday social practice through which community bonds are reinforced and knowledge is transmitted across generations (Smith, 2006).

A representative of Rusynfolk.sk understands the preservation of the authentic folklore of the Ulič Valley as a living process of building local identity, rather than as the archiving of traditions. Her statement that "just as forests know no borders, neither does the Rusyn nation" suggests that the Carpathian landscape constitutes a shared symbolic space that transcends state borders. Here, the landscape is not merely a natural environment – it is a source of collective identity and a motivation for joint action. A representative of MAS Terchovská dolina links the revival of shepherding traditions and a children's open-air museum in Orava with the necessity of capturing practical knowledge before its bearers disappear forever. OZ Košiar in Topoľa has established a craft centre focused on traditional bread-making, in which educational, social, and economic functions intersect. Furthermore, the folklore group Rusynfolk.sk also serves as an informal educational institution for young people in the remote Ulič Valley. All these examples confirm that cultural heritage can serve as a living resource for community cooperation, rather than merely an object of protection.

Respondents also emphasized that cultural heritage serves not only as an object of protection but also as a practical tool for strengthening community engagement and encouraging local participation. Activities based on traditional crafts, folklore, local history, and regional customs create opportunities for intergenerational exchange, stimulate volunteer involvement, and foster a sense of shared responsibility for the development of the region. In this perspective, heritage-related initiatives become an important mechanism for activating local communities, strengthening social cohesion, and building long-term relationships among residents, local institutions, and non-governmental organizations.

2.4. Institutional barriers and sustainability

Despite respondents' high level of motivation, their initiatives encounter several systemic obstacles, which can be summarized into four areas. The first is the administrative complexity of cross-border projects, particularly within the INTERREG program. Extensive bureaucracy burdens smaller organizations with limited capacities and, rather than supporting project implementation, complicates it. The second is the co-financing system, which favours financially stronger entities and restricts smaller initiatives' access to project opportunities. The third is the insufficient coverage of personnel costs under grant schemes, which forces organizations to rely on volunteering and short-term contracts – a model that undermines their long-term stability. The fourth is what a representative of TAKE NAŠE, o. z. terms a "mental barrier" – the tendency of certain public institutions to perceive non-governmental organizations more as recipients of support than as equal partners possessing professional expertise.

Respondents also pointed out that limited human resources constitute a significant challenge for many local non-governmental organizations. In small organizations, the same individuals are often responsible for project preparation and implementation, administrative tasks, partnership development, and communication activities. In their opinion, this makes long-term planning more difficult and limits the capacity to undertake new initiatives. Respondents, however, do not remain passive. They turn to crowdfunding, smaller foundation grants, and support from self-governing regions, while maintaining networks of mutual assistance. Although such solutions cannot substitute for systemic support, they enable organizations to continue functioning even when standard grant mechanisms prove insufficient.

The overall image of the local leader emerging from the discussion is that of an individual who combines project management, community work, institutional negotiation, and a value-

based commitment to the region. This combination is a source of their effectiveness, yet it simultaneously renders them vulnerable to burnout and growing administrative burden.

3. CONCLUSIONS

The FGI with representatives of Carpathian non-governmental organizations yields empirically valuable material for research into the motives and barriers of regional development, as well as into mindful decision-making. Respondents are not merely project administrators – they are individuals who, amid insufficient institutional support, have taken on responsibility for the cultural heritage, natural environment, and community of their surroundings.

The interpretive framework of project manager → person → landscape → sustainability → region is confirmed by the analysis as a productive one. The project manager is not merely an administrator, but a being anchored in a relationship to place, to the Carpathian landscape, its traditions, and its natural values. It is precisely this anchoring that constitutes the source of authenticity resonating within communities and shaping regional identity. Commitment to place ranks among the most natural foundations of socially responsible behaviour (Lewicka, 2011).

Within this framework, sustainability is not merely an ecological or economic category – it is, above all, a human one. It depends on whether engaged individuals have adequate conditions for long-term work. As long as the non-governmental sector remains dependent on volunteering without systemic support, there is a risk of exhausting precisely those who generate change. Society thus draws freely on social and cultural capital in which it does not sufficiently invest.

The findings of the analysis give rise to four concluding statements. First, local leaders in the Carpathian region constitute an empirically relevant example of mindful action with measurable impacts on regional development. Second, effective project management in this environment presupposes a personal commitment to the community – without which the long-term trust and reputation necessary for genuine cooperation cannot be built. Third, the systemic conditions for the work of local leaders remain inadequate, sustaining the structural vulnerability of the non-governmental sector. Fourth, the identified organizations offer concrete models of sustainable behaviour – ranging from the authentic promotion of the region, through the integration of tradition with modern tourism and mountain-land management practices, to the intergenerational transmission of cultural heritage. These individuals stand as living evidence that a relationship to place and community constitutes a fundamental precondition for lasting social change.

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REFERENCES

1. Højrup, T. (2003). State, culture and life-modes: the foundations of life-mode analysis. London, Routledge. https://doi.org/10.4324/9781315194530

2. Kaputa V., Maťová H., Rácz A., & Wanat L. (2024). Achieving sustainability - with the consumer or the citizen? In Jelačič D. (Ed.), Achieving Sustainability In Forest-Based Industry (pp. 1–18). WoodEMA, i.a. https://www.woodema.org/book_2024.html.
3. Kaputa, V., Lapin, K., Leregger, F., Gekic, H. (2020). Economic Dimensions of Environmental Citizenship. In: Hadjichambis, A.C., et al. Conceptualizing Environmental Citizenship for 21st Century Education. vol 4. Springer, Cham. https://doi.org/10.1007/978-3-030-20249-1_3
4. Kaputa, V., Nizioł, A., Nycz, E., Pieniążek, A., Stopa, M., & Szpara, K. (2026). Local entrepreneurship in protected areas of the Carpathians: cross-border insights from stakeholder dialogues. Agricultural and Resource Economics, 12(1), 57–91. https://doi.org/10.51599/are.2026.12.01.03
5. Korsgaard, S., Wigren-Kristoferson, C., Brundin, E., Hellerstedt, K., Alsos, G. A., & Grande, J. (2022). Entrepreneurship and embeddedness: process, context and theoretical foundations. Entrepreneurship & Regional Development, 34(3 4), 210 221.
6. Lewicka, M. (2011). Place attachment: How far have we come in the last 40 years? Journal of Environmental Psychology, 31(3), 207–230. https://doi.org/10.1016/j.jenvp.2010.10.001
7. Maťová, H., Triznová, M. O., Kaputa, V., Loučanová, E., & Vlosky, R. P. (2024). Strategic Environmental Consumer Segmentation: An Exploratory Case Study in Slovakia. SAGE Open, 14(1), 21582440241240638.
8. Pringle, C. B., Biggs, R., & Sitas, N. (2026). Agents of change: clarifying terms and their functional roles in shaping social-ecological systems. Ecology and Society, 31(2), 13.
9. Putnam, R. D. (2000). Bowling Alone: The Collapse and Revival of American Community. New York: Simon & Schuster.
10. Rácz A., Kaputa V., Loučanová, E. (2023). Wood products customer - consumer or citizen? In Current trends and challenges for forest-based sector: carbon neutrality and bioeconomy. Zagreb: WoodEMA, a.i. 2023. ISBN 978-953-8446-01-6, p. 246-250. <https://www.woodema.org/proceedings/WoodEMA_2023_Proceedings.pdf>.
11. Smith, L. (2006). Uses of Heritage. London: Routledge.
12. Velvin, J., Bjørnstad, K., & Krogh, E. (2016). Social value change, embeddedness and social entrepreneurship. Journal of Enterprising Communities: People and Places in the Global Economy, 10(3), 262–280. https://doi.org/10.1108/JEC-08-2014-0015
13. Vlasov, M., Bonnedahl, K. J., & Vincze, Z. (2018). Entrepreneurship for resilience: embeddedness in place and in trans-local grassroots networks. Journal of Enterprising Communities, 12(3), 374–394. https://doi.org/10.1108/JEC-12-2017-0100
14. Wigren-Kristoferson, C., Brundin, E., Hellerstedt, K., Stevenson, A., & Aggestam, M. (2022). Rethinking embeddedness: a review and research agenda. Entrepreneurship & Regional Development, 34(1 2), 32–56. https://doi.org/10.1080/08985626.2021.2021298

Authors address:

Rácz, A.[1]; Kaputa, V. [2*] Pieniążek, A.[3]
[1] UNESCO Dept. for Ecological Awareness and Sustainable Development, Technical University in Zvolen, Slovakia
[2] Dept. of Marketing, Trade and World Forestry, Technical University in Zvolen, Slovakia
[3] State University of Applied Sciences in Przemyśl & The Association for the Development and Promotion of Podkarpacie „Pro Carpathia", Poland
[*]Corresponding author: kaputa@tuzvo.sk

CHAPTER E
DIGITAL TRANSFORMATION AND ARTIFICIAL INTELLIGENCE

INDUSTRIAL PARKS IN BULGARIA IN THE CONDITIONS OF INDUSTRY 4.0 AND 5.0: DIGITALIZATION, SMART SOLUTIONS AND SUSTAINABILITY

Bozhidar Chaparov, Katya Antonova

Abstract: The sustainable development of industrial parks is increasingly recognized as a key driver of regional competitiveness, innovation, and industrial resilience. In the context of Industry 4.0 and the emerging Industry 5.0 paradigm, industrial parks are evolving into smart ecosystems integrating digital technologies, sustainable resource management, and human-centered innovation. This study aims to analyze the current state and development prospects of industrial parks in Bulgaria under the conditions of Industry 4.0 and 5.0, focusing on the implementation of digital technologies, smart infrastructure, and sustainable management practices. The research applies analytical, comparative, and literature review methods to examine the adoption of technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, digital twins, and smart energy management systems. Special attention is paid to the opportunities for industrial parks to support circular economy principles, improve energy efficiency, optimize logistics and supply chains, and reduce environmental impacts. A case perspective from the forestry and wood-processing industry is used to illustrate the potential of digital traceability, sustainable resource management, and the integration of bio-based industries within modern industrial ecosystems. The study concludes with recommendations for accelerating the digital and sustainable transformation of industrial parks in Bulgaria through innovation, collaboration, and smart governance.
Keywords: industrial parks; Industry 4.0; Industry 5.0; digitalization; sustainability; smart solutions.

INTRODUCTION

Digital transformation and the transition to sustainable development are establishing themselves as key factors for increasing the competitiveness of the economy. The concept of Industry 4.0 has ushered in a new stage in industrial production based on the integration of digital technologies, automation, the Internet of Things (IoT), artificial intelligence (AI), blockchain and intelligent production systems. Industry 5.0 further develops this approach by focusing on the human-centricity, resource efficiency and sustainability of industrial systems. In this context, industrial parks are transforming into smart industrial ecosystems combining modern infrastructure, digital technologies and sustainable resource management. They play an important role in attracting investment, regional development and technology transfer, while creating conditions for optimizing production, logistics and energy efficiency. Their development is in line with the European Union's strategic objectives for the digital and green transitions, promoting the deployment of smart solutions and the principles of the circular economy. For Bulgaria, industrial parks are an important tool for modernizing the industrial base and increasing the competitiveness of enterprises, including in the forestry and wood processing industries. The sector has significant potential to deploy digital technologies in production management, traceability of raw materials, optimization of supply chains and resource efficiency.

The aim of the authors of this study is to analyze the development of industrial parks in Bulgaria in the context of Industry 4.0 and Industry 5.0, with an emphasis on digitalization, the implementation of smart solutions and the application of the principles of sustainable development and circular economy. The research methods are an analysis of the scientific

literature, the regulatory framework and modern technological solutions applicable to the management of industrial parks, with special attention paid to the possibilities for their application in the forestry and wood processing industry.

1. LITERATURE REVIEW

The development of industrial parks in the last decade is inextricably linked to the entry of the concept of Industry 4.0, which transforms traditional production systems into digitally connected, intelligent and adaptive industrial ecosystems through the integration of digital technologies, cyber-physical systems, Internet of Things (IoT), artificial intelligence (AI), digital twins, cloud technologies, big data analysis (Big Data) and blockchain in manufacturing processes (Xu et al., 2021). At the heart of this concept is the creation of interconnected production systems in which physical assets, machines, infrastructure and information systems exchange data in real time, which allows automated management, continuous monitoring and optimization of production processes.

Smart energy systems that integrate digital technologies, renewable energy sources, smart power distribution networks, energy storage systems and demand management platforms are also becoming increasingly important. Through the combination of IoT, AI and Big Data, digital twins, etc., industrial parks can optimize energy flows, reduce peak loads and carbon emissions in real time, as well as increasing the energy independence and sustainability of industrial infrastructure. These solutions represent one of the main technological pillars of the transition to smart and sustainable industrial parks within Industry 5.0 (Carvalho et al., 2024; da Silva et al., 2024), fulfilling a specific function in the management of production, infrastructure, logistics and resources. Their integration allows the construction of smart industrial ecosystems characterized by a high degree of automation, connectivity and adaptability.

The Internet of Things ensures the continuous collection and exchange of information through sensors and smart devices, which allows monitoring of production equipment, logistics processes, energy consumption and infrastructure status in real time. The accumulated data is processed through **artificial intelligence** algorithms and machine learning, which support predictive maintenance of equipment, optimization of production schedules, risk management, and management decision-making based on data analysis (Javaid et al., 2022). In industrial parks, IoT allows real-time monitoring of energy consumption, infrastructure, water supply, and traffic flows.

Digital twins are virtual models of production systems, equipment or infrastructure and allow virtual modeling of both individual plants and the entire industrial park. They can simulate different production scenarios, analyze the efficiency of processes and identify potential problems even before they occur in a real environment. increasing the reliability of production systems and more efficient resource management. Among other digital technologies**, blockchain** is establishing itself as an important tool for building secure, transparent, and trustworthy industrial ecosystems by ensuring traceability of raw materials, exchanges between enterprises, and compliance with ESG requirements. The decentralized structure of technologies allows for traceability of material flows, secure data exchange between enterprises and increased transparency in supply chains. This is especially important for industrial parks, where multiple enterprises use a common infrastructure and exchange production, logistics and environmental information. In the context of Industry 5.0, blockchain supports not only the digital management of production, but also the traceability of carbon ESG

reporting and the implementation of circular economy principles (Alazab & Alhyari, 2024; Fraga-Lamas et al., 2024).

At the same time**, cloud technologies** and **big data analysis** provide an opportunity for the integration and processing of information from different enterprises and infrastructure systems in industrial parks, which supports coordination between individual participants in the industrial ecosystem and creates prerequisites for more flexible and intelligent management of production and logistics processes. transform from traditional areas into digitally connected production ecosystems characterized by a high degree of automation, integration and operational efficiency.

According to the European Commission, the concept of Industry 5.0 does not replace that of Industry 4.0, but builds on it by integrating three main principles – human-centeredness, sustainability and sustainability of industrial systems (Breque et al., 2021). Industry 5.0 combines digital technologies with the environmental and social dimensions of sustainable development, focusing on creating smart, adaptable and sustainable production ecosystems (Xu et al., 2021; Maddikunta et al., 2022; Carvalho et al., 2024).

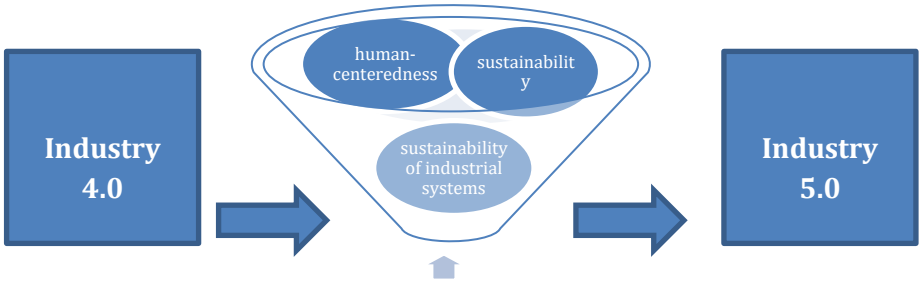

Fig. 1. Transition from Industry 4.0 to Industry 5.0

While Industry 4.0 is primarily aimed at increasing productivity and automation through digital technologies, Industry 5.0 expands their application by putting human-centered, resource efficiency and long-term environmental and social sustainability of industrial development.

Human-centricity is a guiding principle of Industry 5.0, in which technology is seen as a means of enabling rather than replacing humans. The main goal is to build a working environment where digital technologies, artificial intelligence and automated systems increase occupational safety, improve working conditions and support decision-making, while encouraging the development of new knowledge and skills. Manufacturing, Industry 5.0 promotes collaboration between humans and intelligent systems through the use of collaborative robots, operator assistance systems, and intelligent digital platforms (Breque et al., 2021; Maddikunta et al., 2022). For industrial parks, this means creating a high-tech working environment that attracts qualified professionals, stimulates innovation and improves interaction between businesses, scientific organizations and educational institutions.

Sustainability is the second fundamental principle of Industry 5.0 and is aimed at reducing the environmental impact of industrial production through efficient use of resources, limiting waste and carbon emissions, and accelerating the transition to a circular economy. In this context, digital technologies are used to optimize energy consumption, intelligently manage material flows, integrate renewable energy sources, and tracking environmental performance

in real time (Javaid et al., 2022; Carvalho et al., 2024). For industrial parks, this implies the development of a common smart infrastructure, the implementation of energy-efficient technologies, industrial symbiosis and the sharing of resources between enterprises, which creates prerequisites for a lower carbon footprint and higher resource efficiency (Dai & Day, 2022; da Silva et al., 2024).

The resilience of industrial systems has taken on particular importance in the wake of the COVID-19 pandemic, geopolitical conflicts and supply chain disruptions. In the Industry 5.0 concept, resilience is seen as the ability of industrial systems to anticipate, adapt and overcome external shocks without compromising their functionality and competitiveness (Breque et al., 2021; Ivanov, 2023). Achieving this objective is based on the use of digital technologies for risk forecasting, modelling different scenarios through digital twins, real-time data analysis and building more flexible and diversified supply chains. For industrial parks, this means not only the construction of sustainable technical infrastructure, but also the development of cooperation networks between enterprises that allow for faster adaptation to market, technological and environmental changes.

The principles of Industry 5.0 are complementary elements of an integrated concept for smart and sustainable industrial development. That is why industrial parks are seen as one of the most appropriate organizational forms for the practical implementation of the industry 5.0 concept, as they provide an opportunity for the integration of digital infrastructure, smart energy systems, industrial symbiosis and cooperation between multiple stakeholders. In this context, digital technologies are seen not as an end in themselves, but as a means to increase resource efficiency, optimize production processes, reduce carbon emissions and improve working conditions through the integration of artificial intelligence, the Internet of Things, digital twins and intelligent management systems (Xu et al., 2021; Carvalho et al., 2024, Javaid et al., 2022; Maddikunta et al., 2022). Modern scientific research considers industrial parks as key platforms for realizing the digital and green transitions by integrating smart infrastructure, industrial symbiosis, energy-efficient technologies, and circular economy principles (Dai & Day, 2022). This shows that digital maturity, the deployment of innovative technologies, and the exchange of resources between enterprises are among the main factors in increasing economic efficiency, reducing the carbon footprint and improving environmental performance (da Silva et al., 2024). In this sense, industrial parks are establishing themselves as a strategic tool of European industrial policy to achieve climate neutrality, increase competitiveness and accelerate sustainable industrial transformation (Ivanov, 2023).

Despite the growing number of publications on Industry 4.0 and Industry 5.0, research on the development of industrial parks in Bulgaria remains limited. The topic related to the application of digital technologies and smart solutions in industrial parks that specialize in the forestry and wood processing industry is very poorly covered. Sustainable management and their development as industrial ecosystems. According to Mortensen et al. (2024), the concept of an industrial ecosystem is based on the interaction between enterprises, research organizations, public institutions and other stakeholders in order to create added value through cooperation, knowledge exchange and resource efficiency. In this environment, competitiveness does not depend only on the resources of the individual enterprise, but also on the quality of the links between the actors in the ecosystem and their ability to generate collaborative innovations. An essential element of these ecosystems is industrial symbiosis, in which material, energy and information flows between enterprises are organized in such a way that waste products or by-flows from one production activity become a resource for another.

This approach increases resource efficiency, reduces environmental impact and creates prerequisites for the implementation of the principles of the circular economy in industrial production. being particularly applicable to enterprises in the forestry sector, where there are significant opportunities for cascading use of woody biomass, industrial symbiosis and the development of bio-based value chains.

Within Industry 5.0, digital technologies are no longer used solely to optimize production processes, but as a tool to build smart, adaptive and sustainable industrial ecosystems (Xu et al., 2021; Maddikunta et al., 2022; Carvalho et al., 2024). Artificial intelligence supports decision-making related to energy efficiency, emission reduction, and resource management, digital twins enable environmental impact modeling and sustainability assessment of production systems, and IoT provides continuous real-time monitoring of energy consumption, emissions, and raw material use.

This change in the philosophy of digital transformation also leads to a change in the role of industrial parks. Instead of being merely spaces for the concentration of manufacturing plants, they are gradually becoming smart industrial ecosystems in which digital infrastructure supports industrial symbiosis, the integration of renewable energy sources, the smart management of energy networks, the circular use of resources, and cooperation between businesses, scientific organizations and public institutions (Dai & Day, 2022). The development of eco-industrial parks shows that digital maturity, the introduction of innovative technologies and the exchange of resources between enterprises are among the main factors for increasing economic efficiency, reducing the carbon footprint and improving environmental performance (da Silva et al., 2024).

Despite the significant progress made through Industry 4.0 technologies, digitalization and automation are no longer sufficient to ensure sustainable industrial development. Challenges such as climate change, natural resource constraints, supply chain disruptions and growing demands for social responsibility require a rethinking of the role of digital technologies as a tool for building sustainable, adaptable and human-centred production systems.

A particularly suitable environment for the implementation of the principles of Industry 5.0 are industrial parks with enterprises from the forestry and wood processing sectors. The use of renewable resources and the possibilities for cascading recovery of woody biomass allow for the combination of digital technologies with sustainable management and the principles of the bioeconomy. In this context, digitalization covers the entire life cycle of wood resources, from the traceability of raw material to production management, by-product recovery and carbon footprint monitoring.

Technologies such as the Internet of Things, digital twins, artificial intelligence, and blockchain support equipment monitoring, energy efficiency, predictive maintenance, and wood traceability, while smart energy systems and digital platforms facilitate the exchange of resources between enterprises and the development of industrial symbiosis. In this way, industrial parks are establishing themselves as a platform for integrating Industry 4.0 and Industry 5.0, combining digitalization with sustainable resource management and the principles of the circular bioeconomy. This increases the competitiveness of enterprises, reduces environmental impact and supports the transition to climate-neutral production.

The integration of Industry 4.0 technologies provides the digital basis for the transformation of industrial parks, and Industry 5.0 defines its strategic focus on sustainability, human-centricity and resource efficiency. In the forestry and wood processing sector, this

approach creates prerequisites for the development of the circular bioeconomy and increasing the international competitiveness of Bulgarian enterprises.

2. METODOLOGY

The present study is based on a systematic and interdisciplinary approach to the analysis of the possibilities for integrating the principles of Industry 4.0 and Industry 5.0 in the development of industrial parks from the forestry and wood processing sector. Methods of literary analysis, comparative analysis and synthesis of scientific research, strategic documents and good practices related to digital transformation, sustainable industrial development and circular bioeconomy are used.

This article is conceptual in nature and presents the theoretical framework of the study related to the role of industrial parks in the context of Industry 4.0 and Industry 5.0, as well as the opportunities for their digital and sustainable transformation. The study is the basis for the development of an indicator system for assessing the degree of digital and sustainable transformation of industrial parks, as well as a conceptual model, which presents the links between technological transformation, the principles of Industry 5.0 and the sustainable development of industrial parks. The model aims to help assess the potential of industrial parks to implement digital solutions and build smart, sustainable and competitive industrial ecosystems.

3. INDUSTRIAL PARKS IN BULGARIA: REGULATORY FRAMEWORK AND DEVELOPMENT

The regulatory framework for industrial parks in Bulgaria is based on the Industrial Parks Act (ZIP, 2021). This is the first specialized normative act that regulates the conditions and procedure for the creation, construction, operation and development of industrial parks in the country. The law defines the three types of industrial parks – general (type A), specialized (type B) and high-tech (type C), as well as the requirements for their design, management and registration. According to Art. 21 of the Land Use Act, the Minister of Economy and Industry shall establish and maintain an Electronic Register of Industrial Parks, which shall ensure publicity, transparency and electronic exchange of information regarding the registered parks. Entry in the register is a prerequisite for the application of a simplified administrative regime, for access to the measures under the Investment Promotion Act and to funding through national and European programs. The law also provides an opportunity to apply local incentives through decisions of municipal councils, including exemption from certain local fees. The strategic framework for the development of the sector is further developed in the Concept for the Development of Industrial Parks and Zones for the period 2024-2028, which focuses on regional specialization, attracting strategic investors and developing industrial parks with high added value in accordance with the goals of green and digital transformation.

The practical implementation of this policy is accompanied by the expansion of the network of industrial parks. According to the data from the Electronic Register of Industrial Parks, the number of parks registered in 2022 increased from 9 to 14, which represents an increase of 55.6%. At the same time, the state is expanding investments in industrial infrastructure through the National Recovery and Resilience Plan and other European programs aimed at building and modernizing industrial parks, improving transport and technical infrastructure, increasing energy efficiency and promoting high-tech industries. These policies are in line with the European priorities for digitalization, sustainability and industrial

competitiveness and create prerequisites for the gradual implementation of the principles of Industry 5.0 in Bulgarian industrial parks.

For the management of industrial parks in Bulgaria, a regulatory framework is applied, which covers mandatory laws and strategic documents that define policies and priorities without creating immediate legal obligations. The main ones are presented in Table 1 and Table 2.

Table.1. Normative acts for regulation of industrial parks in Bulgaria

Normative act	Scope of regulation and significance
Industrial Parks Act	It regulates the establishment, registration, construction, management and development of industrial parks.
Investment Promotion Act	Regulates the conditions and measures for promoting investments and certification of investment projects, provides administrative and financial incentives for investors in industrial parks.
Spatial Development Act	It regulates spatial planning, investment design and construction. Determines the procedures for the construction of industrial infrastructure and production sites.
Environmental Protection Act	It regulates environmental assessment, EIA and complex permits, ensures the environmental requirements for the construction and operation of industrial parks.
Waste Management Act	It regulates the management, recovery and recycling of waste, creates a regulatory basis for the application of the principles of the circular economy and industrial symbiosis.
Water Law	Regulates the use and protection of water resources, determines the conditions for water supply, water use and discharge of wastewater.
Energy Act	Regulates the production, transmission and consumption of energy, supports the construction of energy infrastructure, RES and smart energy systems.
Local Taxes and Fees Act	It regulates local taxes and fees, provides an opportunity for local tax incentives to support investments.

Table 2. Strategic documents related to the development of industrial parks

Strategy Paper	Importance for industrial parks
Concept for the Development of Industrial Parks and Zones in the Republic of Bulgaria (2024–2028)	Defines the national policy for the development of industrial parks and their role in economic growth, modernization of industrial infrastructure
National Recovery and Resilience Plan	Provides funding for the construction and modernization of industrial parks, investments in green and digital transformation
Competitiveness and Innovation in Enterprise Programme (2021-2027)	Supports enterprises located in industrial parks, provides support for innovation, digitalization and competitiveness.

Regional Development Programme (2021-2027)	It finances industrial and logistics parks, including in regions in transition.

At the beginning of 2022, 9 industrial parks were entered in the register: Pleven-Telish, Sofia-Bozhurishte, Vidin, Karlovo, Suvorovo-Varna West, Simitli, Shumen, LVZ and Hemus. By mid-2022, the number of registered parks increased to 14, with Sofia-Bozhurishte establishing itself as the most developed - with 37 implemented investment projects with a total value of over EUR 543 million. BGN. and nearly 1800 newly created jobs. The state-owned operator National Company Industrial Zones EAD manages seven existing projects (Sofia, Burgas, Vidin, Ruse, Svilengrad, Stara Zagora, Varna) and five more in the process of development (Suvorovo, Kardzhali, Telish, Karlovo, Stara Zagora).

A significant impetus for the development of industrial parks has been provided through the National Recovery and Resilience Plan under the AttractInvestBG programme (Component 3: Smart Industry). The programme has approved funding for 11 industrial park and industrial zone projects across ten Bulgarian cities—Ruse, Shumen (two parks), Svishtov, Lovech, Sofia, Burgas, Stara Zagora, Vidin, Targovishte and Sliven—with a total investment of approximately BGN 280 million, of which around BGN 207 million represents non-repayable EU funding. Seven projects support the expansion of existing industrial parks established before 28 April 2022, while four are aimed at developing entirely new parks. Priority was given to projects located in Northern Bulgaria to help reduce regional economic disparities.

In parallel, under the Regional Development Programme 2021–2027, which includes a dedicated measure for coal regions in transition, seven additional industrial and logistics park projects focusing on clean energy have been approved, with a total value of EUR 142.7 million. One example is the Industrial Park Pernik project, which received a grant of EUR 15.9 million. These findings demonstrate a clear policy direction towards expanding the national network of industrial parks while prioritizing economically lagging regions and increasingly linking public investment to energy efficiency and climate neutrality objectives. This policy orientation is fully consistent with the principles of Industry 5.0.

4. RESULTS AND DISCUSSION

The analysis shows that in recent years a comprehensive regulatory and strategic framework for the development of industrial parks has been created in Bulgaria. The adoption of the Industrial Parks Act in 2021 lays the legal basis for their creation, registration and management, and its interaction with the Investment Promotion Act, the Spatial Development Act, the Environmental Protection Act and other regulations forms a complex mechanism for regulating the investment, development and environmental environment.

The results obtained also show a pronounced positive dynamic in the development of industrial parks. In 2022 alone, the number of industrial parks entered in the Electronic Register increased by 55.6%, which indicates an increased interest in this model of industrial development. Further acceleration is observed as a result of investments under the National Recovery and Resilience Plan and the programs of the European Union, which direct significant financial resources to the construction and modernization of industrial infrastructure.

The analysis shows that state policy is gradually shifting from the traditional construction of industrial zones to the development of integrated industrial ecosystems. Digitalisation, energy efficiency, the use of renewable energy sources, smart infrastructure and the principles of the circular economy are becoming increasingly important. This is in line with European

industrial policy and creates favorable conditions for the implementation of the Industry 5.0 concept.

Despite the progress reported, a number of challenges can also be identified. First of all, there is a lack of a unified system for monitoring and evaluating the economic, social and environmental results of the functioning of industrial parks. Secondly, the regulatory framework still does not contain sufficient mechanisms to promote industrial symbiosis, the exchange of resources between businesses and the integration of digital technologies to manage material and energy flows. This limits the possibilities for the full implementation of the principles of Industry 5.0.

In conclusion, it can be summarized that Bulgaria already has a stable regulatory and institutional basis for the development of industrial parks. The combination of the legislative framework, strategic documents and European investment programs creates prerequisites for industrial parks to gradually transform into smart, sustainable and competitive production ecosystems. The next stage in their development should be aimed at deeper integration of digital technologies, industrial symbiosis and the principles of Industry 5.0, which will increase resource efficiency, reduce environmental impact and strengthen the competitiveness of Bulgarian industry. Future research should focus on developing a framework for assessing Industry 5.0 readiness of industrial parks in the forest-based sector.

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References:

1. Alazab, M., & Alhyari, S. (2024). *Industry 4.0 innovation: A systematic literature review on the role of blockchain technology in creating smart and sustainable manufacturing facilities*. Information, 15**(**2), 78. https://doi.org/10.3390/info15020078
2. Carvalho, N. G. P., Gerolamo, M. C., Gonçalves, R., Rytter, N. G. M., Gladysz, B., & van Erp, T. (2024). *Industry 5.0: A new strategy framework for sustainability management and beyond*. *Journal of Cleaner Production, 461*, 142271.

https://doi.org/10.1016/j.jclepro.2024.142271

3. Breque, M., De Nul, L., & Petridis, A. (2021). *Industry 5.0: Towards a sustainable, human-centric and resilient European industry*. Publications Office of the European Union.
1. Dai, Y., & Day, S. (2022). A synthesized framework of eco-industrial park transformation and stakeholder interaction. Business Strategy and the Environment, 31(7),3122–3151.https://doi.org/10.1002/bse.3067
2. da Silva, L. T., Koch, C. M., Rodrigues, G. S., Butturi, M. A., & Sellitto, M. A. (2024). Evaluating digital maturity and innovative technologies in an eco-industrial park. Smart and Sustainable Built Environment. https://doi.org/10.1089/scc.2024.0022
3. Fraga-Lamas, P., Fernández-Caramés, T. M., Rosado da Cruz, A. M., Pires da Cruz, A., & Lopes, S. I. (2024). *An overview of blockchain for Industry 5.0: Towards human-centric, sustainable and resilient applications*. IEEE Access, 12, 116162–116201. https://doi.org/10.1109/ACCESS.2024.3435374

4. Ivanov, D. (2023). *The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives*. *International Journal of Production Research, 61*(5), 1683–1695. https://doi.org/10.1080/00207543.2022.2118892
5. Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). *Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability*. *Sustainable Operations and Computers, 3*, 203–217. https://doi.org/10.1016/j.susoc.2022.05.008
6. Maddikunta, P. K. R., Pham, Q.-V., Prabadevi, B., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., & Liyanage, M. (2022). *Industry 5.0: A survey on enabling technologies and potential applications*. *Journal of Industrial Information Integration, 26*, 100257. https://doi.org/10.1016/j.jii.2021.100257
7. Mortensen, L., Kørnøv, L., Gjerding, A. N., Rattigan, E., & Schlüter, L. (2024). *Middle-out evolution of greenfield eco-industrial parks: The journey of GreenLab, Denmark*. *Journal of Industrial Ecology, 28*(6), 1816–1829. https://doi.org/10.1111/jiec.13569
8. Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). *Industry 4.0 and Industry 5.0-Inception, conception and perception*. *Journal of Manufacturing Systems, 61*, 530-535.

Authors address:
Chaparov, B.
Business, Investments, Real Estate, University of Economics - Varna, Bulgaria
Antonova, K.
Business, Investments, Real Estate, University of Economics - Varna, Bulgaria
Corresponding author: katia_antonova@ue-varna.bg

WOOD MARKETS IN THE DIGITAL BIOECONOMY: MODERN GOVERNANCE MODELS

Rumen Dombashov

Abstract: The transformation in the global economy related to climate change, resource insecurity and digitalization requires modern governance approaches. Within the digital bioeconomy, the governance and market interaction toolkit covers the interconnected levels from data and digital technologies, through management decisions and market mechanisms, to policies and the social framework. This report provides a systematic review of the scientific literature on contemporary governance models for wood markets in the digital bioeconomy. The review was conducted in the indexed scientific databases Web of Science and Scopus for the period until the end of March 2026. The report consists of three parts. In the first part, the research framework is formed, on which the review was conducted, and the classification of the publications is performed. The second part summarizes the results of this study and includes a systematic and network analysis of the connections between the key sources. The third part discusses the results of the research. According to the research conducted, four key directions are outlined: digital management models, scenario models for assessing uncertainty, the relationship between carbon mechanisms and economic models, and the role of institutional and social factors. This study derives and structures contemporary models of management of wood markets, which can be used for strategic planning in the forest sector and the development of innovative management methodologies.
Keywords: digital bioeconomy, management tools, wood markets

1. INTRODUCTION

The sustainable management of organizations, including those within the forest sector, in the context of the digital economy necessitates the implementation of contemporary analytical, control, and evaluation models, alongside economic analyses that underpin managerial decision-making (Angelova-Stanimirova, 2024), (Lambovska et al., 2019), (Angelova-Stanimirova, 2025). Han (2026), Xu (2026), and Newton (2025) assess climate impacts and develop long-term scenarios through the application of simulation frameworks and optimization algorithms. Policy- and scenario-based models demonstrate how regulations and market mechanisms affect yield, carbon dynamics, and sustainability (Hansen et al., 2024), (Liu et al., 2023). In this context, timber markets are shaped by the interaction of technologies, policies, and institutional practices, which determines the direction of development under conditions of digital transformation (Heder Brandt et al., 2023), (Stevanov & Krott, 2021).

The purpose of this report is to provide a systematic review of the scientific literature on contemporary models for managing timber markets under conditions of the digital bioeconomy.

The review was conducted using the indexed scientific databases Web of Science and Scopus, covering the period up to the end of March 2026. Methodologically, the search protocol is based on the elements for a systematic review of the scientific literature recommended by Moher et al. (2009).

The report consists of three parts. The first part presents the research framework, which serves as the methodological basis for the literature review. The second part systematizes the

main findings, identifying four key directions: digital management models, scenario-based models for uncertainty assessment, the relationship between carbon mechanisms and economic models, and the role of institutional and social factors. The third part interprets the results in the context of the study's objectives. The review identifies and structures contemporary models for managing timber markets, which can be integrated into the processes of long-term forest resource management and the development of modern managerial concepts.

2. METHODOLOGY

A systematic literature review was conducted in the Web of Science and Scopus databases following the PRISMA methodology. Based on the functionalities of these databases, the following search strategies were applied:

WoS: (management NEAR/0 tools) AND ((wood NEAR/0 products) OR timber)

Scopus: (management PRE/0 tools) AND ((wood PRE/0 products) OR timber)

The following limitations were applied:

- Publication Years: 2021-2026
- Document Types: Article, conference paper
- Web of Science Categories: Management, Social Sciences, Business, Economics
- Open Access

These search limitations yielded 15 publications in Web of Science and 27 entries in Scopus. After reviewing abstracts and contents, entries unrelated to the topic or lacking open access were excluded. The final number of sources used was reduced to 14.

3. RESULTS

The results of the review of the scientific literature on the topic studied are presented in Figure 1.

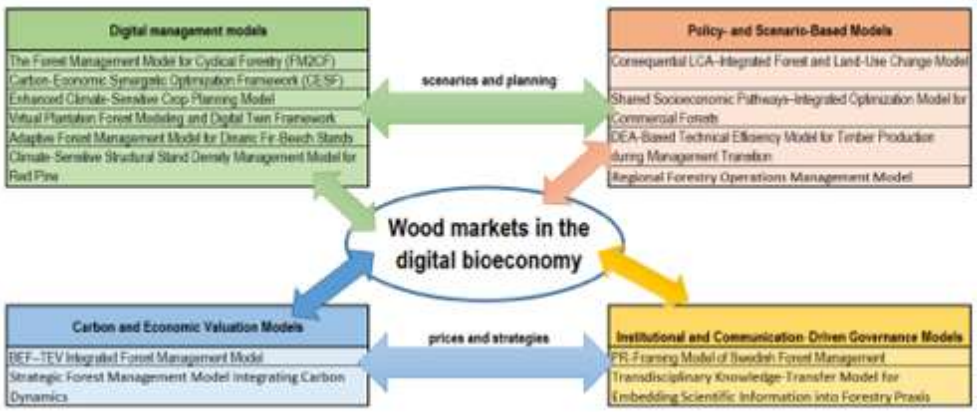

Figure 1. Models for wood markets in the digital bioeconomy

4. DISCUSSION

Research into timber markets within the context of the digital bioeconomy requires the systematic organisation of contemporary digital management models and the integration of concepts related to carbon dynamics, ecological impacts, and economic returns - elements that constitute the foundation of sustainable strategic forest planning.

4.1. Digital management models

Digital management models integrate digital data, simulation environments, optimisation algorithms, and spatial analytical techniques to support sustainable decision-making in forest management. These models enable the assessment of management scenarios and the forecasting of forest stand dynamics by incorporating climatic, ecological, and economic parameters into the strategic planning process.

The Forest Management Model for Cyclical Forestry (FM2CF) was developed to optimise timber supply while accounting for environmental impacts (regulatory factors, CO_2 stocks) and the economic environment (regional markets) (Han et al., 2026). The model employs a backcasting approach, whereby a desired forest condition is defined for a 100-year horizon, from which the necessary management decisions and interventions are derived to achieve that target state. Simulation proceeds forward in time, examining the long-term consequences for yield, changes in CO_2 stocks, the age structure of the timber, and the supply-demand balance across regions. According to Han, despite an anticipated decline in global stocks, simulations indicate a consistent increase in timber supply, reflecting improved resource efficiency and optimised forest management operations (Han et al., 2026).

The CarbonEconomic Synergistic Optimization Framework (CESF) is another contemporary model for optimising management decisions, one that simultaneously accounts for carbon benefits and economic returns (Hu et al., 2026). The model combines growth functions and evaluates market scenarios shaped by objective weights, carbon and timber prices, and thinning levels, applying a multi-objective optimisation approach. The analysis demonstrates that economic gains from carbon credits effectively offset losses arising from lower yield intensities, rendering the model particularly relevant to policies oriented towards carbon neutrality. CESF constitutes a tool for balancing ecological and economic objectives within the digital bioeconomy, characterised by a high degree of predictability (Hu et al., 2026).

The Enhanced Climate-Sensitive Crop Planning Model is an advanced forest management model that integrates climatic, biophysical, and structural parameters into the decision-making process (Newton, 2025). The model combines conventional and evolving management objectives - timber yield volume, wood quality, carbon sequestration, and biodiversity. The integration of climatic variables and species-specific characteristics enhances the accuracy of yield and carbon sequestration projections, providing a reliable framework for adaptive planning under conditions of climate change (Newton, 2025).

The primary approach of the Virtual Plantation Forest Modelling and Digital Twin Framework is the construction of a digital twin of an experimental plantation forest (Li et al., 2023). The model incorporates tree modelling, data analysis, and interaction mechanisms between the physical and virtual environments; the framework theoretically analyses the three main entities of the physical world, the digital world, and researchers (Li et al., 2023). LiDAR point cloud data and a translational particle flow method, combined with the AdTree algorithm

for tree structure reconstruction and integration with other models and optimisation algorithms, were employed for virtual modelling. In the data analysis component, a growth monitoring database was established in which tree growth equations were derived by fitting the diameter at breast height data, enabling the forecasting of growth dynamics and trends for parameters that are difficult to measure experimentally. The system encompasses 2,160 trees and growth simulations that together constitute a preliminary digital twin-oriented poplar plantation system. The model demonstrates how digital twins may be used for integrated management, visualisation, and optimisation of plantation forests, thereby providing a foundation for intelligent decision-making in the digital bioeconomy (Li et al., 2023).

The Adaptive Forest Management Model for Dinaric Fir-Beech Stands is a dynamic model developed for the selection of optimal management of Dinaric mixed fir-beech forests, ensuring sustainable increment under varying biotic and abiotic conditions (Teslak et al., 2023). The model utilises a permanent experimental plot of "Hrvatske šume" and the MOSES simulator version 3.0, with four distinct models applied to simulate the future development of forest stands (Teslak et al., 2023). The results indicate that uneven-aged forest management (selection system) yields a more stable structure and greater forest vitality, whereas even-aged management produces higher short-term timber yield but lower long-term resilience. Within this context, the model offers a methodological framework for selecting management strategies that balance productivity with ecological sustainability (Teslak et al., 2023).

The Climate-Sensitive Structural Stand Density Management Model for Red Pine is a modular, climate-sensitive management model integrating six interrelated modules for the forecasting of growth, yield, carbon sequestration, product structure, and economic value up to the year 2100 (Newton, 2022). It is based on a dynamic SDMD framework combined with a biophysical site-index height-age model. The model enables the forecasting of mean annual volume increment, biomass/carbon increments, sawlog and pole production, wood-quality attributes, and economic returns under varying thinning regimes, genetic improvements, and climatic scenarios. The author emphasises that the SSDMM provides scenario- and locale-specific rotational estimates of volumetric yields, carbon outcomes, product distributions, and fiscal worth, thereby significantly extending the possibilities for climate-smart crop planning (Newton, 2022).

Niemi et al. (2023) developed a model for the automated identification of appropriate water-protection zones in peat forests. The spatial analysis model is based on a digital terrain model derived from high-precision laser scanning (LiDAR) scanning and digital elevation model, incorporating hydrological terrain processing via water-path correction algorithms. Topographic indices - including terrain flatness, slope, and water-retention capacity - are additionally applied to identify locations meeting strictly defined criteria for the placement of water-protection structures (Niemi et al., 2023).

4.2. Policy- and Scenario-Based Models

This group encompasses models that evaluate the effects of policies, scenarios, and strategic decisions on forests, carbon and economic performance.

The Consequential LCA–Integrated Forest and Land-Use Change Model assesses the ecological consequences of the transition towards timber construction in Denmark over the period 2022–2050, accounting for projections of building stock development, material flows, overall environmental impact, and forest renewal patterns (Hansen et al., 2024). The model employs consequential LCA - an approach that identifies affected suppliers and examines how

changes in demand influence market mechanisms (Hansen et al., 2024). The analysis combines an IPCC-based carbon model with an assessment of indirect land-use change (iLUC) following Schmidt et al. (2015). The results indicate an increased impact on biodiversity as a consequence of rising timber demand. The environmental benefits of timber construction are strongly dependent on building typology, market mechanisms, and the dynamics of biogenic carbon (Hansen et al., 2024).

The Shared Socioeconomic Pathways–Integrated Optimization Model for Commercial Forests is a spatially and temporally structured optimisation model developed to forecast future carbon sequestration and timber yields from Chinese forests under the five Shared Socioeconomic Pathways (SSPs) (Liu et al., 2023). The model combines standardised growth functions, a yield module, a carbon-capture module (IPCC volume–biomass method), and an optimisation block that maximises the total net present value of timber and carbon with equal weights. Sensitivity analysis shows that social preferences, carbon prices, and harvesting and silvicultural practices exert a strong influence on carbon sequestrations, while harvesting technologies are key to increasing timber yields. The model provides a reliable framework for assessing the ecological potential of forests under varying socioeconomic scenarios and highlights the necessity of long-term afforestation and regeneration policies (Liu et al., 2023).

The DEA-Based Technical Efficiency Model for Timber Production during Management Transition is a non-parametric model based on Data Envelopment Analysis (DEA), developed to assess the technical efficiency of timber production in Polish state forests (Banaś et al., 2021). The model employs annual data on sold timber volume, forest area, standing stock, and costs related to felling, afforestation, protection, and labour. The results indicate that timber yield volumes could be increased without additional inputs. Partial technical efficiency analysis reveals the strongest growth in land, stocks, and labour, while the efficiency of felling cost utilisation declines owing to the adoption of costlier but environmentally sustainable methods and the restriction of clear-cutting. The model illustrates how multifunctional management affects production efficiency and cost structures in state forests(Banaś et al., 2021).

The Regional Forestry Operations Management Model is a system dynamics model developed to quantify unused forest biomass under conditions of sustainable forest management and constrained labour resources (Yoshioka et al., 2025). The model simulates 60- and 120-year scenarios for harvesting, thinning, and reforestation, determining, through SD-based optimisation, the sustainable annual volume of operations and the extent of managed area. The results indicate that long-term yields decline, while small-diameter timber stabilises following the felling of old-growth stands. The approach demonstrates the potential of system dynamics to support the strategic planning of biomass resources in contexts of limited labour capacity (Yoshioka et al., 2025).

4.3. Carbon and Economic Valuation Models

This group encompasses models that quantify carbon stocks, economic values, efficiency, and biomass.

The BEF–TEV Integrated Forest Management Model is a combined model for calculating forest carbon stocks and assessing total economic value (Zhao et al., 2022). The model applies the biomass expansion factor (BEF) method to quantify five carbon pool components: tree biomass, shrub biomass, deadwood, litter, and harvested wood products. A Gompertz model - identified as the most appropriate biological growth model - was applied to forecast stock growth, enabling 100-year projections of volume by tree species. The results show that the

value of forest land and timber resources substantially exceeds the value of carbon fixation, with broadleaved and young trees exhibiting the highest carbon fixation efficiency. The model provides an integrated management framework that simultaneously optimises carbon benefits and economic value through the selection of appropriate species, age classes, and long-life-cycle products (Zhao et al., 2022).

The Strategic Forest Management Model Integrating Carbon Dynamics is an advanced strategic forest management model that integrates the algorithms of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to simultaneously optimise timber yield and carbon sequestration (Carle et al., 2021). Its primary contribution is the introduction of a novel unit - the carbon-ton-year (CTY) - which enables the aggregation of carbon stocks across different pools, including in cases where decomposition extends beyond the planning horizon (Carle et al., 2021). The model simulates live biomass dynamics by assessing the effects of varying harvest intensities, thinning regimes, and natural growth on the carbon flows of a mixed-species forest in Québec. The results indicate that increases in carbon stocks are insufficient to offset losses at higher harvest intensities, underscoring the necessity of integrating carbon dynamics into strategic planning (Carle et al., 2021).

4.4. Institutional and Communication-Driven Governance Models

These models explain the influence of institutions in forest governance.

The PR-Framing Model of Swedish Forest Management is an analytical framework examining how the three largest private forest companies in Sweden - SCA, Stora Enso, and Holmen - construct the public image of the dominant Swedish Model (SM) and of alternative clear-cut-free/CCF practices through their controlled PR channels (Heder Brandt et al., 2023). Based on an analysis of 286 corporate articles published between 2019 and 2022, the authors demonstrate that the industry consistently presents the SM as the most profitable and sustainable approach, while CCF practices are rarely mentioned and, when they are, frequently in a negative context. The model identifies three principal modes of representation: economic, ecological, and social; following 2021, the ecological framing became dominant under the influence of the EU Forest Strategy 2030. In a broader context, the model reveals that corporate communication constructs representational frameworks that shape perceptions of sustainability, influence the behaviour of forest owners, and sustain existing management practices in timber markets (Heder Brandt et al., 2023).

The Transdisciplinary Knowledge-Transfer Model for Embedding Scientific Information into Forestry Practice complements the institutional perspective by examining how scientific knowledge is integrated into practical forest management through transdisciplinary projects in Germany (Stevanov & Krott, 2021). The model is grounded in three key components - knowledge production, knowledge translation, and knowledge application - and the authors emphasise that the successful integration of knowledge requires its co-creation among scientists, practitioners, and institutions (Stevanov & Krott, 2021). The analysis indicates that the effectiveness of knowledge integration depends on the degree of practitioner involvement, the transparency of communication, and the capacity of research teams to adapt complex information to operational decisions. In the context of the digital bioeconomy, the model demonstrates that effective governance of timber markets depends not only on technological tools, but also on institutional structures that facilitate the exchange, comprehension, and application of knowledge - including in the implementation of climate-adaptive practices and digital solutions (Stevanov & Krott, 2021).

5. CONCLUSION

This report presents a systematic review of the scientific literature on contemporary models for managing timber markets under conditions of the digital bioeconomy. The review encompasses publications indexed in the Web of Science and Scopus scientific databases for the period up to the end of March 2026. Methodologically, the search protocol is based on the elements for a systematic review of the scientific literature recommended by Moher et al. (2009).

The outlined contemporary models for managing timber markets can be integrated into strategic planning in the forestry sector and can serve as a basis for the development of innovative management methodologies.

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REFERENCES

1. Angelova-Stanimirova, A. (2024). Perception of the Term Audit in the Forest Sector. *WoodEMA 2024 - Green Deal Initiatives, Sustainable Management, Market Demands, and New Production Perspectives in the Forestry-Based Sector - Proceedings of Scientific Papers*, 313–318.
2. Angelova-Stanimirova, A. (2025). Main Indicators for Evaluating the Social Impact of Research Projects in the Forestry-Based Sector. *WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers*, 273–278.
3. Banaś, J., Utnik-Banaś, K., Zięba, S., & Janeczko, K. (2021). Assessing the technical efficiency of timber production during the transition from a production-oriented management model to a multifunctional one: a case from Poland 1990–2019, *Forests*, *12*(9). doi.org/10.3390/f12091287.
4. Carle, M. A., D'Amours, S., Azouzi, R., & Rönnqvist, M. (2021). A strategic forest management model for optimizing timber yield and carbon sequestration. *Forest Science*, *67*(2), pp.205-218. doi.org/10.193forsci/fxaa043.
5. Han, Z., Oosawa, K., Kanematsu, Y., Teah, H. Y., & Kikuchi, Y. (2026). Simulating Forest Transition for Sustainable Forestry Planning in Japan: A Backcasting Model of Roundwood Supply and Carbon Stocks with Operational and Regional Considerations. *Resources, Conservation & Recycling Advances*. doi.org/10.1016/j.rcradv.2026.200314.
6. Hansen, R. N., Eliassen, J. L., Schmidt, J., Andersen, C. E., Weidema, B. P., Birgisdóttir, H., & Hoxha, E. (2024). *Environmental consequences of shifting to timber construction: The case of Denmark. Sustainable Production and Consumption 46, pp.54–67*. doi.org/10.1016/j.spc.2024.02.014.
7. Heder Brandt, P., Olsson, A., Dahlquist, K., & Inal, T. (2023). "Profitability is sustainability:" Framing of forest management practices by the Swedish forest industry. *Scandinavian Journal of Forest Research*, *38*(7-8), pp.429-441. doi.org/10.1080/02827581.2023.2252740.

8. Lambovska, M., Rajnoha, R., & Dobrovic, J. (2019). From quality to quantity and vice versa: How to evaluate performance in the budgetary control process. *Journal of Competitiveness*, *11*(1), 53–69. https://doi.org/10.7441/joc.2019.01.04
9. Li, W., Yang, M., Xi, B., & Huang, Q. (2023). Framework of virtual plantation forest modeling and data analysis for digital twin. *Forests*, *14*(4). doi.org/10.3390/f14040683.
10. Liu, F., Hu, M., Huang, W., Chen, C. X., & Li, J. (2023). Future carbon sequestration and timber yields from Chinese commercial forests under shared socioeconomic pathways. *Forests*, *14*(1). doi.org/10.3390/f14010153.
11. Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Altman, D., Antes, G., & Clark, J. (2009). Preferred reporting items for systematic reviews and meta_analyses: the PRISMA statement (Chinese edition). Journal of Chinese Integrative Medicine, 7(9), 889-896. https://doi.org/10.3736/jcim20090918
12. Newton, P. F. (2025). Enhanced climate-sensitive crop planning models for multiple criteria decision-making when managing jack pine and red pine forest types. *Forests*, *16*(4). doi.org/10.3390/f16040610.
13. Newton, P. F. (2022). Development of a climate-sensitive structural stand density management model for red pine. *Forests*, *13*(7). doi.org/10.3390/f13071010.
14. Niemi, M. T., Ojanen, P., Sarkkola, S., Vasander, H., Minkkinen, K., & Vauhkonen, J. (2023). Using a digital elevation model to place overland flow fields and uncleaned ditch sections for water protection in peatland forest management. *Ecological Engineering*, *190*. doi.org/10.1016/j.ecoleng.2023.106945.
15. Stevanov, M., & Krott, M. (2021). Embedding scientific information into forestry praxis: Explaining knowledge transfer in transdisciplinary projects by using German case. *Forest Policy and Economics*, *129*. doi.org/10.1016/j.forpol.2021.102508.
16. Teslak, K., Andabaka, M., Mertini, A., Beljan, K., & Vedriš, M. (2023). Choice of adaptive forest management model based on long-term projection in dinaric fir-beech stands. *Šumarski list*, *147*(1-2), pp.21-36. doi.org/10.31298.
17. Xu, Y., Zhang, X., Liu, Z., Wu, Y., Luo, H., Yu, Z., ... & Ou, G. (2026). A carbon-economic synergistic framework to optimize management decisions for plantations: A case on Pinus kesiya var. langbianensis forests. *Industrial Crops and Products*, *239*. doi.org/10.1016/j.rcradv.2026.200314.
18. Yoshioka, T., Kaneko, S., Kim, H. B., & Nitami, T. (2025). Amounts of Unutilized Forest Biomass Resources Under Sustainable Forest Management, Limited by Labor–Input Constraints. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, *46*(2), pp.397-408. doi.org/10.5552/crojfe.2025.2938.
19. Zhao, J., Hu, H., & Wang, J. (2022). Forest carbon reserve calculation and comprehensive economic value evaluation: A forest management model based on both biomass expansion factor method and total forest value. *International Journal of Environmental Research and Public Health*, *19*(23). doi.org/10.3390/ijerph192315925.

Authors address:
Chief asst. Prof., Dr. Rumen Dombashov
Department of Management, University of National and World Economy, Sofia, Bulgaria

DIGITAL TIMBER TRACEABILITY, EITI REPORTING AND EUDR COMPLIANCE AS TOOLS FOR MANAGING UKRAINE'S FOREST SECTOR IN THE CONTEXT OF THE BIOECONOMY

Anna Kostyakova, Natalia Zakharova

Abstract: The transformation of Ukraine's forest sector requires the implementation of digital traceability systems, integration with the Extractive Industries Transparency Initiative (EITI) and alignment with the EU Deforestation Regulation (EUDR). In the context of post-war reconstruction and European integration, transparency and accountability in forest management have become critical prerequisites for the sustainable development of the bioeconomy. The study analyzes the current state of electronic timber accounting in Ukraine, identifies key gaps in tracking, auditing and data integration, and assesses the sector's readiness to meet EUDR requirements. Particular attention is paid to the role of digital technologies, including GIS, GPS tracking and blockchain, in ensuring end-to-end supply chain transparency. The paper proposes a conceptual model for integrating EITI reporting with the next-generation digital timber traceability system (EAW 2.0) aimed at increasing market transparency, reducing illegal logging, and strengthening Ukraine's competitiveness in EU timber markets. The study's findings demonstrate that digital traceability, combined with international reporting standards, can serve as the basis for a resilient, transparent, and sustainable forest-based bioeconomy.
Keywords: digital timber traceability; EUDR compliance; EITI reporting; forest governance; bioeconomy.

1. INTRODUCTION

The Ukrainian forest sector is currently in a state of profound transformation, balancing between outdated models of the shadow economy and the need to transition to eco-innovative management. The total timber stock in the country is estimated at an impressive 2.3 billion m³, and the forest fund occupies 15.9% of the territory (about 9.6 million hectares) (Kyiv School of Economics, 2024). However, this potential is offset by chronic problems: illegal logging and corruption risks. According to official data, 30.3 thousand m³ of illegally harvested wood were recorded in 2023, although experts suggest that due to military operations, the real scale may be much larger (ForestCom, 2024).

The entry into force of EU Regulation 2023/1115 (EUDR) radically changes the rules of the game. This document effectively prohibits the circulation of products associated with forest degradation on the European market (European Commission, 2023). Since Ukraine provides about 10–12% of the European timber market, any delay in modernizing the management system threatens to lose strategic export positions (Stopfer L., et al., 2024). Currently, the State Forestry Agency has already laid the foundation for digitalization: EDI 1.0, electronic logging tickets, e-TTN and online auctions have been implemented (State Agency of Forest Resources of Ukraine, 2024). However, the existing system remains fragmented, which requires the creation of an integrated model «Electronic Authentic Wood Fingerprint» (EAW 2.0) (FSC Ukraine, 2024).

2. METHODOLOGY AND PROBLEM STATEMENT

The restoration of the forest sector in the context of European integration requires a synergy of three components: digital traceability (GPS, GIS, blockchain), transparency of financial flows (EITI) and unconditional compliance with environmental standards (EUDR). The

study aims to identify the shortcomings of current systems, assess Ukraine's readiness by 2026 (when large EU companies will begin to require full "greenness" of origin) and conceptually link the digital platform "Electronic Authentic Wood Footprint" (EAW 2.0) with EITI reporting and full compliance with EUDR. Thus, this article is intended to become the basis for the formation of a new policy in the forest sector in the context of sustainable development of the bioeconomy - the transition to renewable resources without damaging natural systems.

3. RESULTS AND DISCUSSION

3.1. Analysis of the current state of digitalization (EDI 1.0)

Ukraine has demonstrated significant progress in creating one of the most advanced electronic timber accounting (ETA) systems among the Eastern Partnership countries. Key achievements include (State Agency of Forest Resources of Ukraine, 2024):

- electronic logging ticket: provides geospatial identification of felling sites via GPS coordinates;
- e-TTN with photo fixation: allows for real-time control of timber movements;
- electronic stock auctions: minimized the shadow market for unprocessed timber.

However, the ETA 1.0 architecture is outdated. In 2023-2024, cases of manipulation of cash transactions and unauthorized access were recorded (ForestCom, 2024). The main problem is the lack of data on communal and private forests, which creates «gray zones» in the overall timber balance. This necessitates the transition to EDI 2.0 with support for API integration and automated auditing (SFI Ukraine, 2025).

3.2. EUDR readiness: challenges and opportunities

The EUDR requires that each consignment of timber has the exact geographical coordinates of the harvesting site and confirmation of the absence of forest degradation. For Ukraine, the situation is complicated by the consequences of military aggression: by the beginning of 2024, more than 82.9 million m³ of forest resources were lost or damaged, which significantly complicates verification via satellites (Kyiv School of Economics, 2024), there is no comprehensive law on implementation; risk management in frontline forests.

Despite this, in May 2025, the EU granted Ukraine the status of a «low-risk» country, which is a high credit of trust. In response, the Cabinet of Ministers of Ukraine adopted Resolution No. 1552, which launches a pilot «electronic exporter's office». This tool will allow automatic generation of documentation for the European TRACES platform, using GeoJSON-compatible data formats (SFI Ukraine, 2025).

3.3. The technology stack of the future: Blockchain, GIS and AI

To ensure absolute transparency, it is necessary to implement innovative technologies:

1. GIS and satellite monitoring (Copernicus): allow detecting illegal logging in almost real time by automatically comparing issued permits with actual changes in forest cover. Ukrainian projects provide for the introduction of an integrated satellite monitoring platform «Forest Protection Network» (Forest Europe, 2022), but the disadvantage is uneven coverage (only state forests); lack of unified geometadata standards.

2. Blockchain: distributed ledger technology guarantees data immutability (Yatsukh, O., Zhuravlova, I., Tsap, V., 2025). Each operation - from issuing a logging ticket to crossing the border - is recorded in a chain that cannot be forged. The use of smart contracts allows transactions to be automatically blocked if the origin of the wood is not confirmed (Damaševičius R., Rytis Maskeliūnas, 2025). Not integrated with existing systems; it is necessary to guarantee the reliability of input data (Stopfer L., Kaulen A., Purfürst T., 2024)

3. Artificial Intelligence (AI) and Internet of Things (IoT): sound sensors are already used abroad to detect the sound of chainsaws (Montaser, N.A. Ramadan, Mohammed, A.H. Ali, Shin, Yee Khoo, Mohammad, Alkhedher, 2024). In Ukraine, the use of ML algorithms for risk profiling and detecting anomalies in forest management reporting is promising, for example, detecting anomalous patterns («too high demand» or «price-volume mismatch») in combination with traditional methods and human auditing will increase the reliability of control.

3.4. EAW 2.0 model and EITI integration

International assessments confirm the effectiveness of the implemented tools, for example, at the AWBA seminar it was noted that Ukraine «has one of the most advanced digital systems in Europe» for timber tracking (State Agency of Forest Resources of Ukraine, 2026). Experts emphasize: electronic documents have significantly increased the trust of partners. At the same time, the EDI 1.0 system has limitations: it uses an outdated architecture, there is no unified technology for the private sector (State Agency of Forest Resources of Ukraine, 2024). On the one hand, as of 2026, 100% of state forestry enterprises are registered, but private wood processors and agriculture (which harvest significant volumes) have not yet been integrated into the system. Without entering their data, traceability is incomplete. Therefore, the key challenge is the transition to EDI 2.0 - new software with open APIs, which will guarantee the integrity and availability of data.

According to ForestCom, when all digital modules are operational, this will effectively transform the Ukrainian forest sector into an «example of transparent management» (ForestCom, 2024). However, «black holes» in the databases have been identified to date. For example, a «single register» of forest users does not exist in practice: there is no centralized database of wood processing enterprises. This hinders the tracking of wood in the production cycle. In addition, data on actual auction prices and payments are stored in national registers that are not accessible to the general public. The lack of integration of EDI with such registers means that an independent analyst cannot fully verify the correctness of the submitted reports. Participation in the EITI would allow for the disclosure of payments and concessions at the state level (Diia OpenData, 2021), filling this gap.

An innovative approach is to combine resource traceability with financial transparency according to EITI (Extractive Industries Transparency Initiative) standards (SFI Ukraine, 2025). Ukraine has been a member of EITI since 2013 (EITI International, 2025), and extending this practice to the forest sector will allow comparing the volumes of harvested timber with actual tax revenues and auction revenues (Kostyakova A., 2025).

We see this as an opportunity to increase accountability. The implementation of EITI transparency would mean, for example, publishing information on all forest land allocations, user fees, and sales volumes. Such data would be conveniently uploaded from the modernized EDI 2.0 system and published on the state portal.

This will create a mechanism for public monitoring and anti-corruption control over

resource flows.

Currently, the EITI program in Ukraine is already successfully implementing data disclosure in extractive industries. Transferring this experience to the forest sector could simplify verification: for example, an official EITI report could become the basis for auditing forest companies exporting timber. The novelty of the EAW 2.0 approach is that EITI reporting is integrated «at the digital chain level». That is, EDI 2.0 acts simultaneously as a goods register and as a register of financial transactions - all data is linked.

Structurally, it will look like this (Figure 1): the EDI 2.0 platform is the core of forest fund data, which will transfer information on timber purchases and sales and fees paid to the EITI common database in order to form public reporting on financial flows and auction prices, and will also ensure the transfer of geoinformation to TRACES/EUDR; blockchain registry as a record of all critical supply chain events.

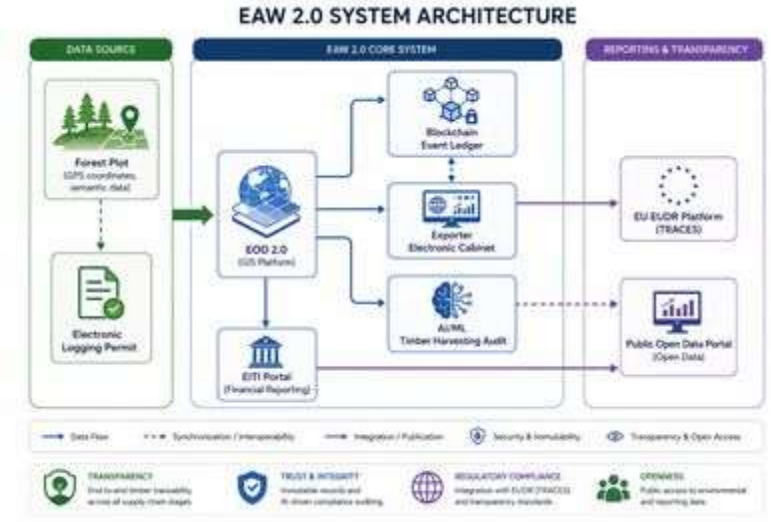


Figure 1. EAW 2.0 System Architecture

Source: developed by the author

Thus, the «exporter's electronic cabinet» will be able to automatically collect all confirmations and become an interface for direct interaction with EU regulators. Importantly, the EITI element not only enhances transparency, but also stimulates business to comply with the rules: open data increases the risk of exposing dishonest actions, which will directly affect the improvement of environmental policy and the effectiveness of environmental taxation in this industry (Novakova, R., Plaksiuk, O., & Habinakova, E., 2025).

Such a conceptual model makes it impossible for «white elephants» (wood without origin) to appear on the market, since each cubic meter will be tied to specific coordinates and a financial transaction.

4. CONCLUSIONS AND RECOMMENDATIONS

The integration of digital technologies with EUDR requirements and EITI principles has important policy implications. First, it increases Ukraine's competitiveness in global markets. The obtained «low-risk status» already facilitates exports and stimulates investments (investors

are convinced of environmental stability). Second, it contributes to the sustainable development of the bioeconomy: transparent timber trade stimulates the economical use of forest resources and reduces illegal fishing. Third, the implementation of such systems creates a platform for green financing - forest conservation, reforestation and forest management certification projects become more attractive. For example, programs focused on carbon reductions (Carbon credits) will require reliable evidence of the legality and accounting of timber, and our system will provide this.

At the same time, there are risks and uncertainties. The lack of full monitoring of antagonistic abuses (for example, hidden illegal logging in vulnerable regions) may prevent the final verification of the integrity of the entire chain. We do not have open data on timber smuggling, so this analysis assumes that its impact is minimal (according to official statistics), but the real volumes are unknown. We also have to assume that Resolution No. 1552 and the pilot are working as planned; we rely on press releases and expert reports. If it turns out that documents from different sources contradict each other, the model will need to be updated. Another uncertainty is the impact of future climate change and war on forest infrastructure. Indeed, the State Forestry Agency has already reported losses of hundreds of millions of cubic meters during the war years. We assume that modernization will require investment, so integrated systems should allocate resources efficiently (for example, focusing on covering the greatest risks).

In conclusion, the combination of EUDR, EITI and digital systems creates a comprehensive forest governance platform, where data itself becomes a tool for control and decision-making. Policymakers should allocate resources to fully implement this model, and researchers should continue to monitor its effectiveness.

Further research should focus on the cost-effectiveness of implementing blockchain solutions for small and medium-sized enterprises in the forest sector.

REFERENCES

1. State Agency of Forest Resources of Ukraine. (2024). Electronic accounting of wood and digitalization.URL: https://surl.li/kdwpqk
2. Kostyakova A. (2025). Transparency in accounting and auditing of Ukrainian timber: EITI reporting as a factor of sustainable development. *Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025.* URL: WoodEMA_2025_proceedings.pdf
3. European Commission. (2023). *Regulation (EU) 2023/1115 on deforestation-free products*. URL: https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en
4. ForestCom. (2024). *Illegal logging in Ukraine in 2023: analytical report*. URL: https://forestcom.org.ua/en/news-post/illegal-logging-ukraine-2023-according-forest-users-data-analytical-report
5. Stopfer L., Kaulen A., Purfürst T. (2024). *Potential of blockchain technology in wood supply chains*. Computers and Electronics in Agriculture. URL: https://doi.org/10.1016/j.compag.2023.108496
6. SFI Ukraine. (2025). The State Forest Resources Agency has demonstrated a high level of readiness for the implementation of the European EUDR Regulation for tracking timber shipments in Ukraine. URL: https://surl.li/vfyrvp/

7. Damaševičius R.,Rytis Maskeliūnas.(2025). Blockchain-enabled smart contracts for secure and transparent timber traceability. *Journal of Industrial Information Integration.* URL: https://doi.org/10.1016/j.jii.2025.100934
8. Kaunas University of Technology (KTU). (2025). *System to block illegal timber from entering the EU market.* URL: https://surl.li/xnkgry
9. FSC Ukraine. (2024). *Steps for successful Ukraine's adaptation to EUDR requirements*. URL: https://ua.fsc.org/ua-en/newsfeed/…
10. Kyiv School of Economics. (2024). Ukraine's Forestry at a Glance: Lessons from Sweden. URL: https://fsc.org/en/newscentre/eudr/fsc-on-eudr-a-pragmatic-step-forward-for-forests
11. EITI International. (2025). Ukraine - EITI national progress. URL: https://eiti.org/countries/ukraine
12. Forest Europe. (2022). Supporting the recovery and sustainable management of Ukrainian forests and its forest sector. URL: https://surl.li/zwpjek
13. Montaser, N.A. Ramadan, Mohammed, A.H. Ali, Shin, Yee Khoo, Mohammad, Alkhedher. (2024). AI-powered IoT and UAV systems for real-time detection and prevention of illegal logging. *Results in Engineering.* URL: https://doi.org/10.1016/j.rineng.2024.103277
14. Yatsukh, O., Zhuravlova, I., Tsap, V. (2025). Digital platforms for the financial and economic support of forestry enterprises: the experience of ukraine. *Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025.* URL: https://www.woodema.org/proceedings/WoodEMA_2025_proceedings.pdf
15. Novakova, R., Plaksiuk, O., & Habinakova, E. (2025). Environmental taxes as a means of supporting sustainable development of the country with a focus on the forestry industry. *Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025.* URL: WoodEMA_2025_proceedings.pdf
16. State Agency of Forest Resources of Ukraine. (2026). *EU Regulation EUDR: how Ukraine is preparing for new export conditions*. URL: https://surl.li/ymkllf
17. Diia OpenData. (2021). *Extractive Industries Transparency Initiative (EITI) - a project in Ukraine.* URL: https://diia.data.gov.ua/info-center/eiti

Authors address:

Kostyakova, A.[1] Zakharova, N.[2]
[1] Department of Finance, Accounting and Taxation, Faculty of Economics and Business, Dmytro Motornyi Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
[2]Department of Management and Administration, Bogdan Khmelnitsky Melitopol State Pedagogical University, Zaporizhzhia, Ukraine
Corresponding author: anna.kostyakova@ukr.net

ASSESSING THE COMPETITIVENESS OF WOOD-BASED BUSINESSES IN THE DIGITAL AGE

Leszek Wanat, Łukasz Sarniak

Abstract: This study evaluates the digital competitiveness of wood-based enterprises by investigating the synergy between supply chain digitisation and digital sales maturity. Utilising a predictive machine learning simulation on a cohort of 5,000 virtual enterprises, the research demonstrates that isolated, asymmetrical digitisation generates operational friction and reduces market agility. Conversely, simultaneous integration across both dimensions identifies a technological tipping point that unlocks exponential competitive advantage. The proposed Digital Synergy Threshold Model proves that digital co-opetition networking and traceability systems are the most critical determinants for ensuring long-term resilience in the digital bioeconomy.
Keywords: circular economy, wood-based sector, digital competitiveness, machine learning simulation.

1. INTRODUCTION

The competitiveness paradigm within the forest-based sector has profoundly evolved. Historically evaluated via traditional cost structures [17] and early green economy indicators [11], sectoral resilience during economic uncertainty relied on intersectoral cooperation, industrial symbiosis [9, 19], and strategic programming [21, 22]. Securing alternative capital [20] and optimising regional agri-development [23] also proved essential. Concurrently, transitioning towards a circular bioeconomy [2, 10] demanded enhanced resource efficiency - such as utilising stump wood [12] and adding value to products [1] - supported by sustainability assessments, consumer engagement [6], and robust chain-of-custody certification [15].

Currently, intense digital pressure necessitates the adoption of comprehensive digital business models [16]. Operational focus is rapidly shifting towards digital innovations [14], integrating global supply chains [13] with advanced ERP systems to drive efficiency and competitiveness [18]. True market agility now depends on mesoeconomic analysis using Big Data tools [7], requiring enterprises to transcend rudimentary digitisation and build a robust data-driven culture [4].

Consequently, integrating Artificial Intelligence (AI) [3] and machine learning-driven Wood Informatics [5] has emerged as a critical determinant of sustainable management [8]. Addressing this shift towards predictive, data-centric strategies, this paper investigates the digital competitiveness of wood-based businesses. It proposes a machine learning simulation to assess "digital synergy" by evaluating the interplay between back-end supply chain analytics and front-end digital sales, aiming to identify the technological tipping points that guarantee long-term enterprise resilience in the digital age.

2. MATERIAL AND METHODOLOGICAL BACKGROUND OF THE STUDY

The primary aim is to evaluate the digital competitiveness of wood-based enterprises by determining the synergistic impact of integrating back-end supply chain analytics with front-end digital sales. The study addresses three Research Questions: how isolated digitisation affects competitiveness (RQ1); at what "tipping point" simultaneous integration generates quantifiable market resilience (RQ2); and which digital competencies yield the highest strategic return under economic uncertainty (RQ3).As traditional empirical surveys inadequately capture complex, non-linear digital interactions, this study employed a predictive machine learning simulation. The research material comprised a synthetic dataset of N=5,000 virtual wood-based enterprises, parameterised using expert criteria from current digital maturity literature.

The analytical scenario involved three phases. First, virtual enterprises were assigned varying adoption levels across two dimensions: Supply Chain Digitisation and Digital Sales Maturity. Second, a Random Forest algorithm calculated the target variable - the Market Agility Index (MAI) - reflecting the capacity for profitable order fulfilment amidst volatility. Finally, outputs were transposed into a visual synergy matrix. Inference is drawn by analysing algorithmic "feature importance" and identifying structural bottlenecks, ultimately translating complex outputs into transparent, strategic management recommendations.

3. SELECTED RESULTS

To robustly address the formulated research questions, the predictive machine learning simulation evaluated a synthetic cohort of N=5,000 virtual wood-based enterprises. By applying advanced data science techniques and algorithmic processing via Python, the simulation calculated the Market Agility Index (MAI) for various technological configurations. The descriptive analysis of these results exposes a profound non-linear relationship between digital investments and market resilience within the sector.

Table 1 presents the Digital Synergy Matrix, structurally cross-tabulating two primary variables. The rows represent the level of Supply Chain Digitisation (ranging from basic spreadsheets to advanced Internet of Things {IoT} tracking), whilst the columns illustrate the degree of Digital Sales Maturity (from static web presences to fully integrated B2B/B2C platforms). The intersections display the aggregated MAI scores, serving as a direct response to RQ1 and RQ2.

Table 1. The Digital Synergy Matrix: The impact of asymmetrical and integrated digitisation on the Market Agility Index (MAI) within the simulated cohort (N=5,000)

Level of Supply Chain Digitisation (Back-end)	**Low Sales Maturity (Static Web Presence)**	**Medium Sales Maturity (Basic E-commerce)**	**High Sales Maturity (Integrated B2B/B2C Platform)**
Low (Basic spreadsheets, no ERP)	**MAI = 32.4** (Operational Stagnation)	**MAI = 41.2** (Operational Bottleneck)	**MAI = 38.7** (*Agility Decline / Congestion Effect*)
Medium (Basic ERP / Standard IMS)	**MAI = 45.8** (Market Stability)	**MAI = 59.3** (Linear Growth)	**MAI = 64.1** (Moderate Agility)
High (IoT, Algorithmic Resource Planning)	**MAI = 52.1** (Unexploited Potential)	**MAI = 71.5** (Strong Agility)	**MAI = 94.8 (Digital synergy)**

Source: Own elaboration.

The matrix reveals that isolated, asymmetrical digitisation yields negligible or even detrimental effects (RQ1). For instance, enterprises investing exclusively in advanced front-end e-commerce without corresponding back-end supply chain integration experience severe operational friction, causing the MAI to drop to 38.7. This decline is attributed to the operational inability to handle complex order fulfilment, ensure transparent sourcing, and manage raw material recycling effectively. Conversely, the algorithm identifies a distinct "tipping point" (RQ2). When a highly developed back-end, utilising modern tracking systems like IoT, is synergised with an advanced B2B/B2C digital market platform, the MAI surges exponentially to 94.8. This confirms that securing long-term resilience demands the full integration of management systems (IMS) with sustainable development and circular economy requirements.

To address RQ3 regarding which specific digital competencies yield the highest strategic return, a Random Forest feature importance analysis (Mean Decrease Impurity) was conducted. Table 2 structurally ranks these competencies, detailing the specific digital feature, its calculated Gini Importance weight, and the underlying theoretical justification integrated into the predictive model.

Table 2. Hierarchy of digital competitiveness determinants (Mean Decrease Impurity) supporting survival and co-opetition strategies

Rank	Digital Competence Feature	Algorithmic Feature Importance (Gini)	Theoretical Justification Extracted for the Model
1.	Digital Co-opetition Networking	**28.4%**	Amidst economic uncertainty, sectoral survival relies on co-opetition strategies and integrated business networks.
2.	Traceability Systems (IoT & Blockchain)	**22.7%**	Advanced tracking controls the wood life cycle, optimising recycling logistics and lowering operational costs.
3.	Integrated Management Systems (IMS)	**18.5%**	Integrating structural norms optimises business procedures, minimises errors, and enhances cross-sectoral communication.
4.	Digital Eco-labelling & Certification	**14.2%**	Transparent communication regarding product origin fundamentally drives conscious and sustainable consumer choices.

Source: Own elaboration.

The algorithmic output highlights that 'Digital Co-opetition Networking' is the absolute critical determinant of competitiveness, capturing 28.4% of the model's predictive weight. This aligns perfectly with recent empirical findings suggesting that during prolonged crises, the forestry and wood-based sector must transition from pure competition to collaborative networking to secure resource availability. Furthermore, advanced traceability systems (22.7%) and Integrated Management Systems (18.5%) are essential for harmonising business procedures and proving a commitment to sustainable development. Finally, digital eco-labelling (14.2%) acts as a crucial interface with the end-user, translating environmental compliance into tangible market advantage.

To visually synthesise these machine learning outputs for executive application - designed to function within a business intelligence dashboard logic, such as Power BI - we propose a two-dimensional Cartesian model: *The Digital Synergy Threshold Model* (Figure 1).

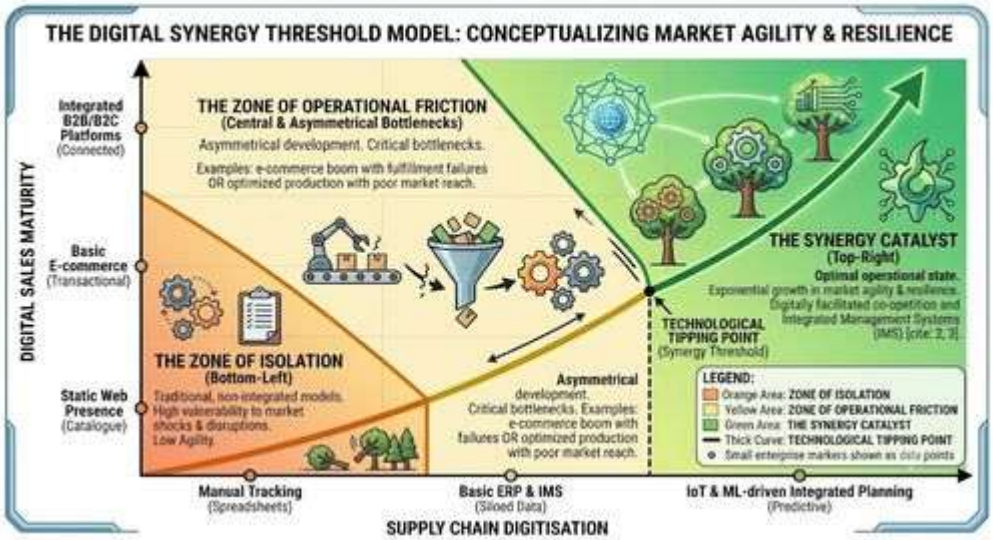


Figure 1. The Digital Synergy Threshold Model.
Source: Own elaboration.

Figure 1 provides a visual synthesis of our machine learning results, framing digital maturity via a Cartesian coordinate system with Supply Chain Digitisation (horizontal) and Digital Sales Maturity (vertical) as core variables. The model clarifies the non-linear relationship between asymmetrical investments and market agility identified in Table 1 and Table 2. The visual space is segmented into three zones: the Zone of Isolation, representing traditional, vulnerable models; the Zone of Operational Friction, which captures critical bottlenecks where either digital market reach lacks physical fulfilment or optimised production remains market-invisible; and the Synergy Catalyst zone. The latter is separated from friction by a Technological Tipping Point, marking the achievement of full algorithmic integration. Beyond this threshold, synergistic effects from integrated data and co-opetition drive exponential growth in agility and resilience, equipping enterprises to thrive amidst economic uncertainty and manage the complexities of a circular economy.

4. CONCLUSIONS

This empirical simulation confirms that linear technological adoption is fundamentally insufficient in the contemporary bioeconomy. Isolated digitisation - whether exclusively in back-end logistics or front-end e-commerce - generates severe operational friction, causing a quantifiable decline in overall market agility (RQ1). The study identifies a critical "technological tipping point" (RQ2). Genuine resilience requires entering the *Synergy Catalyst zone*, where integrating data-driven resource planning with advanced digital sales yields an exponential competitive advantage. Algorithmic analysis highlights digital co-opetition networking and IoT traceability as the most valuable competencies for securing strategic returns amidst economic uncertainty (RQ3).

From a managerial perspective, industry leaders must dismantle technological silos by ensuring investments are strictly dual-dimensional, seamlessly integrating digital market expansion with data-driven physical fulfilment. To facilitate this transition, strategists should utilise the proposed *Digital Synergy Threshold Model* as an active benchmarking tool to

diagnose asymmetrical development and pinpoint operational bottlenecks before scaling operations. Finally, to thrive amidst market volatility, enterprises must prioritise data-driven co-opetition, leveraging digital platforms to build transparent, collaborative regional networks and decisively shifting from reactive survival tactics to proactive, systemic resilience.

REFERENCES

1. Calvano, S., Negro, F., Blanc, S., Bruzzese, S., Brun, F., Zanuttini, R. (2025). Adding value to wood-based products: A systematic literature review on drivers. *Forests*, 16(4), 590.
2. Candelier, K., Brancheriau, L., Gérard, J., Thévenon, M. F., Zoveda, F., de Prado Viargues, L. (2026). Pathways to increase supply of sustainable wood from planted forests and trees to address bioeconomy needs: A review. *iForest: Biogeosciences and Forestry*, 19, 168-185.
3. Cao, C., Zhuang, J., Wu, J. J., Zhou, W. (2026). Impact of Progress of AI on Circular Bioeconomy: Applications, Challenges, and Future Directions. In: Handbook of Circular Bioeconomy (pp. 397-440). Cham: Springer Nature Switzerland.
4. Hashim, M. A., Che Ibrahim, C. K. I., Jaafar, N. A. L., Kordi, N. E., Haron, A. T., Umeokafor, N. (2025). Building data driven culture for digital competitiveness in construction industry: a theoretical exploration. *International Journal of Construction Management*, 25(3), 334-346.
5. Hwang, S. W. (2026). Machine learning-driven research in wood science: from prediction to understanding through the framework of Wood Informatics. *Journal of Wood Science*, 72(1), 7.
6. Kaputa, V., Maťová, H., Rácz, A., Wanat, L. (2024). Achieving sustainability – with the consumer or the citizen? In: D. Jelačić (ed.), Achieving sustainability in forest-based industry (pp. 1-18). WoodEMA, i.a., Zagreb.
7. Klus, S., Topczewska, A., Urbanowicz, Z., Wanat, L. (2022). Mesoeconomic market analysis based on selected Big Data tools – the case of wood market trends in Poland under economic uncertainty. *Annals of the Polish Association of Agricultural and Agribusiness Economists*, XXIV(3), 94-107. https://doi.org/10.5604/01.3001.0016.0009 .
8. Kumar, S., Kumar, P. (2026). Innovations Sustainable Management Practices and Future Perspectives in Forest Management. In: Harnessing AI for Invasive Species Management and Biodiversity Conservation (pp. 219-252). IGI Global Scientific Publishing.
9. Kusiak, W., Mikołajczak, E., Wanat, L. (2018). Institutional and Industrial Symbiosis Case Study of Cooperation for Development in Forestry and Wood-Based Sector. In: Increasing the use of wood in the global bio-economy. Glavonjic B. (ed.), September 26th-28th, 2018, University of Belgrade, Belgrade, Serbia, 388-399.
10. Kusiak, W., Wanat, L., Klus, S., Styma-Sarniak, K. (2019). Circular Economy from the Perspective of Scientific Research Papers in the Forestry and Wood-Based Sector in Poland. In: Chobanova R.(ed.) Digitalisation and Circular Economy: forestry and forestry based industry implications, USB and WoodEMA, i.a., 33-38.
11. Lis, W., Wanat, L. (2014). Competitiveness vs. green economy? Confronting traditional and "green" indicators of the competitive position of the forest-and wood-based industry in Poland. In: Position and role of the forest based sector in the green economy (pp. 76-82). WoodEMA, i.a., Zagreb, Croatia.

12. Majchrzak, L., Wanat, L., Kusiak, W., Sikora, J., Sarniak, Ł. (2025). The Economic Potential of Stump Wood as an Energy Resource - A Polish Regional Case Study. *Forests*, 16(8), 1243. https://doi.org/10.3390/f16081243 .
13. Mensah, P., Pimenta, A. S., de Melo, R. R., Amponsah, J., Tuo, G., Chakurah, I., Ampadu, S. D., Buckman, I., Nikoi, M., Minkah, E., Miranda, N. d. O., de Medeiros, P. L. (2025). The Global Supply Chain of Wood Products: A Literature Review. *Forests*, 16(7), 1036. https://doi.org/10.3390/f16071036 .
14. Nylén, E. J., Klitkou, A. (2025). Digital Innovations in Wooden Construction for a Circular Economy. *Circular Economy and Sustainability*, 1-23.
15. Paluš, H., Parobek, J., Vlosky, R. P., Motik, D., Oblak, L., Jošt, M., Glavonjić, B., Dudík, R., Wanat, L. (2018). The status of chain-of-custody certification in the countries of Central and South Europe. *European Journal of Wood and Wood Products*, 76(2), 669-710.
16. Pinto, A. S., Costa, E., Guimarães, L., Passos, R. (2022). A Digital Business Model for the Wood Industry. In: Marketing and Smart Technologies: Proceedings of ICMarkTech 2021, Volume 2 (pp. 623-634). Singapore: Springer Nature Singapore.
17. Teshome, B., Kassa, H., Bekele, T., Pretzsch, J. (2026). Competitiveness and cost structure analysis of selected wood-processing industries in Ethiopia. *Wood and Fiber Science*, 58(1), 2-13.
18. Vukman, K., Klarić, K., Greger, K., Perić, I. (2024). Driving efficiency and competitiveness: Trends and innovations in ERP systems for the wood industry. *Forests*, 15(2), 230.
19. Wanat L., Potkański T., Chudobiecki J., Mikołajczak E., Mydlarz K. (2018). Intersectoral and Intermunicipal Cooperation as a Tool for Supporting Local Economic Development: Prospects for the Forest and Wood-Based Sector in Poland. *Forests* 9 (9), 531, 1.
20. Wanat, L., Sarniak, Ł., Mikołajczak, E. (2019). Initial public offering (IPO) as a potential source of capital for the development of the wood-based industry enterprises in Poland. *Quality Production Improvement-QPI*, 117-123. Sciendo.
21. Wanat, L., Sarniak, Ł., Mikołajczak, E. (2020). The competitiveness of the wood-based sector in Poland in the economic crisis conditions. In: D. Jelačić (ed.), Sustainability of forest-based industries in the global economy (pp. 117-121). WoodEMA, i.a., University of Zagreb, Faculty of Forestry, Zagreb, Croatia.
22. Wanat, L., Sarniak, Ł., Sikora, J., Kusiak, W., Wieruszewski, M., Czarnecki, R., Smętkiewicz, K., Kaputa, V. (2026). Development programming in the forest-based sector under economic uncertainty - the case of Poland during the pandemic and post-pandemic crisis. *Economics and Environment*, 96(1), 928. DOI: 10.34659/eis.2026.96.1.928.
23. Wanat, L.; Sikora, J.; Majchrzak, L.; Sarniak, Ł.; Czarnecki, R.; Smętkiewicz, K.; Ornoch, M. (2025). The Economic and Technological Challenges of the Agri-Development Implementation Model in the Case of the Wielkopolska Region in Poland. *Agriculture*, 15, 412. DOI: https://doi.org/10.3390/agriculture15040412 .

Authors address:

Wanat, L.[1*]; Sarniak, Ł.[2].
[1] Department of Social Sciences, Kozminski University, Warsaw, Poland.
[2] Department of Finance and Accounting, Faculty of Economics, Poznań University of Life Sciences, Poznań, Poland.
[*] Corresponding author: leszek.wanat@kozminski.edu.pl .

THE DATA-DRIVEN FOREST: ETHICAL AND SOCIO-ECONOMIC DILEMMAS IN WOOD-BASED BIOECONOMY POLICY WITHIN THE WEB OF BIG DATA

Leszek Wanat

Abstract: This study examines the socio-economic and ethical dilemmas of algorithmic management within the wood-based bioeconomy. Drawing on an expert survey (N=90), it identifies a profound paradigm conflict between the wood industry's techno-optimism and forestry professionals' concerns over technocratic alienation. The findings reveal that AI systematically undervalues the socio-cultural functions of forests. Consequently, the study advocates for a hybrid, data-driven framework integrating industrial efficiency with rigorous ethical stewardship.
Keywords: data-driven forestry, algorithmic management, bioeconomy ethics, circular economy, AI.

1. INTRODUCTION

Is the forest merely a data resource in the algorithmic machinery of the modern bioeconomy? While the transition towards a circular bioeconomy demands holistic and responsible business practices [4, 6, 14, 16], forest management is increasingly subjugated to digitalisation, artificial intelligence (AI), and data-driven systems [2, 9, 10, 12]. Although these technologies optimise ecosystem functions, biodiversity, and industrial supply chains [1, 3], they simultaneously provoke profound socio-economic dilemmas. Algorithmic resource optimisation fundamentally clashes with the postulates of integral human development and landscape economics [17, 18, 20]. Global assessments confirm that forests act as crucial pillars of socio-economic resilience, not mere industrial bio-assets [5, 7]. This is evident in inclusive 'people-forest-wood' models, particularly within urban therapeutic environments [21, 23]. Assessing the sector solely through data extraction and life cycle sustainability metrics [8, 28] risks alienating traditional stewardship and the socio-cultural value of the university idea [19, 22]. Furthermore, navigating today's post-pandemic macroeconomic uncertainty [25] requires more than algorithms; it demands rigorous chain-of-custody certification [15], intersectoral cooperation [24], specific agri-development models [26], industrial symbiosis [11], and the ecological utilisation of wood by-products like stump wood [13, 27].

Therefore, this paper critically evaluates the socio-economic and ethical dilemmas of data-driven bioeconomy policies. It aims to bridge the epistemological gap between technocratic optimisation and socio-ecological responsibility by mapping stakeholder paradigm conflicts and recommending a hybrid management model that balances industrial efficiency with the dignity of human-nature relationships.

2. MATERIAL AND METHODOLOGICAL BACKGROUND OF THE STUDY

The primary objective of the research was to evaluate the socio-economic and ethical perceptions of algorithmic management within the wood-based bioeconomy. Given the interdisciplinary nature of digital transition, the study required a methodical approach to capture the cognitive dissonance between technological, ecological, and economic paradigms [12, 28].

2.1. Study Period and Data Source

The research was conducted during the first half of 2026. Primary data was gathered using the Computer-Assisted Web Interview (CAWI) method. Invitations were distributed to 120 carefully selected professionals, yielding a final, validated sample of N=90 experts (a 75% response rate). To ensure structural comparative analysis, the purposive sample was divided into three equal cohorts (n=30 each): (A) **Wood Industry:** Production managers, technologists, and sawmill representatives focused on supply chain optimisation and circular economy implementation [4, 27]; (B) **Forestry:** Forest managers, directorate officials, and rangers representing traditional stewardship and ecosystem conservation [1, 19]; (C) **Economics:** Market analysts and economic policy specialists assessing trends and digital innovation [6, 25].

2.2. Research Questions

The study was designed to address three fundamental research questions regarding the data-driven forest [2, 9]: (1) How do different stakeholder groups perceive the algorithmic management of forest resources in the context of the circular bioeconomy?; (2) Does the digitalisation of the wood-based sector generate a risk of technocratic alienation and data monopolisation?; (3) To what extent are the socio-cultural and ethical functions of forests - such as integral human development and social resilience [7, 17, 23] - represented or undervalued in contemporary AI-driven models?

2.3. Method and Research Tool

Data collection utilised an original diagnostic questionnaire based on a 5-point Likert scale (1: 'strongly disagree', 5: 'strongly agree'). The tool was structured into three thematic blocks designed to test theoretical constructs: (a) *Algorithmic Management vs. Stewardship*, (b) *Data Ethics and Power Distribution*, and (c) *Socio-Economic Models in the Bioeconomy* [10, 16].

2.4. Analysis Scenario and Data Compilation

To obtain robust answers to the research questions, the analytical procedure followed a strict, step-by-step scenario: **(1) Data Validation:** Raw survey data was screened for completeness and consistency; **(2) Aggregation and Averaging:** Responses were aggregated to calculate mean scores (*M*) for each variable within the three distinct expert cohorts and **(3) Paradigm Mapping:** The data was compiled into comparative matrices to highlight the extreme ends of the spectrum (the percentage of 'strongly agree' and 'agree' responses), effectively isolating the core areas of epistemological conflict.

2.5. Evaluation Assumptions for Results Synthesis

The transition to the results section is based on the theoretical assumption that a unified view of the digital bioeconomy does not exist. It is hypothesised that the Wood Industry cohort will exhibit techno-optimism driven by efficiency metrics, whilst the Forestry cohort will demonstrate a defensive stance prioritising ethical stewardship and landscape economics [20]. Identifying these precise points of polarisation is essential for formulating the hybrid management recommendations presented in the subsequent sections of this paper.

3. SELECTED RESULTS AND DISCUSSION

The empirical analysis of the survey data (N=90) validates the hypothesis regarding the epistemological rupture between key bioeconomy stakeholders. The aggregated mean scores for the thematic blocks are presented in Table 1, whilst Table 2 illustrates the extreme polarisation by showing the percentage of affirmative responses ('agree' and 'strongly agree').

Table 1. Mean evaluation scores of ethical and socio-economic dilemmas in data-driven forestry (scale 1–5, where 5 = strongly agree)

Thematic Block / Variable	Wood Industry (n=30)	Forestry (n=30)	Economics (n=30)	Overall Mean
Block 1: Algorithmic Management vs. Stewardship				
Big Data primarily serves financial optimisation, not ecology.	1.80	4.30	3.10	3.07
Supply chain decisions should be fully automated via AI.	4.60	1.90	2.80	3.10
AI marginalises traditional forestry knowledge and stewardship.	1.90	4.70	3.20	3.27
Block 2: Data Ethics and Power Distribution				
Risk of forest data monopolisation by tech corporations.	2.10	4.50	3.40	3.33
Digitalisation introduces excessive employee surveillance.	2.00	4.20	3.10	3.10
New ethical codes are required for AI in environmental management.	2.30	4.90	3.00	3.40
Block 3: Socio-Economic Models in Bioeconomy				
Big Data is the key enabler of the Circular Economy in the sector.	4.80	4.00	2.70	3.83
Social and relational functions of forests are undervalued in AI models.	2.00	4.80	3.20	3.33

Source: Own elaboration based on expert survey data (N=90).

3.1. Descriptive Analysis and Discussion

The compiled data directly addresses the formulated research questions. Regarding **Question 1**, the perception of algorithmic management is deeply fractured. The Wood Industry cohort exhibits radical techno-optimism; 97% of respondents in this group consider Big Data a key enabler of the Circular Economy [4, 6], and M=4.60 strongly supports the full automation of supply chains [27]. In stark contrast, the Forestry cohort perceives algorithms primarily as financial optimisation tools (M=4.30) rather than ecological assets, reflecting concerns previously identified in the literature regarding sustainable management paradigms [1, 10]. Addressing **Question 2**, the data confirms a substantial fear of technocratic alienation and data colonialism. As visible in Table 2, 93% of foresters believe AI marginalises traditional forestry knowledge, and 87% warn of the monopolisation of forest data by tech corporations. The Economics cohort, exhibiting the highest internal variance, moderately validates these macroeconomic risks (47% agreement on monopolisation), aligning with current debates on data sharing constraints and digital sovereignty [2, 8, 12]. Finally, in response to **Question 3**, the empirical evidence highlights a critical ethical deficit in contemporary AI models. The Forestry cohort overwhelmingly agrees (97%, M=4.80) that data-driven systems undervalue the socio-cultural and relational functions of forests. This empirical finding corroborates the theoretical postulates that algorithmic reductionism threatens integral human development and the 'people-forest-wood' inclusive model [17, 21, 23]. Consequently, the near-unanimous demand from foresters for new ethical codes (M=4.90) sets a clear foundation for the concluding recommendations towards a hybrid bioeconomy model.

Table 2. The paradigm conflict: Distribution of 'agree' and 'strongly agree' responses across selected key variables (%)

Selected polarising variables	Wood Industry	Forestry	Economics
Technocratic approach: Supply chain decisions should be fully automated via AI.	93%	3%	27%
Techno-optimism: Big Data is the key enabler of the Circular Economy.	97%	73%	23%
Knowledge alienation: AI marginalises traditional forestry knowledge.	7%	93%	37%
Ethical deficit: Social functions of forests are undervalued in current AI models.	10%	97%	40%
Data colonialism: There is a high risk of forest data monopolisation.	13%	87%	47%

Source: Own elaboration based on expert survey data (N=90).

4. CONCLUSIONS

The study reveals a profound paradigm conflict within the data-driven bioeconomy. Whilst the wood industry embraces algorithmic management for supply chain optimisation, forestry experts warn against technocratic alienation and the undervaluation of socio-ecological functions. Reconciling this cognitive dissonance requires a hybrid management model. Policymakers must urgently integrate AI-driven industrial efficiency with rigorous ethical frameworks, safeguarding traditional stewardship and the integral dignity of human-nature relationships.

REFERENCES

1. Achim, F., Dinca, L., Chira, D., Raducu, R., Chirca, A., Murariu, G. (2025). Sustainable management of willow forest landscapes: A review of ecosystem functions and conservation strategies. *Land*, 14(8), 1593.
2. Berntzen, L., Johannessen, M. R., Collalti, A., Morichetti, M., Mitter, H., Linser, S., Cheval, S. (2026). Designing a Data-Driven Decision Support System for Sustainable and ClimateResilient Forest Management: Lessons Learned from the OptForEU Project. In: ICDS 2026: The Twentieth International Conference on Digital Society (pp. 23-28). IARIA.
3. Candelier, K., Brancheriau, L., Gérard, J., Thévenon, M. F., Zoveda, F., de Prado Viargues, L. (2026). Pathways to increase supply of sustainable wood from planted forests and trees to address bioeconomy needs: A review. *iForest: Biogeosciences and Forestry*, 19, 168-185.
4. Cao, C., Zhuang, J., Wu, J. J., Zhou, W. (2026). Impact of Progress of AI on Circular Bioeconomy: Applications, Challenges, and Future Directions. In: Handbook of Circular Bioeconomy (pp. 397-440). Cham: Springer Nature Switzerland.
5. Carmenta, R., McKinley, K., Akamany, K., Delgado-Serrano, M. M., Larson, A., Allen, C., Swiderska, K. (2025). Options for Enhancing the Contributions of Forests to Social and Economic Resilience. *Forests as Pillars of Social and Economic Resilience*, 159-201.

6. Dorrego-Viera, J. I., Urbinati, A., Hansen, E. G., Lazzarotti, V. (2026). Open innovation for circular and sustainable business models: Case evidence from the bioeconomy sector. *Innovation*, 28(1), 124-162.
7. Ferreira, J., Izquierdo-Tort, S., Delgado-Serrano, M. M., Akamani, K., Dhyani, S., Djenontin, I. N., Pulhin, J. M. (2025). Relationships between forests and social and economic resilience. Forests as Pillars of Social and Economic Resilience. A Global Assessment Report, 45.
8. Ghose, A., Pizzol, M. (2024). Data sharing-challenges and opportunities for LCA. In SETAC Europe 26th LCA Symposium: Making LCA Meaningful: Good Data, Better Models, Sustainable Decisions.
9. Kannamma, R., Khan, M., Senthil Ragavan, V. K., Ambhika, C. (2026). Data-Driven Decision Making: Utilizing Big Data for Forest Health. In: Smart Forestry 5.0 for Powered AI Sustainable Environment and Climate (pp. 201-214). Cham: Springer Nature.
10. Kumar, S., Kumar, P. (2026). Innovations Sustainable Management Practices and Future Perspectives in Forest Management. In: Harnessing AI for Invasive Species Management and Biodiversity Conservation (pp. 219-252). IGI Global Scientific Publishing.
11. Kusiak, W., Mikołajczak, E., Wanat, L. (2018). Institutional and Industrial Symbiosis Case Study of Cooperation for Development in Forestry and Wood-Based Sector. In: Increasing the use of wood in the global bio-economy. Glavonjic B. (ed.), September 26th-28th, 2018, University of Belgrade, Belgrade, Serbia, 388-399.
12. Kusiak, W., Wanat, L., Klus, S., Styma-Sarniak, K. (2019). Circular Economy from the Perspective of Scientific Research Papers in the Forestry and Wood-Based Sector in Poland. [In:] Chobanova R.(ed.) Digitalisation and Circular Economy: forestry and forestry based industry implications, USB and WoodEMA, i.a., 33-38.
13. Majchrzak, L., Wanat, L., Kusiak, W., Sikora, J., Sarniak, Ł. (2025). The Economic Potential of Stump Wood as an Energy Resource - A Polish Regional Case Study. Forests, 16(8), 1243. https://doi.org/10.3390/f16081243 .
14. Olaniran, A. F., Malomo, A. A., Akinsanola, B., Olaniran, O. D. (2025). Resources Recovery Potential from Solid Waste and Bioeconomy Model toward Sustainable Production and Responsible Consumption. In: Sustainable Biotechnological Remedial Frameworks for the Rejuvenation of Heavily Polluted Environments (pp. 220-233), CRC.
15. Paluš, H., Parobek, J., Vlosky, R. P., Motik, D., Oblak, L., Jošt, M., Glavonjić, B., Dudík, R., Wanat, L. (2018). The status of chain-of-custody certification in the countries of Central and South Europe. *European Journal of Wood and Wood Products*, 76(2), 669-710.
16. Rosário, A. T., Lopes, P., Rosário, F. S. (2024). Sustainability and the circular economy business development. *Sustainability*, 16(14), 6092.
17. Szary, S. (2020). Las i jego nie-zastępowalność w integralnym rozwoju człowieka (Forest and its non-substitutability in integral human development), *Przegląd Leśniczy*, 10: 18-20.
18. Wanat, L. (2016). Gospodarka leśna: zrównoważona czy integralna? Dylematy badawcze z perspektywy polskiego rynku drewna okrągłego (Forest Economy: Sustainable or Integral? Research Dilemmas from the Perspective of the Polish Roundwood Market). *Przegląd Leśniczy*, 26(09), 26-27.
19. Wanat, L. (2023). The Idea of Sylvicultura Oeconomica as a Tool to the University Renew and Promotion Forest Sciences for the Bioeconomy Development. In: R. Dudik (ed.), Current Trends and Challenges for Forest-Based Sector: Carbon Neutrality And Bioeconomy, WoodEMA, i.a. and Czech University of Life Sciences, Prague, 201-205.

20. Wanat, L. (2024). Kazimierza Zimniewicza drogowskazy ekonomii krajobrazu (Kazimierz Zimniewicz's pathfinders of landscape economics). *Biuletyn Parków Krajobrazowych Wielkopolski*, 31: 11-14.
21. Wanat, L. (2024). Selected creating factors of the integrated urban forest - the case of Kobierzyn garden in the Kraków metropolitan area in Poland. In: D. Jelačić (ed.), Achieving sustainability in forest-based industry, WoodEMA, i.a., Zagreb, pp. 59-68.
22. Wanat, L. (2025). Integrated development of forest and wood-based sciences on the background of the university idea. In: Ž. Meloska, M. Miloshevska Janakieska (eds.), Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA, i.a., Ohrid, pp. 325-330.
23. Wanat, L., Klimek, J., Kusiak, W., Sarniak, Ł. (2025). People - forest - wood: inclusive integration models. The case of the Kobierzyn urban forest park in the Kraków metropolitan area in Poland. In: Ž. Meloska, M. Miloshevska Janakieska (eds.), Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA, WoodEMA, i.a., Ohrid, pp. 307-312.
24. Wanat L., Potkański T., Chudobiecki J., Mikołajczak E., Mydlarz K. (2018). Intersectoral and Intermunicipal Cooperation as a Tool for Supporting Local Economic Development: Prospects for the Forest and Wood-Based Sector in Poland. *Forests* 9 (9), 531, 1.
25. Wanat, L., Sarniak, Ł., Sikora, J., Kusiak, W., Wieruszewski, M., Czarnecki, R., Smętkiewicz, K., Kaputa, V. (2026). Development programming in the forest-based sector under economic uncertainty - the case of Poland during the pandemic and post-pandemic crisis. *Economics and Environment*, 96(1), 928. DOI: 10.34659/eis.2026.96.1.928.
26. Wanat, L.; Sikora, J.; Majchrzak, L.; Sarniak, Ł.; Czarnecki, R.; Smętkiewicz, K.; Ornoch, M. (2025). The Economic and Technological Challenges of the Agri-Development Implementation Model in the Case of the Wielkopolska Region in Poland. Agriculture, 15, 412. https://doi.org/10.3390/agriculture15040412 .
27. Wieruszewski, M.; Wanat, L.; Kusiak, W.; Sarniak, Ł. (2023). Aspects of the Green Use of Wood By-products from the Sawmill Industry. In: R. Dudik (ed.), Current Trends and Challenges for Forest-Based Sector: Carbon Neutrality and Bioeconomy, WoodEMA, i.a. and Czech University of Life Sciences, Prague, 251-258.
28. Zeug, W., Bezama, A., Thrän, D. (2020). Towards a holistic and integrated Life Cycle Sustainability Assessment of the bioeconomy: Background on concepts, visions and measurements (No. 7/2020). UFZ Discussion Paper.

Author address:

Wanat, L.[1*].
[1] Department of Social Sciences, Kozminski University, Warsaw, Poland.
[*] Corresponding author: leszek.wanat@kozminski.edu.pl .

DIGITIZATION OF AUDITING AND FINANCIAL CONTROL IN THE BIOECONOMY: ENSURING TRANSPARENCY AND EFFICIENCY IN THE WOODWORKING INDUSTRY

Sakhno Liudmyla, Daria Trachova

Abstract: This article examines the digital transformation of audit and financial control systems in the bioeconomy, with a particular focus on the woodworking industry. Against the backdrop of growing global demand for sustainable resource management and transparency, traditional approaches to auditing and financial control are no longer sufficient to ensure efficiency and accountability.

The study substantiates the role of digital technologies, particularly artificial intelligence, big data analytics, and automated monitoring systems, in enhancing the effectiveness of audit procedures and financial control mechanisms. It is argued that digitalization enables continuous auditing, improves risk detection, and supports data-driven decision-making processes.

Particular attention is paid to the specific characteristics of the woodworking industry, which is characterized by complex production chains, dependence on natural resources, and strict environmental standards. The article analyzes the challenges of ensuring transparency in financial flows, particularly in the context of public funding and international grants aimed at supporting sustainable development in the bioeconomy.

The study proposes a conceptual framework for integrating digital audit tools into financial control systems within the bioeconomy. This framework combines traditional audit methods with innovative digital solutions to improve accountability, reduce fraud risks, and enhance operational efficiency.

The study's findings indicate that the implementation of digital audit and control systems helps build stakeholder trust, increase transparency, and support sustainable development goals in the woodworking industry. The article highlights prospects for further research related to the practical implementation of digital audit models in developing bioeconomy sectors.

Keywords: digital audit, financial control, bioeconomy, wood-based industry, artificial intelligence, sustainability

1. INTRODUCTION

The global transition to a bioeconomy has intensified the demand for sustainable resource management, transparent financial governance, and robust accountability mechanisms. The wood-based industry occupies a central position within the bioeconomy, linking primary forest resource extraction to advanced manufacturing, bioenergy production, and carbon sequestration services. Yet despite its strategic importance, the sector remains characterised by fragmented production chains, heavy dependence on natural and climatic conditions, and strict environmental regulations that impose significant reporting obligations on enterprises.

Against this background, traditional audit methods — largely paper-based, periodic, and reliant on retrospective sampling — are no longer sufficient to ensure timely detection of financial irregularities or to provide the continuous oversight demanded by regulators, investors, and civil society. The emergence of digital technologies has fundamentally altered the landscape of audit and financial control, opening pathways toward real-time monitoring, predictive risk assessment, and automated compliance verification.

This paper addresses the intersection of these trends by examining how digital transformation reshapes audit and financial control in the wood-based bioeconomy. The paper is structured

as follows: Section 2 reviews the specific challenges of financial control in the wood sector; Section 3 analyses the key digital technologies enabling audit transformation; Section 4 proposes a conceptual integration framework; Section 5 discusses implications for transparency and sustainable development; and Section 6 offers conclusions and directions for further research.

2. FINANCIAL CONTROL CHALLENGES IN THE WOOD-BASED SECTOR

The wood-based industry presents a distinctive set of challenges for financial control and audit that distinguish it from other manufacturing sectors. These challenges arise from three interrelated dimensions: the complexity of production chains, the dependence on natural resources, and the specificities of public and international funding mechanisms.

2.1. Complex Production Chains and Traceability

Wood-based enterprises typically operate across multiple value chain stages, from forest concession management and primary harvesting to sawmilling, panel production, bioenergy conversion, and final product marketing. Each transition point creates a potential vector for financial misreporting, including transfer pricing manipulation, understated harvest volumes, and misclassification of production costs. Studies have documented that inadequate chain-of-custody tracing is associated with higher rates of illegal logging and associated financial crimes (Nellemann et al., 2012).

The multiplicity of legal entities, subcontractors, and cross-border transactions further complicates consolidated financial reporting. Auditors face significant difficulties in reconciling physical wood flows — measured in cubic metres or tonnes — with the corresponding monetary flows recorded in accounting systems, particularly when multiple species, quality grades, and end-product forms are involved.

2.2. Public Funding and Grant Accountability

A substantial share of the wood-based bioeconomy is supported by public instruments, including EU Rural Development Programme funds, national forestry subsidies, Horizon Europe research grants, and carbon credit schemes. The receipt of public funding imposes rigorous accountability requirements, yet the administrative capacity of many forest enterprises — especially small and medium-sized holdings — is often inadequate to meet these obligations.

Transparency International and the European Court of Auditors have repeatedly flagged weaknesses in the financial control of agricultural and forestry subsidies, citing inadequate verification of land use claims, double-funding risks, and insufficient monitoring of environmental conditionality compliance (European Court of Auditors, 2021). These deficiencies underscore the urgent need for more sophisticated and continuous financial control tools.

Table 1. Key financial control challenges in the wood-based bioeconomy

Challenge Area	Principal Risk	Traditional Control Limitation
Supply chain complexity	Volume misreporting	Sampling-based verification
Public grant management	Double funding / misuse	Ex-post controls only
Environmental compliance	Fraudulent offsetting	Lack of real-time data
Cross-border transactions	Transfer pricing abuse	Jurisdictional gaps

3. DIGITAL TECHNOLOGIES ENABLING AUDIT TRANSFORMATION

The convergence of several digital technology families is transforming the audit function from a periodic, retrospective activity into a continuous, data-driven process. Three technology clusters are particularly relevant to the wood-based bioeconomy.

3.1. Artificial Intelligence and Machine Learning

AI-driven audit tools employ machine learning algorithms to analyse large transaction datasets and identify statistical anomalies indicative of error or fraud. Supervised learning models can be trained on historical audit findings to classify transactions by risk level, allowing auditors to concentrate attention on high-risk items rather than conducting random sampling across entire populations. In the wood sector, AI systems have been piloted for automated invoice matching between procurement orders and delivery notes, flagging discrepancies in species designation, weight, or unit price that may indicate document falsification.

Natural language processing (NLP) capabilities extend AI applications to the review of unstructured data — including supplier contracts, grant applications, environmental impact statements, and board minutes — for inconsistencies or misrepresentations relevant to financial audit. These capabilities substantially reduce the time required for document review while improving detection rates.

3.2. Big Data Analytics and Remote Sensing Integration

Big Data analytics enables the integration of financial records with non-financial operational data, creating a multidimensional audit evidence base that is far more robust than financial records alone. In the forestry context, satellite remote sensing data — including multispectral imagery from platforms such as Sentinel-2 and LiDAR point clouds — can be cross-referenced with declared harvest volumes and land use claims to verify the physical basis of financial transactions.

The European Forest Information System (FISE) and national forest inventories provide geospatial reference data that, when integrated with enterprise financial systems through data analytics platforms, enable automated plausibility checks on reported production quantities. Such integrations have been successfully implemented in Finland and Sweden as part of broader forest monitoring programmes (Kangas et al., 2018).

3.3. Blockchain and Distributed Ledger Technologies

Blockchain technology offers a tamper-resistant infrastructure for recording wood product provenance, certifications, and financial transactions across supply chain participants. Smart contracts encoded on permissioned blockchain platforms can automatically trigger payment releases, subsidy disbursements, or penalty assessments based on verified fulfilment of contractual or regulatory conditions. This automation reduces the scope for discretionary manipulation and creates an immutable audit trail that external auditors can access in real time. Pilot implementations within the timber certification ecosystem — including trials conducted under the Forest Stewardship Council (FSC) digital chain-of-custody initiative — have demonstrated that blockchain-based systems can reduce audit evidence gathering time by up to 40%, while significantly improving the completeness and verifiability of the evidence base (Carter et al., 2020).

4. CONCEPTUAL FRAMEWORK FOR DIGITAL AUDIT INTEGRATION

Building on the technology analysis above, this section proposes a conceptual framework for integrating digital audit tools into financial control systems within the wood-based bioeconomy. The framework rests on three mutually reinforcing pillars: data infrastructure, process automation, and governance architecture.

4.1. Data Infrastructure Layer

The foundation of any effective digital audit system is a unified data infrastructure that aggregates financial records, operational data, and external reference datasets into a semantically consistent and queryable repository. For wood-based enterprises, this infrastructure should incorporate enterprise resource planning (ERP) system outputs, supply chain management data, environmental monitoring feeds (including satellite imagery), and regulatory reporting submissions.

Interoperability standards — including the European Single Electronic Format (ESEF) for financial reporting and the UN/CEFACT trade data exchange standards — provide the semantic backbone for cross-system data integration. Investment in data quality management, including automated validation routines and master data governance processes, is a prerequisite for the reliability of downstream analytics.

4.2. Process Automation and Continuous Monitoring

The process automation pillar encompasses the deployment of robotic process automation (RPA) tools for routine audit procedures — such as reconciliation of bank statements, confirmation of supplier balances, and recalculation of depreciation schedules — as well as the implementation of continuous monitoring dashboards that alert risk managers and auditors to threshold breaches in real time.

Table 2. Proposed digital audit integration framework — key components

Framework Pillar	Core Components	Expected Outcome
Data Infrastructure	ERP integration, satellite feeds, ESEF	Unified audit evidence base
Process Automation	RPA, continuous monitoring, AI analytics	Real-time anomaly detection
Governance Architecture	Role-based access, blockchain trail, ISAE 3402	Accountability and trust

4.3. Governance Architecture

The governance pillar addresses the organisational, regulatory, and ethical dimensions of digital audit. Effective governance requires clearly defined roles and responsibilities for data ownership, access control, and audit trail management. Enterprises should align their digital audit governance with recognised standards, including ISAE 3402 (Assurance Reports on Controls at a Service Organisation) and the COSO Internal Control — Integrated Framework, adapted to reflect digital operating environments.

Data protection obligations under the EU General Data Protection Regulation (GDPR) must be reconciled with the data sharing requirements of collaborative digital audit platforms, particularly where multi-enterprise supply chain data is involved. Governance frameworks should include data processing agreements, anonymisation protocols where appropriate, and clear procedures for responding to data subject access requests.

5. IMPLICATIONS FOR TRANSPARENCY AND SUSTAINABLE DEVELOPMENT

The implementation of integrated digital audit systems carries significant implications for stakeholder trust, regulatory compliance, and the broader sustainable development agenda in the wood-based bioeconomy.

From a transparency perspective, continuous digital audit substantially reduces the information asymmetry between enterprise management and external stakeholders — including investors, regulators, certification bodies, and civil society organisations. Real-time reporting dashboards and automated compliance alerts enable a move from annual statutory audit as the primary accountability mechanism toward an ongoing assurance model that is more consistent with the dynamic character of forest resource management.

In the context of the EU Green Deal and the associated Forest Strategy for 2030, digital audit systems are positioned to play a critical role in verifying the environmental integrity of bioeconomy operations. The proposed EU Regulation on Deforestation-Free Products (EUDR) explicitly requires due diligence documentation of the geographic origin of timber products, a requirement that digital chain-of-custody systems and geospatial verification tools are uniquely equipped to support. Compliance with EUDR is estimated to impose significant compliance costs on the sector, but digital audit infrastructure can substantially reduce these costs by automating the evidence gathering and documentation processes required for market access.

From a fraud prevention perspective, the deterrence effect of continuous monitoring — the awareness among employees and managers that transactions are subject to real-time

algorithmic scrutiny — has been shown empirically to reduce the incidence of minor financial irregularities and expense misreporting, even in the absence of detected violations (ACFE, 2022). This behavioural dimension of digital control reinforces the technical detection capabilities of AI analytics.

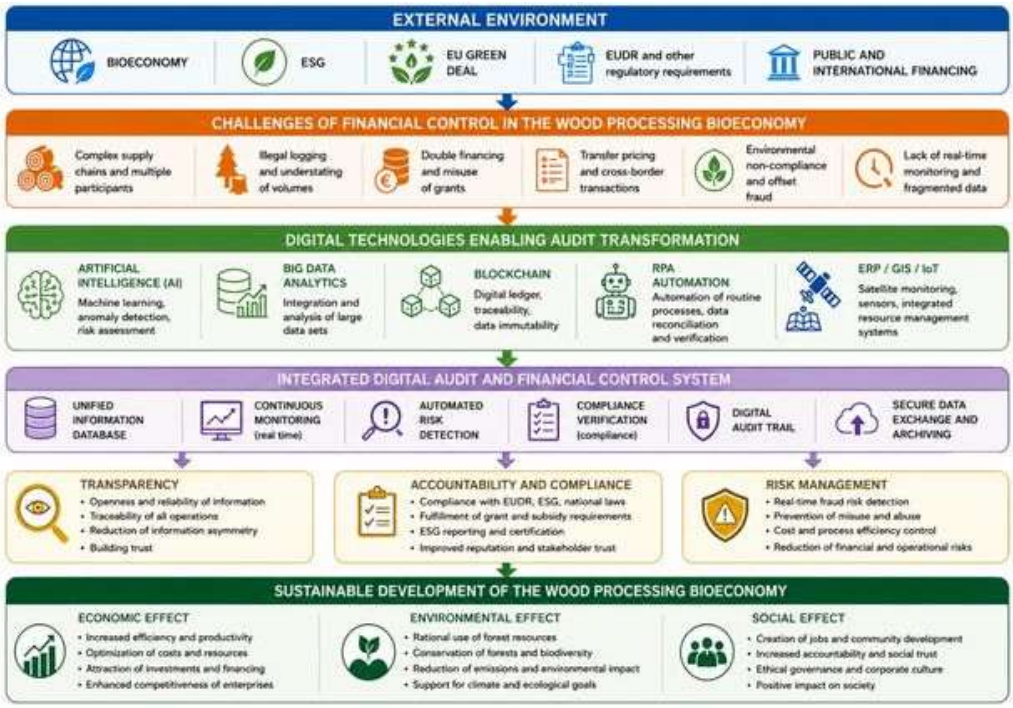


Figure 1. Integrated Digital Audit Framework for Financial Control in the Wood Processing Bioeconomy

6. CONCLUSIONS

This paper has examined the digital transformation of audit and financial control systems in the wood-based bioeconomy, proposing a conceptual framework that integrates artificial intelligence, Big Data analytics, blockchain technology, and governance mechanisms into a coherent architecture for continuous assurance.

The analysis demonstrates that the specific characteristics of the wood-based sector — complex production chains, dependence on natural resources, regulatory intensity, and significant exposure to public funding flows — create both the need and the opportunity for advanced digital audit systems. Traditional, periodic audit approaches are structurally inadequate to address the accountability demands of modern bioeconomy enterprises operating within the evolving EU regulatory landscape.

The proposed three-pillar framework — encompassing data infrastructure, process automation, and governance architecture — provides a practical roadmap for enterprises seeking to upgrade their financial control capabilities. Implementation should be pursued incrementally,

beginning with data integration and basic continuous monitoring before advancing to AI-driven analytics and blockchain-based provenance verification.

Future research should address the practical implementation barriers facing small and medium-sized forest enterprises, which represent the majority of wood-based bioeconomy actors but face significant capacity and resource constraints in adopting digital audit systems. Comparative studies across different national regulatory environments and forest tenure systems would also contribute to a more nuanced understanding of the conditions under which digital audit transformation delivers the greatest accountability benefits.

Acknowledgements: We wish to thank the WoodEMA 2026 Scientific Committee for the opportunity to present this research.

REFERENCES

1. ACFE — Association of Certified Fraud Examiners (2022): Report to the Nations: 2022 Global Study on Occupational Fraud and Abuse. ACFE, Austin, TX.
2. Carter, S.; Herold, M.; Avitabile, V.; de Bruin, S.; Damasceno-Garcia, J.; Jantz, P.; Requena Suarez, D.; Skidmore, A. K.; Strey, R.; Wiriyanto, S.; Sy, V. D. (2020): Small contributions of deforestation to CO2 emissions. Nature Climate Change 8 (8): pp. 639-640.
3. European Court of Auditors (2021): Special Report No 04/2021: Customs controls — insufficient harmonisation hampers EU financial interests. Publications Office of the European Union, Luxembourg.
4. Kangas, A.; Astrup, R.; Breidenbach, J.; Fridman, J.; Gobakken, T.; Korhonen, K.T.; Maltamo, M.; Nilsson, M.; Nord-Larsen, T.; Naesset, E.; Olsson, H. (2018): Remote sensing and forest inventories in Nordic countries — roadmap for the future. Scandinavian Journal of Forest Research 33 (4): pp. 397-412.
5. Kostyakova A. (2025). Transparency in accounting and auditing of Ukrainian timber: EITI reporting as a factor of sustainable development. Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025.
6. Nellemann, C.; Henriksen, R.; Kreilhuber, A.; Stewart, D.; Kotsovou, M.; Raxter, P.; Mrema, E.; Barrat, S. (eds.) (2012): The Rise of Environmental Crime: A Growing Threat to Natural Resources, Peace, Development and Security. United Nations Environment Programme (UNEP), Nairobi.
7. European Commission (2023): EU Deforestation Regulation — Frequently Asked Questions. URL: https://ec.europa.eu/environment/forests/deforestation_regulation.htm
8. ISO 19011:2018 — Guidelines for auditing management systems. International Organization for Standardization, Geneva.

Authors address:
Sakhno L.A.*; Trachova D.M.
[1]Department of Finance, Accounting and Taxation, Faculty of Economics and Business, Dmytro Motornyi Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
[2] Accounting and Taxation Department, National Scientific Center “Institute of Agrarian Economics”, Kyiv, Ukraine
*Corresponding author: liudmyla.sakhno@tsatu.edu.ua

AI IN WOOD SERVICES: HOW ARTIFICIAL INTELLIGENCE CHANGES MARKETING COMMUNICATIONS IN THE FURNITURE INDUSTRY

Andrea Tománková, Eva Habiňáková

Abstract: Digitalization, growing competition, and increasing customer demands are leading businesses in traditional industries like furniture to leverage artificial intelligence (AI) to improve customer interactions, optimize sales processes, and increase the effectiveness of marketing communications. Today's consumers expect personalized content, relevant offers, and communications tailored to their preferences and purchasing behaviour, placing new demands on marketing departments and data platforms. AI offers solutions for automated customer segmentation, predictive behaviour analysis, and dynamic, real-time content personalization, enabling businesses to respond to these challenges efficiently and at lower cost. The paper also analyses how AI is changing marketing communications in the furniture industry and identifies its specific benefits for campaign effectiveness and content personalization. The paper presents a case study of ASKO – NÁBYTOK, which implemented the AI-powered Bloomreach Engagement platform to centralize customer data and automate personalized marketing campaigns. The analysis of the results shows a significant increase in email marketing revenue, a reduction in the volume of distributed communications, and an increase in campaign relevance. The case study confirms that the integration of artificial intelligence enables the transition from mass marketing to data-driven, customer-oriented communications, which has a significant impact on the performance of a company in the furniture sector.
Keywords: artificial intelligence, marketing communication, marketing personalization, digital marketing, furniture industry, customer data platform

INTRODUCTION

Digital transformation is fundamentally changing the way businesses communicate with customers, build their brands, and create value in a competitive environment. Artificial intelligence (AI) has become a key tool in digital marketing, significantly influencing content personalization, the customer experience, and the effectiveness of marketing communications. AI enables detailed analysis of consumer behavior, predictive targeting, and the automation of marketing processes, particularly in the online environment. Its importance is also growing in the furniture retail sector, which faces increased demands for product visualization, offer customization, and the integration of digital technologies.

Artificial intelligence is also becoming a strategic factor that enables companies in the furniture industry to transition from traditional mass communication to data-driven, customer-centric approaches. Its implementation not only increases marketing efficiency but also enhances the ability of companies to remain competitive in a rapidly evolving digital environment.

The aim of this paper is to analyze the significance of artificial intelligence in digital marketing, focusing on personalization, customer engagement, and its practical application in the furniture industry.

1. DIGITIZATION AND MARKETING COMMUNICATION OF BUSINESSES

Digitalization is a key driver of marketing transformation, as it changes how businesses operate, their strategies, and their communication channels. It enables companies to respond to dynamic technological and consumer changes and to effectively utilize data generated through customer interactions (Ziółkowska, 2021).

As a result of digitization, marketing communication has transformed from a one-way dissemination of information into an interactive process in which digital channels enable the building of direct and personalized relationships with customers in real time (Ziakis & Vlachopoulou, 2023).

At the same time, the integration of digital technologies into marketing activities enables market segmentation at the micro-level and the tailoring of content to individual customer preferences, thereby increasing the relevance of marketing communication (Mojsovska Salamovska, 2024). Digitalization thus not only changes communication tools but also the very marketing strategies and organizational processes of companies, with the ability to adapt to the digital environment becoming a key factor in competitiveness (Reisberger et al., 2025).

2. ARTIFICIAL INTELLIGENCE AS A MARKETING COMMUNICATION TOOL: PERSONALIZATION, SEGMENTATION AND PREDICTIONAL ANALYTICS

Artificial intelligence is a key tool in modern marketing, as it enables the processing of large amounts of data, the identification of customer behavior patterns, and the generation of personalized communications (Amin, 2025).

Personalization of Marketing Communication

Personalization is the process of tailoring marketing content to individual customer characteristics. AI enables so-called hyper-personalization, i.e., the dynamic adaptation of communication in real time based on a customer's digital footprint (Hardcastle, 2025). This approach leads to increased engagement, conversion rates, and customer loyalty, while simultaneously fostering the development of a continuous relationship between the brand and the customer (Bano et al., 2025).

Customer Segmentation

AI transforms segmentation from a traditional static process into a dynamic mechanism based on machine learning. It enables the creation of granular customer segments based on behavioral, demographic, and transactional data and updates them in real time (Ali & Zeebaree, 2025).

Predictive Analytics

Predictive analytics uses historical data to forecast future customer behavior. It enables the optimization of marketing campaigns, more efficient budget allocation, and the identification of customers with high purchasing potential (Amin, 2025; Bano et al., 2025).

Ethical considerations

The implementation of AI also presents challenges, particularly in the areas of data protection and algorithmic transparency. Compliance with regulatory frameworks, such

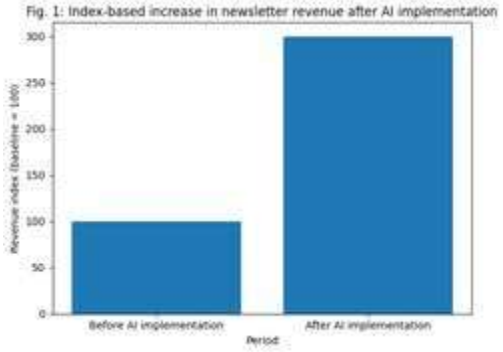
as the GDPR, is essential for the responsible use of these technologies (Bano et al., 2025).

3. SPECIFICITIES OF MARKETING COMMUNICATION IN THE FURNITURE INDUSTRY

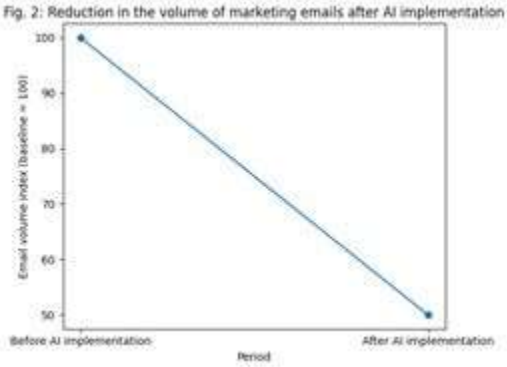
Marketing communication in the furniture industry is influenced by the nature of the products, which are durable, more expensive, and require a more complex customer decision-making process (Štarchoň et al., 2022).
For this reason, communication must reflect not only price but also the quality, design, and functional features of the products. Marketing strategies therefore combine traditional tools with digital forms of communication, with the online environment growing in importance.
Digital technologies, such as 3D visualizations and augmented reality, allow customers to better imagine the product in a real-world setting, thereby increasing trust and shortening the decision-making process (Artisan Furniture, 2023).
Artificial intelligence is primarily used in personalized product recommendations, automated marketing campaigns, and customer service via chatbots.
Nevertheless, implementing AI requires high-quality data inputs and technological capabilities, which can be a limitation, especially for smaller businesses.

4. THE USE OF ARTIFICIAL INTELLIGENCE IN MARKETING COMMUNICATIONS IN THE FURNITURE SECTOR: CASE STUDY OF ASKO – FURNITURE

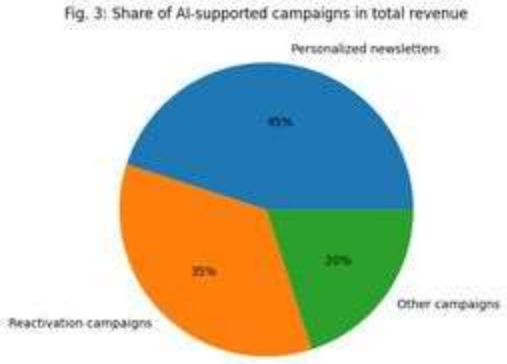
ASKO – NÁBYTOK operates in the Czech and Slovak markets and combines brick-and-mortar stores with an e-commerce platform. Given the high volume of customer interactions, it generates a vast amount of data from both online and offline sources.
Before implementing AI, this data was processed in a fragmented manner, which limited its use in marketing communications (BLOOMREACH, 2024). Campaigns were predominantly mass-market in nature and only partially reflected individual customer behavior.
The company therefore implemented the Bloomreach Engagement platform, which functions as a Customer Data Platform with integrated artificial intelligence elements. Its goal was to centralize customer data and create a comprehensive customer profile. The AI component analyzes customer behavior, purchase history, and interactions with marketing content, automatically creating segments and optimizing both content and the timing of communications.
In practice, AI is primarily used in email marketing and automated campaigns, such as abandoned cart campaigns or customer reactivation campaigns.
The results of the implementation highlight the significant benefits of artificial intelligence:



- an approximately 200% increase in revenue from email marketing (figure 1),



- an approximate 50% reduction in the volume of outgoing traffic (figure 2),



- increase conversion rates and campaign relevance (figure 3).

The case study of ASKO – NÁBYTOK confirms that artificial intelligence can be effectively used even in traditional sectors such as furniture. The implementation of AI tools has not only led to technological modernization, but also to a change in the

philosophy of marketing communication towards a customer-oriented and data-driven approach. These findings are in line with the professional literature, which points to the growing importance of artificial intelligence in the field of marketing personalization.

Based on the analysed case, it can be concluded that the use of artificial intelligence in marketing communication of ASKO – NÁBYTOK has brought a significant improvement in campaign effectiveness, increased sales from digital channels and optimized communication with customers. This example represents relevant empirical evidence of the practical benefits of artificial intelligence for companies operating in the woodworking and furniture sectors.

CONCLUSION

Artificial intelligence is a key factor in enhancing the effectiveness of marketing communications and the quality of the customer experience. It enables more precise personalization, a better understanding of customer needs, and the optimization of marketing processes in real time.

In the furniture sector, its significance is linked primarily to digitization, product visualization, and the customization of offerings.

Successful use of AI requires not only technological solutions but also a strategic approach, organizational changes, and an emphasis on ethical principles of data processing.

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REFERENCES

1. Ali, C. S. M., & Zeebaree, S. R. M. (2025). Personalization in digital marketing: Leveraging machine learning for e-commerce. *American Journal of Research Communication and Social Sciences, 18*(3), 105–129.
2. Amin, M. R. M. (2025). Artificial intelligence (AI) adoption in marketing strategies. *Elsevier*
3. Bano, R., et al. (2025). The role of artificial intelligence in personalized marketing: Enhancing customer experience, predictive targeting, and brand engagement. *The Critical Review of Social Sciences Studies, 3*(2), 1–25.
4. Hardcastle, K. (2025). Understanding customer responses to AI-driven personalized journeys: Impacts on the customer experience. *Journal of Advertising Research*.

5. Mojsovska Salamovska, S. (2024). Digital transformation in marketing and business – implications on retail technologies and customer engagement. *Ekonomski vjesnik / Econviews, 37*(1), 45–60.
6. Reisberger, T., Reisberger, P., Copš, P., et al. (2025). The linkage between digital transformation and organizational culture. *Journal of the Knowledge Economy*. Springer.
7. Štarchoň, P., Hitka, M., Miklošík, A., & Kočišová, L. (2022). Furniture marketing and product development. In *Conference proceedings*. Comenius University Bratislava.
8. Ziakis, C., & Vlachopoulou, M. (2023). Artificial intelligence in digital marketing: Insights from a comprehensive review. *Information, 14*(12), 1–26.
9. Ziółowska, M. J. (2021). Digital transformation and marketing activities in small and medium-sized enterprises. *Sustainability, 13*(5), 1–18.

Online references

10. Artisan Furniture UK. (2023). Budúcnosť maloobchodu s nábytkom: 3D obchod a transformácie AI v roku 2024. Retrieved from https://www.artisanfurniture.net/sk/news/furniture-retails-future-3d-commerce-and-ai-transformations-in-2024
11. Bloomreach. (2024). ASKO – nábytok: AI-driven customer data platform and personalized marketing communication. Retrieved March 14, 2026, from https://www.bloomreach.com/en/case-studies/asko-nabytek-epace
12. Stratégie HN. (2023). ASKO mení marketingovú stratégiu a posilňuje digitálne kanály. Retrieved March 14, 2026, from https://strategie.hnonline.sk

Authors address:
Mgr. Tománková, Andrea, PhD., PaedDr. Habiňáková, Eva, PhD.
Faculty of Mass Media Communication, University of Ss. Cyril and Methodius in Trnava, Námestie J. Herdu 2, Trnava, Slovakia
Corresponding author: eva.habinakova@ucm.sk

DIGITAL TRANSFORMATION IN FURNITURE ENTERPRISES IN BULGARIA

Vyara Kyurova, Blagovesta Koyundzhiyska-Davidkova, Anita Kyurova-Kalpakova

Abstract: The accelerated pace of economic digitalization poses a serious challenge to furniture enterprises in Bulgaria. The adoption of digital technologies, which constitute the foundation of digital transformation in these enterprises, is evolving from a source of competitive advantage into a necessary condition for their market sustainability. At the same time, digital transformation plays a key role not only in the strategic development of enterprises in the furniture industry, but also in the comprehensive restructuring of their business processes, which, in turn, enables a qualitative enhancement of organizational capacity.

In this context, examining the current state of digital transformation in furniture enterprises in Bulgaria is of particular interest. To achieve the research objective, enterprises from the furniture industry were surveyed using the convenience sampling method. The application of this method is appropriate given its suitability to the specific characteristics of both the units under study and the data to be collected. The results of the analysis make it possible to formulate general conclusions regarding the role of digital transformation in optimizing business processes in furniture enterprises in Bulgaria.

Keywords: digital transformation, furniture enterprises, digital technologies

1. INTRODUCTION

In the context of dynamic changes in the economy, directly affecting its digitalization, furniture enterprises in Bulgaria are facing serious challenges. In these complex conditions, digital transformation, providing technological and organizational capabilities, is the main driver for achieving sustainability and competitive advantage (Rahnama et al., 2026). Moreover, it contributes to strengthening competitiveness and facilitating sustainable growth (Wang et al., 2024) of enterprises in the furniture industry. At the same time, digital transformation is crucial not only for the strategic development of enterprises in the furniture industry, but also for the comprehensive restructuring of their business processes, which in turn allows for a qualitative increase in organizational capacity. Moreover, digital transformation is perceived by business as a main strategic direction for development (Cheng et al., 2024). Clearly, digital transformation is becoming a strategic choice for these enterprises (Pu et al., 2024). In addition, it has an important contribution to the creation and capture of value, but also to improving the economic performance of enterprises in the furniture industry, as well as to increasing the satisfaction of consumers of their products. Digital transformation is also a prerequisite for strengthening the market orientation and decision-making capabilities of managers in furniture enterprises (Ghosh et al., 2022; Gupta et al., 2020; Heredia et al., 2022).

At the same time, digital transformation is based on restructuring, both driven and created by digital technologies (Li et al., 2024). In turn, digital technologies are those that contribute to improving competitive advantages by using company resources and creating new opportunities (Liu et al., 2011). Considering that digital technologies are at the heart of digital transformation in furniture industry enterprises, their application turns from a competitive advantage into a

mandatory condition for the market sustainability of these enterprises. It is no coincidence that some researchers emphasize that modern digital technologies contribute to improving the activities and sustainable development of enterprises (Chen et al., 2024), to internal business operations, as well as to increasing organizational productivity (Nasiri et al., 2020; Seyedghorban et al., 2020).

In this context, it is of interest to study the state of digital transformation in furniture industry enterprises in Bulgaria. The study is based on a survey of the opinions of 67 representatives of enterprises operating in the furniture industry in the period January-March 2026.

2. LITERATURE REVIEW

Digital transformation as an innovative approach to achieving sustainable development and competitive advantages in a turbulent digital environment is the subject of a number of scientific studies. The analysis of the literature reveals that there is no unified opinion of the authors regarding the substantive aspects of digital transformation. This is supported by the opinion of Matt et al. (2015). However, a group of authors unite around the view of digital transformation as a process, linking it to the use of digital technologies. An important feature is that digital transformation is viewed as a multifaceted and continuous process, primarily directed by enterprises towards the use and integration into business operations of such technologies as artificial intelligence (AI), blockchain, cloud computing, and big data (Cheng et al., 2026) in order to ensure significant organizational changes and improvements (Vial, 2019), as well as improvements that, in turn, relate to a significant extent to innovations and information processing capabilities (Peng et al., 2022). Yu's (2024) position regarding the technologies considered by Cheng et al. is that digital transformation relies primarily on them. This is not accidental, due to the fact that it is digital technologies that lead to fundamental changes in terms of production methods and the organizational structure of enterprises (Nambisan et al., 2017). At the same time, Gong and Ribiere (2021) in their work, based on a study of the works of a number of authors, develop the idea of digital transformation as "A fundamental change process, enabled by the innovative use of digital technologies accompanied by the strategic leverage of key resources and capabilities, aiming to radically improve an entity and redefine its value proposition for its stakeholders".

The theory shows that the main emphasis of the works of a number of researchers dealing with the problems of digital transformation at a theoretical level also refers to the same, albeit different, change. It is associated with a fundamental change in the approach applied to creating and capturing value in the conditions of increasing the degree of digitalization of the economy (Cheng et al., 2026). Digital transformation is also considered as a form of organizational change, conditioned by the widespread presence of digital technologies (Currie et al., 2024; Hanelt et al., 2021). At the same time, Li et al. (2024) have a more specific view in this regard, specifying the digital technologies to which they refer big data, business analytics, cloud computing, mobility, and social media platforms.

3. RESULTS AND DISCUSSION

Of great importance for the development of furniture enterprises and the strengthening of their competitiveness is the possibility of implementing digital transformation and the use of

digital technologies in them. Through them, enterprises in the furniture industry manage to increase resource efficiency, reduce operating costs, accelerate decision-making processes, and adapt more quickly to the dynamic market environment and changing consumer expectations. In addition, digital transformation is also a key factor in the innovation capacity of enterprises, as it creates conditions for the development of new products, services and distribution channels. In this context, the results of the survey show that not a very large share of respondents (38.7%) have implemented digital transformation (see Figure 1).

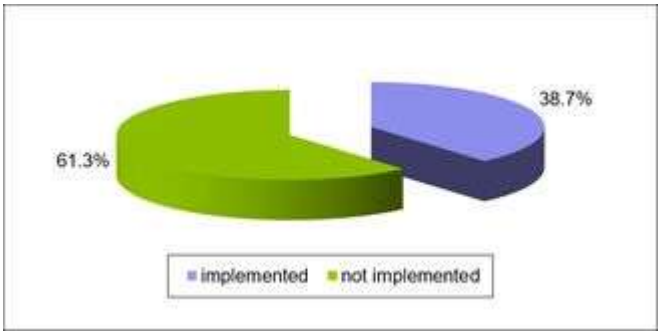

Figure 1. Distribution of enterprises according to the digital transformation implementation - %

It is noteworthy that among the main barriers to digital transformation in furniture enterprises are the lack of finances for its implementation (78.6%) and the lack of trained personnel (69.3%). An important issue for furniture companies is the presence or absence of a developed digital transformation strategy for the next 3-5 years. In this regard, it was found that a small part of them (16.5%) have developed such a strategy (see Figure 2).

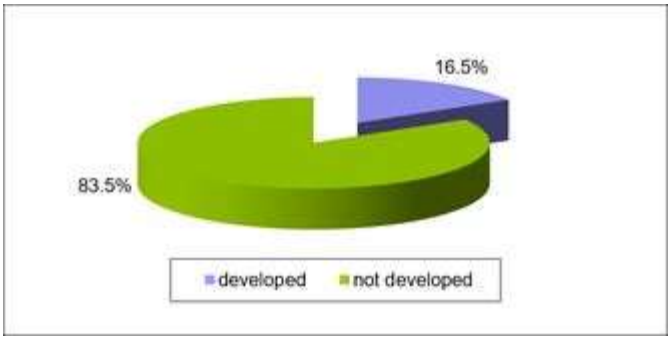

Figure 2. Distribution of enterprises by the presence of a developed digital transformation strategy for the next 3-5 years - %

The share of respondents (13.6%) who present the digital transformation strategy inside and outside the company is also relatively small. It was also found that a relatively small part of the representatives of furniture companies (18.4%) have the opportunity and allocate appropriate resources for the creation, management and implementation of the digital strategy. Of interest is the opinion of the respondents regarding their conviction whether digital transformation is a mandatory condition for survival in the furniture market in Bulgaria. In this

context, it was found that over half of the respondents (56.8%) expressed a positive opinion on this issue, 21.8% believe that it is not a mandatory condition and 21.4% cannot asses.

From the point of view of the use of digital technologies in furniture companies, it is striking that the share of those who use such technologies in their activities is not large (31.9%). It was found that the most used digital tool by the surveyed companies is social media platforms. At the same time, a small part of them offer 3D visualization to their customers (30.1%) and only 2.9% use digital technologies for augmented reality (AR).

An additional analysis of the use of digital technologies for different purposes shows that a significantly small share of respondents (19.8%) use these technologies to regularly inform employees about the development of their company, and an even lower share of those (9.7%) who use them for project management. The survey data show that a small share of respondents (21.7%) also direct their efforts to the use of digital tools to promote innovation, among which product innovations occupy the largest share.

Regarding the allocation of funds from the annual budget of enterprises in the furniture industry for digital technologies and training, the results of the survey show that a relatively small proportion (29.8%) of them allocate such funds.

Objective assessment requires establishing the presence of the necessary digital skills for working with new technologies by employees in furniture enterprises. In this regard, it was found that the share of enterprises (21.7%) in which employees possess such skills is not large. At the same time, it is of particular importance for furniture enterprises to conduct internal training on improving the digital qualifications of their employees. In this regard, a relatively small part of the respondents (20.3%) stated that they conduct such training among their employees.

4. CONCLUSION

Knowing the specifics of digital transformation is a prerequisite for achieving lasting market success and ensuring competitive advantages in a world with trends towards globalization and digitalization. In this context, the analysis of the results of the study reveals that enterprises in the furniture industry are facing serious problems in the implementation and use of digital technologies in them.

The analysis of the literary sources outlines digital technologies as the main driver of transformation processes in enterprises in the furniture industry. They not only support internal business operations and organizational productivity, but also contribute to the creation of new competitive advantages and the more effective use of available company resources. In this sense, the implementation of digital technologies by enterprises in the furniture industry should be perceived not as an optional option, but as a necessary condition for achieving a sustainable market position and long-term competitiveness.

The empirical study shows a serious gap between the perceived need for digital transformation and its real practical application among furniture enterprises in Bulgaria. The main barriers - financial, personnel and strategic - form a complex problem, the overcoming of which requires targeted policies for financial support, investments in training and qualification of personnel, as well as institutional support for the development and implementation of long-term strategies for digitalization. These conclusions can serve as a basis for formulating specific recommendations to businesses and institutions aimed at accelerating the digital

transformation and increasing the sustainability and competitiveness of the furniture industry in Bulgaria.

REFERENCES

1. Chen, Y.; Zhang, M.; Matthews, L.; Guo, H. (2024): *Digital transformation and nvironmental information disclosure in China: The moderating role of top management team's ability*. Business Strategy and the Environment 33: pp. 8456–8470.
2. Cheng, L.; Mei, N.; Yi, G. (2026): *How digital transformation enhances firm performance: Underlying knowledge and mechanisms from the perspective of value creation*. Journal of Innovation & Knowledge 14, 100952. https://doi.org/10.1016/j.jik.2026.100952
3. Cheng, W.; Li, C.; Zhao, T. (2024): *The stages of enterprise digital transformation and its impact on internal control: evidence from China.* Int. Rev. Financ. Anal. 92 103079. https://doi.org/10.1016/j.irfa.2024.103079
4. Currie, W. L.; Weerakkody, V.; Vliet, B. V. (2024): *Digital transformation: The geopolitical-organizational nexus*. Journal of Information Technology 39(4): pp. 618–629. DOI: 10.1177/02683962241299822
5. Ghosh, S.; Hughes, M.; Hodgkinson, I.; Hughes, P. (2022): *Digital transformation of industrial businesses: A dynamic capability approach.* Technovation, 113, Article 102414. https://doi.org/10.1016/j.technovation.2021.102414
6. Gong, C.; Ribiere, V. (2021): *Developing a unified definition of digital transformation*. Technovation 102: 102217. DOI: 10.1016/j.technovation.2020.102217
7. Gupta, S.; Drave, V. A.; Dwivedi, Y. K.; Baabdullah, A. M.; Ismagilova, E. (2020). *Achieving superior organizational performance via big data predictive analytics: A dynamic capability view.* Industrial Marketing Management, 90: pp. 581-592. https://doi.org/10.1016/j.indmarman.2019.11.009
8. Hanelt, A.; Bohnsack, R.; Marz, D.; et al. (2021): *A systematic review of the literature on digital transformation: Insights and implications for strategy and organizational change*. Journal of Management Studies 58(5): pp.1159–1197.
9. Heredia, J.; Castillo-Vergara, M.; Geldes, C.; Gamarra, F. M. C.; Flores, A.; Heredia, W. (2022): *How do digital capabilities affect firm performance? The mediating role of technological capabilities in the "new normal.* Journal of Innovation & Knowledge, 7(2), Article 100171. https://doi.org/10.1016/j.jik.2022.100171
10. Li, Z.-G.; Wu, Y.; Li, Y.-K. (2024): *Technical founders, digital transformation and corporate technological innovation: empirical evidence from listed companies in China's STAR market*. International Entrepreneurship and Management Journal 20: pp. 3155–3180. https://doi.org/10.1007/s11365-023-00852-7
11. Liu, D.-Y.; Chen, S.; Chou, T.-C. (2011): *Resource fit in digital transformation*. Management Decision 49(10): pp. 1728–1742. https://doi.org/10.1108/00251741111183852
12. Matt, C.; Hess, T.; Benlian, A. (2015): *Digital Transformation Strategies.* Bus Inf Syst Eng 57: pp. 339-343. https://doi.org/10.1007/s12599-015-0401-5
13. Nambisan, S.; Lyytinen, K.; Majchrzak, A.; Song, M. (2017): *Digital innovation management: reinventing innovation management research in a digital world.* MIS Q 41: pp. 223-238.

14. Nasiri, M.; Ukko, J.; Saunila, M.; Rantala, T. (2020): *Managing the digital supply chain: the role of smart technologies.* Technovation 96-97 102121. https://doi.org/10.1016/j.technovation.2020.102121
15. Peng, Y.; Tao, C. (2022): *Can digital transformation promote enterprise performance? - from the perspective of public policy and innovation.* J. Innov. Knowl. 7 100198. https://doi.org/10.1016/j.jik.2022.100198
16. Pu, T.; Li, Y.; Zulkafli, A. H. (2024): *Digital transformation and corporate innovation: Empirical discovery based on machine learning*. Asian Academy of Management of Accounting and Finance 20(2): pp. 121–153. https://doi.org/10.21315/aamjaf2024.20.2.4
17. Rahnama, H.; Johansen, K.; Rönnbäck, A. Ö. (2026): *The twin transition: Driving sustainability through digital transformation in manufacturing*. Technovation 155, 103582. https://doi.org/10.1016/j.technovation.2026.103582
18. Seyedghorban, Z.; Samson, D.; Tahernejad, H. (2020): *Digitalization opportunities for the procurement function: pathways to maturity.* Int. J. Oper. Prod. Manag. 40: pp. 1685-1693. https://doi.org/10.1108/IJOPM-04-2020-0214
19. Vial, G. (2019): *Understanding digital transformation: A review and a research agenda*. The Journal of Strategic Information Systems 28(2): pp. 118–144. https://doi.org/ 10.1016/j.jsis.2019.01.003
20. Wang, G.; Lamadrid, R.L.; Huang, Y. (2024): *Digital transformation and enterprise outward foreign direct investment*. Financ. Res. Lett. 65, 105593. https://doi.org/ 10.1016/j.frl.2024.105593
21. Yu, G. (2024): *Digital transformation, human capital upgrading, and enterprise ESG performance: Evidence from Chinese listed enterprises*. Oeconomia Copernicana 15(4): pp. 1465–1508. https://doi.org/10.24136/oc.3058

Authors address:

Kyurova, V.[1]; Koyundzhiyska-Davidkova, B.[2]; Kyurova-Kalpakova, A.[3]
[1] Department of Business Management and Marketing, Faculty of Economics, South-West University "Neofit Rilski", Blagoevgrad, Bulgaria
*Corresponding author: vesi_k@swu.bg; vesi_8808@abv.bg

BARRIERS AND ENABLERS OF INDUSTRY 4.0 AND QUALITY 4.0 IMPLEMENTATION IN THE FURNITURE INDUSTRY

Robert Ulewicz

Abstract: The aim of the article is to identify the main barriers and enablers of Industry 4.0 and Quality 4.0 implementation in the furniture industry, with particular emphasis on small and medium-sized enterprises. The study integrates digital transformation, quality management, and sustainability. Industry 4.0 supports automation, process integration, product personalization, and real-time data use, while Quality 4.0 enhances traditional quality management through digital traceability, data analytics, and decision support. The research was based on a multiple case study of three SME furniture manufacturers using a mixed-methods approach. The findings show that the analyzed companies are still at an early stage of digital transformation. The main barriers include limited financial resources, outdated machinery, shortages of specialists in automation, robotics, and IT, weak process integration, and organizational resistance to change. The most important enablers were management commitment, employees' openness to new competencies, integrated CAD/CAM tools, digital traceability, and quality dashboards. The results indicate that even partial implementation of Industry 4.0 and Quality 4.0 can improve OEE, delivery timeliness, complaint reduction, material utilization, and root-cause analysis time.
Keywords: Industry 4.0, Quality 4.0, furniture industry, digital transformation, sustainability

1. INTRODUCTION

The ongoing digitalization of manufacturing processes has made Industry 4.0 one of the most important directions of development in modern industry. The fourth industrial revolution is based on the integration of cyber-physical systems, the Internet of Things, artificial intelligence, and data analytics, and its main objective is to increase the flexibility, productivity, and intelligence of production processes. For manufacturing enterprises, including those from the SME sector, this transformation creates opportunities to improve operational efficiency, enhance process coordination, and reduce resource consumption. At the same time, however, it requires investment, new competencies, and organizational change. With the development of Industry 4.0, the importance of the Quality 4.0 concept is also increasing, understood as an extension of traditional quality management under conditions of digital transformation. Quality 4.0 makes use of the potential of big data, IIoT, and AI, shifting the focus from final inspection to ongoing monitoring, faster decision-making, root cause analysis, and real-time process improvement [1,2]. In this approach, quality becomes an area strongly supported by data and digital technologies, which contributes to improving both enterprise efficiency and competitiveness.

These issues are of particular importance in the furniture industry, which remains an important sector of the economy while simultaneously being exposed to increasing market, environmental, and technological pressure. The furniture sector generates a significant environmental burden related to raw material consumption, waste generation, and emissions throughout the entire product life cycle. At the same time, research on sustainable development in this sector is focused mainly on sustainable design, supply chain management, and environmental management, while still remaining fragmented [3].

Previous studies on furniture enterprises indicate that the implementation of Industry 4.0 is still limited, especially in the SME group [4]. In enterprises from southern Poland, a low level of automation and robotization has been observed, together with the sporadic use of product and process modelling tools, weak system integration, and only marginal application of such solutions as artificial intelligence, mass customization, or CIM systems. The most frequently indicated barriers include an outdated and incompatible machinery park, high automation costs, a shortage of specialists in automation, robotics, and IT, the lack of pull-type systems, and concerns related to the changing role of humans in the production process [5,6]. On the other hand, the literature also indicates factors supporting digital transformation in the furniture industry. These include the development of digital competencies, employee openness to acquiring new skills [7], the integration of design and manufacturing, and the use of digital platforms supporting data flow between design, production planning, and execution [8]. Such solutions enable the generation of 3D models, BOMs, CAM/G-code, nesting, and prototyping data, thereby shortening design time, reducing material waste, and facilitating product customization. In this context, the joint analysis of Industry 4.0 and Quality 4.0 in the furniture industry appears fully justified. Industry 4.0 provides tools for automation, integration, and flexible production, whereas Quality 4.0 allows process data to be transformed into knowledge that supports quality, reliability, traceability, and decision improvement. Nevertheless, there is still a visible research gap resulting from the limited number of studies that simultaneously address implementation barriers, supporting factors, the quality dimension, and the requirements of sustainable development within the specific context of the furniture industry.

The aim of this article is to identify and analyze the key barriers and enablers of Industry 4.0 and Quality 4.0 implementation in the furniture industry. It is assumed that effective digital transformation in this sector requires not only technological investments, but also process integration, competency development, organizational maturity, an appropriate approach to quality management, and the alignment of modernization activities with sustainable development goals [9].

2. RESEARCH METHODOLOGY

The study adopted a multiple case study design supported by a mixed-methods approach, combining quantitative and qualitative data. This methodological choice is consistent with previous research on the implementation of Industry 4.0 in the SME sector. In the furniture industry, questionnaire surveys combined with expert interviews have been used to assess enterprise readiness, while more recent studies on Industry 4.0 transformation in SMEs have employed case studies, KPI analysis, and in-depth stakeholder interviews. The aim of the study was to identify the barriers and enablers of Industry 4.0 and Quality 4.0 implementation in three furniture manufacturers from the SME sector, and to estimate the impact of pilot implementations on selected operational, quality, and environmental indicators. Quality 4.0 was operationalized as the use of process data, digital traceability, quality analytics, and digital decision support for faster root cause analysis, nonconformity reduction, and improved quality-related decision-making. This approach is consistent with the literature, which treats Quality 4.0 as an extension of quality management aligned with the capabilities of Industry 4.0, particularly in the areas of IIoT, industrial big data, and AI.

Three companies located in southern Poland were purposely selected for the study. The selection criteria included SME status, at least 10 years of business activity, willingness to

provide operational data, and diversity in production types. The selection was intended to reflect the structure of the furniture sector, in which unit and batch production enterprises predominate, accompanied by a low level of automation, limited use of integrated systems, and only marginal application of AI.

Data collection was conducted in four stages. In the first stage, an Industry 4.0 and Quality 4.0 maturity audit was carried out. The research instrument was based on the logic of previous studies in the furniture industry, extending the assessment from 19 to 24 factors grouped into six dimensions: automation and robotization, system integration, digital data collection, Quality 4.0 management, competencies and change management, and sustainability and material efficiency. For production operations, a 1-5 scale was applied and transformed into the range of 0.1-0.9. For the degree of use of digital solutions, the response categories "I do not know," "no," "sometimes," and "yes" were also transformed into the 0.1-0.9 scale.

In the second stage, 15 semi-structured interviews were conducted, with five interviews in each company. The respondents included the owner or plant director, production manager, quality representative, maintenance representative, and foreman or shift leader. The interviews focused on implementation barriers, availability of competencies, organizational readiness, data quality, and the influence of implementation on quality processes. In the third stage, workplace observations and an analysis of internal documents were carried out, including technological cards, complaint records, quality reports, production plans, and monthly performance reports. In the fourth stage, data collected before the pilot implementation were compared with data obtained after 12 months of operation.

Table 1. Characteristics of the surveyed enterprises from the SME sector

Company profile	Employment	Type of production	Scope of the Industry 4.0 / Quality 4.0 pilot
A. Custom-made wooden furniture manufacturer	38	unit and small-batch	barcodes for materials, digital register of nonconformities, basic CAD/CAM integration, complaint dashboard
B. Cabinet furniture manufacturer	96	serial	integration ERP-CAD-CAM, BOM i G-code, nesting, monitoring OEE, SPC online, dashboard quality
C. Upholstered furniture manufacturer	142	large-batch	digital work instructions, tracking of material and semi-finished product batches, electronic defect reporting, quality and delivery timeliness panel

To evaluate implementation effects, a set of KPIs inspired by previous SME case study research was adopted and then adjusted to the specifics of the furniture industry and Quality 4.0 [10]. The study used the following indicators: OEE, delivery timeliness, complaint rate, material utilization, digital traceability coverage, and root cause closure time for nonconformities. The selection of these indicators is supported by industry literature, which emphasizes the importance of design automation, BOM, G-code, nesting, and the reduction of material losses, as well as the growing importance of sustainability in design, supply chain management, and the environmental impact of products.

Data analysis was conducted in two steps. First, a within-case analysis was performed separately for each case. This was followed by a cross-case analysis, comparing the three

enterprises in order to identify similarities and differences. Barriers and enablers were additionally assessed on a 1-5 scale during an expert workshop, using conclusions derived from interview coding. It should be emphasized that the results presented in the next section are simulated in nature; however, their levels were referenced to the findings of the literature concerning the low digital maturity of furniture SMEs, the significant role of financial and competence-related barriers, and the potential benefits resulting from the integration of data, quality, and design-to-production automation.

3. RESULTS

All three enterprises began the transformation process from a relatively low level of maturity, which is consistent with previous findings for the furniture industry, where a low level of automation and robotization, weak use of CIM, AI, VSM, and JIT/Kanban, as well as a particularly low level of automation in warehousing operations, were identified [11].

The highest initial and final maturity level was recorded in Case B, i.e. the cabinet furniture manufacturer. This resulted from greater process repeatability, easier standardization of product data, and the higher usefulness of such solutions as CAD/CAM, nesting, BOM, and OEE monitoring. The lowest initial level was observed in Case A, where the unit production character and greater order variability limited the economic justification for broader automation. This confirms earlier findings that a narrow or unstable product portfolio and uncertainty regarding return on investment hinder Industry 4.0 implementation in furniture SMEs. The study assumed a 12-month pilot implementation of Industry 4.0 and Quality 4.0 solutions, the core of which was not the full deployment of AI, but rather the integration of design and quality data, digital traceability, performance monitoring, and the digital circulation of nonconformity-related information. Such an approach is consistent with the Quality 4.0 literature, which emphasizes the use of data for faster root cause analysis, improved quality-related decision-making, and reduced subjectivity of control.

Table 2. Industry 4.0 and Quality 4.0 maturity level before and after pilot implementation

Case	Industry 4.0 maturity index (before)	Industry 4.0 maturity index (after)	Quality 4.0 maturity index (before)	Quality 4.0 maturity index (after)
A	0.27	0.44	0.22	0.41
B	0.41	0.61	0.34	0.58
C	0.36	0.52	0.29	0.47

Table 3. Changes in selected operational, quality, and material-related indicators before and after implementation

Case	OEE [%] before / after	Delivery timeliness [%] before / after	Complaints [% of orders] before / after	Material utilization [%] before / after	Root cause closure time [days] before / after	Digital traceability coverage [% of orders] before / after
A	51 / 60	72 / 83	4.9 / 3.3	67 / 74	4.8 / 2.6	18 / 63
B	58 / 69	78 / 90	4.1 / 2.2	71 / 80	4.1 / 1.9	25 / 78
C	55 / 62	75 / 84	4.6 / 3.1	76 / 82	5.2 / 3.1	21 / 65

The greatest improvement in indicators was observed in Case B, where ERP-CAD-CAM integration, automation of technological data preparation, and nesting resulted in an 11 percentage point increase in OEE, a 12 percentage point improvement in delivery timeliness, and an almost 50% reduction in complaints. In Case A, the improvement was mainly of a quality-organizational nature. The digital nonconformity register, basic material traceability, and CAD/CAM integration reduced the root cause closure time by 2.2 days and increased delivery timeliness by 11 percentage points, while the increase in OEE remained moderate. This indicates that in unit production enterprises, the benefits of Quality 4.0 appear earlier in the area of information transparency and quality management than in deep automation. In Case C, the weakest point remained processes with a high share of manual labor, typical of upholstered furniture manufacturing, which limited OEE growth despite improvements in complaint rate and traceability. This result is consistent with earlier observations that machine-manual workstations still dominate in furniture SMEs, while full robotization is constrained by both costs and process structure.

At the cross-case level, the largest increase was recorded in digital traceability coverage and root cause closure time. This means that Quality 4.0 in the analyzed cases functioned primarily as a mechanism for structuring quality, nonconformity, and complaint-related data, which is consistent with studies emphasizing the ranking and optimization of detection methods and inspection points in the Industry 4.0 environment [12]. The reduction in complaint rates and the improvement in material utilization additionally indicate that even limited 4.0 implementations may support environmental objectives and reduce losses. The structure of barriers strongly reflects earlier findings from both furniture-sector studies and general SME research. Financial constraints ranked first, followed by an outdated machinery park and a shortage of specialists in automation, robotics, and IT. On the enabler side, the strongest factors were management commitment, employee openness to acquiring new competencies, access to technology partners, and the organization of product and quality data. This is of particular importance, since Quality 4.0 does not initially require advanced AI, but rather stable data, traceability, and a coherent decision-making process. It is also worth emphasizing that the literature on SME cooperation indicates that resource sharing and knowledge exchange may reduce entry barriers, although the scale of such solutions is often limited by conflicts of interest, spatial constraints, and coordination difficulties.

Table 4. Barriers and enablers of Industry 4.0 and Quality 4.0 implementation in the surveyed enterprises

Implementation barriers	Mean significance (1-5)	Enablers	Mean significance (1-5)
Limited financial resources	4.8	Management commitment	4.7
Outdated and incompatible machinery park	4.6	Employee openness to training	4.4
Shortage of automation, IT, and data specialists	4.5	Cooperation with technology providers / external funding	4.4
Weak process integration and lack of pull logic	4.2	CAD/CAM integration and standardization of product data	4.3

Uncertain ROI under variable order structure	4.1	Digital nonconformity register and quality dashboards	4.2
Organizational resistance and concerns about the changing human role	3.9	Product modularity and standardization	3.8
Cybersecurity and data quality issues	3.2	Inter-organizational cooperation and knowledge sharing	3.6

4. CONCLUSION

A multiple case study indicates that the implementation of Industry 4.0 and Quality 4.0 in furniture SMEs should be viewed as a sequential process rather than a one-time technological leap. The starting point is usually not advanced AI, but the integration of design and production data, digital traceability, nonconformity recording, quality dashboards, and basic performance monitoring. In the analyzed cases, these solutions generated the greatest improvements in delivery timeliness, complaint rates, quality problem closure time, and material utilization. This is consistent with the literature, which shows that in the furniture industry the most promising solutions include CAD/CAM, BOM, G-code, and nesting automation, while in Quality 4.0 the key issue is faster and more accurate data-based decision-making.

At the same time, the results confirm that the main barriers remain financial constraints, outdated equipment, and a shortage of specialists. In enterprises with more repetitive production, transformation progresses faster because investments in integration and automation are easier to justify economically. In companies characterized by unit production and high order variability, greater importance is attached to solutions that organize data, support standardization, and shorten response time to nonconformities. This means that the implementation of Industry 4.0 and Quality 4.0 in the furniture industry should be adjusted to process logic, product portfolio, and absorptive capacity rather than directly transferred from large-scale manufacturing plants. From a practical perspective, the most rational path for furniture SMEs includes the digitalization of quality-related data, the implementation of simple traceability tools, CAD/CAM integration, employee competency development, and a gradual shift from final inspection to real-time quality management [13]. This, in turn, requires the widespread implementation of digital twins, the creation of which requires a combination of DoE [14] and machine learning [15] methodologies. Such a model strengthens not only operational efficiency but also sustainability through reduced material losses, fewer complaints, and improved process transparency. Since the literature on sustainability in the furniture industry remains fragmented, combining the Industry 4.0, Quality 4.0, and sustainability perspectives may be regarded as one of the most promising directions for further research.

REFERENCES

1. Fonseca, L.: Amaral, A.: Oliveira, J. (2021). Quality 4.0: The EFQM 2020 Model and Industry 4.0 Relationships and Implications. Sustainability, 13(6), 3107. DOI: 10.3390/su13063107
2. Nguyen, V.; Nguyen, H.; Hoang, T.; Nguyen, T.; Tran, N.; Vu, D. (2026): *Comparison of deep feature extraction for quality prediction in injection molding*. Production Engineering Archives 32 (1): pp. 96-102. DOI: 10.30657/pea.2026.32.8.
3. Siwiec, D.; Pacana, A. (2024): *Analysis of Companies' Approach to Sustainable Products Development: Quality, Environment, Society, Cost.* System Safety: Human - Technical Facility - Environment 6 (1): pp. 79-88. DOI: 10.2478/czoto-2024-0010.

4. Červený, L.: Sloup, R.: Červená, T.: Riedl, M.: Palátová, P. (2022). Industry 4.0 as an Opportunity and Challenge for the Furniture Industry-A Case Study. Sustainability, 14(20), 13325. https://doi.org/10.3390/su142013325
5. Ingaldi, M.; Ulewicz, R.: *A Digital Sustainability Maturity Framework for Assessing Industry 4.0 and ESG Integration*, Production Engineering Archives 2026, 32(2), 262-277. DOI: 10.30657/pea.2026.32.21
6. Suchacka, M.; Pabian, A.; Ulewicz, R. (2023): *Industry 4.0 and socio-economic evolution*. Polish Journal of Management Studies 28 (1): pp. 311-329. DOI: 10.17512/pjms.2023.28.1.18.
7. Malec, M.; Stańczak, L. (2025): *Human Capital for Industrial Innovation: Competence Development, Job Satisfaction and Entrepreneurship at a Mining Institute*. Production Engineering Archives 31(3): pp. 410-418. DOI: 10.30657/pea.2025.31.38
8. Ingaldi, M.; Ulewicz, R.; Klimecka-Tatar, D. (2023): *Creation of the university curriculum in the field of Industry 4.0 with the use of modern teaching instruments - Polish case study*. Procedia Computer Science 217: pp. 660-669. DOI: 10.1016/j.procs.2022.12.262.
9. Ingaldi, M., Ulewicz, R. (2026). A Digital Sustainability Maturity Framework for Assessing Industry 4.0 and ESG Integration. Production Engineering Archives, 32(2): pp.262–277. DOI: 10.30657/pea.2026.32.21.
10. Czerwińska, K.; Pacana, A. (2024): *Model of Human Resource Management in Manufacturing Companies Using Key Performance Indicators (KPIs)*. System Safety: Human - Technical Facility - Environment 6 (1): pp. 69-78. DOI: 10.2478/czoto-2024-0009.
11. Sousa, R.M.; Dinis-Carvalho, J.; Hines, P. (2026): *Value Stream Mapping: some Pragmatic Aspects.* Production Engineering Archives 32 (1). DOI: 10.30657/pea.2026.32.10.
12. Ulewicz, R.; Czerwińska, K.; Pacana, A. (2023). *A Rank Model of Casting Non-Conformity Detection Methods in the Context of Industry 4.0.* Materials, 16(2), 723. https://doi.org/10.3390/ma16020723
13. Rodrigues, T.; Sá, J.C.; Oliveira, A.R.; Hines, P.; Ulewicz, R.; Bonamigo, A. (2025): *Using the Lean-Based Safety Leadership Framework to Improve Operational Efficiency and Reduce Occupational Risk: Evidence from a Case Study*. System Safety: Human - Technical Facility - Environment 7 (1): pp. 108-117. DOI: 10.2478/czoto-2025-0011.
14. Pietraszek, J. (2012). *Fuzzy Regression Compared to Classical Experimental Design in the Case of Flywheel Assembly*. Artificial Intelligence and Soft Computing, Pt I, 7267: pp. 310-317. DOI: 10.1007/978-3-642-29347-4_36
15. Pietraszek, J. (2003): *Response surface methodology at irregular grids based on Voronoi scheme with neural network approximator*. Neural Networks and Soft Computing: pp. 250-255. DOI: 10.1007/978-3-7908-1902-1_35

Authors address:
Ulewicz, R.[1]
[1]Department of Production Engineering and Safety, Faculty of Management, Czestochowa University of Technology, Czestochowa, Poland
*Corresponding author: robert.ulewicz@pcz.pl

CHAPTER F
MARKETS, TRADE, MARKETING AND CONSUMER BEHAVIOUR

CULTURAL SPECIFICS AND THEIR INFLUENCE ON THE CREATION OF COMMUNICATION POLICY IN THE FURNITURE INDUSTRY

Miriam Olšiaková, Erika Loučanová, Martina Nosáľová

Abstract: Although the elements of the marketing mix are interconnected, communication policy is considered the most sensitive component to cultural differences, as it directly reflects the values, symbols, and meanings rooted in a particular culture. While furniture products can be standardized to a certain extent on a global scale, communication strategies must be culturally adapted to reflect local values, norms, and social expectations. Based on a comparative analysis and secondary data from various regions, this paper examines distinct ways in which furniture promotion is differentiated when considering the unique characteristics and cultural specifics of selected countries. For furniture companies to succeed in an international environment, it is necessary to modify the visual and textual elements of campaigns, which increases brand relevance and, consequently, consumers' purchase intent within a specific cultural context. Ultimately, a successful international strategy requires the sensitive adaptation of visual narratives to ensure that brand integrity is maintained while fully respecting local cultural identity.
Keywords: marketing communication, cultural differences, furniture industry, consumer behaviour

1. INTRODUCTION

In the modern furniture industry, companies operate in a very competitive environment characterized by constant changes in the market and shifting consumer preferences. To be able to create a solid competitive advantage and ensure a positive brand perception in a saturated market environment, furniture firms should implement appropriate marketing strategies based on the current market situation. Enterprises all over the world, especially those from the furniture industry, make use of various tools for marketing communication. Since communication channels keep on changing, companies always find new ways to communicate with their target audience (Loučanová et al., 2018).

As mentioned by practitioners, building a customer base and penetrating target segments require thorough research, detailed planning, and execution of marketing communication strategies (Lauridsen, 2021). In this regard, marketing communication plays a crucial role in connecting the goals of companies and behaviours of consumers. In the international furniture market, these communication strategies are affected by cultural factors which define the way in which advertising messages and product presentations are perceived by international audiences (Olšiaková, Loučanová, 2021).

Cultural characteristics are of crucial importance in determining communication strategies in the furniture sector due to their role in influencing consumers' perceptions, preferences, and purchase behaviour. Cultural specifics affect marketing communication through multiple aspects, including visual presentation of products, the depiction of family and individual lifestyles, use of symbolism and colours, perception of living space, and communication style. In accordance with Hofstede (2001), cultural values impact the perception of an individual in terms of their connection with other people, which is expressed in advertisement campaigns

focused on the promotion of either family orientated or individual lifestyles. Moreover, Hall (1976) states that different cultures have distinct communication styles: high-context cultures tend to use a larger proportion of non-verbal communication involving implicit messages and symbols, whereas low-context cultures rely on explicit and straightforward ways of communication. The significance of cultural values when developing marketing communication strategies is also stressed by De Mooij (2019), who emphasizes that consumers 'reactions to advertising content, colours, symbols, and messages of brands may differ in various cultural contexts. Additionally, cultural differences related to the perception of private and shared living spaces may also have some implications for the way in which furniture products and interiors are presented to target audiences.

With increasing internationalization of furniture firms, it is vital to consider these specifics while formulating appropriate communication strategies to address diverse consumers and increase brand competitiveness. Formulating the local marketing strategy, the furniture stores need to properly match their communication with the purchase behaviour and requirements of the domestic target audience (Loučanová et al., 2024). In the process of formulation of international communication policy, it is possible to use the positive image associated with the country where the particular brand originates. Thus, the country-of-origin is the critical element affecting both communication strategies and furniture brand perception in the foreign markets (Usunier, 2006; Rosembloom & Haefner, 2009). As Anholt (2007) emphasizes, the competitive reputation of the country can directly affect the competitiveness of the firm in the foreign markets. This relationship can be observed in the case of furniture sale in the consistent association of brand identity with the elements of Scandinavian culture.

Nevertheless, as White (2012) emphasizes, there is a need for additional studies that would address the topic of the influence of marketing strategies on the successful interaction of firms with cultural heritage in certain international markets; this allows discussing the issue of transformation of visual stories in greater detail. Complexity of the problem in question can be seen in historical examples of market entries, where the line separating cultural adaptation from fundamental brand values became ambiguous. An illustrative example of this challenge in the furniture industry is IKEA's visual adaptation for the Middle Eastern market.

1.1. The Tension Between Global Brand Identity and Local Cultural Norms

In 2012, the Swedish furniture company IKEA received worldwide criticism because it excluded women from several pictures in the Saudi Arabian version of the catalogue whereas the very same pictures in the Swedish and English versions contained women. In the Saudi version of the catalogue, published by one of the local franchises of the company, one can find the same pictures depicting family settings and lifestyles but without any women at all, like a picture showing a woman standing next to a child in a bedroom setting or a picture depicting five women eating. The structural differences between these localized communication strategies and the original international imagery are visually demonstrated in Figure 1.

IKEA made an official apology, admitting that "excluding women from the Saudi Arabian version of the catalogue is in conflict with the IKEA Group values" and promising to review their internal routines to avoid similar situations (Ritter, 2012; The Week, 2012). This incident demonstrates the difficulty of maintaining a common brand identity when confronted with local cultural norms since Saudi Arabia uses a very rigid interpretation of the Islamic Sharia Law which has always restricted the public presence of women even on magazine covers and TV screens. Although extreme cases of visual modifications are not common today, this example

serves as an effective demonstration of the importance of being culturally sensitive when doing marketing in the furniture industry, showing how cultural specificity may affect communication methods, especially those that involve visuals that represent family life. Current marketing techniques seek to find the balance between localization and maintaining the key values of the brand.

Figure 1. Visual modification of promotional material: Comparison of the original Swedish/English IKEA catalogue layout (left) and the altered Saudi Arabian version excluding the female figure (right)
Source: IKEA catalogue (Saudi Arabia version), reported by BBC

1.2. Strategic Adaptation of Visual Narratives in Diverse Global Markets

Apart from Saudi Arabia, IKEA has also adjusted its marketing strategy in response to cultural peculiarities of other nations. For instance, in China, the furniture company emphasizes small-scale multifunctional pieces in catalogues and in showrooms that would suit several generations of people who live together; advertising pictures include older relatives as per Confucian culture (Forbes, 2019). Indian advertisements feature images of multi-generational families, traditional domestic ceremonies and festivals like Diwali, as well as avoiding any clothing and postures that might be considered as inappropriate (Business Standard, 2018). In Japan, the images of small-scale minimalistic interior with single occupants – mainly young adults – dominate in advertising materials (Marketing Journal, 2020).

Even though the practice of removing women from advertising campaigns is not applied nowadays anymore, these examples prove that adaptation in accordance with cultural peculiarities should remain relevant in terms of brand values, inclusiveness and consumers' requirements.

1.3 Collectivism vs. Individualism in Visual Advertising: Family Paradigms

The cultural aspect of Individualism vs. Collectivism (Hofstede, 2001) acts as one of the key criteria for shaping up visual storyboards in furniture marketing. Individualistic Western societies value marketing visuals, which promote personal freedom, individual comfort, individuality, and atypical household composition (such as singles and childless couples). Furniture, in these cases, is positioned as an extension of personality.

At the same time, collectivist cultures of Asia (such as China and India), where the concept of the extended family prevails, require a completely different approach to marketing

communications, which should be focused on social integration, respect for parents and the family system in general. In other words, for Asians, home is not a place for oneself, but a place where relationships within the family are cultivated.

1.4 Pop-Culture Narratives as a Universal Tool for Multicultural Communication

In such heterogeneous markets, there arises a situation for cross-cultural marketing communication wherein different ethnic groups need to be addressed at once. One example of how the situation can be sorted out is the campaign known as "IKEA Real Life Series" run in the United Arab Emirates (UAE). Due to the overwhelming presence of immigrants and expatriates in the UAE demographic, it is impossible to resort to a single localized cultural narrative. Therefore, the cross-cultural marketing communication employed global icons of pop culture as a form of universal language.

The campaign centered on the idea of a family – conventional families, contemporary families, and "families by choice". Three living rooms taken from popular global television shows were chosen by IKEA, which were recreated with the help of 3D rendering along with products picked only from IKEA catalogue (Ads of the World, 2019).

Figure 2 demonstrates an excellent replication of one example of the living room from a popular television series within the mystery-thriller genre. This serves as a perfect representation of how the campaign utilized a pop-culture environment to create a universal domestic setting.

Figure 2. Universal appeal through pop-culture: Replicating a globally recognized television living space to target diverse expat demographics.
Source: IKEA & Publicis Spain (2019), via Ads of the World.

2. CROSS-CASE ANALYSIS AND STRATEGIC IMPLICATIONS

Analysing various international marketing campaigns conducted by furniture companies proves the point that visual storytelling is not only an aesthetical concept but also the culturally embedded message that influences consumer engagement. If a company decides to expand its operations across the globe, then there is a need for a balance between standardization and total localization of the furniture business. The examples discussed above demonstrate that culturally sensitive marketing in the furniture industry requires careful adaptation of visual communication to local cultural contexts while preserving a consistent brand identity.

According to the examples of Saudi Arabia, China, India, and Japan, the product should have the same appearance but the way it is presented within a certain socio-cultural context should be adapted to regional needs regarding the family structure and space limitations. Moreover, in the case of a culturally heterogeneous market, such as the UAE, using cross-cultural pop-culture symbols can help to achieve broad cultural appeal without offending any segment of consumers. Therefore, the effective use of cultural details in visual storytelling is more than just another marketing strategy; it is an essential element in building brand equity in the long run. The furniture companies need to consistently regard the visuals used in promotion as an essential form of communication which demands ongoing empirical investigation and adjustment.

3. CONCLUSION

The global growth of furniture companies is not possible without considering dynamic adaption of marketing mix components across national boundaries. Although it may be easy to reach certain consistency regarding the core products design and logistics of production process, communication policy must maintain flexibility regarding specific cultural environments of target countries. As is seen from the variety of different global strategies discussed in this paper, images of native lifestyle, functions of space and family organization become major objects of intercultural decoding for foreign customers.

Extremely exaggerated and excluding visual changes present a serious threat to brand globalization and CSR activities. The modern marketing strategy must involve more refined glocalization tactics. It means that competitive advantage of the country of brand origin should be used but the promotional story has to be carefully adapted according to specific cultural patterns of society.

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REFERENCES (alphabetical order)

1. ***: Ads of the World (2019): *IKEA Real Life*. URL: https://www.adsoftheworld.com/campaigns/ikea-real-life
2. ***: Business Standard (2018): *IKEA India Adapts Marketing to Local Culture.* URL: https://www.business-standard.com/article/companies/ikea-india-adapts-marketing-to-local-culture

3. ***: Forbes (2019): *How IKEA Adapts Its Stores for Chinese Consumers*. URL: https://www.forbes.com/sites/forbesagencycouncil/2019/05/20/how-ikea-adapts-its-stores-for-chinese-consumers/
4. ***: Marketing Journal (2020): *IKEA in Japan: Adapting Global Design to Local Taste*. URL: https://www.marketingjournal.jp/2020/07/ikea-japan-local-adaptation.html
5. ***: The Week (2012): *Why IKEA Is Erasing Women from Saudi Arabian Catalogs*. URL: https://theweek.com/articles/471878/why-ikea-erasing-women-from-saudi-arabian-catalog
6. Anholt, S. (2007): Competitive Identity. London: Palgrave Macmillan.
7. De Mooij, M. (2019): *Consumer Behavior and Culture: Consequences for Global Marketing and Advertising*. 3rd ed. Thousand Oaks: Sage Publications.
8. Hall, E. T. (1976): Beyond Culture. New York: Anchor Press.
9. Hofstede, G. (2001): *Culture's Consequences: Comparing Values, Behaviors, Institutions and Organizations Across Nations*. Thousand Oaks: Sage Publications.
10. Lauridsen, N. Ø. (2020): How to Build a Marketing Strategy for Furniture Businesses [2023 Edition]. URL: https://www.cadesignform.com/blog/furniture-marketing-strategy
11. Loučanová, E.; Olsiaková, M.; Dzian, M. (2018): *Suitability of Innovative Marketing Communication Forms in the Furniture Industry*. Acta Facultatis Xylologiae Zvolen 60 (1): pp. 159-171.
12. Loučanová, E.; Olsiaková, M.; Nosáľová, M. (2024): *Market Requirements and Innovative Perspectives in the Furniture Industry*. In: Proceedings of the 17th International Scientific Conference WOODEMA 2024 "Green Deal Initiatives, Sustainable Management, Market Demands, and New Production Perspectives in the Forestry-Based Sector". pp. 153-160.
13. Olšiaková, M.; Loučanová, E. (2021): *Practices of Innovative Marketing Communication Tools in Furniture Sector*. In: WoodEMA 2021: The Response of the Forest-Based Sector to Changes in the Global Economy. Proceedings of the 14th International Scientific Conference of the International Association for Economics and Management in Wood Processing and Furniture Manufacturing (WoodEMA). pp. 251-257.
14. Ritter, K. (2012): IKEA Deleted Women from Saudi Version of Catalogue. URL: https://www.cnbc.com/2012/10/01/ikea-deleted-women-from-saudi-version-of-catalogue.html
15. Rosenbloom, A.; Haefner, J. E. (2009): *Country of Origin Effect and Global Brand Trust: A First Look*. Journal of Global Marketing 22 (4): pp. 267-278.
16. Usunier, J. C. (2006): *Relevance in Business Research: The Case of Country-of-Origin Research in Marketing*. European Management Review 3 (1): pp. 60-73.
17. White, C. L. (2012): *Brands and National Image: An Exploration of Inverse Country-of-Origin Effect.* Place Branding and Public Diplomacy 8 (2): pp. 110-118.

Authors address:
Miriam Olšiaková[1*]; Erika Loučanová[1], Martina Nosáľová[1]
[1] Department of Marketing, Trade and World Forestry, Department of Marketing, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Masaryka 24, 960 01 Zvolen, Slovakia
[*]Corresponding author: olsiakova@tuzvo.sk

FROM SUSTAINABLE PRACTICES TO MARKET COMPETITIVENESS IN FURNITURE MANUFACTURING MSMEs: EVIDENCE FROM BULGARIA

Ivaylo Iliev

Abstract: The growing pressure for environmentally responsible production is transforming the competitive logic of the furniture industry, particularly for micro, small and medium-sized enterprises. In this context, sustainable practices should not be viewed solely as a response to ecological concerns or regulatory requirements, but also as a potential source of market competitiveness. The present paper examines how sustainability-oriented practices in furniture manufacturing can contribute to improved competitive positioning through resource efficiency, product differentiation, customer value creation and trust-building. The study focuses on the specific context of Bulgarian furniture manufacturing MSMEs, where limited resources, price sensitivity and uneven consumer awareness coexist with flexibility, adaptability and opportunities for niche positioning. The paper argues that sustainable practices generate competitive advantages only when they are strategically integrated into production processes, product characteristics and market communication. On this basis, the study outlines the main conditions under which sustainability can function as a practical and market-relevant strategic resource.
Keywords: sustainable practices; market competitiveness; furniture manufacturing; MSMEs; customer value

1. INTRODUCTION

Sustainability has become an increasingly important strategic issue in contemporary furniture manufacturing. In recent years, environmental responsibility has moved beyond the sphere of regulatory compliance and has begun to influence the market logic of the sector, including the ways in which firms organize production, position their products, and communicate value to customers. This tendency is especially relevant for micro, small and medium-sized enterprises, as they operate with more limited resources than large manufacturers, but often display higher flexibility and a greater capacity for adaptation in niche markets (Borga et al., 2009).

In the furniture industry, sustainable practices such as responsible sourcing, waste reduction, energy efficiency, and product durability are increasingly associated not only with environmental performance but also with opportunities for improved competitiveness. Their strategic relevance, however, should not be overstated or treated as automatic. Sustainable practices can contribute to lower operational costs, stronger product differentiation, and higher customer trust, but only when they are integrated into the broader logic of firm positioning and market communication. In this sense, sustainability should be examined not only as a production-related issue, but also as a market-oriented and managerial one (Dangelico & Vocalelli, 2017; Dimitrova, 2024).

This perspective is particularly important in the Bulgarian context. Existing research indicates that consumer interest in sustainability is present, yet willingness to pay more for

environmentally friendly furniture remains limited, while knowledge of eco-certifications is uneven. This suggests that sustainable practices alone are not sufficient to secure market advantage unless they are accompanied by visible product value and credible communication (Ilieva, 2025). At the firm level, this challenge is further shaped by the specific characteristics of furniture MSMEs, whose competitiveness depends on flexibility, quality, customization, and managerial capacity for long-term orientation and adaptation (Iliev, 2024; Gatzova, 2021).

Against this background, the present paper examines how sustainable practices can be transformed into market competitiveness in furniture manufacturing MSMEs in Bulgaria. The paper argues that sustainability creates competitive potential only when it is strategically embedded in production efficiency, product value, and trustworthy market communication.

Methodologically, the paper is conceptual in nature and draws on a naarrative, integrative review of the relevant international and Bulgarian literature. The Bulgarian evidence discussed below is therefore not based on new primary data, but on the secondary analysis and interpretation of existing empirical findings, which are used to ground the argument in the specific conditions of the national market.

2. SUSTAINABLE PRACTICES AS A SOURCE OF MARKET COMPETITIVENESS

2.1. Resource efficiency and cost rationalization

For furniture manufacturing MSMEs, one of the most direct ways in which sustainable practices contribute to market competitiveness is through improved resource efficiency. In smaller firms, where financial reserves are limited and production margins are often tight, the reduction of material losses, excessive energy use, and avoidable waste has immediate strategic importance. In this sense, sustainability should not be interpreted only as an environmental orientation, but also as a practical logic of operational discipline. Earlier research on small furniture enterprises has shown that sustainability in such firms is most meaningful when it is linked to concrete managerial and production practices rather than to formal commitment alone (Borga et al., 2009; Iliev, 2025).

From this perspective, better material planning, more precise cutting, lower defect rates, reuse of residual materials, and basic energy management measures can improve the cost structure of furniture MSMEs without requiring a radical transformation of the business model. Their importance becomes even greater in markets where customers remain highly sensitive to price and are reluctant to reward sustainability with a significant premium. Under such conditions, sustainable practices create competitive value primarily when they help firms protect margins, offer more stable pricing, or improve the value-to-price ratio of the final product (Ilieva, 2025). Even relatively simple energy management routines have been associated with measurable efficiency gains in industrial settings, which is particularly relevant for smaller manufacturers seeking incremental but economically meaningful improvements (Thollander & Ottosson, 2010). For furniture MSMEs, therefore, sustainability begins as an internal efficiency mechanism before it becomes an external market message.

2.2. Product differentiation and customer value creation

Sustainable practices contribute to market competitiveness when they enhance the customer value of the product rather than remain only part of the internal production logic. In the furniture sector, this effect is strongest when sustainability is embedded in attributes that

customers already associate with rational purchase decisions, such as durability, material quality, safety, reliability, and long-term usability. The broader literature on green marketing shows that environmental characteristics create market value only when they are translated into clear and credible customer benefits, not when they are communicated as abstract moral claims alone (Dangelico & Vocalelli, 2017). At the same time, research on sustainable consumption has repeatedly demonstrated that environmental concern does not automatically lead to sustainable purchasing behaviour, because price, quality, and functionality continue to dominate many buying decisions (Young et al., 2010).

This logic is highly relevant to furniture manufacturing MSMEs. Their competitive potential does not usually stem from scale, but from specialization, flexibility, and the ability to present a more distinctive product offer. In this context, sustainability can support differentiation when it is tied to visible product advantages, including product longevity, better material transparency, lower maintenance needs, and credible proof of responsible production. Bulgarian evidence supports this interpretation. Ilieva's study shows that customers do pay attention to material choice, but most are not willing to pay a substantial premium for environmentally friendly furniture, which means that sustainability is unlikely to function as a differentiator if it is communicated only through general "green" positioning. It becomes more commercially relevant when supported by understandable value arguments and by credible signals such as certifications and labels, whose influence on consumer behaviour has also been confirmed in international research (Ilieva, 2025; Testa et al., 2015).

2.3. Trust, positioning and sustainability communication

Sustainable practices do not create market competitiveness through declaration alone. Their competitive value depends on whether they are communicated in a way that is specific, credible, and consistent with the actual production behaviour of the firm. In the broader literature, this issue is closely linked to the problem of greenwashing. When environmental claims are exaggerated, vague, or weakly substantiated, they do not simply fail to create value; they can also undermine trust in both the firm and the wider market for sustainable products. For that reason, sustainability communication should be understood as a strategic component of competitiveness rather than as a purely promotional activity (Delmas & Burbano, 2011; Lyon & Montgomery, 2015; Dimitrova, 2024).

This argument is especially relevant for furniture manufacturing MSMEs. Their market positioning often relies on closer customer relationships, customization, and reputational signals that are more fragile than those of large corporations. In such a context, credible sustainability communication can strengthen differentiation only when it is supported by visible product attributes, transparent information about materials and production, and a consistent long-term message. Otherwise, sustainability risks remaining a symbolic label with limited market effect. Dimitrova's discussion of the boundary between authentic green marketing and greenwashing is useful here because it reinforces the idea that sustainability becomes strategically valuable only when communication reflects real organizational commitment rather than opportunistic positioning. Thus, for smaller furniture firms, trust is not an accompanying effect of sustainability communication, but one of the central conditions under which sustainability can function as a source of market competitiveness (Dimitrova, 2024; Delmas & Burbano, 2011).

3. EVIDENCE FROM BULGARIA: OPPORTUNITIES AND LIMITATIONS FOR FURNITURE MANUFACTURING MSMES

The Bulgarian context confirms that the market value of sustainability in furniture manufacturing MSMEs depends less on abstract environmental positioning and more on the firm's ability to connect sustainability with efficiency, product value, and credibility. This interpretation is consistent with the broader literature. Porter and van der Linde argue that environmental improvements can support competitiveness when they stimulate innovation and resource productivity, while Hart's natural-resource-based view suggests that environmental capabilities may become a source of strategic advantage when they are embedded in the firm's long-term development logic (Porter & van der Linde, 1995; Hart, 1995). In a similar vein, Ambec and Lanoie show that environmental practices contribute economically when they create either cost reductions or revenue-related benefits such as differentiation and market access (Ambec & Lanoie, 2008).

In Bulgaria, however, these mechanisms operate under the conditions of a price-sensitive market and resource-constrained smaller firms. Although based on a single national study, Ilieva's findings indicate that customer awareness of sustainability exists, but willingness to pay more for environmentally friendly furniture remains limited, which means that sustainability is unlikely to function as a strong competitive factor on symbolic grounds alone. For Bulgarian furniture MSMEs, its market relevance is more likely to emerge when it improves the value-to-price ratio of the product and is supported by credible communication rather than generic green claims (Ilieva, 2025; Delmas & Burbano, 2011).

Another important consideration is that Bulgarian furniture manufacturing MSMEs often operate in market segments where flexibility and direct contact with customers can compensate for their limited scale. This creates favourable conditions for sustainability to function not as a mass-market signal, but as a niche-oriented competitive factor. In smaller production settings, firms may more easily align material choices, design solutions, and communication practices with specific customer expectations, especially in customized and higher-involvement purchases. Under such conditions, sustainability is more likely to support competitiveness when it is integrated into a coherent offer built around reliability, product longevity, and transparent value communication.

Taken together, these characteristics suggest that in the Bulgarian context sustainability can support the competitiveness of furniture manufacturing MSMEs only when it is translated into practical business value. This means that environmental practices are unlikely to generate market advantage if they remain detached from cost efficiency, product quality, and credible communication. Their competitive relevance emerges when firms are able to connect internal operational improvements with visible customer benefits and trustworthy market positioning. Under such conditions, sustainability functions not as a symbolic attribute, but as a strategic resource that can strengthen the long-term market viability of smaller furniture manufacturers.

4. CONCLUSION

The paper supports the view that sustainable practices can strengthen the market competitiveness of furniture manufacturing MSMEs, but not in an automatic or purely symbolic way. Their strategic value emerges when they improve resource efficiency, enhance product value, and are communicated through credible market signals. In this sense, sustainability becomes economically relevant not simply as an environmental commitment, but as a practical

mechanism for differentiation, trust-building, and long-term market positioning. This interpretation is consistent with the broader literature, which links environmental practices to competitiveness through innovation, productivity, and market advantage, while also warning that weakly substantiated green claims can undermine rather than support competitive performance.

In the Bulgarian context, this logic appears particularly important for smaller furniture firms operating in a price-sensitive environment. Since customer willingness to pay a premium for environmentally friendly furniture remains limited, the competitive relevance of sustainability depends on whether firms can embed it in tangible product and process benefits rather than rely on general environmental positioning alone. For Bulgarian furniture manufacturing MSMEs, sustainability is therefore most likely to function as a strategic resource when it is linked to value-for-money, product reliability, and trustworthy communication.

From a managerial perspective, this implies that sustainability should be treated not as an isolated environmental initiative, but as a long-term business capability embedded in operations, product development, and market communication.

The conceptual nature of the study and its reliance on a limited body of Bulgarian empirical evidence constrain the generalisability of the conclusions. Future research should test the proposed relationships using primary data from furniture manufacturers and customers and examine whether sustainability practices translate into measurable improvements in costs, differentiation, and firm performance.

REFERENCES

1. Ambec S., Lanoie P. (2008). Does It Pay to Be Green? A Systematic Overview. Academy of Management Perspectives, 22 (4): 45-62.
2. Borga F., Citterio A., Noci G., Pizzurno E. (2009). Sustainability report in small enterprises: case studies in Italian furniture companies. Business Strategy and the Environment, 18 (3): 162-176.
3. Dangelico R. M., Vocalelli D. (2017). Green Marketing: An analysis of definitions, strategy steps, and tools through a systematic review of the literature. Journal of Cleaner Production, 165: 1263-1279.
4. Delmas M. A., Burbano V. C. (2011). The Drivers of Greenwashing. California Management Review, 54 (1): 64-87.
5. Dimitrova R. (2024). Avtentichni marketingovi praktiki – liniyata mezhdu zelen marketing i grinuoshing [Authentic marketing practices – the line between green marketing and greenwashing]. Upravlenie v biznesa i publichniya sektor [Management in Business and Public Sector].
6. Gatzova V. (2021). Savremenniyat lider. Vremeva perspektiva i upravlenski stil [The modern leader. Time perspective and management style]. Sofia: Izdatelstvo “Sv. Grigoriy Bogoslov”.
7. Hart S. L. (1995). A Natural-Resource-Based View of the Firm. Academy of Management Review, 20 (4): 986-1014.
8. Ilieva G. (2025). Sustainability Preferences of Customers and Their Impact on Purchasing Furniture. In Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA 2025: 389-394.

9. Iliev I. (2024). Scaling Furniture Manufacturing Micro Companies into SMEs. In Green Deal Initiatives, Sustainable Management, Market Demands, and New Production Perspectives in the Forestry-Based Sector. Proceedings of Scientific Papers, 17th International Scientific Conference WoodEMA 2024: 51-56.
10. Iliev I. (2025). Sustainable Practices in the Furniture Manufacturing Process for Micro, Small and Medium-Sized Enterprises (MSMEs). In Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA 2025: 127-132.
11. Lyon T. P., Montgomery A. W. (2015). The Means and End of Greenwash. Organization & Environment, 28 (2): 223-249.
12. Porter M. E., van der Linde C. (1995). Green and Competitive: Ending the Stalemate. Harvard Business Review, 73 (5): 120-134.
13. Testa F., Iraldo F., Vaccari A., Ferrari E. (2015). Why Eco-labels can be effective marketing tools: Evidence from a study on Italian consumers. Business Strategy and the Environment, 24 (4): 252-265.
14. Thollander P., Ottosson M. (2010). Energy management practices in Swedish energy-intensive industries. Journal of Cleaner Production, 18 (12): 1125-1133.
15. Young W., Hwang K., McDonald S., Oates C. J. (2010). Sustainable consumption: Green consumer behaviour when purchasing products. Sustainable Development, 18 (1): 20-31.

Authors address:
Iliev, Ivaylo, PhD, Associate Professor at Marketing & Management Department, University of Insurance and Finance (UIF), 1 Gusla Street, 1618 Sofia, Bulgaria
*Corresponding author: i.iliev@uzf.bg

CONSUMER ATTITUDES TOWARD THE REUSE OF WOOD

Silvia Lorincová, Mária Osvaldová, and Marek Potkány

Abstract: In the context of increasing emphasis on the circular economy and sustainable consumption, the study of consumer attitudes towards product reuse is becoming increasingly important. The aim of the research is to determine the extent to which respondents perceive wood products as intended for single use only, without the possibility of reuse, and to identify whether this perception differs according to respondents' gender, age, and level of education. Data collected through an electronic questionnaire from 1,446 respondents were analysed using descriptive statistics and the Kruskal–Wallis test. Where statistically significant differences were identified, post hoc comparisons with Bonferroni correction were applied. The results showed statistically significant differences according to respondents' gender and age, while no statistically significant differences were confirmed for education. Further research could therefore include a broader range of attitudinal, economic, and behavioural variables. The findings may be applied in practice by companies in the wood-processing sector when developing marketing communication, informing customers, and supporting the principles of the circular economy.
Keywords: circular economy, recycling, wood, consumer attitudes, Kruskal–Wallis test

1. INTRODUCTION

The implementation of circular economy principles, particularly reduction, reuse, recycling, and recovery, contributes to reducing waste generation, limiting the extraction of primary resources, and lowering environmental impacts (Shah et al., 2025; Balsalobre-Lorente et al., 2024). Within these principles, wood recycling and reuse represent important mechanisms for closing material flows and supporting more sustainable use of wood resources (Garcia et al., 2024; Ghobadi and Sepasgozar, 2023; Forster et al., 2023). However, the transition to a circular economy requires not only technological and policy changes, but also changes in consumer behaviour and purchasing decisions (Knickmeyer, 2020; Barčić et al., 2021).

Previous research shows that consumers generally perceive wood and reused wood products positively, especially when their environmental and aesthetic benefits are clearly communicated (Viholainen et al., 2020). Acceptance of reused or recycled products is influenced by environmental awareness, knowledge of circular economy principles, trust, perceived quality, and consumer values (Masud et al., 2025; Sabbir, 2025). Demographic characteristics may also play a role. Earlier studies indicate differences in recycling behaviour and green purchasing according to gender, age, and education (Witek and Kuźniar, 2021; Chirilli et al., 2022). Nevertheless, the extent to which these factors influence attitudes toward the reuse of wood products requires further examination.

The aim of the research is to determine the extent to which respondents perceive wood products as intended for single use only, without the possibility of reuse, and to identify whether this perception differs according to respondents' gender, age, and level of education.

2. METHODOLOGY

The research on recycling behaviour focused on identifying consumer attitudes towards the reuse of wood. Data were collected in 2025 through an electronic questionnaire distributed via e-mail, social networks, and institutional websites. The research sample consisted of 1,446 respondents, of whom 46.96% were men and 53.04% were women. The largest age group was represented by respondents under 30 years of age (51.59%), and respondents with higher secondary education predominated in the educational structure (57.61%). The following hypotheses were tested: (H0a/H1a) perceptions of wood products as intended for single use only, without the possibility of reuse, do not/do differ significantly by gender; (H0b/H1b) perceptions do not/do differ significantly by age; and (H0c/H1c) perceptions do not/do differ significantly by education level.

Differences between groups were verified using the Kruskal–Wallis test, as the dependent variable was ordinal and measured on a five-point Likert scale. Respondents' answers were compared according to gender, age, and level of education. When statistically significant differences were found, post hoc comparisons with Bonferroni correction were applied. Effect size was assessed using epsilon squared (ε^2), and the level of statistical significance was set at $\alpha = 0.05$.

3. RESULTS

Before verifying differences between individual groups of respondents, a descriptive evaluation of answers to the analysed attitudinal item was carried out using a five-point Likert scale, where 1 indicated complete disagreement and 5 indicated complete agreement. Of the total number of 1,446 respondents, the most frequent answer was 1 (39.56%), followed by 2 (24.90%) and 3 (22.13%). Responses 1 and 2 together represented 64.46%, which indicates that most respondents did not identify with the statement that wood products are intended exclusively for single use, without the possibility of reuse. By contrast, responses 4 and 5 were reported by 13.42% of respondents. The mean response value was M = 2.15 (SD = 1.18), the median was Me = 2, and the interquartile range was 1–3.

Descriptive indicators by gender, age, and level of education are presented in Table 1. In all analysed groups, the median response was 2 and the interquartile range was 1–3, indicating a generally low level of agreement with the analysed statement. Differences between groups were therefore mainly reflected in mean values and mean ranks. Men reached a higher mean value and mean rank than women, while in terms of age, both indicators gradually increased with respondents' age. The highest values were recorded among respondents aged 60 years and over. In the case of education, the differences were less clear, with the highest values recorded among respondents with lower secondary education and the lowest among respondents with university education.

Table 1. Descriptive indicators by gender, age, and level of education

Factor		Category	n	Mean	Median	Q1–Q3
Gender	Women	767	2.05	2	1–3	694.17
	Men	679	2.25	2	1–3	756.63
Age	Up to 30 years	746	2.02	2	1–3	685.75
	31–44 years	318	2.16	2	1–3	721.82

	45–59 years	263	2.33	2	1–3	784.05
	60 years and over	119	2.50	2	1–3	830.81
Education	Primary education	96	2.23	2	1–3	764.46
	Lower secondary education	143	2.36	2	1–3	787.84
	Higher secondary education	833	2.14	2	1–3	720.05
	University education	374	2.06	2	1–3	696.06

The results of the Kruskal–Wallis test, which was used to verify differences in respondents' answers according to gender, age, and level of education, are presented in Table 2. The Kruskal–Wallis test showed statistically significant differences according to respondents' gender, $H(1, N = 1,446) = 8.841631$; $p = 0.0029$; $\varepsilon^2 = 0.005$, as well as according to age, $H(3, N = 1,446) = 21.38972$; $p = 0.0001$; $\varepsilon^2 = 0.013$. Men achieved a higher mean rank than women, indicating a slightly higher level of agreement with the perception of wood products as products intended exclusively for single use, without the possibility of reuse. In terms of age, the mean rank increased with respondents' age, with the lowest values recorded among respondents under 30 years of age and the highest among respondents aged 60 years and over. In the case of level of education, no statistically significant difference was confirmed, $H(3, N = 1,446) = 6.574133$; $p = 0.0868$; $\varepsilon^2 = 0.002$. The ε^2 values also indicate a very low practical effect size; therefore, the identified differences should be interpreted as statistically significant but substantively weak.

Table 2. Results of the Kruskal–Wallis test by gender, age, and education

Factor	N	H	df	p	ε^2	Conclusion
Gender	1,446	8.841631	1	0.0029	0.005	significant difference
Age	1,446	21.38972	3	0.0001	0.013	significant difference
Education	1,446	6.574133	3	0.0868	0.002	difference not confirmed

Since the Kruskal–Wallis test showed a statistically significant difference according to respondents' age, post hoc comparisons of age groups with Bonferroni correction were subsequently performed. The results of these comparisons are presented in Table 3.

Table 3. Post hoc comparisons of age groups with Bonferroni correction

Comparison of age groups	|z|	p after correction	Result
31–44 years vs. up to 30 years	1.289675	1.000000	not significant
31–44 years vs. 45–59 years	1.787985	0.442671	not significant
31–44 years vs. 60 years and over	2.428820	0.090888	not significant
Up to 30 years vs. 45–59 years	3.282477	0.006174	significant
Up to 30 years vs. 60 years and over	3.519127	0.002598	significant
45–59 years vs. 60 years and over	1.013582	1.000000	not significant

Post hoc comparisons showed statistically significant differences between respondents under 30 years of age and respondents aged 45–59 years ($p = 0.006174$), as well as between respondents under 30 years of age and respondents aged 60 years and over ($p = 0.002598$). The other comparisons between age groups were not statistically significant. The results

indicate that differences in attitudes were concentrated mainly between the youngest age group and older respondents, with older respondents perceiving wood products as single-use products to a greater extent.

Based on the results, it can be stated that hypotheses H1a and H1b were accepted, as the differences according to gender and age were statistically significant. Hypothesis H1c was rejected, as statistically significant differences according to level of education were not confirmed. At the same time, it should be emphasised that the effect size values were low for all analysed factors. Therefore, the statistical significance of the results indicates the existence of differences between groups; however, their practical significance is limited.

4. DISCUSSION

The research results showed that respondents generally did not perceive wood products as products intended exclusively for single use, without the possibility of reuse. This finding provides a favourable basis for supporting the reuse, repair, renovation, and material recovery of wood products. The results are consistent with recent research emphasising the importance of the circular use of wood in reducing environmental burden. Forster et al. (2023) point to the role of cascading wood use in decarbonisation, while Garcia et al. (2024) highlight the importance of recycling post-consumer wood in the wood industry. Similarly, Ghobadi and Sepasgozar (2023) emphasise that the circular use of wood requires the integration of design, processing, waste collection, and material recovery. Since the environmental benefits of the circular economy have also been confirmed by Shah et al. (2025) and Balsalobre-Lorente et al. (2024), it can be considered positive that respondents in this research predominantly did not accept the perception of wood products as single-use products.

The difference according to gender was statistically significant, with men achieving a higher mean rank than women. This means that men perceived wood products as products intended for single use to a greater extent. However, the effect size was very small, indicating only limited practical importance of the observed difference. This result is consistent with research pointing to gender differences in environmental attitudes and recycling behaviour, although such differences are also influenced by knowledge, trust, social norms, and the type of product being evaluated (Chang et al., 2025). A significant difference was also confirmed according to age. The mean rank increased with respondents' age, and post hoc comparisons showed differences mainly between the youngest group and respondents aged 45–59 years and 60 years and over. Younger respondents may be more exposed to the discourse on sustainability and the circular economy, which may support their openness to product reuse. Similar conclusions appear in research focused on Generations Y and Z, sustainable consumption, and circular behaviour (Henao-Hincapié et al., 2024). At the same time, however, these studies point out that a positive attitude does not necessarily lead to actual behaviour. The identified trend suggests that younger generations may perceive the principles of sustainability and the circular economy more naturally than older respondents. By contrast, no difference according to level of education was confirmed. This result partly differs from research that associates education with higher environmental awareness and knowledge of the circular economy (Henao-Hincapié et al., 2024). A possible explanation is that the analysed variable was based on a single Likert item. Thus, education may not be directly reflected in the response to a simple attitudinal item, but rather in more complex aspects of consumer decision-making, such as environmental values, knowledge of the material cycle, trust in recycled products,

perceived quality, or willingness to pay for a more environmentally friendly product (Masud et al., 2025).

From a theoretical perspective, the research contributes to knowledge on the circular use of wood by linking wood product reuse with consumer attitudes. While much of the literature focuses on technological and material solutions, the results show that the acceptance of circular principles also depends on how consumers understand product lifetime, repairability, and further use. At the same time, the small effect sizes indicate that demographic variables have only limited explanatory power. Future models should therefore combine demographic characteristics with psychological and contextual factors, such as trust, perceived behavioural control, quality, price, product transparency, and knowledge of circular principles (Masud et al., 2025). From a practical perspective, the results highlight the need for clear communication about wood reuse. Companies should emphasise environmental benefits, product lifetime, repairability, quality, and safety. Communication for older consumers should explain how the product life cycle can be extended, while communication for younger groups may focus on circularity and responsible consumption. Sabbir (2025) confirms the importance of perceived quality and furniture lifetime, while Chang et al. (2025) emphasise trust, transparency, and appropriate communication. Several limitations should be considered. The research was based on declared attitudes and a single Likert item, which may not fully reflect actual behaviour or the complexity of wood reuse perceptions. Due to the cross-sectional design, causal conclusions cannot be drawn. Although gender and age differences were statistically significant, their practical importance was limited by small effect sizes. Further research should include multi-item scales and variables such as environmental awareness, circular economy knowledge, trust, perceived quality, willingness to pay, and actual repair, renovation, or recycling behaviour.

5. CONCLUSION

The research results indicate that respondents generally do not perceive wood products as products intended exclusively for single use, without the possibility of reuse. Most respondents rather did not identify with the analysed attitude, which indicates positive potential for supporting the principles of the circular economy in the field of wood products. The statistical analysis showed significant differences in attitudes according to respondents' gender and age. Men showed a slightly higher level of agreement with the perception of wood products as single-use products compared with women. A more pronounced difference was recorded according to age, with older respondents showing a higher level of agreement than younger respondents. In the case of level of education, no statistically significant difference was confirmed. However, given the low effect size values, the identified differences should be interpreted with caution. From a practical perspective, the results highlight the need for targeted communication aimed at explaining the possibilities of reuse, repair, and recycling of wood products. Particular attention should be paid to consumer groups that may have a lower level of awareness of the circular use of wood. Supporting awareness and trust in reused wood products may contribute to the more effective application of circular economy principles in the wood-processing sector.

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REFERENCES

1. Balsalobre-Lorente, D.; Shah, S.; Huseynova, R. (2024): *Do Circular Economy, Public-Private Partnership and Carbon Policy Manage the Environmental Stress? Developed countries' situation under the Prism of COP27.* Heliyon 10 (13): e33532.
2. Barčić, A.; Kuzman, M.; Vergot, T.; Grošelj, P. (2021): *Monitoring Consumer Purchasing Behavior for Wood Furniture before and during the COVID-19 Pandemic.* Forests 12 (7).
3. Chang, K.; Qu, R.; Bititci, U.; Xuan, J.; Xu, B. (2025): *Consumer Perception and Adoption of a Circular Chemical Economy.* Cleaner and Responsible Consumption 17: 100283.
4. Chirilli, C.; Molino, M.; Torri, L. (2022): *Consumers' Awareness, Behavior and Expectations for Food Packaging Environmental Sustainability.* Foods 11 (16): 2388.
5. Forster, E.J.; Healey, J.R.; Newman, G.; Styles, D. (2023): *Circular Wood Use Can Accelerate Global Decarbonisation but Requires Cross-Sectoral Coordination.* Nature Communications 14: 6766.
6. Garcia, R.; Calvez, I.; Koubaa, A.; Landry, V.; Cloutier, A. (2024): *Sustainability, Circularity, and Innovation in Wood-based Panel Manufacturing in the 2020s: Opportunities and Challenges.* Current Forestry Reports 10: pp. 420-441.
7. Ghobadi, M.; Sepasgozar, S.M.E. (2023): *Circular Economy Strategies in Modern Timber Construction.* Sustainable Materials and Technologies 77: 107229.
8. Henao-Hincapié, L.J.; Leyes, M.; Loeber-Vizcaíno, G.E.; Cruz-Pérez, A.; Romero-Perdomo, F.; González-Curbelo, M.Á. (2024): *Assessing Consumer Knowledge, Attitudes, and Adoption of Circular Economy Practices in Colombia.* Sustainable Production and Consumption 46: 256-267.
9. Knickmeyer, D. (2020): Social *Factors Influencing Household Waste Separation.* Journal of Cleaner Production 245: 118605.
10. Masud, M.; Islam, A.; Sultana, S.; Akhtar, R.; Noman, A.; Al-Mamun, A. (2025): *Understanding Malaysian Consumers' Intentions to Purchase Recycled Products.* Environmental Research Communications 7: 085021.
11. Sabbir, M. (2025): *Product Feature and Lifespan as a Quality Indicator for Inducing Eco-friendly Furniture Purchase.* Heliyon 11 (3): e42422.
12. Shah, S.; Abbas, N.; Serbanescu, L.; Niu, R.; Nassani, A. (2025): *The Key Challenges and Best Alternatives to Environmental Sustainability.* Scientific Reports 15: 7042.
13. Viholainen, N.; Kylkilahti, E.; Autio, M.; Toppinen, A. (2020): *A Home Made of Wood*. International Journal of Consumer Studies 44 (6): pp. 542-551.
14. Witek, L.; Kuźniar, W. (2021): *Green Purchase Behavior: The Effectiveness of Sociodemographic Variables for Explaining Green Purchases in Emerging Market.* Sustainability 13 (1): 209.

Authors address:
Lorincová, S.; Osvaldová, M.; Potkány, M.
Department of Economics, Management and Business, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia
*Corresponding author: potkany@tuzvo.sk

AGENDA-SETTING IN MARKETING COMMUNICATION

Daniela Kollárová, Magdaléna Ungerová

Abstract: IKEA, the market leader in the production and sale of furniture, sets one main topic in marketing communication every twelve months, which is later disintegrated into six smaller activities over the course of the months, explaining how the offered solutions create a better everyday life for as many people as possible. In recent years, these have included, for instance, cooking and dining in the comfort of home, ideas for getting a better sleep, furniture reuse, mental well-being, gender equality, or a sustainable future. We focus our attention on the issues related to a sustainable posterity and the repeated utilization of household properties. We also analyze the reasons leading to the selection of the themes, the tools, and media outlets of marketing communication applied to introduce them to consumers. In conclusions, we endeavour to compile a marketing communication model suitable for furniture manufacturers and sellers to raise the issues.
Keywords: marketing communication, agenda-setting, furniture

1. SCIENTIFIC LITERATURE REVIEW

To communicate, in the context of the marketing concept, means, on the one side, to inform, to get acquainted with the products, to explain their features, to highlight their benefits, quality, value, usefulness and usage, on the other side, to listen, to accept incentives, and to respond to consumer suggestions and demands. The general goal of marketing communication is to have an impact on the behaviour of target groups (Labská et al, 2014). In order to have an influence on the consumer conduct, various types of tools and media are put to use that disseminate messages based on rational, emotional, or moral contents. It is exactly these communications that inform target audiences about the reasons they should pay attention to a product or an idea, what makes them specific, beneficial, or valuable. Thus, companies prioritize certain topics over others through marketing communication, i.e., they set the agenda. This concept operates on two levels: first, through the selection of issues for discussion and second, through the framing of these themes by emphasizing specific facts and downplaying others (Agenda-Setting theory, n.d.). In this way, they have an impact on which criteria customers will consider as the most important when making decisions. For setting the agenda, with the aim to achieve the highest possible frequency of displaying the desired themes, the enterprises choose dominant opinion-forming media (Višňovský & Baláž, 2012), in Slovakia, these include, for example, the TV channel Markíza, the daily DenníkN, or the news portal aktuality.sk. In addition to setting the agenda, the media also offer frames, i.e., their own interpretations of the presented information, which not only leads to the preference of specific issues among the target groups, but also to influencing their attitudes and opinions on the given topics, and to the adopting the offered frames.

2. METHODOLOGY

The objects of the study are the news releases of the company IKEA, a multinational market leader in the production and sale of furniture. Our research focuses on identifying the topics raised by the investigated object in marketing communication by means of press releases distributed through dominant types of media outlets. We have examined 204 news releases issued in the period from 2019 to 2025 inclusive, available on the website ikea.com/sk in the section called Press Centre. We have directed our attention to identifying press releases on long-term campaigns and their partial activities setting issues for a period of 12 months. In total, there were 27 such news releases, while focusing the content analysis on identifying the raised topics, the selection of tools and media outlets for marketing communication. The overview of the scholarly bibliography has been compiled from available scientific and professional sources discussing the marketing communication and agenda-setting. Based on the results of the analysis, we have identified and summarized the tools and media suitable for marketing communication of furniture manufacturers and retailers when setting the topics. See Table 1.

3. RESULTS

Company IKEA, the multinational market leader in the production and sale of furniture, raises one main global topic in its marketing communication once every twelve months, which is later disintegrated into smaller activities over the months, explaining how the offered solutions create a space for a better ordinary life for as many people as possible. Table 1 shows a survey of the issues set in the period from 2019 to 2025.

Table 1. Overview of topics and media

Year	Topic	Marketing communication and media
2019	Second life of furniture	Spots broadcast on TV, in the cinemas and on YouTube. Formats of outdoor advertising. Contents on social media. PR on LinkedIn. Cooperation with influencers. News releases on sitelinks of IKEA.
2020	Supporting communities	
2021	For a safe home	
2022	For mental well-being	
2023	Furniture that changes with you	
2024	You can live fully even when resting	
2025	A better life starts in the kitchen	

In Slovakia, the campaign with the set issue usually lasts from August of the corresponding calendar year for the following 12 months. Over the course of the months, by means of storytelling and attractive product prices, IKEA focuses on six partial activities linked to the main theme, which, although they mention the practical function of the products, primarily support the IKEA brand as a trademark that understands the essence of the home. The main issue is usually global, but individual countries can adapt it to their local needs. It reflects global social themes (e.g., aging populations, availability of smaller flats, rising energy prices, environmental issues, or remote working) and the results of the research study The IKEA Life at Home Report, which has been mapping the global trends, habits, needs, and emotions associated with housing and lives in households around the world since 2014. More information

can be found at https://lifeathome.ikea.com/. The timing may seem illogical, but IKEA follows the fiscal year. The new trade year, to which new products and marketing campaigns for IKEA in Slovakia are bound, lasts from September 1 to August 31.

In line with its commitment to be even more environmentally friendly, IKEA Bratislava launched a program called "Second Life for Furniture" in 2019. This became the main IKEA theme in 2019 and the program is still available to customers even in our times. As a part of the program, customers can return used, but still functional furniture back to an IKEA shop. Then, the company IKEA sells it for the same price it bought it for. The original owner receives a refund card that can be used for another purchase in the shop (Nábytkom k udržateľnej budúcnosti - Furniture for a Sustainable Future, 2019).

During the COVID-19 pandemic and the necessity of adopting multiple anti-pandemic measures in Slovakia in 2020, 2021, and 2022, IKEA raised topics emphasizing the need to support communities, e.g., doctors, people experiencing homelessness, seniors in social facilities, or single parents (IKEA pomáha rodičom samoživiteľom počas koronakrízy – IKEA helps single parents during coronacrisis, 2020), a safer home for everyone, but especially for women (IKEA otvára tému nasial páchaného na ženách a spúšťa kampaň za bezpečný domov – IKEA raises the topic of violence against women and launches a campaign for a safe home, 2021) and mental well-being (Ako naše domovy určujú našu duševnú pohodu - How our homes determine our mental well-being, 2022). In 2023, after the pandemic, IKEA returned to the circular economy, this time with the issue called "Furniture that changes with you". Again, the customers of IKEA were motivated to repair, to sell, or to utilize the adjusted household properties in each stage of their lives (IKEA v novej dlhodobej kampani zameranej na obehové hospodárstvo podporuje ľudí, aby oätovne používali nábytok – IKEA encourages people to reuse furniture in a new long-term campaign focused on the circular economy, 2023).

"You can live fully even when resting." That was the main theme of IKEA´s 2024 long-term campaign, which aimed to prevent the threat of burnout and provide a better sleep accessible to consumers of all ages in various life situations, at prices everyone can afford. The topic emerged from the results of The IKEA Life at Home Report, which declared that the quality of sleep is affected by multiple health, financial, or climate issues (IKEA spúšťa dlhodobú kampaň zameranú na spánok – IKEA launches a long-term campaign focused on sleep, 2024). The latest long-term campaign of IKEA from 2025 deals with cooking and dining. "Kitchen is more than just a place to cook. It is the heart of your home." With this movement, IKEA aims to remind its target audiences that cooking and dining are manifestations of taking care and togetherness (Lepší život sa začína v kuchyni – ako aj nová kampaň IKEA, ktorá sa výnimočným spôsobom zameriava na varenie a stolovanie - A better life starts in the kitchen – as does IKEA´s new campaign, which focuses on cooking and dining in a unique way, 2025).

4. DISCUSSION AND CONCLUSIONS

We pay our attention to the issues related to a sustainable future and repeated use of household properties. By means of the program called Second Life of Furniture, IKEA brings to the foreground of the public debate the topic of sustainability and circular economy. Traditionally, the second-hand furniture was considered as something inferior, however, through the process of agenda-setting, IKEA has been changing this narrative into socially casual and normal. It even changes the values of the target groups from the desire to possess

constantly new things into a pride based on the fact of prolonging life cycle to an already existing product.

Raising the theme called Second Life of Furniture is not only a theoretical conception, but it is firmly connected with a genuine service. IKEA has created a specific ecosystem, in the framework of which customers may return already used, but still fully functional furniture back into the IKEA shop in exchange for a refund card, which then can be used for a follow-up purchase in the shop. Afterwards, such gathered furniture items are brought back into circulation in a special section of the shop for affordable prices. In order to make this topic significant for the public, IKEA has been applying dominant media (TV and social media), and tools of marketing communication (advertising and Public Relations). See Table 1.

While setting the topic, IKEA has reacted to the criticism that mass production of cheap furniture burdens the environment. Furthermore, it managed to strengthen the loyalty of its customers, while drawing them back into the in-store purchasing cycle by means of refund cards, and it also succeeded in elevating the company´s public image from a fast-furniture chain (business model akin to the "fast fashion" model) to a leader in the area of sustainable living. Agenda-setting in this context means that IKEA does not only offer the furniture buy-back service; but it actively encourages society to start taking into account concepts, such as waste, recycling, and sustainability as natural components of everyday life.

In conclusion we wish to state that the issues raised during the monitored period seem, at first glance, to have little in common with the product portfolio of the company IKEA: sustainability, support of communities and vulnerable groups, mental well-being, threat of burnout, taking care, and a sense of belonging. Yet, the themes framed in such a compelling and natural way possess a significant potential to raise public awareness of both the issues themselves and the IKEA brand – while building credibility through major influential media outlets. However, it needs to mentioned here that conversely, if IKEA were to focus on communicating details of its products to the target audiences, such as the unique features distinguishing its goods from the competition, it would be forced to rely on random selection of the target groups, or on hope that they might happen to search for that type of information.

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REFERENCES

1. Agenda-setting theory. (2022). Retrieved on June 8, 2026. URL: https://www.ebsco.com/research-starters/communication-and-mass-media/agenda-setting-theory
2. *IKEA. (b.d.). Ako naše domovy určujú našu duševnú pohodu.* Retrieved on June 5, 2026. URL: https://www.ikea.com/sk/sk/newsroom/corporate-news/ako-nase-domovy-urcuju-nasu-dusevnu-pohodu-puba3d9fba7/
3. *IKEA. (b.d.). IKEA spúšťa dlhodobú kampaň zameranú na spánok.* Retrieved on June 8, 2026.

URL: https://www.ikea.com/sk/sk/newsroom/corporate-news/ikea-spusta-dlhodobu-kampan-zameranu-na-spanok-pub6832da90/
4. *IKEA. (b.d.). Lepší život sa začína v kuchyni – ako aj nová kampaň IKEA, ktorá sa výnimočným spôsobom zameriava na varenie a stolovanie*. Retrieved on June 7, 2026. URL: https://www.ikea.com/sk/sk/newsroom/range-news/lepsi-zivot-sa-zacina-v-kuchyni-ako-aj-nova-kampan-ikea-ktora-sa-vynimocnym-sposobom-zameriava-na-varenie-a-stolovanie-pub1b50e5d0/
5. *IKEA. (b.d.). Nábytkom k udržateľnej budúcnosti.* Retrieved on June 5, 2026. URL: https://www.ikea.com/sk/sk/newsroom/corporate-news/nabytkom-k-udrzatelnej-buducnosti-pubc92264b7/
6. *IKEA. (b.d.). IKEA otvára tému násilia páchaného na ženách a spúšťa kampaň za bezpečný domov*. Retrieved on June 7, 2026. URL: https://www.ikea.com/sk/sk/newsroom/corporate-news/ikea-otvara-temu-nasilia-pachaneho-na-zenach-a-spusta-kampan-za-bezpecny-domov-pubb7fe574e/
7. *IKEA. (b.d.). IKEA pomáha rodičom samoživiteľom počas koronakrízy.* Retrieved on June 5, 2026. URL: https://www.ikea.com/sk/sk/newsroom/corporate-news/ikea-pomaha-rodicom-samozivitelom-pocas-koronakrizy-pube08da454/
8. *IKEA. (b.d.). IKEA v novej dlhodobej kampani zameranej na obehové hospodárstvo podporuje ľudí, aby opätovne používali nábytok. Retrieved on June 8, 2026.* URL: https://www.ikea.com/sk/sk/newsroom/corporate-news/ikea-v-novej-dlhodobej-kampani-zameranej-na-obehove-hospodarstvo-podporuje-ludi-aby-opaetovne-pouzivali-nabytok-pub7f80fd60/
9. Jirák, J; Köpplová, B. *(2015). Masové media.* Portál.
10. Labská, H.; Loydlová, M.; Miklošík, A.; Plevová, K. (2014). *Marketingová komunikácia*. Vydavateľstvo EKONÓM.
11. Višňovský, J.; Baláž, M. (2012). Nastoľovanie tém a vplyv lokálnych médií na formovanie verejnej agendy – prípadová štúdia*. Communication Today* 12 (3): pp. 104-120.

Authors address:
Kollárová, D.[1]; Ungerová, M.[2]
[1] Department of Marketing Communication, Faculty of Mass Media Communication, University of SS Cyril and Methodius, Trnava, Slovakia
[2] Department of Language Communication, Faculty of Mass Media Communication, University of SS Cyril and Methodius , Trnava, Slovakia
*Corresponding author: daniela.kollarova@ucm.sk

IS FAMILIARITY WITH FAST FURNITURE ASSOCIATED WITH CONSCIOUS FURNITURE CONSUMPTION?

Hana Maťová, Ján Parobek, Dominika Košútová

Abstract: This study examines whether familiarity with the term *fast furniture* is associated with differences in furniture purchasing preferences and with indicators of conscious furniture consumption. Based on a non-probability sample of 558 respondents in the Slovak Republic, differences between the groups were analysed using the Mann–Whitney U test. Particular attention was paid to the factors influencing furniture purchasing decisions, namely price, quality, functionality, ease of assembly, environmental properties of the materials used, country of origin, and brand. The results showed that respondents who reported familiarity with the term *fast furniture* attached significantly greater importance to the environmental properties of the materials used, the manufacturer's country of origin, and brand. In contrast, respondents who did not know the term placed greater emphasis on price, overall furniture quality, functionality, and ease of assembly. No statistically significant differences were found for the remaining factors. The findings suggest that familiarity with the term *fast furniture* may be associated with a stronger orientation towards environmental and value-based aspects of furniture purchasing, whereas unfamiliarity with the term appears to be more closely linked to practical and economic decision-making criteria. These results offer valuable implications for furniture marketers and policymakers in promoting sustainable consumer behavior.

Keywords: *fast furniture*, sustainable consumption, conscious consumption

1. INTRODUCTION

Conscious consumption has gained attention as a perspective for understanding how consumers incorporate environmental, social and economic considerations into purchasing and consumption decisions (Balderjahn et al., 2013). In this paper, it is understood as a broad framework that includes not only the purchase of eco-friendly products, but also consideration of product origin, materials, durability, repairability, reuse and the wider consequences of consumer choice. It overlaps with related concepts such as sustainable, responsible and mindful consumption, which share the aim of reducing negative environmental and social impacts while acknowledging the practical and economic conditions of consumer decision-making (Sheth et al., 2011; Lim, 2017).

In the Slovak context, responsible and sustainable consumption has been discussed in relation to green purchasing behaviour and sustainable consumption patterns (Triznová et al., 2020). Environmental attitudes are present in Slovak society, with ecocentric attitudes being the most strongly represented in the New Ecological Paradigm study by Marcineková et al. (2024). However, environmental concern does not automatically translate into purchasing decisions. Research on environmental consumer segmentation in Slovakia shows that green consumers differ in motivations, price sensitivity, image orientation and perceived barriers (Maťová et al., 2024).

Furniture is a relevant area for examining conscious consumption because it is material-intensive, bulky and traditionally associated with long-term use. In the Slovak wood-based sector, wood has traditionally been used in construction and furniture production, while quality

and costs remain important considerations for final consumers (Sedlák et al., 2020). At the same time, the furniture sector has seen the emergence of *fast furniture*, understood here as a mode of production and consumption associated with rapid and low-cost manufacture and distribution, mass availability, short-lived interior trends and shortened use cycles. In this model, furniture is more likely to be replaced than maintained, repaired or reused (Cooper et al., 2021; Furmston and Braithwaite, 2025). However, *fast furniture* should not be automatically equated with poor-quality furniture; the concept primarily refers to the speed and low cost of the processes through which furniture is produced, purchased, consumed and disposed of. Barriers to extending furniture lifetimes include limited repairability, insufficient reuse infrastructure and business models that support replacement sales (Cooper et al., 2021; Furmston and Braithwaite, 2025). From an environmental perspective, *fast furniture* is relevant because a substantial share of furniture-related environmental impacts occurs before the use phase, particularly in pre-production and material use (Yang et al., 2025). Premature replacement may therefore generate not only waste but also repeated demand for material- and energy-intensive production processes.

Affordability is central to this issue and should be interpreted as a contextual condition of consumer decision-making rather than as a moral failing. This is consistent with the Attitude–Behaviour–Context framework, which emphasises that behaviour is shaped not only by attitudes, but also by contextual and economic conditions (Guagnano et al., 1995; Kaluvilla et al., 2025). Furniture purchasing, particularly in the context of sustainable and green furniture, is therefore multidimensional and involves practical, economic, aesthetic and sustainability-related considerations (Kamarubahrin et al., 2025; Dangelico et al., 2026; Shi et al., 2026). At the same time, not all affordable furniture should be equated with *fast furniture*; the problematic combination is low price, short lifespan, limited repairability, trend-driven replacement and limited motivation for long-term use (Cooper et al., 2021; Furmston and Braithwaite, 2025). Against this background, this paper examines whether consumers' self-reported familiarity with *fast furniture* is associated with differences in the perceived importance of selected furniture purchase factors.

2. MATERIAL AND METHODS

Data were collected using a structured Google Forms questionnaire in the Slovak Republic from December 2025 to February 2026. A non-probability sampling approach was used. The questionnaire was distributed by students among their acquaintances, with students personally present during completion. Participation was voluntary and anonymous.

The final sample consisted of 558 respondents aged 18 years and over. The questionnaire included six demographic questions and twelve questions concerning furniture purchasing behaviour. The final question asked whether respondents were familiar with the term *fast furniture* ("yes"/"no"). Respondents were divided into two groups: FF=0, unfamiliar with the term *fast furniture* (n=380), and FF=1, familiar with the term (n=178).

The analysis focused on 14 furniture purchase factors, treated as indicators of furniture purchasing preferences and conscious furniture consumption. Respondents evaluated the factors on a five-point Likert-type scale, where 1 = definitely yes and 5 = definitely no; lower scores therefore indicate greater perceived importance.

Analyses were performed in jamovi 2.6 using the bmtest module (The jamovi project, 2024; Karch, 2023). Group differences were assessed using the Mann–Whitney U test.

Because the data were ordinal Likert-type responses and group sizes were unequal, the Brunner–Munzel test was also applied as a robust complementary non-parametric procedure. The significance level was set at α = 0.05, and p-values for the 14 purchase factors were adjusted using the Benjamini–Hochberg false discovery rate procedure.

Mean scores (M) and Brunner–Munzel probability estimates were reported descriptively. As a robustness check for potential Simpson's paradox, group differences were additionally examined within demographic subgroups defined by gender, age, education, place of residence and income.

3. RESULTS

Table 1 Results

Furniture purchase factor	M FF=0	M FF=1	q MWU	q BM	$\widehat{P}$	Interpretation
Price	1.43	1.63	**0.0202**	**0.0201**	0.562	significantly greater importance in FF=0
Overall furniture quality	1.35	1.49	**0.0306**	**0.0389**	0.551	significantly greater importance in FF=0
Design	1.53	1.57	0.9472	0.9474	0.499	no significant difference
Environmental properties of the materials used	2.73	2.39	**0.0202**	**0.0201**	0.427	significantly greater importance in FF=1
Manufacturer's country of origin	3.03	2.72	**0.0282**	**0.0259**	0.434	significantly greater importance in FF=1
Warranty terms	2.16	2.28	0.2263	0.2186	0.537	no significant difference
Colour finish	1.75	1.81	0.3077	0.3040	0.529	no significant difference
Brand / brand image	2.86	2.57	**0.0435**	**0.0439**	0.441	significantly greater importance in FF=1
Product safety	1.70	1.74	0.7964	0.7984	0.508	no significant difference
Functionality	1.31	1.51	**0.0202**	**0.0201**	0.563	significantly greater importance in FF=0
Cleaning and maintenance of furniture	1.74	1.80	0.4626	0.4606	0.522	no significant difference
Delivery time	2.46	2.40	0.7884	0.7806	0.489	no significant difference
Ease of assembly	1.99	2.19	**0.0244**	**0.0201**	0.567	significantly greater importance in FF=0
Repairability	1.90	2.08	0.1903	0.2003	0.539	no significant difference

Note: $\widehat{P} = \widehat{P}(0 < 1) + \frac{1}{2}\widehat{P}(0 = 1)$

Table 1 presents differences in the perceived importance of 14 furniture purchase factors between respondents unfamiliar with *fast furniture* (FF=0) and respondents familiar with the term (FF=1). M denotes the mean score on a 1–5 scale, where lower values indicate greater perceived importance. q MWU and q BM are Benjamini–Hochberg adjusted p-values. The Brunner–Munzel probability estimate $\widehat{P}$ indicates the direction of group differences; values

above 0.50 indicate greater importance in FF=0, whereas values below 0.50 indicate greater importance in FF=1.

Descriptively, practical, utility-related and aesthetic factors, especially functionality, overall furniture quality, price, design, product safety and colour finish, had relatively low mean scores and were therefore rated as more important overall. Sustainability-, provenance- and service-related factors generally had higher mean scores, indicating lower overall importance.

The Benjamini–Hochberg correction did not change the substantive conclusion: seven factors remained statistically significant. Respondents unfamiliar with *fast furniture* assigned greater importance to price, overall furniture quality, functionality and ease of assembly, whereas respondents familiar with the term assigned greater importance to environmental material properties, the manufacturer's country of origin and brand/brand image. Both tests produced consistent conclusions, and the probability estimates were close to 0.50, indicating small differences in magnitude.

4. DISCUSSION AND CONCLUSION

The results suggest that familiarity with *fast furniture* is associated with a different emphasis in furniture purchasing preferences. Respondents familiar with the term attached greater importance to environmental material properties, the manufacturer's country of origin and brand/brand image. These factors may be interpreted as more value-oriented criteria, since they go beyond immediate product functionality and relate to provenance, trust and the broader consequences of consumer choice. The higher importance of brand/brand image may also relate to corporate identity, which in wood-processing and furniture companies is linked to visual presentation, image, reputation and market differentiation (Jelačić et al., 2010). Brand may therefore signal trustworthiness or value orientation rather than mere prestige, an interpretation compatible with the "Image Conscious Greens" segment identified in Slovak green-consumer research (Maťová et al., 2024).

In contrast, respondents unfamiliar with *fast furniture* placed greater emphasis on price, overall furniture quality, functionality and ease of assembly. This should not be interpreted as a lack of interest in sustainability, but rather as reflecting the practical and economic dimension of furniture purchasing. Consumers do not decide only according to what is environmentally preferable, but also according to what is affordable, functional and practically manageable. This is consistent with green furniture research showing that perceived behavioural control and economic constraints also matter (Xu et al., 2020; Shahsavar et al., 2020).

More broadly, the findings are in line with the Attitude–Behaviour–Context framework, according to which purchasing decisions are shaped not only by attitudes, but also by contextual and economic conditions (Guagnano et al., 1995; Kaluvilla et al., 2025). They also correspond with research describing furniture purchasing as a multidimensional process involving practical, economic, aesthetic and sustainability-related considerations (Kamarubahrin et al., 2025). The non-significant result for repairability is noteworthy: although repairability is important for circular consumption, it may not yet be a salient purchase criterion or may be perceived as practically limited by consumers (Cooper et al., 2021).

The FF=0/FF=1 group differences reported in Table 1 were small in magnitude, as the Brunner–Munzel probability estimates in the $\hat{P}$ column were close to 0.50. As a robustness check for potential *Simpson's* paradox, the analyses were repeated within demographic subgroups; these checks did not indicate a complete reversal of the FF=0/FF=1 pattern,

although they should be interpreted cautiously because some strata were small. Several limitations should be acknowledged: the study used a non-probability sample from the Slovak Republic, self-reported preferences, a single yes/no measure of familiarity with *fast furniture*, and a cross-sectional design. Therefore, the answer to the research question is cautious: familiarity with *fast furniture* is associated with selected purchase criteria that may reflect elements of conscious furniture consumption, particularly environmental material properties, provenance-related considerations and brand/brand image; however, these associations are modest and cannot be interpreted causally.

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REFERENCES

1. Balderjahn, I.; Buerke, A.; Kirchgeorg, M.; Peyer, M.; Seegebarth, B.; Wiedmann, K.-P. (2013): Consciousness for Sustainable Consumption: Scale Development and New Insights in the Economic Dimension of Consumers' Sustainability. AMS Review 3 (4): pp. 181–192. DOI: 10.1007/s13162-013-0057-6.
2. Cooper, T.; Kaner, J.; Furmston, K.; Cutts, A. (2021): Furniture lifetimes in a circular economy: A state of the art review. In: Proceedings of the 4th PLATE 2021 Virtual Conference. Limerick, Ireland. 26–28 May 2021. DOI: 10.31880/10344/10203.
3. Dangelico, R. M.; Fraccascia, L.; Schiaroli, V. (2026): Merging Psychological, Social, and Rational Perspectives: A Study of the Determinants of Consumer Choices for Sustainable Furniture. Business Strategy and the Environment 35 (4): pp. 4985–4999. DOI: 10.1002/bse.70428.
4. Furmston, K.; Braithwaite, N. (2025): How "Fast" is Fast Furniture? In: Proceedings of the 6th Product Lifetimes and the Environment Conference "PLATE2025". Aalborg, Denmark. 2–4 July 2025. DOI: 10.54337/plate2025-10320.
5. Guagnano, G. A.; Stern, P. C.; Dietz, T. (1995): Influences on Attitude-Behavior Relationships: A Natural Experiment with Curbside Recycling. Environment and Behavior 27 (5): pp. 699–718. DOI: 10.1177/0013916595275005.
6. Jelačić, D.; Maťová, H.; Bičanić, K. (2010): Perception of Corporate Identity in Croatian and Slovakian Wood Processing and Furniture Manufacturing Companies. Drvna Industrija 61 (2): pp. 103–110.
7. Kaluvilla, B. B.; Mulla, T.; Zahidi, F. (2025): Driving sustainable choices through understanding consumer behaviour and underlying factors that influence the purchasing intention of refurbished furniture. Discover Sustainability 6: 734. DOI: 10.1007/s43621-025-01497-y.
8. Kamarubahrin, A. F.; Saadun, N.; Aziz, A. (2025): Consumer Purchasing Behavior on Furniture: A Systematic Literature Review and Future Research Agenda. Journal of Management and Muamalah 15 (2): pp. 34–46. DOI: 10.53840/jmm.v15i2.250.
9. Karch, J. D. (2023): bmtest: A Jamovi Module for Brunner–Munzel's Test—A Robust Alternative to Wilcoxon–Mann–Whitney's Test. Psych 5 (2): pp. 127–141. DOI: 10.3390/psych5020026

10. Lim, W. M. (2017): Inside the Sustainable Consumption Theoretical Toolbox: Critical Concepts for Sustainability, Consumption, and Marketing. Journal of Business Research 78: pp. 69–80. DOI: 10.1016/j.jbusres.2017.05.001.
11. Marcineková, L.; Štěrbová, M.; Výbošťok, J.; Hajdúchová, I.; Giertliová, B.; Šulek, R.; Sarvašová, Z.; Šálka, J. (2024): Slovakia and its environmental transformation: Measuring environmental attitudes using the new ecological paradigm. Frontiers in Psychology 15: 1320451. DOI: 10.3389/fpsyg.2024.1320451.
12. Maťová, H.; Oravcová Triznová, M.; Kaputa, V.; Loučanová, E.; Vlosky, R. P. (2024): Strategic Environmental Consumer Segmentation: An Exploratory Case Study in Slovakia. SAGE Open 14 (1): pp. 1–19. DOI: 10.1177/21582440241240638.
13. Sedlák, P.; Bednár, J.; Búryová, D. (2020): Air permeability of OSB and its influence to heating energy costs. In: *Sustainability of Forest-Based Industries in the Global Economy: Proceedings of Scientific Papers*. Zagreb: WoodEMA; University of Zagreb, Faculty of Forestry, pp. 279–284. ISBN 978-953-57822-8-5.
14. Shahsavar, T.; Kubeš, V.; Baran, D. (2020): Willingness to pay for eco-friendly furniture based on demographic factors. Journal of Cleaner Production 250: 119466. DOI: 10.1016/j.jclepro.2019.119466.
15. Sheth, J. N.; Sethia, N. K.; Srinivas, S. (2011): Mindful Consumption: A Customer-Centric Approach to Sustainability. Journal of the Academy of Marketing Science 39 (1): pp. 21–39. DOI: 10.1007/s11747-010-0216-3.
16. Shi, T.; Yu, S.; Zhang, L.; Li, D. (2026): The Impact of Product Perceived Value on Green Furniture Purchase Intention: The Mediating Role of Customer Value. BioResources 21 (1): pp. 95–115. DOI: 10.15376/biores.21.1.95-115.
17. The jamovi project (2024): jamovi. Version 2.6. Computer Software.
18. Triznová, M.; Maťová, H.; Kaputa, V.; Drličková, E.; Dovčíková, A. (2020): Sustainable Consumption Patterns – The Case from Slovakia. In: Proceedings of the 13th International Scientific Conference WoodEMA 2020 / 31st International Scientific Conference ICWST 2020 "Sustainability of Forest-Based Industries in the Global Economy". Vinkovci, Croatia. September 28–30, 2020. pp. 129–134.
19. Xu, X.; Hua, Y.; Wang, S.; Xu, G. (2020): Determinants of consumer's intention to purchase authentic green furniture. Resources, Conservation and Recycling 156: 104721. DOI: 10.1016/j.resconrec.2020.104721.
20. Yang, D.; Vezzoli, C.; Su, H. (2025): Comprehensive life cycle assessment of 25 furniture pieces across categories for sustainable design. Scientific Reports 15: 13968. DOI: 10.1038/s41598-024-84025-8.

Authors address:
Maťová, H.[1]; Parobek, J.[1]; Košútová, D.[2]
[1] Department of Marketing, Trade and World Forestry, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Slovak republic
[2] Department of Wooden Constructions, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Slovak republic
*Corresponding author: matova@tuzvo.sk

MODELLING SUBSTITUTION IN CONIFEROUS SAWNWOOD CONSUMPTION IN SLOVAKIA

Barbora Barborová, Hubert Paluš

Abstract: This paper analyses the substitution relationship between domestic production and imports of coniferous sawnwood in Slovakia. The main objective is to quantify the influence of relative prices on the share of imports in domestic consumption. The study is based on the Armington approach, which assumes product differentiation by country of origin and employs a Constant Elasticity of Substitution (CES) function. After logarithmic transformation, the model is estimated as a linear econometric specification, allowing the parameters to be interpreted as substitution elasticities. The empirical analysis draws on annual data for the period 2013–2023, encompassing domestic production, imports, exports, and price data for domestic and imported sawn wood. The dependent variable is defined as the ratio of imports to domestic production, while the key explanatory variable is the relative price of domestic to imported sawn wood. The estimated model confirms a statistically significant substitution effect thus suggesting that the Slovak sawn wood market is moderately responsive to price signals, exhibiting partial but economically meaningful substitution between domestic and imported products. These findings underscore the importance of price competitiveness and international trade dynamics in shaping wood product markets.
Keywords: *coniferous sawnwood, substitution elasticity, Armington model, CES function, econometric modelling, Slovakia*

1. INTRODUCTION

Coniferous sawnwood is one of the most important products of primary wood processing. It represents a basic raw material for the construction industry, furniture manufacturing, packaging production, and other sectors of the wood-processing industry. The Slovak coniferous sawnwood market operates within the framework of an open economy, where international trade plays a significant role. During the period 2013–2023, the production of coniferous sawnwood in Slovakia ranged from approximately 1.1 to 1.4 million m³ annually, while imports varied between 205 and 480 thousand m³ and exports reached approximately 500 thousand to 1.1 million m³. Consequently, a substantial share of domestic production was directed to foreign markets, while apparent domestic consumption amounted to approximately 600–850 thousand m³ per year**.** Domestic demand is therefore satisfied through a combination of domestic production and foreign supplies, making it relevant to examine the substitution relationship between these sources of supply. The relative importance of domestic and imported sawnwood is influenced by several factors, particularly their relative prices. Given the relatively homogeneous nature of the product, price represents one of the key factors affecting the choice of supply source and, consequently, the structure of sawnwood consumption according to its origin (Paluš, 2010; Paluš et al., 2018).

From the perspective of microeconomic theory, domestic and imported sawnwood can be regarded as substitute goods that satisfy the same demand but differ in their origin. The degree to which these sources can be substituted for one another is expressed by the elasticity of substitution, which represents one of the fundamental parameters used in the analysis of

substitution relationships between products or production inputs. A higher elasticity of substitution indicates a stronger response of consumers or firms to changes in relative prices, whereas a lower elasticity suggests limited possibilities for replacing one source with another (Varian, 2014; Mas-Colell et al., 1995).

In international trade analysis, substitution relationships are frequently examined using the Armington approach, which assumes that products are differentiated according to their country of origin and are therefore not perceived as perfectly identical, even when they perform the same function (Armington, 1969). This approach is widely applied in the modelling of trade flows and substitution relationships between domestic and foreign products. Empirical studies have shown that price changes may significantly affect the consumption structure of wood products and lead to shifts in demand between domestic and imported sources of raw material (Uusivuori and Kuuluvainen, 2001).

The aim of this paper is to analyse the substitution relationship between domestic production and imports of coniferous sawnwood in Slovakia and to quantify the effect of relative prices on the consumption structure according to the origin of sawnwood. The analysis is based on the Armington approach to product differentiation by country of origin and employs a Constant Elasticity of Substitution (CES) framework. Based on economic theory, an econometric model is derived to estimate the elasticity of substitution between domestic and imported sawnwood and to assess the importance of price factors in shaping the consumption structure of coniferous sawnwood according to its origin in the Slovak Republic.

2. METHODOLOGY AND DATA SOURCES

3.

3.1. Derivation of the Substitution Model

In accordance with the Armington approach, domestic and imported coniferous sawnwood are assumed to represent two alternative sources satisfying market demand. To describe the substitution relationship between these sources, a Constant Elasticity of Substitution (CES) function was employed, allowing the degree of substitutability between domestic and imported sawnwood to be captured. The aggregate demand for sawnwood can be expressed by the following CES function:

$$Q = \mathrm{A}[\delta \mathrm{M}^{-\rho} + (1-\delta)\mathrm{P}^{-\rho}]^{-1/\rho}$$

Where Q denotes the aggregate quantity of sawnwood, *M* is the quantity of imported sawnwood, *P* represents domestic sawnwood production, A is an efficiency parameter, δ is a distribution parameter, and *ρ* determines the degree of substitution between the two sources.

Companies are assumed to behave rationally and to minimize costs while securing a required quantity of sawnwood. The corresponding cost function is defined as:

$$C = P_m M + P_d P$$

Where *Pm* denotes the price of imported sawnwood and *Pd* represents the price of domestic sawnwood.

Cost minimization subject to a given level of aggregate demand yields the conditional demand for individual sources of sawnwood. The first-order conditions imply that the optimal ratio of imported to domestic sawnwood depends on their relative prices and the elasticity of substitution. After algebraic manipulation, the demand equation can be derived in the following form:

$$\frac{M}{P} = A\left(\frac{P_d}{P_m}\right)^{\sigma}$$

where σ denotes the elasticity of substitution between domestic and imported sawnwood.

The equation indicates that the ratio of imports to domestic production depends on the relative prices of domestic and imported products. An increase in the relative price of domestic sawnwood leads companies to increase the share of imported sawnwood in their consumption. The magnitude of this response is determined by the value of the elasticity of substitution.

3.2. Econometric Quantification and Verification of the Substitution Model

For econometric estimation, the demand equation derived from the CES framework was transformed into a logarithmic form, yielding the following specification:

$$\ln\left(\frac{M}{P}\right) = \alpha + \sigma \ln\left(\frac{P_d}{P_m}\right) + \mu$$

where *M/P* denotes the ratio of imports to domestic production, P_d/P_m represents the relative price of domestic and imported sawnwood, α is a constant term, σ denotes the elasticity of substitution, and μ is the stochastic error term.

The logarithmic transformation enables the direct interpretation of the estimated coefficient σ as the elasticity of substitution. In accordance with the Armington approach, it is assumed that an increase in the relative price of domestic sawnwood leads to an increase in the ratio of imports to domestic production, indicating a substitution relationship between domestic and imported sawnwood.

The model parameters were estimated using the Ordinary Least Squares (OLS) method. The statistical significance of the estimated coefficients was evaluated using Student's t-test, while the overall significance of the model was assessed by means of the F-test. The explanatory power of the model was evaluated using the coefficient of determination (R^2). Given the time-series nature of the data, the Durbin–Watson statistic was used to examine the presence of autocorrelation in the residuals. All calculations and econometric analyses were performed using IBM SPSS Statistics software.

3.3. Data Collection and Variable Construction

The empirical analysis was conducted using annual data covering the period 2013–2023. Data on the production, imports, and exports of coniferous sawnwood were obtained from the FAOSTAT database (FAO, 2026). Information on domestic prices of coniferous sawnwood was collected from the Forestportal database (FORESTPORTAL, 2024). Data on the EUR/USD exchange rate were retrieved from the European Central Bank (ECB, 2024), while data on the Harmonised Index of Consumer Prices (HICP) were obtained from Eurostat (EUROSTAT, 2024). Domestic consumption was defined as:

$$\mathrm{D} = \mathrm{P} - \mathrm{E}$$

Where *P* denotes the production of coniferous sawnwood and *E* represents exports.

Total sawnwood consumption can be expressed as:

$$S = P - E + M$$

where *M* denotes imports of coniferous sawnwood. These variables were used to characterise the market structure and were not included as dependent variables in the econometric model. In accordance with the derived substitution model, the ratio of imports to domestic production was used as the dependent variable *M/P,* which reflects the consumption structure according to the origin of sawnwood. The explanatory variable was defined as the ratio of domestic to imported sawnwood prices P_d/P_m.

To ensure comparability over time, price data were converted into real terms using constant 2015 prices. Import prices were converted into euros using the average annual EUR/USD exchange rate and subsequently adjusted for inflation using the Harmonised Index of Consumer Prices (HICP).

4. RESULTS AND DISCUSSION

The results of the econometric model estimation are presented in Table 1. The signs of the estimated parameters are consistent with the theoretical assumptions of the derived substitution model. The relative price of domestic and imported sawnwood proved to be a statistically significant factor affecting the consumption structure of coniferous sawnwood according to its origin. The obtained results also confirmed the formulated assumption regarding the existence of a substitution relationship between domestic and imported sawnwood.

The estimated elasticity of substitution reached a value of 0.612, indicating that a 1% increase in the relative price of domestic sawnwood results in an approximately 0.612% increase in the ratio of imports to domestic production. Companies therefore respond to changes in relative prices by shifting their consumption towards the relatively cheaper source. Since the estimated elasticity of substitution is lower than one, it can be concluded that substitution between domestic and imported coniferous sawnwood is incomplete. Similar conclusions were reported by Sauquet et al. (2011), who estimated Armington elasticities for sawnwood and found that domestic and imported sawnwood behave as imperfect substitutes. Domestic and imported sawnwood cannot therefore be considered perfect substitutes. Purchasing decisions are likely influenced not only by prices but also by other factors, such as differences in sawnwood quality, transportation costs, long-term trade relationships, and specific requirements of wood processors.

The coefficient of determination (R^2 = 0.556)) indicates that approximately 55.6% of the variability in the ratio of imports to domestic production is explained by the relative prices of domestic and imported products. Furthermore, the value of the Durbin–Watson statistic (*D* = 2.065) does not indicate the presence of autocorrelation in the residuals.

The obtained results support the Armington assumption of imperfect substitution between products differentiated by country of origin (Armington, 1969). Similar evidence of substitution relationships in international wood markets was reported by Uusivuori and Kuuluvainen (2001). Furthermore, Sun (2017) demonstrated that relative prices influence sourcing decisions among wood products originating from different sources, which is consistent with the results obtained in this study.

Table 1. Results of the econometric model estimation

Explanatory variable	Value
a	-1.268
P_d / P_m	***0.612
	(3.35)
R	0.745
	(11.252)
R^2	0,556
D	2.065
$S_{u(r)}$	0.130

Note:
*** $p < 0.01$; *Values reported in parentheses represent the calculated t-statistics used to test the statistical significance of the estimated model parameters.*

5. CONCLUSION

The aim of this paper was to analyse the substitution relationship between domestic production and imports of coniferous sawnwood in Slovakia and to quantify the effect of relative prices on the consumption structure according to the origin of sawnwood. The results of the analysis confirmed the formulated assumption that relative prices represent an important factor affecting the consumption structure of coniferous sawnwood according to its origin. At the same domestic and imported sawnwood cannot be considered perfect substitutes and the response of companies to sawnwood price changes is only partial.

The findings indicate that price factors play an important role in shaping the consumption structure of coniferous sawnwood in Slovakia. However, the decisions of companies are likely influenced not only by prices but also by other factors, such as the level of economic activity, the income situation of consumers, developments in the construction sector, transportation costs, quality characteristics of sawnwood, long-term trade relationships, and the specific requirements of wood processing companies.

A limitation of the study is that the analysis was based on a relatively short time series and focused exclusively on the price determinant of substitution behaviour. Future research could therefore extend the model by incorporating additional non-price factors, such as indicators of economic growth, developments in the construction industry, or more detailed data with a higher frequency, which could contribute to a deeper understanding of the factors influencing the consumption of coniferous sawnwood according to its origin.

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REFERENCES

1. Armington, P. S. (1969). A theory of demand for products distinguished by place of production. IMF Staff Papers, 16(1), 159–178.
2. Buongiorno, J. (1978). Income and Price Elasticities in the World Demand for Paper and Paperboard, Forest Science. 24(2), 231-246.

3. European Central Bank. (2024). Euro foreign exchange reference rates. Retrieved June 10, 2026, from: https://www.ecb.europa.eu/
4. Eurostat. (2024). Harmonised Index of Consumer Prices (HICP). Retrieved June 10, 2026, from: https://ec.europa.eu/eurostat/
5. FAO. (2023). FAOSTAT – Forestry Production and Trade. Retrieved June 10, 2026, from: https://www.fao.org/faostat/
6. Forestportal. (2024). Market information sheets on wood markets – coniferous sawnwood prices. Retrieved June 10, 2026 from: https://www.forestportal.sk/
7. Hurmekoski, E. (2021). Substitution in forest product markets under climate change mitigation policies. Environmental Research Letters, 16, 123004.
8. Mas-Colell, A., Whinston, M. D., Green, J. R. (1995). Microeconomic Theory. New York, NY: Oxford University Press, ISBN-13: 978-0195073409.
9. Paluš, H. (2010). Trh a obchod s drevom a výrobkami z dreva. Zvolen, Slovakia: Technical University in Zvolen, ISBN 978-80-228-2126-8.
10. Paluš, H., Parobek, J., Dzian, M., Šupín, M. (2018) Determinants of Sawnwood Consumption in Slovakia. BioResources.13(2), 3615-3626.
11. Sauquet, A., Lecocq, F., Delacote, P., Caurla, S., Barkaoui, A., Garcia, S. (2011). Estimating Armington Elasticities for Sawnwood and Application to the French Forest Sector Model. Resource and Energy Economics, 33(4), 771–781.
12. Sun, C. (2017). Competition of Wood Products with Different Fiber Transformation and Import Sources. Forest Policy and Economics, 74, 30–39.
13. Uusivuori, J., Kuuluvainen, J. (2001). Substitution in Global Wood Imports in the 1990s. Canadian Journal of Forest Research. 31(7), 1148–1155.
14. Varian, H. R. (2014). Microeconomic Analysis (3rd ed.). New York, NY:W. W. Norton & Company, ISBN-10: 0393957357.

Authors address:
Barborová, B[1]; Paluš, H[1]
[1] Department of Marketing, Trade and World Forestry, Faculty of Wood, Science and technology, Technical university in Zvolen, Slovakia
*Corresponding author: xbarborova@is.tuzvo.sk

WOOD BUSINESSES ON THE MARGINS: THE WOOD-BASED MICRO-MARKET OF THE SOCIALLY EXCLUDED – PATHOLOGY OR OPPORTUNITY

Leszek Wanat, Jan Adam Klimek, Łukasz Sarniak

Abstract: The study discusses the socio-economic perception of a wood-based micro-market created by the socially excluded and mentally ill. A pilot study (CAWI, N=120) evaluated whether commercialising forest occupational therapy offers a reintegration opportunity or a stigmatising anomaly. Data was collected via a proprietary questionnaire from wood technology, forestry, psychology, and theology students. Results revealed strong polarisation: engineering students perceive micro-business and circular economy potential, whereas humanities students fear commercialisation, emphasising work dignity. Ultimately, developing inclusive wood processing requires a hybrid management model, blending technological optimisation with ethical sensitivity.
Keywords: wood-based micro-market, social inclusion, circular economy, forest therapy, bioeconomy.

1. INTRODUCTION

The historical garden city concept highlights the vital link between public health and accessible green spaces [2]. Today, integrated urban forests are crucial not just for recreation, but as pillars of landscape economics and integral human development [15, 17, 18]. A prime example is the historic forest park at the psychiatric hospital in Krakow's Kobierzyn [5, 14], integrating medical, therapeutic, and pastoral care for over a century [8]. Forest therapy is a proven tool for stress reduction, mood regulation, and clinical psychiatric support, even via virtual reality [7, 11, 21]. The measurable benefits of nature-based interventions on adult mental health are increasingly recognised [9, 13]. However, transitioning from passive recreation to active patient engagement remains a research challenge. The Inclusive Integration Model, based on Kobierzyn, identifies the people–forest–wood value chain [19]. Consequently, direct woodworking, including joint material sourcing, basic processing, and crafting-provides a targeted response to dysfunctions like loneliness, neuroses, and a lack of work-life balance [19]. Undertaking such activities in natural settings, also explored from a legal perspective [16], helps patients regain dignity and agency, reflecting fundamental human values [20].

Here, wood-based occupational therapy intersects with economic sociology and materials engineering. Utilising local wood waste or urban green resources by marginalised individuals (e.g., in hospital carpentry workshops) aligns with Circular Economy principles, offering an innovative, bottom-up approach to sustainable urban transition [1, 10]. Macroeconomically, bodies like the European Environment Agency and the International Labour Organization highlight that material circularity not only optimises natural resources but creates powerful opportunities for social inclusion and decent employment [3, 4, 6]. This synergy between forestry, wood processing, and social policy creates a niche economy: a wood-based micro-market of the socially excluded. Patient-crafted items, such as wooden toys or charitable gifts, acquire an added value that is symbolic, relational, and potentially commercial. However, its

acceptability among future experts, forestry stakeholders, and psychosocial support networks remains questionable [12]. The core research question asks: is this marginal micro-business perceived as a genuine reintegration opportunity, or a market illusion and pathology driven by stigmatisation and pity-based demand? This paper addresses this dilemma.

2. MATERIAL AND METHODOLOGICAL BACKGROUND OF THE STUDY

This pilot study evaluated the socio-economic perception of wood-based work performed by socially excluded and mentally ill individuals. The intersection of materials engineering, forestry, economic sociology, and psychosocial care necessitated an interdisciplinary approach. Following the Inclusive Integration Model [19], it was essential to examine how future experts and policymakers evaluate this niche wood-based micro-market [12]. Empirical data was collected via a Computer-Assisted Web Interview (CAWI) survey. A purposive student sample yielded N=120 valid responses, deliberately contrasting two distinct cognitive perspectives: technological-environmental (wood technology and forestry) and socio-humanistic (psychology and theology). This selection provided a multidimensional view of the bioeconomy, where Circular Economy metrics intersect with integral human development and the dignity of labour [6, 15, 20]. The primary research tool was an original 5-point Likert scale questionnaire (1: 'strongly disagree', 5: 'strongly agree'). To minimise semantic gaps between engineering and humanities terminologies, the initial questions were validated via Individual In-depth Interviews (IDIs). Involving target groups refined the variables to reflect market and therapeutic contexts without compromising respondent sensitivity [12, 19].

The validated questionnaire comprised two diagnostic sections based on the theoretical model [19]. The psychological-theological aspect evaluated woodworking as a therapeutic tool for recovering human agency, testing whether: (a) hospital carpentry work primarily serves integral human development rather than mere financial gain; (b) crafting wooden ornaments and religious souvenirs fosters relationships and social responsibility; and (c) collaborative wood sourcing prevents loneliness. Conversely, the economic-technological aspect examined commercialisation potential and engineering conditions [1, 10], assessing if: (a) patients' products should be sold on the open market rather than just donated; (b) utilising wood waste for handicrafts constitutes an innovative Circular Economy micro-model; and (c) marketing these inclusive goods risks stigmatising creators via pity-based demand.

The survey concluded with a decisive question categorising the phenomenon. Respondents had to determine whether this inclusive wood-based micro-market represents an OPPORTUNITY (a tool for genuine social reintegration and a viable micro-business) or a PATHOLOGY/ILLUSION (hidden exploitation or a market anomaly driven solely by consumer pity). The resulting quantitative data were then subjected to a structural comparative analysis.

3. SELECTED RESULTS

The May 2026 CAWI pilot study yielded N=120 valid responses for statistical analysis. The purposive sample was structured by educational profile, comprising psychology (n=35), wood technology (n=32), forestry (n=30), and theology (n=23) students. The analysis aimed to determine whether future experts perceive the wood-based micro-market of the socially excluded as an opportunity (an inclusive business model, reintegration) or an illusion/pathology (stigmatisation risk, exploitation, artificial demand). The results are summarised in Table 1.

Table 1. Perception of the wood-based micro-market created by the socially excluded, by students' field of study (N=120)

Field of study	Sample size (n)	OPPORTUNITY (reintegration tool and micro-business)	PATHOLOGY / ILLUSION (stigmatisation, exploitation)
Wood technology	32	75,0% (n=24)	25,0% (n=8)
Forestry	30	86,7% (n=26)	13,3% (n=4)
Psychology	35	48,6% (n=17)	51,4% (n=18)
Theology	23	56,5% (n=13)	43,5% (n=10)
TOTAL	**120**	**66,7% (n=80)**	**33,3% (n=40)**

Source: Own elaboration.

The results reveal stark polarisation. Forestry (86.7%) and wood technology (75.0%) students optimistically see a pragmatic opportunity to advance the Circular Economy and commercialise niche urban resources [10, 19]. Conversely, 51.4% of psychology students fear that commercialising patients' work is a market "illusion" or pathology driven by stigmatisation and pity. Theology students display moderate optimism (56.5%), emphasising the dignity of this work over its commercial value [20]. To identify the sources of these attitudes, mean scores for specific variables describing the integration model were analysed (see Table 2). Ratings were measured on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

*Table 2. Mean ratings (*M) – according to students – of specific aspects of wood-based work performed by the socially excluded on a 1-5 Likert scale (N=120)*

Factor (Variable)	Wood technology*	Forestry*	Psychology*	Theology*
Psychological-theological aspect (mental health & spirituality)				
1. Woodworking as a work-life balance tool for both the healthy and the excluded	3,2	3,6	4,5	4,7
2. Crafting souvenirs/ornaments builds relationships and responsibility	3,4	3,8	4,8	4,9
3. Hospital carpentry work is integral development, not income	3,0	3,3	4,7	4,8
4. Gathering wood together in the forest prevents loneliness	3,1	4,2	4,4	4,6
Economic-technological aspect (dignity of labour)				
5. Patients' wood products should be sold on the market, not donated	4,6	4,3	2,4	2,8
6. Wooden goods have primarily social (image) rather than market value	2,8	3,1	4,5	4,2
7. Marketing wood-based products may stigmatise their creators	2,1	2,4	4,6	3,8

8. Wood technology expertise significantly increases market value	4,8	4,5	3,1	3,0
9. Excluded people utilising wood waste models an innovative Circular Economy	4,5	4,8	3,4	3,6

Source: Own elaboration.

The analysis of specific predictors (Table 2) refutes the assumption of homogeneous views on social bioeconomy, confirming fundamental cognitive differences based on educational profile. Psychology and theology students highly value relational, dignity, and therapeutic factors (means: 4.4–4.9). However, they fear commercial mechanisms, arguing that sales profit may lead to stigmatisation (psychology: 4.6) and that the products hold almost exclusively social-image value [12]. Conversely, forestry and wood science students view this model through the lens of economic and engineering agency. They strongly support market commercialisation, favouring direct sales over charitable donation (wood technology: 4.6; forestry: 4.3). Furthermore, they see this as an excellent implementation of Circular Economy principles (forestry: 4.8) and an opportunity to effectively utilise urban wood waste [1, 3, 10].

4. CONCLUSIONS

The pilot study evaluated a wood-based micro-market for socially excluded and mentally ill individuals. Whether this constitutes a market opportunity or pathology depends heavily on respondents' educational profiles:

(1) Engineering and forestry students view this work through the lens of agency, seeing it as an innovative Circular Economy implementation and resource optimisation. Conversely, psychology and theology students perceive market threats, fearing creator stigmatisation and consumer 'pity pathology'.

(2) Humanities students view wood sourcing and crafting primarily as social inclusion tools, where therapeutic and dignity dimensions outweigh commercial value. In contrast, future engineers recognise genuine business potential, recommending the full marketisation (sale) of these goods.

Based on these findings, two key recommendations emerge:

(1) Hybrid management models: Marginal micro-businesses cannot be evaluated solely by hard economic metrics; they require hybrid bioeconomy models that combine technological optimisation (wood product quality) with rigorous ethical safeguards (protecting patient agency and dignity).

(2) Interdisciplinary education: To foster cross-sectoral communication, foresters and wood technologists need training in social sensitivity, while psychologists and therapists require foundations in entrepreneurship and sustainable resource management to avoid hindering patients' market potential out of fear of exploitation.

This pilot study faces limitations: the small, purposive sample (N=120 Polish students) precludes broad generalisation, and the survey method may overlook nuances of ethical sensitivity.

Future research must expand geographically via cross-cultural studies and involve actual stakeholders - wood sector employers, therapists, and the excluded creators themselves - to shift the focus from mere perception to evaluating real economic and clinical effectiveness.

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REFERENCES

1. Cakaj, A., Hesse, L., Krause, A., Speth, H., Lüdtke, J. (2025). Barriers and Potentials for Circular Use of Waste Wood in Construction and Demolition Sector with Special Focus on Germany. *Urban Science*, 9(9), 367. DOI: 10.3390/urbansci9090367.
2. Dobrzyński, W. (1911). Zdrowie publiczne a idea miast-ogrodów (Public health and the garden city concept), Warszawa.
3. European Environment Agency (EEA). (2025). Material stocks in a circular economy. European Environment Agency, Copenhagen. URL: https://www.eea.europa.eu/en/analysis/publications/material-stocks-in-a-circular-economy (accessed on: 07.07.2026).
4. European Environment Agency (EEA). (2026). Unlocking the circular economy: investment needs, barriers and enabling conditions. European Environment Agency, Copenhagen. URL: https://www.eea.europa.eu/en/analysis/publications/unlocking-the-circular-economy-investment-needs-barriers-and-enabling-conditions (accessed on: 07.07.2026).
5. Galus, E.; Klimek, J.; Wąchol, G. (2023). Kobierzyn wczoraj i dziś (Kobierzyn yesterday and today), Kraków.
6. International Labour Organization (ILO). (2025). Employment in the Circular Economy: Leveraging circularity to create decent work. International Labour Organization, Geneva. URL: https://www.ilo.org/regions-and-countries/europe-and-central-asia/european-union-eu/poland (accessed on: 07.07.2026).
7. Kim, G., Kang, S., Paek, K., Choi, H., Choi, S., Lee, J. (2025). Analysis of Program Activities to Develop Forest Therapy Programs for Improving Mental Health: Focusing on Cases in Republic of Korea. *Healthcare*, 13(7), 760. DOI: 10.3390/healthcare13070760.
8. Klimek, J. (2019). Duszpasterstwo w kobierzyńskiej kapelanii na przestrzeni wieków (Pastoral care at the Kobierzyn chaplaincy over the centuries), Kraków.
9. Kotte, D., Li, Q., Shin, W. S.; Michalsen, A. (Eds.). (2019). International handbook of forest therapy. Cambridge Scholars Publishing.
10. Longo, S., Derito, M., Cellura, M., Di Dio, S., Guarino, F. (2026). Circular Cities: A Systematic Literature Review of Urban Strategies for Sustainable Transitions. *Sustainability*, 18(6), 2980. DOI: 10.3390/su18062980.
11. Martins, R., de Sousa, S., Viana, J., Fortuna, R., Henriques, A., Silva, A., Simões de Almeida, R. (2026). The impact of virtual reality-based forest therapy in psychiatric inpatient care: a pilot study. *Advances in Mental Health*. DOI: 10.1080/18387357.2026.2615679.
12. Miassi, Y. E., Gélinas, N., Dossa, K. F., Bah, I. (2026). Analysis of the perception and acceptability of circular economy strategies by stakeholders in the wood and forestry

sector in Benin. *Frontiers in Forests and Global Change*, 9, 1755893. DOI: 10.3389/ffgc.2026.1755893.
13. Shang, X., Lu, J., Tao, M., Fei, C., Fei, J. (2025). Benefits of forest therapy for adult mental health: a systematic review and meta-analysis based on the Profile of Mood States (POMS). *Frontiers in Psychology*, 16, 1670804. DOI: 10.3389/fpsyg.2025.1670804.
14. Staniewska, A., Petryshyn, H., Lukashchuk, H., Kliusa, T., Koprynia, K. (2021). Values of the Historical Parks and Gardens of Psychiatric Hospitals in Kulparków and Kobierzyn as the Basis for Their Revalorization. *Wiadomości Konserwatorskie – Journal of Heritage Conservation*, 67: 22–34.
15. Szary, S. (2020): Las i jego nie-zastępowalność w integralnym rozwoju człowieka (Forest and its non-substitutability in integral human development), *Przegląd Leśniczy*, 10: 18-20.
16. Tamašauskaitė-Janickė, G., Petruševičienė, D. (2026). Nature-Based Environment as a Workplace of Forest Therapy Specialist in Healthcare Context: Legal Perspective. *Healthcare*, 14(7), 933. DOI: 10.3390/healthcare14070933.
17. Wanat, L. (2024). Kazimierza Zimniewicza drogowskazy ekonomii krajobrazu (Kazimierz Zimniewicz's pathfinders of landscape economics). *Biuletyn Parków Krajobrazowych Wielkopolski*, 31: 11-14.
18. Wanat, L. (2024). Selected creating factors of the integrated urban forest - the case of Kobierzyn garden in the Kraków metropolitan area in Poland. In: D. Jelačić (ed.), Achieving sustainability in forest-based industry, WoodEMA, i.a., Zagreb, pp. 59-68.
19. Wanat, L., Klimek, J., Kusiak, W., Sarniak, Ł. (2025). People - forest - wood: inclusive integration models. The case of the Kobierzyn urban forest park in the Kraków metropolitan area in Poland. In: Ž. Meloska, M. Miloshevska Janakieska (eds.), Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers, 18th International Scientific Conference WoodEMA, WoodEMA, i.a., Ohrid, pp. 307-312.
20. Wąchol, G.; Wanat, L. (2023). Perspektywa λόγος i ἀρετή w procesie integracji osób z dysfunkcjami psychicznymi (The λόγος and ἀρετή perspective in the integration process of people with mental dysfunctions). *Paideia / Παιδεία*, 5: 67-88.
21. Zhang, Y., Feng, L., Duan, W. (2023). The impact of forest therapy programs on stress reduction: a systematic review. *Forests*, 14(9), 1851.

Authors address:
Wanat, L.[1*]; Klimek, J.A.[2]; Sarniak, Ł.[3].
[1] Department of Social Sciences, Kozminski University, Warsaw, Poland.
[2] Department of Theology and Pastoral Psychology, The Pontifical University of John Paul II in Kraków, Poland.
[3] Department of Finance and Accounting, Faculty of Economics, Poznań University of Life Sciences, Poznań, Poland
[*] Corresponding author: leszek.wanat@kozminski.edu.pl .

ADVANCING MYCELIUM-BASED PRODUCTS: PERSPECTIVES FOR WOOD PRODUCT MARKETS

Manja Kitek Kuzman, Mirko Karič, Sebastian Pablo Galarco

Abstract: This paper explores the potential of mycelium-based materials as sustainable alternatives for design and architecture, and wood-product applications applications. Derived from the root structure of fungi, mycelium enables the conversion of agricultural residues into biodegradable composites suitable for packaging, interior products, and lightweight building components. The research examines how fungal species, substrate composition, and growth conditions influence material properties, formability, and aesthetic qualities. Framed within the principles of the New European Bauhaus and contemporary bioeconomy discourse, the study highlights the contribution of mycelium materials to circular production systems, reduced environmental impact, and innovative design solutions..Selected case studies from Slovenia and Argentina, together with student-developed wood–mycelium prototypes, demonstrate their practical applications and design potential. The paper also discusses current challenges related to durability, scalability, and standardization, emphasizing the importance of interdisciplinary collaboration in advancing mycelium-based materials as sustainable solutions that integrate ecological responsibility with functional and aesthetic requirements.

Keywords: mycelium-based materials; circular bioeconomy; sustainable design; wood-based composites

1. INTRODUCTION

Mycelium-based materials have emerged as promising bio-based alternatives for sustainable product and construction applications. Produced through the growth of fungal mycelium on agricultural and lignocellulosic residues, these biodegradable composites combine low environmental impact with unique structural and aesthetic properties. During growth, mycelium binds substrate particles into a lightweight porous material, enabling the valorization of biomass waste within circular production systems (Jones et al., 2017; Hyde et al., 2019). Owing to their renewable origin, low resource requirements, and design versatility, mycelium-based products (Figure 1, 2) are increasingly considered as potential substitutes for selected wood-based and petroleum-derived materials.

Figure 1. Representative images, e.g. chairs, wall panels, lamps, acoustic tiles made of mycelium, fashion accessories, or small home décor items

Figure 2. Representative images, e.g. photos of mycelium bricks, wall elements, sculptures, façade panels, or pavilion structures

Mycelium-based products development aligns with contemporary bioeconomy strategies and regenerative design principles, creating new opportunities for sustainable innovation in wood product markets (Attis et al, 2020). In this context, mycelium-based materials can support the transition toward regenerative design by integrating ecological responsibility with functional and aesthetic requirements.

2. STUDENT RESEARCH AND PROTOYPE DEVELOPMENT

The performance of mycelium-based materials is strongly influenced by the interaction between fungal species, substrate composition, and cultivation conditions. Different fungal species exhibit varying growth rates and bonding capabilities, which directly affect the mechanical strength, density, and durability of the resulting composite. Similarly, the choice of substrate, including agricultural by-products such as straw, hemp, or sawdust, determines the availability of nutrients and influences the material's texture, porosity, and structural characteristics. Growth conditions such as temperature, humidity, oxygen availability, and incubation time play a critical role in regulating mycelial development and material formation (Appels, 2019). Optimizing these parameters can improve formability, surface quality, and consistency while enabling the production of components with specific functional and aesthetic properties.

A selected case study from Slovenia demonstrates the practical applications, design potential, and regional adaptability of mycelium-based materials. In this case study, students from the Department of Wood Science and Technology at the Biotechnical Faculty conducted a research project within the course Construction and Innovation, exploring the development and application of mycelium-based materials and products. This example highlights how locally available resources, industrial capacities, and research initiatives can support the development of mycelium-based products within different economic and environmental contexts.

To investigate the practical potential of fungal biocomposites, student research projects explored their application in combination with wood-based materials. The objective was to develop products in which mycelium biocomposites fulfilled clearly defined structural, insulating, or decorative functions. Particular attention was given to innovative approaches, including material densification, hot pressing, molding, and the development of hybrid wood–mycelium structures and sandwich panels. The studies involved the design and fabrication of prototypes, documentation of manufacturing processes, and evaluation of selected material properties, including mechanical, thermal, acoustic, visual, and bonding performance. Based on the experimental results, the suitability of the materials for their intended applications was critically assessed, and potential improvements were identified (Figure 4).

Figure 4. Experimental products fabricated from mycelium-based composites and wood, illustrating the design potential and material versatility of bio-based hybrid structures.

3. CASE STUDIES OF MYCELIUM -BASED MATERIAL DEVELOPMENT IN SLOVENIA AND ARGENTINA

Mycelium-based composites and insulating panels are of particular interest to the wood products sector due to their thermal and acoustic properties, aesthetic characteristics, low environmental impact, and compatibility with timber-based building systems. These characteristics offer opportunities for the development of low-carbon housing, bio-based construction, innovative wood–mycelium products, furniture, and interior design applications. However, broader adoption will require further improvements in material performance, as well

as the establishment of appropriate standards and certification frameworks for building applications.

2.1. Slovenia

In Slovenia, the development of mycelium-based materials is supported by the country's strong forestry tradition, well-established wood-processing industry, and commitment to the circular bioeconomy. Research institutions, including the University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology and the Slovenian National Building and Civil Engineering Institute, have investigated bio-based and sustainable construction materials, while designers and architects have increasingly incorporated mycelium into experimental products, interior applications, and exhibition installations. Slovenia's abundant availability of wood-processing residues, combined with its focus on sustainable innovation, provides favorable conditions for developing mycelium-based composites, packaging materials, insulation products, and solutions for the wood sector.

Slovenian companies also provide valuable case studies of commercial implementation. The company EcoFungi d.o.o. develops biodegradable products from fungal mycelium using agricultural and forestry residues, with applications ranging from sustainable packaging to eco-friendly consumer products. The company emphasizes replacing conventional plastic and polystyrene-based materials with biodegradable alternatives. Similarly, Mycopor, Rutina d.o., a Slovenian producer of mycelium-based biomaterials, manufactures packaging, insulation panels, acoustic panels, and other molded products using mycelium combined with agricultural and wood-based waste streams. Its activities demonstrate the potential for integrating mycelium technologies into Slovenia's existing forestry and wood-processing value chains.

These efforts align with national sustainability objectives and broader European initiatives promoting circular, resource-efficient, and low-carbon material systems, positioning Slovenia as a promising environment for the further development and commercialization of mycelium-based materials.

2.2. Argentina

In Argentina, the mycelium-based products sector is rapidly developing, with applications ranging from sustainable packaging and bioleather to nutritional supplements. One of the most notable examples is Fungipor (Salta), which uses mycelium and agro-industrial residues to produce biodegradable packaging as an alternative to expanded polystyrene. Research conducted by CONICET and the Universidad Tecnológica Nacional has also explored mycelium-based insulating panels and packaging materials derived from agricultural by-products. Other initiatives include Mycorium Biotech, which develops mycelium-based bioleather, and MyCelium®, a producer of medicinal mushroom extracts.

Argentina offers favorable conditions for the expansion of mycelium-based materials due to its abundance of agricultural residues, including corn stover, rice husks, sugarcane bagasse, and sawdust. Combined with strong scientific and technological capacities provided by institutions such as CONICET, INTI, INTA, and national universities Universidad Nacional de La Plata, these resources create significant opportunities for innovation. The availability of large volumes of agricultural by-products provides a sustainable feedstock for mycelium cultivation while supporting the valorization of biomass residues. Furthermore, the growing interest in sustainable construction creates opportunities for integrating mycelium-based insulating materials into timber-based and low-carbon building systems.

2.3. Perspectives for Wood Product Markets

Both Slovenia and Argentina provide favorable conditions for the development of mycelium-based materials due to the availability of forestry and agricultural residues and growing interest in bio-based products. In Slovenia, opportunities are closely linked to the forestry and wood-processing sectors, whereas in Argentina, agricultural by-products represent an important resource for mycelium cultivation and composite production.

Mycelium-based materials may complement conventional wood products through the development of hybrid structures, insulation panels, acoustic elements, furniture components, and biodegradable packaging. Their ability to utilize low-value biomass streams supports circular economy principles and more efficient resource use.

Future market development will depend on improvements in material performance, production scalability, economic feasibility, and standardization. Further collaboration among researchers, manufacturers, and designers will be necessary to establish certification frameworks and facilitate broader industrial adoption. As demand for renewable and low-carbon materials continues to increase, mycelium-based products may become an important component of sustainable wood-based value chains.

An ongoing collaborative project between Slovenia and Argentina further supports the development of mycelium-based products through knowledge exchange, joint research activities, and the utilization of locally available biomass resources in both countries.

4. CONCLUSION

Mycelium-based materials represent a promising bio-based alternative for sustainable design, construction, and wood-product applications. The case studies from Slovenia and Argentina demonstrate how locally available agricultural and forestry residues can be utilized to produce biodegradable materials that support circular economy principles and low-carbon material systems. In addition, the student-developed prototypes illustrate the potential of combining mycelium biocomposites with wood to create innovative structural, insulating, and decorative products.

The results highlight the importance of fungal species, substrate composition, and cultivation conditions in determining material properties and application potential. Consistent with the principles of the New European Bauhaus, mycelium-based materials offer opportunities to integrate sustainability, functionality, and aesthetics through renewable resources and localized production.

Despite their considerable potential, challenges related to durability, large-scale manufacturing, certification, and material standardization remain. Further interdisciplinary research and industry collaboration are needed to improve material performance and facilitate broader market adoption. As technological development continues, mycelium-based materials may become an important component of future sustainable and circular wood-based value chains.

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REFERENCES

1. Appels, F. V. W., Camere, S., Montalti, et al. (2019): *Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites*. Materials & Design, 161, 64–71. *https://doi.org/10.1016/j.matdes.2018.11.027*
2. Attis, N.; Danai O.; Abitbol, T., et al. (2020): *Mycelium bio-composites in industrial design and architecture: Comparative review and experimental analysis*. Journal of Cleaner Production, 246 (2020) 119037. *https://doi.org/10.1016/j.jclepro.2019.119037*
3. Hyde, K.D., Xu, J., Rapior, S., et al. (2019): *The amazing potential of fungi: 50 ways we can exploit fungi industrially.* Fungal Divers. https://doi.org/10.1007/s13225-019-00430-9.
4. Jones, M., Huynh, T., Dekiwadia, C., Daver, F., John, S. (2017): *Mycelium composites: a review of engineering characteristics and growth kinetics.* J. Bionanoscience 11, 241e257. *https://doi.org/10.1166/jbns.2017.1440.*

Authors address:
Manja Kitek Kuzman[1], Mirko Karič[2], Sebastian Pablo Galarco[3]
[1,2] Department of Wood Science and Technology, Biotechnical faculty, University of Ljubljana, Slovenia
[3] Techonological Wood REsearch Centre Universidad Nacional de La Plata, Buenos Aires, Argentina
*__Corresponding author: manja.kuzmen@bf.uni-lj.si__

ETHICAL BOUNDARIES IN FURNITURE ADVERTISING: ANALYSIS OF PUBLIC COMPLAINTS AND REGULATORY FINDINGS IN SR

Martina Nosáľová, Erika Loučanová, Miriam Olšiaková

Abstract: The paper examines the ethical aspects of advertising in the furniture sector in Slovakia, focusing on problematic and controversial advertising practices that have provoked public reactions. The analysis is based on consumer complaints and submissions handled by The Advertising Standards Council of Slovakia between 2014 and 2024. The aim of the paper is to identify the most frequent violations of ethical advertising principles in this segment and to highlight areas perceived by the public as unethical, misleading, or inappropriate. Based on a content analysis of the available decisions of The Advertising Standards Council, the paper maps recurring types of issues. The findings contribute to a better understanding of how consumers perceive advertising ethics and may serve as a basis for more responsible practices in furniture advertising, as well as a contribution to the discussion on advertising self-regulation in Slovakia.
Keywords: furniture advertising, ethical aspects of advertising, complaints, advertising self-regulation.

1. INTRODUCTION

Ethical and legal standards in marketing are key to ensuring transparency, building reputation, and striking a balance between profit and social responsibility (Hanuláková et al., 2021; Kotler and Keller, 2016). In the field of advertising, ethical and legal standards play an important role in ensuring the transparency of marketing communications. Unethical advertising, defined by misleading claims or the creation of unrealistic expectations (Karlíček et al., 2016), is often the target of public criticism and, according to Bartko (2019), is frequently questioned primarily for spreading false information or creating unrealistic expectations.

In the long term, it is beneficial for organizations to adhere to high ethical standards in addition to legal requirements. In the Slovak Republic, therefore, a comprehensive control system is in place, where statutory regulation intersects with self-regulation represented by The Advertising Standards Council (RPR), which, through the Code of Ethics for Advertising Practice, oversees the honesty, decency, and truthfulness of the messages disseminated (Advertising Council, 2015).

Advertisements are most of the times flirting with their forbidden content to catch the attention (Heckler et. al, 2001). A specific and often sensitive area of ethical assessment is the use of sexual appeal, the effectiveness of which varies depending on the type of product being promoted (Dhar and Wertenbroch, 2000). Severn et al. (1990) argues that an advert is successful when the sexual elements are accurate towards the product during the advert. While erotic motives fail for purely utilitarian products, research shows that they are more acceptable for hedonistic products focused on emotions, joy, and aesthetics (Hu et al., 2020).

As Gao and Wu (2025) note in their analysis of consumer preferences, the purchase of furniture today no longer serves merely a practical function but exhibits strong hedonistic traits, with consumers seeking aesthetic value, pleasure, and opportunities for self-expression. The

use of emotional or sensory appeals in furniture advertising is therefore justified, however, audience reactions vary significantly by gender and moral sensibilities, and an inappropriate level of erotic elements without a direct connection to the product often leads to ethical complaints from the public (Severn et al., 1990).

Unethical behaviour is encountered in all areas of the market, and the furniture sector is no exception. Various forms of misleading customers occur in the sale of furniture, whether it be false claims about quality, origin of materials, environmental friendliness of products, or hidden charges and opaque terms and conditions. Despite growing academic interest in business ethics, the furniture retail sector remains underexplored in this regard (Kaputa et al., 2019; Loučanová et al., 2018; Olšiaková and Loučanová, 2025; Olšiaková et al., 2017).

2. METHODS

The research part of the study is based on content analysis. The research sample consists of official decisions issued by the self-regulatory body for advertising: the Arbitration Commission of The Advertising Standards Council of the Slovak Republic (RPR) in years 2014-2024. Specifically, these are rulings assessing the ethical validity of complaints regarding advertisements in the furniture sector. The data were obtained through systematic selection from the organization's publicly available online archive. The criteria for including a ruling in the analyzed sample were the product category (furniture, interior furnishings) and the thematic focus of the advertisement. The empirical data obtained were processed in two phases. The quantitative analysis focused on tracking the number of cases over time (frequency and trends) and categorizing them into upheld and not upheld complaints. The distribution of cases by specific complainants and types of communication media was also monitored. The qualitative analysis subsequently focused on the textual content of the complaints and the findings themselves from an ethical perspective. The aim was to identify the most common themes of public complaints in furniture advertising and a better understanding of how consumers perceive advertising ethics, what may serve as a basis for more responsible practices in furniture advertising.

3. RESULTS

As part of the analysis, we tracked the trend in the number of advertising complaints received by The Advertising Standards Council (RPR) in Slovakia from 2014 to 2024. The total number of complaints has shown a steady downward trend since 2016. Throughout the entire period under review, the not upheld complaints have maintained a clear majority. This suggests that most complaints from the public were unfounded and that the campaigns did not violate the code of ethics. In 2017 upheld complaints reached their peak (40 cases) and, exceptionally, exceeded the number of not upheld complaints. The latest year tracked, 2024, shows a low in both categories, with only 10 violations upheld out of a total of few complaints. This trend is illustrated by the following graph (Figure 1), which combines an overall overview with a detailed breakdown of the Arbitration Commission's rulings. The curve represents the total volume of complaints received, which, after a sharp increase and a peak in 2016 (approximately 120 complaints), shows a long-term downward trend to a level of around 35 complaints in 2024. Upheld complaints, except for a fluctuation in 2017 (40 cases), have generally followed a downward trend from over 30 in 2014 to just 10 in 2024. The number of not upheld complaints

has remained higher than the number of upheld complaints throughout the entire period under review, although their absolute number has also gradually decreased over time from the 52 (in 2014) to 25 (in 2024).

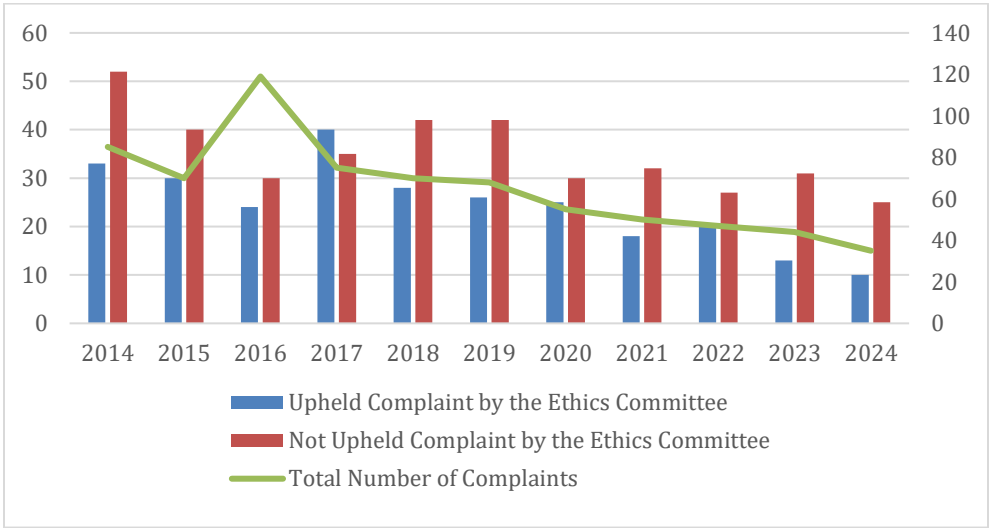

Figure 1. Comparison of the total number of complaints received by the RPR (2014–2024)

We then focused on assessing the furniture sector in the context of the total number of advertisement complaints reviewed (Figure 2).

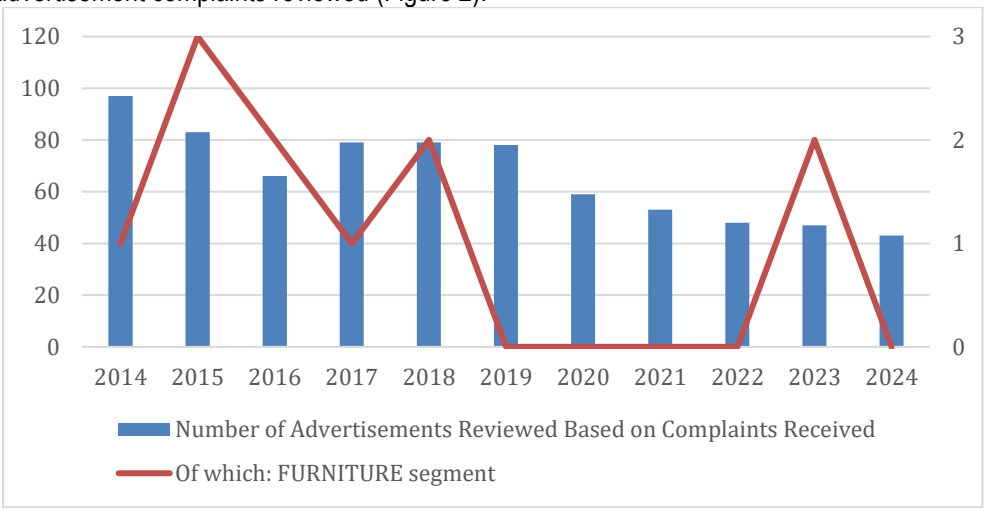

Figure 2. Overview of Reviewed Advertisements and the Furniture Segment (2014–2024)

The data show that the furniture segment accounts for only a minimal share of the RPR's caseload, with the annual number of complaints amounting to just a few cases. The orange curve represents the absolute number of complaints specifically related to the furniture sector. This amounts to only a few cases per year. The highest number of complaints regarding furniture advertising (three cases each) was recorded in 2015 and 2018. Between 2019 and

2022, and subsequently in 2024, no advertisements were reviewed in this sector (with the exception of 2023, which had 2 complaints).

The following content analysis of decisions made by the self-regulatory body, The Advertising Standards Council (RPR), between 2014 and 2024 revealed specific ethical challenges in the furniture sector in Slovakia (Table 1). During the period under review, 11 complaints were identified that were brought before the RPR Arbitration Commission. Of the total 10 cases, 5 cases resulted in the complaint being upheld and 6 cases resulting in the complaints not upheld. In terms of the nature of the complaints, two main themes dominate in this segment: sexualization/erotica (5 cases) and misleading consumers (5 cases). One specific case concerned ethics in relation to animals.

Table 1. Content Analysis Results: Decisions of the RPR, 2014–2024

YEAR	COMPANY	MEDIUM	NATURE OF COMPLAINT	RPR RULING	CODE BREACH ACCORDING TO RPR CODE
2014	Oresi Slovakia s.r.o.	Print advertising	Misleading information about price	Complaint Not Upheld	
2015	Kika Nábytok Slovensko s.r.o.	TV commercial	Misleading information about price	Complaint Upheld	Art. 14 Truthfulness of Advertising, par. 5, let. b) Financial value of a product
2015	Exima s.r.o.	Billboard	Inappropriate depiction of the female body	Complaint Upheld	Art. 11 Decency of Advertising, par. 1, let. e) Depiction of women
2015	PHASE s.r.o.	Billboard	Visual and slogan evoke an immoral meaning	Complaint Not Upheld	
2016	Black Red White a.s.	Radio commercial	Misleading information about price	Complaint Upheld	Art. 14 Truthfulness of Advertising, par. 5, let. b) Financial value of a product
2016	Tempo Kondela s.r.o.	Catalog and website	Misleading information about product origin	Complaint Upheld	Art. 14 Truthfulness of Advertising, par. 5, let. a) Misleading the consumer
2017 2018	Mobelix s.r.o.	TV commercial	Sexual content and broadcasting at inappropriate time	Complaint Not Upheld	
2018	Mobelix s.r.o.	TV commercial	Animal cruelty	Complaint Not Upheld	
2023	XLSK Nábytok s.r.o.	Leaflet	Misleading information about price	Complaint Not Upheld	
2023	Mojaskrina.sk	Internet advertising	Inappropriate depiction of the female body	Complaint Upheld	Art. 11 Decency of Advertising, par. 1, let. e) Depiction of women

The use of the human body and sexual innuendo is a common, yet highly risky, marketing practice in the furniture industry. The analysis shows that public reactions and subsequent RPR rulings depend on the degree of explicitness and the chosen medium of communication.

- Complaints upheld: The cases involving Exima s. r. o. (2015, billboard) and Mojaskrina.sk (2023, online advertisement) elicited negative reactions from some members of

the public due to the "inappropriate depiction of the female body" (Art. 11 Decency of Advertising; Depiction of women).

- Complaints not upheld: The Commission assessed ethical failures in two cases. In the case of a billboard by PHASE s. r. o. (2015), the issue was an inappropriate combination of visuals and a slogan evoking an immoral meaning in an outdoor space that reaches a broad public, including children. In 2017 and 2018, the Commission assessed television commercials by Mobelix s. r. o.: the erotic theme and its inappropriate scheduling for television broadcasts at times when minors are the audience. These cases illustrate an important phenomenon, that the line between what consumers subjectively perceive as distasteful or controversial and what actually violates the self-regulatory code of ethics is relatively thin in Slovak society.

The second major area of conflict concerns the accuracy of information that directly influences consumers' economic behavior.

- Complaints upheld: This category includes three major cases. In 2015, a television commercial by Kika Nábytok Slovensko s. r. o. was found in violation due to misleading information about pricing (Art. 14 Truthfulness of Advertising, par. 5, let. b) Financial value of a product). In 2016, complaints regarding a radio advertisement by Black Red White a. s. (misleading information about a discount) and the website of Tempo Kondela s. r. o. (misleading information about the product's origin) were also considered justified (Art. 14 Truthfulness of Advertising; Misleading the consumer and Financial value of a product).
- Complaints not upheld: In 2014, this involved a print advertisement by Oresi Slovakia s. r. o., which used a misleading slogan about providing free 3D designs. In 2023, the commission assessed a flyer by XLSK Nábytok s. r. o. due to misleading information about the amount of discounts. Although the advertisers did not violate the ethical rules, the very existence of the complaints demonstrates that Slovak consumers closely monitor product claims and are sensitive to any signs of unfair practices.

The public's ethical expectations are no longer limited to the protection of human dignity or the protection of minors. Modern consumers view advertising through a broader social and humanitarian lens, as evidenced by a complaint filed in 2018 against a television commercial by Mobelix s. r. o., which was challenged on suspicion of promoting animal cruelty. In terms of market structure, Mobelix s. r. o. appears repeatedly in the complaints (3 complaints in 2017–2018). This presence reflects a period of a more aggressively oriented communication strategy that worked with controversial themes (erotica, shocking imagery) on the edge of ethical norms. The five-year gap in complaints between 2018 and 2023 may indicate the gradual maturation of the market, a higher degree of self-discipline among advertisers in the furniture segment, or a shift of advertising activities to the online environment.

4. CONCLUSIONS

Ethical issues surrounding eroticism and price and information transparency remain relevant in the furniture industry today. As soon as a creative concept crosses the line of what subscribers perceive as good taste, it can generate an immediate negative public response. And while topics related to sexuality are more visually shocking, purely economic claims (such as misleading information about a product or its price) also pose ethical problems in the furniture industry.

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REFERENCES

1. Dhar, R., Wertenbroch, K. (2000): Consumer Choice between Hedonic and Utilitarian Goods. *Journal of Marketing Research,* 37: pp. 60-71.
2. Gao, S.; Wu, L. (2025): Understanding consumer preferences for hedonic furniture: A push-pull-mooring analysis. *Empirical Studies of the Arts,* 43(1), pp. 123–145.
3. Heckler, S.E., Jackson, S. & Reichert, T. (2001): Sexual Appeals in advertising. *Journal of advertising*, 30(1).
4. Hu, F.; Wu, Q.; Li, Y.; Xu, W.; Zhao, L.; Sun., Q. (2020): Love at First Glance but Not After Deep Consideration: The Impact of Sexually Appealing Advertising on Product Preferences. *Frontiers in Neuroscience*. 14, pp. 465.
5. Kaputa, V.; Olšiaková, M.; Maťová, H.; & Drličková, E. (2019). Do preferences for wood-framed houses' attributes change over time? *Digitalisation and circular economy: Forestry and forestry based industry implications*, pp. 161–168.
6. Karlíček, M. a kol. (2016). *Marketingová komunikace: Jak komunikovat na našem trhu* (2. vyd.). Grada Publishing.
7. Loučanová, E.; Nosáľová, M.; Parobek, J.; & Dopico, A. (2018): The Kano model use to evaluate the perception of intelligent and active packaging of Slovak customers. *Studia Universitatis Vasile Goldis Arad, Seria Stiinte Economice*, 28(1), pp. 35–45.
8. Olšiaková, M.; Loučanová, E. (2025): Unethical Practices in Furniture Sales: Consumer Experiences and Recommendations for Responsible Business. *Drvna industrija, 76* (4), pp. 455-464.
9. Olšiaková, M.; Loučanová, E.; Kalamárová, M. (2017): Application of new trends of marketing communication as a competitiveness tool in furniture industry. *More wood, better management, increasing effectiveness: Starting points and perspective: Proceedings of scientific papers,* pp. 5–10. Czech University of Life Sciences Prague; WoodEMA.
10. Severn, J.; Belch, G. E.; Belch, M. A. (1990): The Effects of Sexual and Non-Sexual Advertising Appeals and Information Level on Cognitive Processing and Communication Effectiveness. *Journal of Advertising*, *19*(1), pp. 14–22.
11. ***: Advertising council (2015): *Ethical Principles of Advertising Practice.* URL: https://rpr.sk/en/ethical-principles/
12. ***: Bartko, T. (2019): *Nekalá súťaž a ochrana pred ňou.* URL: https://www.podnikajte.sk/obchodne-pravo/nekala-sutaz-a-ochrana-pred-nou

Authors address:
Nosáľová, M. [1], Loučanová, E.[1], Olšiaková, M.[1],
[1] Department of Marketing, Trade and World Forestry, Faculty of Wood Sciences and Technology, Technical University, Zvolen, Slovakia
*Corresponding author: nosalova@tuzvo.sk

LINKEDIN AND CEO BRANDING IN THE SLOVAK WOOD INDUSTRY

Simona Mikušová, Lucia Ježeková Havlíková

Abstract: The study focuses on the use of the largest professional network LinkedIn in the wood industry segment. Our goal was to establish to what extent and for what purposes the selected companies utilize it, as well as to identify the most common shortcomings in their communication strategy. The research took place in the form of quantitative content analysis of the profiles of six companies, with the sample comprising two small, two medium, and two large businesses. The analysis included both company and CEO profiles on LinkedIn. In the published posts, we identified the periodicity of publication, post topic, communication goal, target group, type of communication, content form, as well as the post's value framework. The results led us to the conclusion that this segment was poorly visible on the platform and even those who actually use LinkedIn mostly exhibited low activity and failed to fully utilize the opportunities offered by the platform. The findings also suggest that companies do not understand the specifics of this network, which negatively affects the effectiveness of their communication.

Keywords: LinkedIn, social networks, wood industry, CEO personal brand, digital communication

1. LINKEDIN IN CORPORATE COMMUNICATION

LinkedIn is considered the largest professional network interconnecting professionals around the globe. It has more than 850 million members in 200 countries (LinkedIn, 2026). According to data by datareportal.com, this network has 970 000 members in Slovakia, which remains a low number compared to the most used social network Facebook that is used by 2.6 million Slovaks (Kemp, 2025). Nevertheless, LinkedIn remains (within B2B context) an important professional platform used for career development, building a professional network and organizing communication (Khorshidi et al., 2025).

The use of social media comes with the potential to generate higher brand awareness, better visibility, greater traffic, and higher purchasing intent compared to, for instance, traditional marketing, being also more cost-effective. However, many businesses are yet to fully understand the potential benefits of using social media as their marketing communication tool, especially small and medium-sized businesses in the B2B sector (Michaelidou et al., 2011). Creating valuable content for B2B audience requires brands to adopt an approach encompassing a thorough understanding of information needs of the target audience. Valuable content is characterized as useful, relevant, persuasive, and topical. At the same time, content marketing necessitates a shift in corporate culture, from sales-oriented to customer-support-oriented culture, which requires different marketing goals, tactics, metrics, and competencies compared to traditional marketing approaches (Holliman et al., 2018). However, the ever-changing nature of digital marketing requires adaptability. Communicating on LinkedIn should be data-driven, supported by LinkedIn's analytical tools. This ensures that marketing activities are optimized for maximum reach (Saeidi, S., & Hollensen, S., 2024).

2. RESEARCH METHODS

The goal of the submitted study was to find out how companies operating in the wood industry in Slovakia use LinkedIn in their external communication and to propose a series of

recommendations for better utilization of this social network. The research was quantitatively focused.

2.1. Phase 1

In Phase 1, we focused on identifying companies operating in the wood industry in Slovakia. Our intention was to select companies of different sizes (small, medium, large). Our selection was based on the European Commission's classification that defines small businesses as those with fewer than 50 employees and an annual turnover or balance sheet total not exceeding €10 million, medium-sized businesses being those with fewer than 250 employees and an annual turnover below €50 million, and large enterprises as those exceeding the aforementioned limits (European Commission, n.d.). An active LinkedIn profile, either a company or a CEO profile, was a prerequisite for being included in the research sample. We considered a profile to be active if it published at least one post during the period under review, from December 2025 to May 2026. Our final sample consisted of six companies and three CEO profiles. The study featured anonymized specific company names and CEO names; however, in the table below we list identification features such as company size, year of establishment, and area of operation. The reason behind this approach was to focus attention on the studied communication phenomena, not on specific actors.

Table 1 Analyzed companies

Company	Size	Activities	Founded
Company 1 (C1)	small	distributor of wooden decks, facades, and hardwood flooring	2003
Company 2 (C2)	small	construction of wooden houses	2011
Company 3 (C3)	medium	furniture manufacturer	1996
Company 4 (C4)	medium	furniture manufacturer	1954
Company 5 (C5)	large	furniture manufacturer	2003
Company 6 (C6)	large	manufacture of paper products	1990

2.2. Phase 2

In Phase 2 of our research, we conducted a quantitative content analysis of LinkedIn communication by selected companies and their CEOs. The greatest advantages of this type of research are described by Greguš (2026) as representativeness, generalizability, higher degree of objectivity, and clarity. On the other hand, he lists as its limiting factor the fact that researchers cannot go in-depth and answer the question "Why?" The research focused on identifying the main communication topics, communication goals, and presentation forms of this content. In this respect, we formulated the following three research questions:

RQ1: What is the visibility of companies operating in the wood industry in Slovakia and their CEOs on the LinkedIn platform?

RQ2: Which communication strategies of company and CEO profiles proved to be the most and least effective?
RQ3: To what extent do wood industry companies and their CEOs use LinkedIn in a manner that is considered effective in terms of to-date research?

The unit of analysis was an individual post published on the LinkedIn platform during the six-month period from December 2025 to May 2026. The coding process was based on pre-defined categories created based on research questions (Mayring, 2000). Our categories included: post topic, communication goal, target group, communication type, content form, and the post's value framework.

2.3. Research limits

We consider the main limit of our research to be the rather small research sample, which was due to the low utilization rate of this platform among businesses. Several companies, which we identified as suitable for research, did not have any company or CEO profile created or did not meet the minimum platform activity criterion. A similar situation arose in connection with CEO profiles.

3. RESEARCH RESULTS

Early in the initial phase of our research (selection of companies), it was the utilization rate of the social network LinkedIn that proved to be a major limitation for the researched topic. Many identified entities were either not present on the platform or their activity was significantly limited. For instance, they did not meet the criterion of at least one published post during the six-month period under review. Also, out of the six selected businesses, only half of CEOs had an active LinkedIn profile. All that despite the fact that distribution of CEO's views can affect a business (Chatterji & Toffel, 2017) as people active on social networks create connections and build trust with stakeholders, thereby enhancing their personal and company reputation (Tsai & Men, 2017). Personal CEO profiles exhibit a significant communication potential to reach an audience. This was also confirmed by IRF Reputation AG (2025) study, which found that 24 inactive CEO profiles from among the 100 largest Swiss businesses had a combined total of more than 62 000 followers, even though they didn't publish anything or just one or two posts per year. This illustrates the interest in a CEO as a person and also shows how much reach and potential influence remains non-utilized.

RQ1: What is the visibility of companies operating in the wood industry in Slovakia and their CEOs on the LinkedIn platform?

Very early in the pre-research phase, it became clear that companies operating in the wood industry in Slovakia were not sufficiently visible on the LinkedIn platform. Most of the pre-identified businesses were not present on the platform at all and we noted low visibility with others. For instance, C2 published just one post over a six-month period. On the contrary, C1 was the most active with 40 posts. Three out of six CEOs met the criterion of being actively present on the network. Their activity rates varied as well. The most active was CEO3 with 23 posts, followed by CEO2 with 10 posts and, finally, CEO5 with three posts that were however all reshares. While C2 was minimally active (1 post), CEO2 was more active (10 posts) with the average interaction rate per post of 2.16%. We used the following formula to calculate the interaction rate:

$$\text{Interaction rate (\%)} = \frac{\text{likes + comments + shares}}{\text{number of followers}} \times 100$$

When comparing C3 and CEO3 profiles, the personal profile proved to be the more successful in terms of interactions. The average interaction rate per company post reached 1.61% while with CEO3 it came at 1.82%.

RQ2: Which communication strategies of company and CEO profiles proved to be the least and most effective?

With this research question, we identified several intriguing findings. The following strategies proved to be less effective:

1. **Content not taking into account network's specifics.** Companies often focus on mechanically promoting their services and goods and use LinkedIn as an advertising channel. The studied profiles did not take into account the interaction level and the success rate of their posts over time to adapt their publishing strategy on the social network based on them.
2. **Unsuitable for promoting products and services.** The strategy of promoting goods and services proved to be ineffective and did not serve its purpose. Posts lacked an attractive form and content that would boost the audience engagement rate. C1 company serves as an example of this, dedicating up to 92.5% of its posts to promoting services and goods. It has 55 followers on the network, the number of likes mostly range between 0 and 2.
3. **Low publication rate.** The publishing periodicity of posts was also problematic, being inconsistent and irregular.

On the other hand, our research showed the following strategies to be effective:

1. **It is worth investing time and energy into a CEO profile.** Personal profiles achieve higher organic reach than company profiles; a personal profile tends to be the main source of reach and business networking. A well-built CEO profile can fulfill the role of a brand or company ambassador.
2. **A story-based post is valued the most.** Research has shown that posts focusing on a personal story, CEO's or company success, as well as conclusion of new partnerships, generate the most interaction and interest on LinkedIn.
3. **Communicating values makes sense.** Perhaps with the exception of quality that was mainly associated with the promotion of goods and services. The company values highlighting the work of ordinary employees, corporate responsibility, empathy and humanity, as well as belonging and community, all resonated well.

RQ3: To what extent do wood industry companies and their CEOs use LinkedIn in a manner that is considered effective in terms of to-date research?

The results show that companies in the wood industry and their CEOs do not use LinkedIn wholly in line with the principles of effective communication. Companies mostly create content aimed at promoting their products and services. This approach proves to be ineffective and generates very low interaction. Although elements of quality communication do appear within the analyzed profiles, such as stories or presentations of company achievements, partnerships, and employees, their presence is rather sporadic. Little attention is paid to building a brand, presenting corporate values, or actively engaging the community. In many cases, CEO profiles remain inactive or absent, causing businesses to lose an ambassador. All the while a CEO is considered the main corporate communicator and a symbol of the company's identity (Conte et al., 2017). CEO's communication via LinkedIn can influence how the market and stakeholders perceive the company (Frei, 2025). The introduction of social

media as communication tools has changed the way corporations manage their reputation. Those are CEOs in particular who face new responsibilities since they deal with their personal image that also affects their company's reputation (Marx et al., 2020). According to data analysis by Refine Labs, content published on personal LinkedIn profiles achieved 2.75x more views and five times higher engagement rate compared to content published on company websites (Walker, 2023).

3.1. Practical recommendations

From our perspective, the LinkedIn platform is justified to be included in the marketing mix, provided that the company has a clear communication strategy, knows the specifics of this platform, and has an ambassador who can actively and effectively act on behalf of the company. Based on the study results, we formulated 5 basic recommendations for companies and CEOs in the wood industry segment:

1. **Focus more on a story, emotion, or experience rather than on a product or information**
   Posts based on stories behind employees, projects, the company, or the CEO, make audience more interested. Instead of reporting facts, users want to hear a story.
2. **Find a brand ambassador**
   Content posted on personal profiles achieves greater reach than on company profiles. People want to follow people. The most suitable natural ambassador of a company is a CEO who generates greatest interest in the audience. However, any employee who is able to communicate by his/her personal story or experience can also act as an ambassador.
3. **Regular and consistent publishing of posts**
   The greatest shortcoming exhibited by analyzed companies was low and irregular activity. Effective communication requires consistency and regular publication of quality content. The evaluation and analysis of successful content play an important part as well.
4. **Personnel capacities and content**
   A major problem suffered by studied profiles was the lack of quality content and an apparent lack of personnel capacities able to create and publish attractive content. It is crucial to identify personnel capacities within a company.
5. **Creating posts with a potential to generate interaction**
   Both companies and CEOs should create posts encouraging discussion. Ask questions, participate in expert discussions, reply to comments. A higher interaction rate improves natural organic reach of posts and profile visibility, among others.

The above recommendations follow on the findings of the study. By implementing them, businesses and CEOs can effectively strengthen communication and build their brands on LinkedIn.

REFERENCES

1. Conte, F., Siano, A., & Vollero, A. (2017). CEO communication: engagement, longevity and founder centrality: an exploratory study in Italy. Corporate Communications: An International Journal. https://doi.org/10.1108/CCIJ-10-2015-0062
2. European Union. (n.d.). Small and medium-sized enterprises (SMEs). https://eur-lex.europa.eu/SK/legal-content/glossary/small-and-medium-sized-enterprises.html

3. Frei, S. (2025), IRF Reputation AG. (2025). CEO-Positionierung auf LinkedIn 2025: Analyse, Benchmarks und Handlungsempfehlungen https://www.irf-reputation.ch/en/news/irf-study-ceo-positioning-linkedin
4. Greguš, L. (2024): Úvod do kvantitatívnej obsahovej analýzy v mediálnych a komunikačných štúdiách. EQUILIBRIA, s.r.o. ISBN: 978-80-8143-378-8.
5. Holliman, G., & Rowley, J. (2014). Business to business digital content marketing: Marketers' perceptions of best practice. Journal of Research in Interactive Marketing. https://doi.org/10.1108/JRIM-02-2014-0013
6. Chatterji, A. K., & Toffel, M. W. (2017). Do CEO activists make a difference? Evidence from a quasi-field experiment. Harvard Business School Working Paper No. 16-100. https://doi.org/10.2139/ssrn.2742209
7. Kemp, S. (2025), Digital 2025: Slovakia.https://datareportal.com/reports/digital-2025-slovakia
8. Khorshidi, M. S., Merigó, J. M., & Beydoun, G. (2025). Scientific production on LinkedIn: A bibliometric review. Business and Professional Communication Quarterly. https://doi.org/10.1177/23294906251345075
9. LinkedIn. (2026). About LinkedIn. https://about.linkedin.com/cs-cz?lr=1
10. LinkedIn. (2025). DSA transparency report (02/2025). https://content.linkedin.com/content/dam/help/tns/en/February-2025-DSA-Transparency-Report.pdf
11. LinkedIn. (2026). Transparency disclosures under the Digital Services Act. https://www.linkedin.com/help/linkedin/answer/a1678508
12. Marx, J., Mirbabaie, M., & Stieglitz, S. (2020). You are now an influencer! Measuring CEO reputation in social media. arXiv. https://doi.org/10.48550/arXiv.2004.08569
13. Mayring, P. (2014). Qualitative content analysis: theoretical foundation, basic procedures and software solution. https://www.ssoar.info/ssoar/handle/document/39517
14. Michaelidou, N., Siamagka, N. T., & Christodoulides, G. (2011). https://doi.org/10.1016/j.indmarman.2011.09.009
15. Saeidi, N. & Hollensen, S. (2024). Digital marketing on LinkedIn: In-depth strategies for lead generation. American Journal of Industrial and Business Management. https://www.scirp.org/journal/paperinformation?paperid=133009
16. Tsai, W. H. S., & Men, L. R. (2017). Social CEOs: The effects of CEOs' communication styles and parasocial interaction on social networking sites. https://doi.org/10.1177/1461444816643922
17. Walker, Ch., Refine Labs. (2023). Personal LinkedIn profiles outperform company pages with 5x more engagement. Industry Report. Refine Labs

Authors address:
Mikušová, S.[1]; Ježeková Havlíková, L.[2];
[1] University of Ss. Cyril and Methodius in Trnava, Slovakia
[2] PhD. applicant, University of Ss. Cyril and Methodius in Trnava, Slovakia
*Corresponding author: simona.mikusova@ucm.sk

AN OVERVIEW OF FOREST PRODUCTS MARKETS IN THE SVERDLOVSK REGION OF RUSSIA

Natalia Pryadilina, Ph.D., Richard Vlosky, Ph.D.

Abstract: Forest products are widely used in various sectors of national economies. In this article, we focus on the Sverdlovsk region (in the Ural region) of Russia which has abundant forest resources and is an important part of the regional economy. The purpose of the study was to examine the forestry and the timber industry complex of the region. Specifically, we examine competitiveness, production capacity, and market conditions. We share an overview of the forest sector including domestic markets and trade flows as well as providing a SWOT analysis of marketing activities in the regional forest sector. Finally, we present recommendations aimed at identifying new markets that are promising in terms of regional supply and demand dynamics.

1. INTRODUCTION

Wood products are widely used in many industry sectors. Most importantly, production and consumption of wood in housing, furniture, and pulp and paper largely determine economic, social, and cultural levels of many forest-based regions. Accordingly, it is important to assess the forest reserves in the world as a whole, and in those countries that are rich in forest resources. More than half (54%) of the world's forests are in five countries: Russia, Brazil, Canada, the United States of America, and China.

As such, Russia is one of the richest countries in the world in terms of potential forest resources development. As of 2020, Russia accounts for about 22% of the area of global (815 million hectares), almost a quarter of the world's wood reserves and about 60% of industrial forests (FAO. 2020, Abadov et al. 2022). However, the potential for the Russian forestry and timber industry (hereinafter referred to as the FTI) development is far short of what is taking place. During the post–Soviet years, the share of Russia global production of lumber decreased by four times, paper and cardboard – by almost two times, plywood and slabs – by more than 2.1 times (Kolykhalov 2011). Overall, Russia produces only about 2.0% of the total output of the world's FTI, compared to the USA with 12.7% and Canada with 17.3%. Even shares for smaller Scandinavian countries is several times larger; Finland – 8.4% and Sweden – 10.1%.

2. FOREST SECTOR GROWTH IN THE RUSSIAN SVERDLOVSK REGION

An area for potential forest sector growth in Russia is the Sverdlovsk region (**Figure 1**) which ranks tenth in timber harvesting, sixth in lumber production, and fourth in plywood production (Lobovikov and Pryadilina 2020). This production potential is due to the following factors: favorable economic and geographical location, experience in the development of forest industries, significant forest inventory for logging and wood processing, and a wide range of forest products processing facilities. Almost every municipality in the region has forest enterprises.These enterprises significantly influence economic, social, and environmental conditions of local communities.

Figure 1. Sverdlovsk Region

Currently, the forest sector in the Sverdlovsk region produces less than 1.5% of the total volume of shipments of industrial products in the region. Unfortunately, the forest sector is not a priority sector of the economy. As such, the role of forest resources for the region is insignificant relative to its potential (Petrov and Pryadilina 2019). There are no initiatives to raise awareness or promote the industry. The region has ample forest resources to support long-term economic development for manufacturing for domestic and export customers.

The allowable annual cut (AAC) in industrial and protective forests in the region is intended to ensure multiple use, rational, continuous, and sustainable forest use. It is based on logging and reforestation, biodiversity conservation, and water and soil protection. The allowable logging in the Sverdlovsk region is 23.8 million m^3, including 9.8 million m^3 of coniferous species accounting for about 1.3% of the total wood stock in the Russia (102.2 billion m^3). In 2021 there were 1,633 forest leasing agreements covering 5.4 million hectares in Sverdlovsk region. The actual timber harvesting in the region in 2021 amounted to 7.1 million m^3, which is 29.7% of the allowable cut. Of the total wood harvested, coniferous species account for 3.7 million m^3, which is only 38% of the coniferous annual allowable cut.

The forest of the Sverdlovsk region has huge natural and ecological potential. With adherence to environmental requirements, this potential could meet long-term needs of the region. However, there are several regional factors that impede forest development including a lack of objective and reliable forest inventory information, lack of all-season forest roads, nonexistent staffing and training strategies for employees in the forest sector supply chain, insufficient investment and innovation in wood processing, and high wood transportation costs.

The main problematic issue is the absence of a regional forest strategic development program (Pryadilina and Damary 2018, Pryadilina 2019). This program should be an integral part of the federal forest sector program. It should formulate regional priorities and include supply and demand analyses for developing domestic and export wood markets (Pryadilina, Starikov, and Mezentseva 2017, Pryadilina 2019). In addition, the growing demand for wood products, development of modern wood-based materials, introduction of new manufacturing

technologies, growth of wood housing and increased interest in forest investments require innovative approaches to forest marketing.

3. NATIONAL BARRIERS CONTRIBUTING LACK OF FOREST SECTOR DEVELOPMENT

Business confidence nationally has fallen sharply due to the aggravation of the geopolitical situation, economic sanctions, and lingering effects of the coronavirus pandemic. Restricted access of the Russian business to the international financial markets and tightened monetary policy has caused a significant increase in the cost of money borrowing. The higher bank lending rates have caused investment downfall, capital outflow, and a surge in inflation. Unstable oil and gas prices led to a significant depreciation of the national currency. As a result, servicing foreign currency loans has become more difficult (Gurvich and Prilepsky 2016). The prices for high-tech imported machinery and equipment have increased. The soaring prices have questioned success of many ongoing forest investments.

Table 1 represents a SWOT analysis of the marketing activities of the forest sector in the Sverdlovsk region. The range of the main types of products of the forestry sector includes sawn timber, plywood, particle and fiberboard, paper and cardboard, wallpaper, round timber, wood pellets (pallets), furniture, wooden house kits, and wooden crates, charcoal.

The largest enterprises of the forest sector of the Sverdlovsk region include:

1. Private Joint Stock Company (PJSC)"SVEZA Verkhnyaya Sinyachikha" (plywood);
2. ZAO Turin Pulp and Paper Plant (paper, wallpaper, fiberboard);
3. Novolyalinsky Pulp and Paper Mill, LLC (paper, waterproof cardboard);
4. Tavdinsky Plywood and Board Mill, LLC (plywood).

The Russian Export Center promotes exports to enterprises in the Sverdlovsk region. The Center was created as a specialized organization and a "single window" for working with exporters in the field of financial and non-financial support measures. It is associated with the relevant ministries and departments that carry out functions for the development of foreign economic activity.

Table 1. SWOT analysis of the marketing activities of the Sverdlovsk regional forest sector

Strength	Weaknesses
➢ High quality products due to the use of modern best available technology; ➢ A wide range of products; ➢ Work on individual customer orders; ➢ Excellent reputation in the Russian forest market; ➢ Customer loyalty.	➢ Lack of a regional forest sector development program; ➢ Lack of a common marketing strategy; ➢ Passive sales policy; ➢ Narrowness of the database of potential buyers, including exporters; ➢ Underdeveloped dealer network; ➢ Low efficiency of the advertising campaign;

	➢ Lack of analysis of the turnover of goods in the context of individual nomenclature groups; ➢ Remoteness from the main consumer centers, poor development of transport infrastructure and logistics, high transport tariffs.
Opportunities	Threats
➢ Optimization of the production structure and product range; ➢ Changing patterns of movement of commodity flows to ensure savings in current costs, including those associated with the transportation of raw materials and finished products; ➢ Obtaining state support, participation in the implementation of state regional forest programs of the Sverdlovsk region; ➢ Delivery of timber for export; ➢ Increasing demand for sawn timber and woodworking products in the Sverdlovsk Region and nearby regions; ➢ Opening of a regional export timber center; ➢ Development of the biofuel industry; ➢ Use of sales promotion activities.	➢ Aggravation of the geopolitical situation and strengthening of anti-Russian economic sanctions; ➢ Uncertainties related to the coronavirus pandemic; ➢ Low solvency of the population, which reduces the possibility of supplying timber products to the domestic market; ➢ Growing competition from timber processing enterprises of nearby regions (Tyumen region, Khanty-Mansi Autonomous Okrug Yugra, etc.); ➢ Dumping by competitors; ➢ Growth of the market for low-rise individual housing construction made of bricks.

4. DISTRIBUTION OF THE MAIN FLOWS OF FOREST PRODUCTS

Calculations of the output of round timber based on actual harvesting in the Sverdlovsk region in 2021 are shown in Table. 2.

Table 2. Calculation of the round timber volumes based on actual harvesting in the Sverdlovsk region in 2021

Assortment	Volume, 1000 m^3	%
Coniferous saw logs and sleeper wood	1,563.2	22.0
Coniferous pulp wood, total	923.7	13.0
Construction timber and other assortments	142.1	2.0
Veneering wood	753.2	10.6
Deciduous sawlog	739.0	10.4
Broadleaf (hardwood) pulpwood	852.7	12.0

Decayed wood	355.3	5.0
Firewood, total	1,776.3	25.0
TOTAL	**7,105.5**	**100**

The region is almost completely self-sufficient in raw materials. Consumption of small-sized and low-quality wood for industrial processing in the region is insignificant. About 400,000 m3 of pulpwood and technological raw materials are not used, including aspen wood, firewood, and a mixture of varied species. Most of this wood is exported outside the region. Data on the volume of production and sales of forest products in the Sverdlovsk region in 2021, including exports, are shown in **Table. 3**.

Table 3. Type of products manufactured according to the Russian classification of types of economic activity

	Production volume	Consumption volume		Export volume	Share of exports in production volume, %
		Sverdlovsk region	Other regions		
Unprocessed timber (excluding fuel wood), 1000 m^3	5,200.0	3,305.0	1,700.0	195.0	3.7
Fuel wood, 1000 m^3	1,740.0	985.8	700.0	54.2	3.1
Wood sawn or split, divided into layers or peeled with a thickness of more than 6 mm, 1000 m^3	730.0	16.0	-	714.7	97.9
Untreated wooden sleepers for railways, 1000 m^3	4.9	-	-	4.9	100.0
Plywood, 1000 m^3	232.0	23.0	-	209.0	90.0
Fiberboards from wood or other lignified materials, million conditional m^2	11.1	-	9.3	1.8	16.2
Particle boards and similar boards made of wood or other lignified materials, 1000 m^3	56.0	21.1	-	34.9	62.3
Wood pulp and pulp from other fibrous materials, 1000 tons	34.4	33.4	-	1.0	2.9

	Production volume	Consumption volume		Export volume	Share of exports in production volume, %
		Sverdlovsk region	Other regions		
Paper and cardboard, 1000 tons	47.0	-	39.0	8.0	17.0

Exports of round wood from the region is the basis for planning large new investment projects. The timber industry of the region is focused on import substitution. The greatest success in the field of import substitution has been achieved in the production of plywood, cardboard, furniture, paper, packaging, building materials and housing construction. The region is interested in the development of wood chemistry - paints and varnishes, medical cosmetics, and resins from tree extracts.

An important indicator of progressive technologies is the assessment of their export opportunities. According to the customs statistics of the Sverdlovsk region, in 2021, the supply of wood and pulp and paper products (goods of 44-49 groups of Harmonized Commodity Description and Coding System, HCDCS) amounted to US$115 million, i.e., 9.3% of total exports.

The main export items of timber products of the Sverdlovsk region are sawn timber – 54%, plywood –41%, round timber – 5%, paper and cardboard – 0.5%. Small and medium-sized businesses form the basis of the lumber production segment. Most lumber producers are export-oriented due to the economic attractiveness and stability of demand in foreign markets. The most promising direction for the development of woodworking enterprises is modernization of production and transition to sawn wood production with improved geometric dimensions. The share of exported sawn wood in the total wood production since 2013 was about 0.2-0.4% and round timber – almost 15%.

The share of unprocessed timber exports by the enterprises of the forest sector of the Sverdlovsk region in 2021 was small, about 3.7%. Traditionally, hardwood construction timber and fuel wood are shipped as round wood to the CIS countries mainly to Kazakhstan and Uzbekistan. An insignificant part of birch pulpwood and firewood is supplied to China, Bulgaria, and Germany. High rail transportation tariffs and customs duties make this type of export activity unprofitable. In 2021, over half of all sawn timber produced in the region was exported. Uzbekistan and Azerbaijan became the main consumers of lumber in the CIS countries. The major non-CIS importers are Afghanistan and China.

Plywood is the basis of timber industry exports of the Sverdlovsk region. In 2021, 91.0% of plywood produced was exported. Plywood exports are mainly focused on the US and Europe. In terms of the global market, plywood is an interesting export item. More than 60% of Russian plywood products are exported abroad. The export volumes can be increased, since the world shortage of plywood reaches more than five million m^3 per year.

The high share of export products indicates the competitiveness of the forest sector of the Sverdlovsk region in international markets. The development of the domestic construction market and the market of wooden housing construction should reduce the share of plywood exports. A large product group is wooden boards. Particle- and fiberboards are used in the production of low-price furniture both within the Sverdlovsk region and beyond. The

export opportunities of this product are still limited due to the high transportation costs. It is necessary to develop a large regional segment of the Oriented Stand Boards (OSB), Medium Density Fiberboards (MDF) and High-Density Fiberboards (HDF). It is necessary to attract large external investors by employing the method of targeted investment proposals.

In 2021, 62.3% of produced particle boards and 16.2% of fiberboard were sold to the CIS countries. The priority items include industrial housing construction, logging growth, bioenergy and biochemistry, modern board materials, and wood-plastic composites.

The market for wooden housing construction in the Sverdlovsk region is developing at a moderate pace. The export of wooden house sets is insignificant. The development of wooden housing in the Sverdlovsk region has significant potential. Modern wooden building materials make it possible to build environmentally friendly multi-story buildings. Modern technologies are especially promising in the rural housing programs and for resettlement from dilapidated dwellings. Due to the pandemic, it is expected that the volume of construction of wooden country houses should increase in the near future.

The volume of production of pellets and briquettes in the region is approximately 55,000 tons per year. There is no increase in volumes due to the insufficient development of the domestic market for these products. The enterprises of the Sverdlovsk region have significant reserves for increasing the production of biofuel at existing enterprises and at newly created enterprises within the framework of priority investment projects. The main condition is the processing of wood waste, especially bioenergy. With well-organized advertising, an increase in demand for biofuels from private households can be expected. This will promote wood waste recycling, reduce environmental pollution, save energy resources, and guarantee employment.

5. CONCLUSION AND RECOMMENDATIONS

There is significant potential for the forestry sector growth in the Sverdlovsk region. It is driven by the growing demand of the global plywood and pulp market (primarily in Asia) and expansion of the domestic market for packing wood and paper boxes and containers, recycled cardboard, and large format plywood. In the future, the implementation of existing regional investment projects will be aimed at the development of wooden housing construction. It will decrease the sawn timber and plywood exports. The remoteness of the Sverdlovsk region from the main export markets of Europe, America, Africa, and the Middle East make the timber industry more oriented towards the domestic market and cooperation with the CIS Asian states.

The volume of demand for timber products in the domestic and export markets should be established at the federal level in the strategic planning documents. The calculation should consider sectoral and regional priorities. This calculation is not currently available.

Next, it will be important to develop a program for the Sverdlovsk region for the development of the regional forestry sector, which must necessarily include a section on demand assessment. The program should establish the demand for timber products and within the region, outside of the region and for export. Calculations should estimate the demand for timber products and services in the domestic and foreign markets. The plans should orient the forestry sector towards innovative development and new markets.

As an additional recommendation, the opening of a regional timber export center in the Sverdlovsk region should be considered. It will assume all marketing functions, from information to marketing, exhibitions, and congresses in the Russia and abroad.

It is assumed that the center should accompany the forest enterprises throughout their "life cycles" of production and market activities. At the same time, it is important to note the difficulty of integrating the Ural Federal District into international cooperation. Difficulties arise from the poor knowledge of successful experience. There are also no modern mechanisms for embedding regional products in the global supply chains and databases.

The interaction of enterprises with the regional center will allow them to promptly receive consulting services on a wide range of issues on drawing up foreign contracts and promoting wood products. The Center will provide access to extensive marketing information on the state and prospects of timber markets in our country and abroad. This will allow the enterprises of the region to build the right strategy for the development of the forest business.

With the help of the regional timber export center, timber enterprises will be able to expand business ties with potential partners abroad, get acquainted with current commercial foreign proposals and send their own requests to the international, regional, and national business associations. Wood enterprises will be able to participate in all public events organized by the regional forest export center independently or jointly with state or public structures (business meetings, negotiations with representatives of foreign delegations, conferences, seminars, symposiums, round tables, public hearings, exhibitions, etc.).

REFERENCES

1. Abidov O., Eastin I., Palacín J., Aguilar F., Fernholz K., Taylor R., Akim E., Glavonjić B., Valois M., Alderman D., Koskinen A., Vinterbäck J., Benedetti D., Lombard B., Wall J., Bumgardner M., and Mabee W. 2022. Forest Products Annual Market Review, 2021–2022. United Nations Economic Commission for Europe. https://unece.org/forests/fpamr2022. Accessed November 22, 2025.
2. FAO. 2020. Global Forest Resources Assessment 2020 – Key Findings. Rome, 2020. 16 pp. https://doi.org/10.4060/ca8753en. Accessed November 22, 2025.
3. Gurvich, E. T., and I. V. Prilepsky. 2016. The impact of financial sanctions on the Russian economy. *Vopr Ekon*. 1:5–35 (In Russian; English abstract unavailable.)
4. Kolykhalov, I. A. 2011. Foreign investments in the timber industry of the Russia. Dissertation for the degree of Candidate of Economic Sciences. Moscow, Russia. 24 pp. (In Russian; English abstract unavailable)
5. Lobovikov, M. and Pryadilina, N. 2020. Economic priorities of the strategic planning of forest sector in the Russia. IOP Conference Series: Earth and Environmental Science 5 (V Pan-Russian Scientific-Technical Conference – Webinar “Forests of Russia: Policy, Industry, Science and Education”).
6. Petrov, A., and Pryadilina. N. 2019. Priorities in forestry planning. IOP Conference Series: Earth and Environmental Science.
7. Pryadilina, N. K. 2018. Approach to economic planning for the development of the forest sector at the regional level (on the example of the Sverdlovsk region). *Economics: Yesterday, Today, Tomorrow*. 8(1A):122-133. (In Russian; English abstract unavailable)
8. Pryadilina, N. K., R. Damary. 2018. Strategic planning for the forestry sector of the economy of the Sverdlovsk region. In: Increasing the Use of Wood in the Global Bio-Economy – Proceedings of Scientific Papers, Glavonjić, B. (Editor-in-chief), September 26–28, 2018, Belgrade, Serbia. 11:354–360.
9. Pryadilina, N. K. 2019. Forest sector of the economy of the Sverdlovsk region: stages of development, current state, and problems of forest planning. Yekaterinburg: USFEU, Russia. 343 pp. (In Russian; English abstract unavailable).

10. Pryadilina, N. K., Starikov, E. N., and Mezentseva, E. S. 2017. The current state and prospects for the development of the timber industry complex of the Sverdlovsk region. *For. Eng. J*. 7(2):193–204. (In Russian; English abstract available).

Author addresses:
Pryadilina,N.[1]
[1]Department of Economics and Economic Security
Ural State Forest Engineering University
37, Siberian Tract, Yekaterinburg, 620100, Russia
Lotos_nk@inbox.ru
*Vlosky, R.[2]
[2]Professor & Director, Louisiana Forest Products Development Center
School of Renewable Natural Resources
Louisiana State University AgCenter
Baton Rouge, LA 70803 USA
rvlosky@agcenter.lsu.edu

GAMIFICATION IN MARKETING COMMUNICATION OF SUSTAINABLE WOOD PRODUCTS: EFFECTS ON CONSUMER ENGAGEMENT, PERCEIVED SUSTAINABILITY AND PURCHASE INTENTION

Neviana Krasteva, Aleksey Potebnya, Teodor Daskalov

Abstract: The growing importance of sustainable consumption and environmentally responsible production has increased the relevance of wood-based products as renewable and environmentally friendly alternatives to synthetic materials. Despite their ecological benefits, effectively communicating these advantages to consumers remains a challenge for companies operating in the forest-based and wood-processing industries. In recent years, gamification has emerged as an innovative marketing communication strategy that incorporates game elements such as rewards, challenges, and interactive experiences in non-game contexts to enhance user engagement and influence consumer behaviour. The purpose of this study is to examine the effect of gamified marketing communication on consumer engagement, perceived sustainability of wood products, and purchase intention. The research applies a conceptual model based on the Stimulus–Organism–Response framework, where gamification acts as a stimulus influencing internal consumer perceptions and responses. The empirical part of the study was conducted through a quantitative online survey among 256 consumers familiar with wood products and furniture. The data were analysed using descriptive statistics, correlation analysis, and regression modelling. The results indicate that gamified marketing communication positively influences consumer engagement and perceived sustainability, which in turn increase purchase intention toward sustainable wood products. The study contributes to the literature on digital marketing and sustainable consumption by showing how interactive marketing strategies can promote environmentally responsible products in the wood-based industry.
Keywords: gamification, marketing communication, sustainable wood products, consumer engagement, perceived sustainability, purchase intention

1. INTRODUCTION

Sustainable development has increased the demand for resource-efficient production and responsible consumption. Wood products are increasingly recognized as renewable, low-carbon alternatives that support the circular bioeconomy. However, their environmental benefits are often difficult for consumers to evaluate, creating information asymmetry between producers and consumers and limiting informed purchasing decisions.

Digital marketing offers new opportunities to communicate sustainability in a more engaging and accessible way. Among these approaches, gamification has attracted growing attention as a communication strategy that incorporates game design elements into non-game contexts to stimulate consumer participation and engagement. By transforming complex sustainability information into interactive experiences, gamification may improve consumers' understanding of environmental product attributes and strengthen trust in sustainability-related claims.

Although previous studies have demonstrated positive effects of gamification on consumer engagement and behavioural intentions, limited empirical evidence exists regarding its application to sustainable wood products. In particular, little is known about how gamified marketing communication influences consumer engagement, perceived sustainability, and purchase intention within forest-related value chains.

This study addresses this gap by developing and testing a conceptual model based on the Stimulus–Organism–Response framework. It examines the relationships between gamified marketing communication, consumer engagement, perceived sustainability, and purchase intention, contributing to the literature on digital marketing, sustainability communication, and consumer behaviour while providing practical implications for organizations promoting sustainable wood products.

2. LITERATURE REVIEW

Gamification is commonly defined as the use of game design elements in non-game contexts and has become an important approach for increasing consumer engagement in digital marketing communication (Deterding et al., 2011; Zichermann & Cunningham, 2011; Huotari & Hamari, 2017). Previous research shows that gamification can influence motivation, perceived value, satisfaction, brand engagement, loyalty, and purchase intention through mechanisms such as rewards, challenges, competition, enjoyment, and interaction (Hamari et al., 2014; Hammedi et al., 2017; Hsu & Chen, 2018; Leclercq et al., 2018; Mekler et al., 2017; Nobre & Ferreira, 2017; Xu et al., 2020). Recent studies also link gamified digital tools and mobile applications with sustainable behaviour and environmental participation (Tu et al., 2019; Kim & Hall, 2022).

Sustainable consumption and green marketing research show that consumers' choices are shaped by environmental awareness, trust, perceived benefits, green brand perceptions, credible claims, and communication clarity (Zinkhan & Carlson, 1995; Peattie, 2010; Chen, 2010; Joshi & Rahman, 2015; Magnier & Schoormans, 2015; Ottman, 2017; White et al., 2019; Zhu et al., 2013). In forest-related markets, environmental product information, eco-labels, certification schemes, renewable origin, carbon storage, resource efficiency, and water footprint influence consumer preferences and environmental assessment of wood products (Nyrud & Roos, 2009; Aguilar & Cai, 2010; Van Oel & Hoekstra, 2012; Hoekstra, 2017; Schyns et al., 2017).

Despite these contributions, limited empirical research examines the intersection between gamification, sustainability communication, and sustainable wood products. This study addresses this gap by testing a model that links gamified marketing communication with consumer engagement, perceived sustainability, and purchase intention in forest-related value chains.

3. RESEARCH MATERIALS AND METHODS

The study applies a quantitative survey design to examine the relationships between gamified marketing communication, consumer engagement, perceived sustainability, and purchase intention toward sustainable wood products. Primary data were collected through an online questionnaire using five-point Likert-scale items (1 = strongly disagree; 5 = strongly

agree), adapted from validated scales and modified for the context of sustainable wood products. The questionnaire was distributed online through social media, university networks, and consumer groups. A convenience sample of 256 respondents was obtained. Data were analysed through descriptive statistics, correlation analysis, and regression/SEM procedures.

The final sample comprised 256 respondents, of whom 53.9% were female and 44.9% male. Most respondents were aged 25–34 years (32.8%), held a bachelor's (37.5%) or master's degree (39.1%), and were employed (64.8%). More than half reported moderate familiarity with sustainable wood products (52.3%), 57.0% had previously purchased such products, and 49.2% expressed high interest in environmental issues.

The measurement model included four constructs: gamified marketing communication (GMC), consumer engagement (CE), perceived sustainability (PS), and purchase intention (PI), each measured with four five-point Likert-scale items. Mean values ranged from 3.94 to 4.32, indicating generally positive respondent evaluations. Standard deviations ranged from 0.65 to 0.86, suggesting acceptable response variation. Factor loadings ranged from .798 to .903, exceeding the commonly accepted threshold of .70 and indicating adequate item reliability

4. RESULTS

The results support the proposed model. The sample consisted of 256 respondents, and the measurement items showed positive evaluations and acceptable factor loadings. Correlation analysis indicated positive relationships between all constructs (Table 1). Regression analysis supported all hypotheses: gamified marketing communication positively influenced both consumer engagement and perceived sustainability, while consumer engagement and perceived sustainability positively influenced purchase intention (Table 2).

Table 1. Correlation matrix

Construct	GMC	CE	PS	PI
GMC	1			
CE	.68**	1		
PS	.54**	.61**	1	
PI	.49**	.63**	.66**	1

*Note. **p < .01 (two-tailed). N = 256.*

Table 2. Regression / SEM results and hypothesis testing

Hypothesis	Path	β	t-value	p-value	Result
H1	GMC → CE	.68	12.41	< .001	Supported
H2	GMC → PS	.54	8.76	< .001	Supported
H3	CE → PI	.37	5.92	< .001	Supported
H4	PS → PI	.44	6.81	< .001	Supported

Note. Standardized coefficients are reported.

5. DISCUSSION

The findings indicate that gamified marketing communication can promote sustainable wood products by increasing consumer engagement and strengthening perceived

sustainability. This supports the view that interactive elements help reduce information asymmetry by translating complex environmental attributes into more accessible and engaging communication.

Consumer engagement and perceived sustainability were both significant predictors of purchase intention. For companies in forest-related value chains, gamified digital tools can therefore complement traditional sustainability claims and improve communication of renewable origin, responsible forest management, carbon storage, and circularity.

The results should be interpreted with caution due to convenience sampling, self-reported data, and the cross-sectional design. Nevertheless, the study provides useful evidence that gamification can support sustainability communication for wood-based products.

6. CONCLUSIONS

This study confirms that gamified marketing communication can promote sustainable wood products by increasing consumer engagement, perceived sustainability, and purchase intention. It contributes to research on gamification and sustainability communication in forest-related value chains.

For companies, gamified digital tools can make sustainability claims more interactive, credible, and understandable. The main limitations are convenience sampling, self-reported data, and the cross-sectional design. Future research should use larger samples, experimental designs, and variables such as eco-label trust, greenwashing perceptions, and willingness to pay.

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REFERENCES

1. Aguilar, F. X., & Cai, Z. (2010). Consumer preferences for environmentally certified forest products in the U.S. Forest Policy and Economics, 12(4), 302–310.
2. Chen, Y.-S. (2010). The drivers of green brand equity: Green brand image, green satisfaction, and green trust. Journal of Business Ethics, 93(2), 307–319.
3. Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: Defining “gamification”. In Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments (pp. 9–15). ACM.
4. Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? A literature review of empirical studies on gamification. In Proceedings of the 47th Hawaii International Conference on System Sciences (pp. 3025–3034). IEEE.
5. Hammedi, W., Leclercq, T., & Van Riel, A. C. R. (2017). The use of gamification mechanics to increase customer engagement in service encounters. Journal of Service Management, 28(4), 640–661.
6. Hoekstra, A. Y. (2017). Water footprint assessment: Evolvement of a new research field. Water Resources Management, 31, 3061–3081.

7. Hsu, C. L., & Chen, M. C. (2018). How gamification marketing activities motivate desirable consumer behaviors: Focusing on the role of brand love. Computers in Human Behavior, 88, 121–133.
8. Huotari, K., & Hamari, J. (2017). A definition for gamification: Anchoring gamification in the service marketing literature. Electronic Markets, 27(1), 21–31.
9. Joshi, Y., & Rahman, Z. (2015). Factors affecting green purchase behaviour and future research directions. International Strategic Management Review, 3(1–2), 128–143.
10. Kim, J., & Hall, C. M. (2022). Effects of gamified mobile apps on sustainable consumption behaviour. Sustainability, 14.
11. Leclercq, T., Hammedi, W., & Poncin, I. (2018). The boundaries of gamification for engaging customers: Effects of losing a contest in online co-creation communities. Journal of Interactive Marketing, 44, 82–101.
12. Magnier, L., & Schoormans, J. (2015). Consumer reactions to sustainable packaging: The interplay of visual appearance, verbal claim and environmental concern. Journal of Environmental Psychology, 44, 53–62.
13. Mekler, E. D., Brühlmann, F., Tuch, A. N., & Opwis, K. (2017). Towards understanding the effects of individual gamification elements on intrinsic motivation and performance. Computers in Human Behavior, 71, 525–534.
14. Nobre, H., & Ferreira, A. (2017). Gamification as a platform for brand co-creation experiences. Journal of Brand Management, 24, 349–361.
15. Nyrud, A. Q., & Roos, A. (2009). Environmental product information and consumer preferences for wood products. Forest Policy and Economics, 11(1), 19–25.
16. Ottman, J. A. (2017). The new rules of green marketing: Strategies, tools, and inspiration for sustainable branding. Routledge.
17. Peattie, K. (2010). Green consumption: Behavior and norms. Annual Review of Environment and Resources, 35, 195–228.
18. Schyns, J. F., Booij, M. J., & Hoekstra, A. Y. (2017). The water footprint of wood for lumber, pulp, paper, fuel and firewood. Advances in Water Resources, 107, 490–501.
19. Tu, R., Hsieh, P., & Feng, W. (2019). Walking for fun or for "likes"? The impacts of different gamification orientations on environmental behaviour. Computers in Human Behavior.
20. Van Oel, P. R., & Hoekstra, A. Y. (2012). Towards quantification of the water footprint of paper: A first estimate of its consumptive component. Water Resources Management, 26, 733–749.
21. White, K., Habib, R., & Hardisty, D. J. (2019). How to SHIFT consumer behaviours to be more sustainable: A literature review and guiding framework. Journal of Marketing, 83(3), 22–49.
22. Xu, Y., Chen, Z., Peng, M. Y. P., & Anser, M. K. (2020). Enhancing consumer online purchase intention through gamification in China: Perspective of cognitive evaluation theory. Frontiers in Psychology.
23. Zichermann, G., & Cunningham, C. (2011). Gamification by design: Implementing game mechanics in web and mobile apps. O'Reilly Media.
24. Zinkhan, G. M., & Carlson, L. (1995). Green advertising and the reluctant consumer. Journal of Advertising, 24(2), 1–6.

25. Zhu, Q., Li, Y., Geng, Y., & Qi, Y. (2013). Green food consumption intention, behaviours and influencing factors among Chinese consumers. Food Quality and Preference, 28(1), 279–286..

Authors address:
Krasteva, N.[1]; Potebnya, A.[2]; *Daskalov, T.[3]
[1,2,3] Faculty of Economics and Business Administration, Sofia University St. Kliment Ohridski, Sofia, Bulgaria
*Corresponding author: tdaskalov@feb.uni-sofia.bg

GAMIFIED CULTURAL HERITAGE AS A DRIVER FOR SUSTAINABLE TOURISM AND FOREST-BASED SECTOR DEVELOPMENT: THE CASE OF GABROVO REGION

Neviana Krasteva, Aleksey Potebnya, Dessislava Alexova, Teodor Daskalov

Abstract: This study examines how gamification can transform cultural heritage environments into active settings for sustainability-oriented learning and forest-based sector awareness. The research is developed as a qualitative case study of the Gabrovo region in Bulgaria, where craftsmanship, wood processing and water-powered technologies form a historically embedded link between cultural heritage and renewable resource use. The empirical design combines structured observation, semi-structured interviews with visitors and experts, and content analysis of 32 media publications from 2019 to 2024. The findings indicate that interactive and participatory formats increase visitor engagement, support understanding of resource transformation and stimulate reflective attitudes toward sustainability. The study also identifies institutional barriers related to funding, expertise and the need to preserve authenticity. The contribution of the paper is to position cultural heritage as an educational mediator between traditional knowledge, sustainable tourism and the transition toward a circular bioeconomy. The findings have implications for museum practice and regional bioeconomy communication strategies.

Keywords: gamification; cultural heritage; bioeconomy; forest-based sector; sustainable tourism; experiential learning

1. INTRODUCTION

The transition toward a sustainable and circular bioeconomy has become a strategic priority in Europe, especially in sectors that depend on renewable biological resources (European Commission, 2021; Ronzon and M'Barek, 2018). Forest-based sectors are central to this transition because they provide materials, support regional value chains and contribute to resource efficiency and climate mitigation (Hetemaki and Hurmekoski, 2020; Hurmekoski et al., 2021; Kidd, 2017; Packer and Ballantyne, 2016; Pine and Gilmore, 1998; Richards and Wilson, 2006; Tilden, 1957). However, technological and industrial transformation alone is insufficient. The bioeconomy also requires public understanding of where materials come from, how they are transformed and why responsible use matters.

This creates a challenge often described as limited resource literacy. Many visitors and consumers encounter finished products without understanding the ecological, technological and cultural processes behind them (Giurca, 2022). This challenge is particularly relevant in contemporary supply chains, where resource extraction, processing and consumption are increasingly disconnected in both spatial and cognitive terms. Heritage environments can reconnect visitors with these otherwise invisible material flows by making production systems tangible and observable. Cultural heritage sites can address this gap because they make the relationship between people, materials and production visible. In Gabrovo, the historical links between forests, crafts, water power and industrial development create a particularly relevant case for studying this connection.

The purpose of this paper is to explore how gamification (Brundiers et al., 2021; Buhalis and Amaranggana, 2015; Deterding et al., 2011; Hamari et al., 2014) can support sustainability-oriented learning in cultural heritage environments and contribute to sustainable tourism and forest-based sector development. Sustainable destination development depends on competitiveness, conservation, interpretation and local value creation rather than on visitor numbers alone (Ritchie and Crouch, 2003; Moscardo, 1996). The study addresses four research propositions concerning visitor engagement, experiential learning, sustainability attitudes and institutional barriers: RP1 explores whether gamification increases visitor engagement; RP2 explores whether experiential learning improves understanding of forest resource use; RP3 explores whether experiential and gamified activities foster positive attitudes toward sustainability; RP4 explores whether institutional barriers limit the implementation of gamification.

2. CONTEXT AND THEORETICAL FRAMEWORK

The Gabrovo region is historically associated with craftsmanship, water-powered technologies, woodworking and small-scale industrial entrepreneurship. The Open-Air Ethnographic Museum "Etar" was selected because it preserves operational traditional technologies and maintains strong historical links with woodworking and forest-based production systems, allowing direct observation of resource transformation processes. These traditions are not only cultural assets; they also provide a practical narrative for explaining contemporary bioeconomy themes such as renewable materials, efficient production and circular use of residues.

Gamification is understood here as the use of game design elements in non-game contexts to structure attention, motivation and participation (Koivisto and Hamari, 2019). In learning environments, its effects are usually associated with feedback, progression, autonomy, narrative and meaningful challenges (Sailer and Homner, 2020). Experiential learning theory further explains why such mechanisms matter: knowledge is constructed through concrete experience, reflection and active experimentation (Kolb, 1984).

Table 1. Transformation from craft heritage to bioeconomy interpretation

Heritage element	**Industrial link**	**Contemporary technology**	**Bioeconomy interpretation**
Wood carving	Furniture production	CNC and CAD/CAM systems	Material efficiency
Carpentry	Construction materials	Automated processing	Energy and resource efficiency
Water-powered tools	Mechanized production	Small hydropower logic	Renewable energy use
Manual processing	Industrial manufacturing	Production machinery	Efficient production systems
Wood residues	Pellet and biomass use	Biomass technologies	Circular economy

Source: authors 'contribution

Museums and heritage institutions function as informal learning environments in which cognitive, emotional and social dimensions interact (Falk and Dierking, 2013). The educational

potential of heritage sites becomes particularly significant when historical production systems remain visible and operational. Working craft demonstrations and water-powered technologies enable visitors to observe the relationships between natural resources, energy systems and production processes in an authentic setting. Interactive and participatory formats can therefore move the visitor from passive observation to active interpretation. In the context of sustainable tourism, this shift is essential: heritage is not treated only as an attraction, but as a medium for explaining responsible resource use, local production systems and long-term regional development.

3. METHODOLOGY

The study applies a qualitative case study design, appropriate for examining complex phenomena in a real-life context (Yin, 2018). The case is the Gabrovo region, with analytical attention to the Etar museum as a living laboratory for sustainability learning. The study involved a heterogeneous sample of museum visitors, including domestic and international tourists, families and educational groups. Participants were predominantly adults aged 25–55. Purposive sampling was used to recruit visitors who actively engaged with demonstrations and agreed to participate in interviews. Although the sample is not statistically representative, it provides sufficient depth for qualitative analytical generalization consistent with case study methodology. The research combines structured observations, semi-structured interviews with visitors (n=20) and museum professionals (n=5), and content analysis of 32 media publications from 2019 to 2024. Observations focused on visitor interaction with demonstrations, time spent at exhibits, participation in craft activities and communication with craftspeople. Semi-structured interviews explored visitor perceptions of learning, understanding of forest resource use and reflections on sustainability, while expert interviews focused on institutional opportunities and implementation challenges.

The empirical material was examined through thematic analysis (Braun and Clarke, 2021). The coding procedure included familiarization with the empirical material, initial coding, theme development and cross-source comparison. Data saturation was considered achieved when no substantially new themes emerged from consecutive interviews. Interview transcripts and observation notes were coded manually by the research team. Content analysis included descriptive coding of cultural tourism, crafts, events, education and sustainability themes. Triangulation across sources was used to strengthen reliability and reduce dependence on a single type of evidence.

4. RESULTS AND DISCUSSION

The empirical findings provide evidence consistent with RP1. Interactive demonstrations and participatory elements are associated with longer dwell time, higher attention and more active questioning. Visitors appeared to respond more actively when they follow a process, make a choice or interpret the consequences of using a resource. Gamification does not replace authenticity; it creates a structured pathway through authentic content.

Interview findings are consistent with RP2. Visitors more easily understand the transformation from raw material to finished product when they observe working mechanisms and craft practices. Wood, water power and residues can be connected to renewable materials, energy efficiency and circular use. The findings provide partial support for RP3: visitors express

more reflective sustainability attitudes, but there is no longitudinal evidence of durable behavioral change. Interviewees repeatedly emphasized that observing complete production processes substantially improved their understanding of how wood is transformed into finished products and how traditional technologies relate to contemporary sustainable resource use. Several respondents noted that live demonstrations made production processes easier to understand than conventional museum displays.

The expert interviews support RP4. Museum professionals recognize the educational potential of gamification, but identify constraints: limited funding, insufficient digital and pedagogical expertise, and concern that excessive game mechanics may weaken authenticity. Successful implementation therefore requires a balance between engagement and curatorial integrity. Experts further emphasized that successful gamification should preserve interpretive continuity, ensuring that game mechanics emerge from authentic heritage processes rather than being artificially superimposed on museum interpretation. Table 2 summarizes the thematic distribution identified through descriptive coding of the analyzed media publications.

Table 2. Media content distribution in the analyzed publications

Category	**Share**
Cultural tourism	43.75%
Crafts	28.13%
Events	18.75%
Education	9.37%
Sustainability	0.00%

Source: authors 'contribution

This absence reflects media representation rather than the sustainability potential of the heritage itself. The content analysis shows that media narratives are dominated by tourism and craft-related themes, while sustainability is absent as an explicit category. This is a strategic communication gap. The same heritage content that currently functions mainly as cultural tourism can also be reinterpreted as evidence of sustainable resource use, historical circularity and local bioeconomy development. A suitable gamification model would connect four elements: heritage content, role-based participation, feedback on resource decisions and reflective sustainability interpretation.

Taken together, the empirical findings suggest that gamified heritage experiences can support systems thinking by allowing visitors to explore links between raw materials, craft decisions, production constraints and environmental outcomes. This is valuable for the forest-based sector because public support for the bioeconomy depends not only on industrial innovation but also on cultural understanding and social legitimacy. This finding is consistent with previous studies emphasizing that sustainability transitions require not only technological innovation but also public engagement and social learning. By making production processes visible, heritage environments reconnect visitors with material flows that are largely invisible in contemporary supply chains, thereby strengthening resource literacy. In this way, heritage sites function not only as places of preservation but also as active learning environments that make resource systems cognitively accessible.

5. CONCLUSION AND FUTURE DIRECTIONS

The study suggests that gamified cultural heritage can contribute to sustainable tourism and forest-based sector development by strengthening visitor engagement, improving understanding of resource transformation and opening a space for sustainability reflection. The Gabrovo case shows that historical craft environments can be interpreted as active learning systems rather than static cultural displays.

The main limitation of the study is its qualitative and exploratory design. Future research should include pre- and post-visit measurements, control groups comparing gamified and non-gamified experiences, digital analytics and longitudinal indicators of behavioral change. Further work should also examine when game mechanics support learning and when they distract from heritage interpretation. From a policy perspective, cultural heritage institutions could become active partners in regional bioeconomy communication strategies by integrating sustainability narratives into museum interpretation and public engagement. Such an approach would strengthen resource literacy while increasing the societal visibility of the forest-based bioeconomy. From a practical perspective, the next step is to design scalable hybrid tools - mobile missions, role-based simulations and augmented interpretation - developed in cooperation between museums, educational institutions and forest-based industry stakeholders. In this way, cultural heritage can become an active bridge between traditional knowledge, sustainable tourism and the future development of the forest-based bioeconomy.

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REFERENCES

1. Braun, V.; Clarke, V. (2021): Thematic Analysis: A Practical Guide. SAGE Publications.
2. Brundiers, K.; Barth, M.; Cebrian, G.; Cohen, M.; Diaz, L.; Doucette-Remington, S.; Dripps, W.; Habron, G.; Harre, N.; Jarchow, M.; Losch, K.; Michel, J.; Mochizuki, Y.; Rieckmann, M.; Parnell, R.; Walker, P.; Zint, M. (2021): Key competencies in sustainability in higher education. Sustainability Science 16: pp. 13-29.
3. Buhalis, D.; Amaranggana, A. (2015): Smart tourism destinations enhancing tourism experience through personalisation of services. In: Tussyadiah, I.; Inversini, A. (eds.): Information and Communication Technologies in Tourism 2015. Springer, Cham, pp. 377-389.
4. Deterding, S.; Dixon, D.; Khaled, R.; Nacke, L. (2011): From game design elements to gamefulness: defining gamification. In: Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments. ACM, New York, pp. 9-15.
5. European Commission (2021): EU Forest Strategy for 2030. European Commission, Brussels.

6. Falk, J.H.; Dierking, L.D. (2013): The Museum Experience Revisited. Left Coast Press, Walnut Creek, CA.
7. Giurca, A. (2022): Why is communicating the circular bioeconomy so challenging? Circular Economy and Sustainability 3(3): pp. 1223-1232.
8. Hamari, J.; Koivisto, J.; Sarsa, H. (2014): Does gamification work? A literature review of empirical studies on gamification. In: Proceedings of the 47th Hawaii International Conference on System Sciences. IEEE, pp. 3025-3034.
9. Hetemaki, L.; Hurmekoski, E. (2020): Forest bioeconomy development: markets and industry structures. In: Nikolakis, W.; Innes, J.L. (eds.): The Wicked Problem of Forest Policy. Cambridge University Press, Cambridge, pp. 231-258.
10. Hurmekoski, E.; Smyth, C.E.; Stern, T.; Verkerk, P.J.; Asada, R. (2021): Substitution impacts of wood use at the market level: a systematic review. Environmental Research Letters 16(12): 123004.
11. Kidd, J. (2017): Museums in the New Mediascape: Transmedia, Participation, Ethics. Routledge, London.
12. Koivisto, J.; Hamari, J. (2019): The rise of motivational information systems: a review of gamification research. International Journal of Information Management 45: pp. 191-210.
13. Kolb, D.A. (1984): Experiential Learning: Experience as the Source of Learning and Development. Prentice Hall, Englewood Cliffs, NJ.
14. Moscardo, G. (1996): Mindful visitors: heritage and tourism. Annals of Tourism Research 23(2): pp. 376-397.
15. Packer, J.; Ballantyne, R. (2016): Conceptualizing the visitor experience. Visitor Studies 19(2): pp. 128-143.
16. Pine, B.J.; Gilmore, J.H. (1998): Welcome to the experience economy. Harvard Business Review 76(4): pp. 97-105.
17. Richards, G.; Wilson, J. (2006): Developing creativity in tourist experiences: a solution to the serial reproduction of culture? Tourism Management 27(6): pp. 1209-1223.
18. Ritchie, J.R.B.; Crouch, G.I. (2003): The Competitive Destination: A Sustainable Tourism Perspective. CABI Publishing, Wallingford.
19. Ronzon, T.; M'Barek, R. (2018): Socioeconomic indicators to monitor the EU's bioeconomy in transition. Sustainability 10(6): 1745.
20. Sailer, M.; Homner, L. (2020): The gamification of learning: a meta-analysis. Educational Psychology Review 32(1): pp. 77-112.
21. Tilden, F. (1957): Interpreting Our Heritage. University of North Carolina Press, Chapel Hill.
22. Yin, R.K. (2018): Case Study Research and Applications: Design and Methods. 6th ed. SAGE Publications, Thousand Oaks, CA.

Authors address:
Krasteva, N.[1]; Potebnya, A.[1]; Alexova, D.[2], Daskalov, T.[1]
[1] Department of Business Administration, Faculty of Economics and Business Administration, Sofia University St. Kliment Ohridski, Sofia, Bulgaria
[2] International Business School, Botevgrad, Bulgaria
*Corresponding author: tdaskalov@feb.uni-sofia.bg

THE ROLE OF USER-GENERATED CONTENT IN DIGITAL PR COMMUNICATION IN INDIVIDUAL PHASES OF THE CUSTOMER JOURNEY

Katarína Ďurková, Eva Habiňáková

Abstract: In digital PR, user-generated content (UGC) is becoming a significant source of trust. This is particularly true for purchasing decisions involving products that are visually distinctive, represent a significant financial investment, and are purchased infrequently. This paper examines the role of UGC across various stages of the customer journey within the Slovak furniture and interior design market. It focuses on the perceived credibility of customer-generated content compared to corporate communication, the hierarchy of trust sources when selecting a company, the gap between the willingness to create user content and actual sharing behaviour, and demographic differences in attitudes toward such content. The research was conducted using a questionnaire survey with a sample of 307 respondents. The data were analysed using descriptive statistics, Cronbach's alpha, Spearman's correlation, exploratory factor analysis, and binary logistic regression. The results showed that user-generated photos and reviews are perceived as more trustworthy than professional product photography and help consumers better visualize the final product. However, UGC does not replace personal recommendations or the showroom experience, which remain the strongest sources of trust. The research also revealed a significant gap between the stated willingness to share content and actual public sharing. These findings suggest an opportunity for companies to systematically integrate customer content into the customer journey and actively foster conditions for sharing reviews, photos, and post-purchase experiences.

1. THEORETICAL FOUNDATIONS: UGC IN DIGITAL PR COMMUNICATION AND THE CUSTOMER JOURNEY

The rise of social platforms has fundamentally altered the conditions under which organizations build their reputations. While until recently they could—to some extent—control the information circulating about them, today the reputation is shaped primarily by content created by customers themselves. Organizations enter this process more as moderators than as the sole authors of communication (Schröder et al. 2025). In this environment, user-generated content (UGC) has become a crucial driver of reputation. This is not only because it is easily accessible to a wide audience but also because the audience views it as more credible than official brand communication. Reviews, comments, and ratings serve as an unbiased reflection of actual experiences (Lock, 2019; Murár & Piatrov, 2022). This holds true even despite doubts regarding its authenticity.

Within the customer journey, UGC plays a distinct role at each stage of the decision-making process. During the inspiration and need-recognition phase, it serves as a form of social validation (Sharma et al., 2023). This function of UGC is particularly pronounced in the furniture and home accessories category, as these products are closely linked to visions of home, lifestyle, and personal identity—areas where the visual authenticity of a real customer carries more weight than carefully staged product photography.

The nature of UGC shifts during the active search and alternative comparison phase. Customers now purposefully seek out reviews, read comments, and observe how the brand responds to critical posts. For younger customers, a lack of reviews can lead to site abandonment (Kubovics, 2023). The decision-making phase places specific demands on UGC. At this stage, the consumer is not seeking inspiration but rather reassurance—verification that the product looks and performs in real-world conditions just as the brand's communications promise. Photos and videos from actual customers taken after months of use help reduce perceived risk (Sharma et al., 2023).

The post-purchase phase concludes the cycle, yet from a PR perspective, it is the most critical stage. It is here that it is determined whether a customer remains a one-time buyer or becomes an active advocate who shares their experience (Kusá et al., 2022). Consequently, companies should not view user-generated content (UGC) merely as a byproduct of customer interaction, but rather as a strategic communication tool requiring active management throughout the entire customer journey (Kyriakidis, 2025). Companies can encourage the spontaneous creation of UGC by providing a simple platform for reviews, issuing timely calls to action, or offering financial incentives and virtual rewards (Baier et al., 2025).

2. METHODOLOGY

The issue of electronic word of mouth (eWOM) and user-generated content (UGC) has received considerable attention in the literature. Previous review studies and meta-analyses agree that this type of content can strengthen consumer trust and purchase intention. The quality of the argument, the credibility of the source, and the overall trust in the message play a significant role (Cheung & Thadani, 2012, Ismagilova et al., 2019). However, most empirical research has been conducted in tourism, HoReCa, fashion, electronics, or social e-commerce environments (Liu et al., 2024). Several questions remain open when purchasing furniture and interior solutions.

The first is the sector gap. Furniture, joinery and interior solutions have some specificities compared to regular consumer goods. This is a more financially demanding decision that the customer makes rarely and pays more attention to (high involvement purchase). At the same time, these are products with significant visual and haptic properties that cannot be fully assessed in the online environment before purchase. This is why it can be assumed that photographs of real implementations and experiences of other customers will be of greater importance. However, this segment is only marginally represented in the reviewed literature, and the available sources are more marketing than research in nature.

The second is the authenticity gap. In this segment, there is a lack of direct empirical comparison of the perceived credibility of real customer photos compared to professional product shots and corporate advertising.

The third is the gap between viewing and creating UGC. Previous studies have focused mainly on how UGC affects its recipients. Less attention is paid to why people regularly search for and use such content but rarely create it themselves. This disparity is often referred to as participation inequality and is also explained by the 90-9-1 rule (Nielsen, 2006). It has not yet been quantified more precisely in the purchase of furniture, although from the point of view of companies it is a significant problem - without active customers, there is not enough authentic content.

The fourth is the geographical gap. Most published research comes from North America and Asia. The market of Central and Eastern Europe, including Slovakia, remains underrepresented in this.
Based on the identified gaps, we formulated 4 research questions:

(RQ1) To what extent is authentic UGC content perceived as more trustworthy than corporate content?
(RQ2) How are sources of trust prioritized when choosing a company?
(RQ3) Is there a gap between willingness to create UGC and actual behaviour, and what predicts it?
(RQ4) Does trust in UGC vary by demographic characteristics of respondents?

The research was conducted in the form of a questionnaire survey on a sample of N= 307 respondents. Women made up 61.9% and men 38.1%. The most numerous age group were respondents aged 18-26 (42.3%), followed by the group of 27-40 (34.0%), 41-55 (19.2%). The least represented age group were people aged 56 and over. 57.3% of respondents reported secondary education with a high school diploma, 31.9% had a university education. By residence, 61.2% of respondents came from cities, 38.8% from municipalities. Geographically, the Bratislava and Trnava regions prevailed. Since it was an occasional self-selected sample, the results cannot be considered representative of the entire population.
The questionnaire contained single and multiple-choice questions, Likert scales of agreement and influence, as well as a battery of 12 company selection criteria rated on a scale of importance 1-5, where the value 5 expressed the strongest agreement, influence or importance, and the central answer I don't know/I can't judge had a value of 3. Descriptive statistics, Cronbach's alpha, Spearman correlation, Mann-Whitney U test, Kruskal-Wallis test, chi-square test of independence, exploratory factor analysis and binary logistic regression were used in data processing. The corresponding effect sizes were also reported.

3. RESULTS

The results indicate that authentic customer-generated content is perceived by respondents as more credible than corporate communication. More than two-thirds of those surveyed agreed with all five statements regarding the importance of UGC (Fig. 1). The highest level of agreement was found for the statement that companies should showcase real-world examples of their work on their websites and social media channels (75.2%). Strong support was also expressed for the view that photos taken by actual customers in real-life settings appear more trustworthy than professional product photography (68.4%).

However, the declared trust in UGC does not mean that it is the main source of trust when choosing a company. Almost half of the respondents would rely most on a personal recommendation from an acquaintance (49.8%) and more than a quarter on their own visit to a showroom (26.7%). Online reviews from unknown customers were chosen as the most trustworthy source by only 8.8% of respondents, while only 1.3% trust influencer recommendations and company advertising. UGC therefore does not seem to fulfil the role of the final confirmation of trust but rather helps the customer to verify information and better imagine the resulting product. Personal experience, recommendations and physical contact with the product continue to retain decisive weight.

The suitability of the 12-criteria battery for factor analysis was confirmed by the high KMO value (0.916) and the statistically significant Barlett test of sphericity ($\chi^2 = 2116$; $df = 66$; $p < 0.001$). After varimax rotation, three meaningful interpretable factors were created. The first consisted mainly of product and functional features, the second of social proof elements, and the third of additional and value criteria.

When choosing a company, basic product and functional features had the highest weight. Quality received the highest rating (M = 4.38), followed by design, price, and material. Social proof, i.e. reviews, recommendations, and photos of completed projects, was placed right behind this core. It overtook several traditional criteria - The brand itself achieved the lowest average rating (M = 2.93), which indicates that the company's reputation is not decisive in this type of purchase without support in specific experiences and results.

The most striking finding is the gap between interest in UGC and its actual creation. 57.7% of respondents trusted content from customers, and 66.4% said they would be willing to share a photo of the finished product if they were satisfied. However, 36.8% of respondents had actually shared some content, but only 13.7% had done so publicly, for example on a social network or in an online group. The difference between declared willingness and public sharing is 52.8 percentage points.

Binary logistic regression showed that the willingness to share content was most significantly increased by trust in UGC (OR = 1.44). Another significant factor was the age of the respondents (OR = 1.31). People who trust customer content more are also more willing to participate in its creation themselves. Despite this, the share of active creators remains low, which corresponds to the principle of participation inequality 90-9-1. Trust in UGC itself did not differ statistically significantly between age groups (Kruskal-Wallis test, $p = 0.145$), therefore it cannot be described as a phenomenon typical only for the youngest respondents. Gender differences were shown in the influence of the company website and social networks. Women reported a higher influence (M = 3.41) than men (M = 3.01; $U = 12486$; $p = 0.001$; $r = 0.21$). There was also a statistically significant difference in the extent to which UGC helps to visualize the product ($p = 0.019$). Age was associated with reading reviews ($\chi^2 = 38.1$; $p = 0.001$; $V = 0.18$), as well as with preferred source of trust ($\chi^2 = 41.3$; $p = 0.016$; $V = 0.18$). However, the effect size was rather weak.

4. DISCUSSION

The results show that authentic customer content plays an important role in furniture purchases, but its role is not the same in all stages of decision-making. Respondents perceived real photos of realizations as more trustworthy than professional product photos. They also stated that UGC helps them better imagine the final product. This is essential for furniture, because the customer does not only assess the technical characteristics of the product, but also its appearance in real space, scale, colour, method of use.

On the other hand, it was not confirmed that UGC would replace traditional sources of trust. When choosing a company, personal recommendations remained in first place, followed by a personal visit to the showroom. Online reviews and customer photos complement decision-making rather than determining it themselves. They can be understood as an intermediate link between initial interest and the final decision - through them, the customer verifies the experiences of others, compares expectations with reality, and reduces uncertainty with a financially demanding purchase. From a practical perspective, this result suggests that

companies should not base communication exclusively on UGC, but rather combine it with personal advice, material demonstrations, and the opportunity to see live implementations.

Factor analysis also showed that social proof forms an independent part of decision-making. Although reviews, recommendations and photos of implementations did not overtake quality, design, price and material, they were more important than the brand itself. In the furniture segment, the company's reputation may not be a decisive advantage unless the customer finds enough convincing evidence of the quality of its work. This finding is particularly favourable for smaller carpentry and interior design companies. Even without a strong brand, they can build trust through the systematic publication of real implementations and customer references.

The most significant difference appeared between the respondents' willingness to share content and their actual behaviour, which confirmed that most people follow content, but only a minority actively creates it. At the same time, it turned out that trust in UGC increases the willingness to contribute their own content and this group is suitable for targeted outreach with a request for a review or photo after purchase.

5. CONCLUSION

Research has confirmed that authentic content created by customers has a significant impact on perceived trustworthiness and the customer's ability to imagine the final product when purchasing furniture and interior solutions. However, UGC does not stand out as the only and strongest source of trust. Personal recommendations and direct experience with a company or showroom continue to hold the greatest weight. Customer reviews mainly fulfil a verification and visualization function.

The key finding can be considered a significant gap between the declared willingness to create UGC and its real public sharing. This implies the need for companies not to wait for spontaneous customer activity, but to create a simple and motivating system for obtaining content after the completion of the implementation. This can be a personal challenge, a short form, a simple photo upload. The results also show that systematic work with reviews and real implementations can be interesting, especially for smaller companies without a strong brand.

Despite the limitations of the sample, the study provides the first more comprehensive data on the role of UGC in the Slovak furniture and interior segment and creates a basis for further, methodologically broader research.

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REFERENCES

1. Baier, D., Decker, R., Asenova, Y. (2025). *Collecting and Analyzing User-Generated Content for Decision Support in Marketing Management: An Overview of Methods and Use Cases.* In: Schmalenbach Journal of Business Research. Vol. 77. 419–455. DOI: 10.1007/s41471-025-00208-7

2. Cheung, C.M.K., Thadani, D.R. (2012). *The impact of electronic word-of-mouth communication: A literature analysis and integrative model.* In: Decision Support Systems. Vol. 54, No. 1. 461–470. DOI: 10.1016/j.dss.2012.06.008
3. Ismagilova, E., Slade, E. L., Rana, N. P., & Dwivedi, Y. K. (2019). *The effect of electronic word of mouth communications on intention to buy: A meta-analysis*. In: Information Systems Frontiers. Vol. 22. 1203–1226. DOI: 10.1007/s10796-019-09924-y
4. Kubovics, M. (2023). *Digitálne marketingové systémy a platformy.* I. Tribun, EU.
5. Kusá, A., Fašiang, T., & Kollárová, D. (2022). *Retail marketing communication and the consumer behaviour of selected generations*. Peter Lang.
6. Kyriakidis, A. (2025). *Extracting knowledge from customer reviews: An integrated framework for digital platform analytics.* In: International Transactions in Operational Research. Advance online publication. DOI: 10.1111/itor.13537
7. Liu, H.; Jayawardhena, C.; Shukla, P.; Osburg, V.-S.; Yoganathan, V. (2024). *Electronic word of mouth 2.0 (eWOM 2.0) – The evolution of eWOM research in the new age.* In: Journal of Business Research. Vol. 176. Article 114587. DOI: 10.1016/j.jbusres.2024.114587
8. Lock, I. (2019). Explicating communicative organization–stakeholder relationships in the digital age: A systematic review and research agenda. In: Public Relations Review. Vol. 45. No. 4. Article 101829. DOI: 10.1016/j.pubrev.2019.101829
9. Murár, P., Piatrov, I. (2022). *Digitálny marketing.* Fakulta masmediálnej komunikácie UCM v Trnave.
10. Nielsen, J. (2006). *The 90-9-1 Rule for Participation Inequality in Social Media and Online Communities.* URL: https://www.nngroup.com/articles/participation-inequality/
11. Schröder, N., Schultz, C.D., Paetz, F., Grzadziel, A., Clegg, M. (2025). *Exploring the Role of User Generated Content Along the Customer Journey and Understanding its Relevance for Research and Practice.* In: Schmalenbach Journal of Business Research. Vol. 77. 457–496. DOI: 10.1007/s41471-025-00214-9
12. Sharma, P., Ueno, A., Dennis, C., & Paydas Turan, C. (2023). *Emerging digital technologies and consumer decision-making in retail sector: Towards an integrative conceptual framework*. In: Computers in Human Behavior. Vol 140. Article 107913. DOI: 10.1016/j.chb.2023.107913

Authors addresses:
PhDr. Katarína Ďurková, PhD., PaedDr. Habiňáková, Eva, PhD.
Faculty of Mass Media Communication, University of Ss. Cyril and Methodius in Trnava, Námestie J. Herdu 2, Trnava, Slovakia
katarina.durkova@ucm.sk, eva.habinakova@ucm.sk

DEVELOPMENT OF WOOD PELLET TRADE IN THE EU BIOECONOMY: BULGARIA'S COMPETITIVE POSITION AMONG CEE COUNTRIES

Galina Zaharieva

Abstract: Wood pellets are an important component of the bioenergy mix of the European Union and a viable alternative to fossil fuels, contributing to the EU's climate and energy objectives within the framework of the European Green Deal, the EU Bioeconomy Strategy and the Renewable Energy Directive (RED II, Directive 2018/2001). The latest Bioenergy Europe Statistical Report confirms the important role of wood pellets, reaffirming the EU's position as the world's leading producer and consumer, despite a moderate decline recorded in 2023 and 2024. The EU is heterogeneous in terms of both production and consumption, as well as exports and imports. Major economies such as Germany, France, Denmark, Italy, Sweden and the Netherlands function primarily as consumers, while Latvia and Estonia are the dominant exporters. While several CEE EU member states function as net exporters of wood pellets, the region exhibits significant heterogeneity in trade positions and competitive performance, warranting comparative analysis. This paper aims to analyse the development of wood pellet trade in the EU and to assess the competitive position of Bulgaria among ten CEE countries for the period 2018–2024. Trade data from Eurostat Comext (CN 44013100) were used to calculate absolute and relative export and import values, the Trade Specialization Index (TSI) and the Relative Trade Advantage (RTA), complemented by production data from FAOSTAT. Results indicate that despite its resource potential and initially positive comparative advantage, Bulgaria's competitive position in the EU wood pellet market deteriorated consistently throughout the 2018–2024 period.
Keywords: wood pellet, trade specialization index, relative trade advantage

1. INTRODUCTION

In 2009, Directive 2009/28/EC (RED) (European Parliament and Council, 2009) established the first EU-wide framework for the promotion of energy from renewable sources, recognising biomass as a renewable source, and set an EU target of 20% of energy from renewable sources in the Community's total energy consumption. This target was increased to 32% by 2030 by Directive (EU) 2018/2001 (RED II) (European Parliament and Council, 2018), which also introduced mandatory sustainability and emission reduction criteria for the use of forest biomass. The European Green Deal, as well as the energy market problems resulting from the war between Russia and Ukraine, are accelerating the transition to renewable energy sources and the increase in the production of sustainable biomass where feasible, and the EU Bioeconomy Strategy promotes the sustainable use of biological resources and the development of the bioeconomy. The changes in the political and regulatory framework undertaken by the EU play a stimulating role in the use of biomass for energy, including wood pellets. This is also confirmed by the data in the Bioenergy Europe Statistical Report (Geelen, Canon, & Karampinis, 2025), which show an increasing trend in production until 2022, after which a decline is reported. Pellet consumption in industry and households also fell in 2023 and 2024 (Flach & Bolla, 2026). At the same time, the EU is heterogeneous, both in terms of

production and consumption, and in terms of trade flows. Germany, France, Italy, Denmark, Sweden and the Netherlands emerge primarily as consumers, while Latvia and Estonia are the dominant exporters. Most CEE countries are net exporters in all years of the studied period. At the same time, they are distinguished by their trade performance and relative trade advantages. Despite its significant forest and raw material potential, Bulgaria remains relatively understudied in the context of regional competitiveness in the pellet sector, and its position relative to other CEE producers has not been systematically assessed to date. The aim of this article is to analyze the development of wood pellet trade in the EU and to assess Bulgaria's competitive position among CEE countries for the period 2018–2024.

2. MATERIALS AND METHODS

For the purposes of this study, data on exports and imports of pellets (CN 44013100) and total trade volume from Eurostat Comext were used, as well as data on trade and production from FAOSTAT for the period 2018 - 2024. The analysis is based on both absolute and relative data on trade flows, production and consumption of pellets, as well as on the Trade Specialization Index (TSI) and the Relative Trade Advantage (RTA). TSI, also known as the Net export index (Balassa & Noland, 1989; Parobek, Dzian, & Nosáľová, 2025) is one of the simple indices for measuring trade specialization and the net trade position of countries, which is calculated by the formula:

$$TSI_{ij} = \frac{X_{ij} - M_{ij}}{X_{ij} + M_{ij}} \quad (1)$$

Xij – export of good j from country i
Mij – import of good j into country i

Its values range from -1 to +1, with negative values indicating trade despecialization, and positive indicating the dominance of exports over imports. In order to highlight the competitive position of the countries in the wood pellet trade compared to the other CEE countries, the analysis is supplemented by RTA (Vollrath, 1989; Danna, Buitrago & Stellian, 2022). It is calculated as the difference between relative export advantage (RXA) and relative import advantage (RMA):

$$RTA_{ij} = RXA_{ij} - RMA_{ij} = \frac{X_{ij}/X_{in}}{X_{rj}/X_{rn}} - \frac{M_{ij}/M_{in}}{M_{rj}/M_{rn}} \quad (2)$$

RXA_{ij} – relative export advantage
RMA_{ij} – relative import advantage
r = EU27\i (reference group including all EU27 countries excluding country i)
Xin – total exports of goods from country i to the world, excluding good j
Xrj – total exports of good j from EU27\i to the world
Xrn – total exports of goods from EU27\i to the world, excluding good j
Min – total imports of goods into country i from the world, excluding good j
Mrj – total imports of good j into EU27\i from the world
Mrn – total imports of goods from the world into EU27\i, excluding good j

With RXA>1, the country is more specialized in the export of good j than the reference group, i.e. it has a relative export advantage, while RXA<1 indicates the lack of such an advantage. Values equal to 1 indicate that there is no difference between the country's export specialization and that of the reference group. Values of RMA>1 indicate that the country is more specialized in the import of the respective good compared to the reference group, i.e. is more dependent on its imports, while values below 1 confirm the absence of such dependence. RTA>0 indicates the presence of a relative trade advantage, while RTA<0 – of a relative trade disadvantage.

3. RESULTS

The trade specialization index for the CEE countries in the wood pellet trade for the period 2018-2024 shows different dynamics, alternating years of decrease and years of increase in its values. The trends are also different, in some cases increasing, in others decreasing and in others maintaining the degree of specialization. The data shows that six of the CEE countries (Estonia, Croatia, Czech Republic, Latvia, Lithuania, Slovakia) have high or almost full specialization, while the remaining five have very low. It is also striking that the change for almost all countries is in a positive direction, with the exception of Bulgaria and Poland, where this indicator has dropped significantly, which means a decrease in wood pellet trade competitiveness, or a trend towards despecialization (see Table 1). For example, for the period 2018-2024 Bulgaria's wood pellet exports decreased from 161 to 49 ths. tonnes, while imports from 49 to 43 ths. tonnes. In value terms, exports decreased from 29 to 12 mln. euro, while imports increased from 8 to 9 mln. euro.

Table 1. Trade Specialization Index Dynamics of CEE Countries (2018-2024)

	2018	2019	2020	2021	2022	2023	2024	Δ 2024 vs 2018
Bulgaria	0.57	0.43	0.34	0.13	0.06	0.14	0.13	**-0.44**
Croatia	0.81	0.78	0.77	0.82	0.89	0.89	0.90	0.09
Czechia	0.84	0.83	0.85	0.82	0.85	0.84	0.88	0.03
Estonia	0.98	0.98	0.98	0.97	0.98	0.92	0.99	0.01
Hungary	-0.17	-0.22	-0.15	-0.10	-0.01	0.03	0.07	***0.24***
Latvia	0.78	0.79	0.75	0.73	0.69	0.80	0.86	0.07
Lithuania	0.53	0.54	0.50	0.62	0.66	0.78	0.90	***0.38***
Poland	0.56	0.47	0.66	0.51	0.38	0.31	0.06	**-0.50**
Romania	0.66	0.75	0.83	0.65	0.67	0.50	0.66	0.00
Slovakia	0.72	0.67	0.77	0.77	0.82	0.71	0.78	0.06
Slovenia	-0.03	0.00	-0.01	0.11	0.14	0.13	0.18	***0.20***

CEE countries differ in their export and import profile. Among them, the largest exporters are Latvia and Estonia, in whose export structure wood pellets have a share of 1.87% and 1.36% respectively for 2024. In fact, they are the countries with the highest share of pellet exports in total exports among all EU countries, while the remaining countries have it significantly lower than 1%. In terms of the relative share of this product in the import structure, it is below 1%, with the largest share in 2024 being Denmark (0.47%). This specificity is also reflected in the indices of the countries' trade advantages. Table 2 shows that the CEE countries demonstrate a higher propensity to export wood pellets compared to the EU27\i and have a relative export advantage throughout the period. This advantage is greatest for Latvia

and Estonia, followed by Croatia and Lithuania. And with regard to the RXA indices, a different dynamic is established, as a more pronounced upward trend, confirmed by the trend lines, the coefficient of determination and the equations, is outlined for Estonia, and a downward trend - for Bulgaria, Slovenia and Poland. Despite the high values of the RXA index for Latvia, a reliable trend cannot be confirmed due to the low coefficient of determination.

Table 2. Relative Export Advantage Values of CEE Countries (2018-2024)

	2018	2019	2020	2021	2022	2023	2024	Δ 2024 vs 2018
Bulgaria	3.45	3.30	2.76	2.38	2.77	1.88	0.93	-2.51
Estonia	41.08	37.41	33.00	41.33	39.10	48.25	56.19	15.10
Croatia	9.91	9.59	9.85	10.42	12.02	11.40	8.71	-1.20
Czechia	1.29	0.95	0.98	1.16	1.45	1.21	1.15	-0.14
Hungary	0.06	0.04	0.05	0.06	0.06	0.04	0.05	-0.02
Latvia	66.55	78.35	73.94	75.76	46.56	48.81	83.91	17.36
Lithuania	10.16	10.86	9.43	8.82	9.71	8.73	8.38	-1.78
Poland	1.29	1.25	1.00	0.85	1.16	0.95	0.49	-0.80
Romania	1.20	1.70	2.60	2.60	2.69	1.53	1.13	-0.08
Slovakia	0.94	1.02	1.03	1.45	1.86	1.15	1.22	0.28
Slovenia	4.69	3.88	3.20	3.25	2.91	2.65	1.89	-2.80

The RMA values are positive and with different dynamics (see Table 3). For certain countries and certain years, they are > 1, which indicates a higher import specialization compared to the reference group. This includes Latvia, Slovenia - for all years of the period 2018-2024, and also Bulgaria, Lithuania and Estonia - for some years. In 2024, the RMA indices of the CEE countries are < 1, with the exception of two, which outlines a situation of lower import specialization compared to the reference group. Although the general impression is of a decrease in RMA over the period, this trend is confirmed by the trend lines, the coefficient of determination and the equations only for Slovenia, Croatia, Lithuania and Hungary.

Table 3. Relative Import Advantage Values of CEE Countries (2018-2024)

	2018	2019	2020	2021	2022	2023	2024	Δ 2024 vs 2018
Bulgaria	0.73	1.01	1.14	1.47	1.66	1.10	0.51	-0.22
Estonia	0.33	0.28	0.21	0.41	0.21	1.26	0.21	-0.12
Croatia	0.54	0.61	0.75	0.59	0.30	0.30	0.19	-0.35
Czechia	0.10	0.09	0.08	0.11	0.09	0.10	0.07	-0.04
Hungary	0.08	0.06	0.06	0.06	0.04	0.04	0.04	-0.05
Latvia	5.10	5.90	7.24	7.96	4.89	3.36	3.75	-1.35
Lithuania	2.45	2.56	2.73	1.64	1.26	0.77	0.29	-2.15
Poland	0.30	0.39	0.19	0.24	0.37	0.43	0.35	0.05
Romania	0.18	0.16	0.17	0.37	0.29	0.33	0.14	-0.04
Slovakia	0.14	0.18	0.13	0.17	0.14	0.17	0.12	-0.01
Slovenia	4.59	3.50	3.23	2.36	1.74	1.78	1.01	-3.59

With few exceptions, the RTA values by year and country are positive, with dominant positions of Estonia and Latvia, followed by Croatia and Lithuania. This indicates the presence of relative trade advantage, but the strength of this advantage differs between CEE countries (see Table 4).

Table 4. Relative Trade Advantage Values of CEE Countries (2018-2024)

	2018	2019	2020	2021	2022	2023	2024	Δ 2024 vs 2018
Bulgaria	2.72	2.29	1.63	0.90	1.11	0.79	0.42	-2.29
Estonia	40.75	37.13	32.79	40.92	38.90	46.99	55.97	15.22
Croatia	9.37	8.98	9.10	9.83	11.72	11.10	8.52	-0.85
Czechia	1.19	0.86	0.90	1.06	1.36	1.11	1.08	-0.11
Hungary	-0.02	-0.02	-0.01	-0.01	0.01	0.01	0.01	0.03
Latvia	61.45	72.46	66.71	67.80	41.66	45.45	80.15	18.70
Lithuania	7.71	8.30	6.70	7.19	8.45	7.96	8.08	0.37
Poland	0.99	0.86	0.81	0.61	0.79	0.52	0.14	-0.85
Romania	1.03	1.54	2.43	2.24	2.39	1.20	0.99	-0.04
Slovakia	0.80	0.84	0.91	1.28	1.72	0.98	1.09	0.29
Slovenia	0.10	0.38	-0.03	0.88	1.17	0.88	0.88	0.79

In 2024, the leading place is Latvia, followed by Estonia, Croatia, Lithuania, Slovakia and the Czech Republic. Bulgaria occupies only 9th place in the ranking based on RTA values, while in 2018 it was in fifth place. This means that Bulgaria has worsened its relative position compared to the beginning of the period, losing ground to countries such as Romania, Slovakia, Slovenia and the Czech Republic. Within the period, Bulgaria and Poland report an undeniable trend of decreasing relative trade advantages, and only Estonia - of increasing relative trade advantage, confirmed by the trend lines, the coefficient of determination and the equations.

4. DISCISSION AND CONCLUSION

Wood pellets are an important part of the EU energy mix in the search for a substitute for solid fuels, increasing the share of energy from renewable sources and achieving a sustainable and resource-independent economy. Following the increasing trend in consumption stimulated by European legislation, their production and sale may face a number of challenges due to the updated strategic objectives and the relevant regulatory changes. The RED III (European Parliament and Council, 2023a), the LULUCF Regulation (European Parliament and Council, 2023b) and the EUDR (European Parliament and Council, 2023c) adopted in 2023 simultaneously increase the demand for wood pellets through more ambitious renewable energy targets and limit the supply of raw material through the cascading principle, enhanced carbon sequestration requirements and mandatory wood traceability – a combination that outlines a key challenge to the competitiveness of EU producers. Bulgaria has the potential to produce and export wood pellets (Zlateva, Terziev, & Mileva, 2024), but the data from this study indicate that this potential remains untapped. Within the period 2018-2024, Bulgaria gradually lost its trade position compared to most of the CEE EU member states. This is shown by both the TSI and the RTA. The TSI shows a weaker export position of Bulgaria compared to other CEE countries. Only Poland and Hungary rank below it. The situation is similar for the RTA. Both the export advantage and import dependence decreased during the period, but the export advantage decreased more, which reflected in the loss of relative trade advantage compared to other CEE countries. The specific internal factors driving this decline remain beyond the scope of this study and represent a direction for future research.

REFERENCES

1. Balassa, B.; Noland, M. (1989): *The Changing Comparative Advantage of Japan and the United States*. Journal of the Japanese and International Economies: pp. 174-188. https://doi.org/10.1016/0889-1583(89)90003-8
2. Danna Buitrago, J.; Stellian, R. (2022): *A New Class of Revealed Comparative Advantage Indexes*. Open Economies Review 33: pp. 477–503. https://doi.org/10.1007/s11079-021-09636-4
3. European Parliament and Council (2009): *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources*. Official Journal of the European Union, L140, pp. 16–62.
4. European Parliament and Council (2018): *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources*. Official Journal of the European Union, L328, pp. 82–209.
5. European Parliament and Council (2023a): *Directive (EU) 2023/2413 on the promotion of energy from renewable sources (RED III)*. Official Journal of the European Union, L, 2023/2413.
6. European Parliament and Council (2023b): *Regulation (EU) 2023/839 amending Regulation (EU) 2018/841 on land use, land-use change and forestry (LULUCF)*. Official Journal of the European Union, L107, pp. 1–92.
7. European Parliament and Council (2023c): *Regulation (EU) 2023/1115 on deforestation-free products (EUDR)*. Official Journal of the European Union, L150, pp. 206–247.
8. Flach, B.; Bolla, S. (2026): *European Union: Wood Pellets Annual*. USDA. Retrieved 6 30, 2026, from https://www.fas.usda.gov/data/gain/2026/07/european-union-wood-pellets-annual
9. Geelen, J.; Canon, J.; Karampinis, M. (2025): *Bioenergy Europe Statistical Report 2025: Pellets*. Brussels: Bioenergy Europe.
10. Parobek, J.; Dzian, M.; Nosáľová, M. (2025): *Comparative Advantages of Slovak Forest Products in The EU Market*. In: Proceedings of Scientific Papers Wood for the future: integrating sustainability across industries. Ohrid, North Macedonia, September 17th-19th: WoodEMA. pp. 157-162.
11. Vollrath, T. L. (1989): *Competitiveness and Protection in World Agriculture*. Agricultural Information Bulletins 567. United States Department of Agriculture. https://doi.org/10.22004/ag.econ.309494
12. Zlateva, P.; Terziev, A.; Mileva, N. M. (2024): *Sustainable Solutions for Energy Production from Biomass Materials*. Sustainability 16(17): 7732. https://doi.org/10.3390/su16177732

Authors address:
Zaharieva, G.[1]
[1] Economic Research Institute at the Bulgarian Academy of Sciences
*Corresponding author: g.zaharieva@iki.bas.bg

GLOBAL TIMBER TRADE AND THE "BELT-AND-ROAD" INITIATIVE – AN EFFORT TO BROADEN AND IMPROVE GREEN LOGISTICAL CHAINS

Antoaneta Kirova, Daniela Todorova, Krassimir Krastanov, Dimitar Todorov

Abstract: The effects of the Belt and Road Initiative (BRI) have spread over the imports of different products and have accelerated global timber trade by enhancing logistics and reducing trade costs. China's imports of processed wood products are facilitated by providing the country with access to resources from timber products' exporting countries - Southeast Asia and Russia - shifting towards sustainable practices, and increasing the efficiency of timber products supply. The improved transport infrastructure, including railway, highway, and maritime routes, has facilitated faster, more cost-effective transportation of timber products from Central Asia and Europe into China. The international logistics industry, based on transport connectivity, is a critical component of international trade, against the backdrop of a complicated health situation in 2020-2022, and the geopolitical situation caused by the escalating local wars, first between Russia and Ukraine and currently in the Middle East. The imposition of restrictions has led to a decline in production and a lag in the supply chain to meet customer expectations for deliveries, in the context of increasing constraints caused by the Sustainable Development Goals, namely the growing challenges of environmental, social, and governance (ESG) risks faced by companies, industries, and countries.

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Keywords: international trade with timber products, BRI, transport connectivity, ecological and sustainable logistics chains

1. INTRODUCTION

The effects of the Belt and Road Initiative (BRI) have spread to the imports of various products and have accelerated global timber trade by enhancing logistics and reducing trade costs. China's imports of processed wood products are facilitated by providing the country with access to resources to timber products exporting countries - Southeast Asia and Russia - shifting toward sustainable practices, increasing the efficiency of timber products supply. However, due to environmental regulations, the timber trade became more complicated with rising production costs and stricter legal verification requirements, such as the EU Deforestation Regulation. The improved transport infrastructure, including railway, highway, and maritime routes, has facilitated faster, more cost-effective transportation of timber products from Central Asia and Europe into China. The contemporary development of BRI after the COVID-19 pandemic further impacts the regional and global trade of timber products, while certain environmental requirements raise barriers and the need for further analysis and evaluations. On the other hand, the logistics industry, based on transport connectivity, is a critical component of international trade, proving against the geopolitical situation caused by the escalating local wars first between Russia and Ukraine, and currently in the Middle East, following the world health crisis in the recent past. Certain additional restrictions, in the context of increasing constraints caused by the Sustainable Development Goals, namely the growing challenges of environmental, social, and governance (ESG) risks faced by companies,

industries, and countries, bring additional stress to the whole system of international trade, including international logistics in the framework of BRI.

1. Current state of international wood products and the Belt-and-Road Initiative (BRI)

International trade in wood products has become increasingly important over the past 30 years. Global wood products trade increased 143% to US$244 billion between 1990 and 2019 (FAO 2021) (Zixing Gao, 2025). The largest contributor to this expansion in trade has been economic growth and demand from China, with imports of wood products to China increasing 760% to US$49 billion (FAO 2021). In 2024, the global trade of wood products reached approximately $157 billion, marking a slight decrease of 0.8% from the 2023 total of $159 billion. The global market is expected to grow at a CAGR[13] of 4.7% between 2025 and 2030, driven by urbanization and demand for eco-friendly building materials. (Lock Peter) The broader global wood and timber products market, including production and domestic consumption, was valued at nearly $992 billion in 2024 and is projected to grow to over $1.25 trillion by 2030 (Brown, 2020).

The key trade and market figures for the period 2024-2025 show China among the top exporters, with a turnover of US $17.5B, followed by Canada (US $13.4B), and Germany (US $10.1B); among the top Importers for 2024, China is in the second place, with a turnover of US $16.7B), the USA with US $25.2B) in the first place and Japan with US $9.47B in the third place.

The key regional and product trends show the dominance of Asia-Pacific region dominating the wood and timber products market, accounting for roughly 31.8% of the global market in 2024, with China being the largest consumer and importer. However, due to environmental regulations, the timber trade has become more complex due to rising production costs and stricter legality verification requirements, such as the EU Deforestation Regulation European Commission (European Parliament and the Council of Europe, 2023), , while rapid urban expansion in emerging economies like India and China is driving up demand and fast-growing plantations in South America (Brazil and Chile) and Southeast Asia (Indonesia) are increasingly meeting global demand.

The BRI has generally increased trade in wood products through improved trade facilitation and, in some cases, created new opportunities for cooperation in the forestry sector. Timber trade activities have deepened the interconnectivity of global timber supply chains, intensifying the cross-regional flow of timber resources and exacerbating issues such as over-exploitation (Hoang, 2021), (Leblois Antoine, 2017), deforestation and biodiversity loss (Chaves, 2020), (Wei, 2026).

Among many other created opportunities, BRI infrastructure investments have notably increased trade flows in forestry products, especially processed wood, strengthening China's position as a central hub in the global timber supply chain. The initiative has shifted the focus toward importing processed goods from BRI countries, as some exporting nations move toward higher-value-added production, such as Indonesia in Southeast Asia. The key trade corridors involve ASEAN countries (e.g., Vietnam, Thailand, Indonesia), Russia, and Central Asia (e.g., Kazakhstan), marking regions providing essential timber resources for China's furniture and construction industries. Logistics Improvements, such as railway, highway, and maritime

13 Compound Annual Growth Rate

routes, have facilitated faster and cost-effective transportation of timber products from Central Asia and Europe into China.

The major Timber Trade Corridors under BRI are primarily defined within the context of China's increasing forest product imports from key BRI partner countries, often aligning with the logistics routes of the established six economic corridors. The information provided shows these corridors are substantially "green", using railway and maritime modes of transport. Though these trade routes were not formally designated solely for timber, they are defined by the flow of timber and forest products through the following key corridors and regions:

- **Railway routes:**

1) China-Mongolia-Russia Economic Corridor (CMREC) is the primary land route for softwood entering China, starting from Siberia and the Russian Far East, crossing into northern China, allowing for direct railway transport.
2) **China-Indochina Peninsula Economic Corridor (CICPEC)**, through which timber is transported from Southeast Asia (Vietnam, Laos, Thailand) into southern China (Guangxi and Guangdong provinces). The China-Laos railway significantly boosts this connection.
3) **New Eurasian Land Bridge (Central Asia-Russia-Europe)**, facilitating the import of timber products from European Russia and Belarus, particularly using the China-Europe Railway Express, bypassing traditional maritime bottlenecks

- **Timber component of 21st Century Maritime Silk Road** (China's logs and lumber imports: trends in 2025, Outlook, n.d.)**:** from Southeast Asia (Indonesian and Malaysian timber flows through the South China Sea, from Africa and Oceania to China's coastal processing hubs, and from Russia (Arctic/Sea Route), from Russian far east ports for maritime transport to northern Chinese ports.

The direction of the improvised Timber Trade Corridors shows that China's top trading partners in timber products export and import turnover are Russia, Indonesia, Vietnam, Thailand, and Malaysia, which are major sources of timber.

The BRI has increased timber trade connectivity by reducing transport times through new railways and port developments, such as Vladivostok (Russia) and Sihanoukville (Cambodia). In 2026, despite fluctuating volumes, Belarus emerged as a growing supplier via rail corridors, while Southeast Asian routes remain dominant for high-value timber.

2. Contemporary development of BRI

According to data on the results of the BRI development from a report published by the American Enterprise Institute (WANG, 2025) Energy and Transportation projects are leading the construction sector in China. It is also interesting to note that official statistics list 63 countries as part of the BRI, but, according to the PRC government portal, there are 149. To determine the maximum possible scope of the BRI, CGIT documented nearly $380 billion invested and more than $540 billion built since the BRI was launched in 2013, which is about 90% percent of the originally planned.

CGIT[14] and official statistics show that BRI countries are doing better than richer countries during COVID. In cases where projects have run into difficulties, China has stepped in as a "lender of last resort" to prevent BRI countries from falling into debt crises. According to

14 China Global Investment Tracker (CGIT)

research by AidData and other international financial institutions, such as the World Bank, the Harvard Kennedy School, and the Kiel Institute for the World Economy, China provided $104 billion in rescue loans between 2019 and 2021, double the amount provided in the previous two decades.

These issues lead to a fundamental rethinking of the BRI, but the forum on the occasion of the 10th anniversary of its launch announced additional funding of 100 billion US dollars, intended for expanding the program, increasing scientific exchanges and cooperation, and building institutional capacity. Areas that are not traditionally considered China's strengths, such as taxation, finance and the fight against corruption, will also be covered. All this is a result of the Chinese side's position on unilateral sanctions, economic coercion, separation and disruption of the supply chain, etc..

During the Third BRI International Cooperation Forum, eight activities were announced to support the future implementation of the initiative, namely: accelerated high-quality development of railway connectivity between China and Europe; establishment of a pilot zone for e-commerce cooperation along the Silk Road; organization of an annual international digital trade exhibition (Global Digital Trade EXPO); coordinating progress between large and "small but valuable" projects to enhance people's well-being; increasing support for the BRI International Green Development Alliance; further strengthening the BRI Green Innovation Conference, building a dialogue and exchange mechanism in the photovoltaic industry, and creating a network of experts in the field of ecology and low-carbon development; further implementing the Action Plan for Scientific and Technological Innovation and holding the first BRI Scientific and Technological Exchange Conference; increasing the number of joint laboratories built with other countries to 100 in the next five years, and supporting young scientists from various countries to work in China for short periods; holding the Liangzhou Forum to deepen cross-cultural dialogue with BRI countries; establishing the Silk Road Tourism Cities Alliance; further implementing the Silk Road Chinese Government Scholarship Program. These eight activities set a new direction, revealed a new vision, and gave new impetus to the BRI, embracing the global world.

Following the COVID-19 pandemic, China's BRI commitment has stabilized in 2025 with a strong focus on partnerships with countries in renewable energy, mining and related technologies. The volatility in global trade and investment potentially drives additional investment in supply chain resilience and alternative export markets for Chinese companies. Potential future commitments remain unchanged in six project types: manufacturing in new technologies (e.g. batteries), renewable energy, trade-facilitating infrastructure (including pipelines, roads), ICT (e.g. data centers), resource-backed deals (e.g. mining, oil, gas), high-visibility or strategic projects (e.g. rail).

However, among the critics of the further BRI development there are fears of Critical Habitat Intersections meaning BRI infrastructure, including roads, railways, and mining, crosses key biodiversity areas (KBAs) while also there are significant deforestation drivers. Increased trade in wood products is a major driver of deforestation in developing nations within the BRI network, such as in Southeast Asia, which has high deforestation rates.

The logistics industry, based on transport connectivity, is a critical component of international trade, proved against the geopolitical situation caused by the escalating local wars first between Russia and Ukraine, and currently in the Middle East, and the

world health crisis in the recent past. Certain additional restrictions, in the context of increasing constraints caused by the Sustainable Development Goals, namely the growing challenges of environmental, social and governance (ESG) risks faced by companies, industries and countries bring additional stress over the whole system of international trade including international logistics in the framework of BRI.

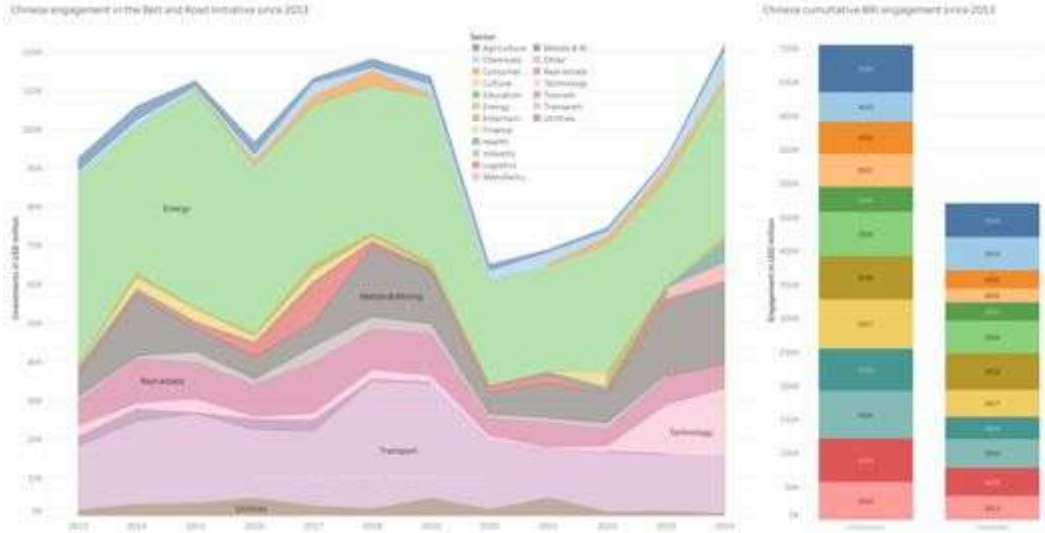


Figure 1. ***China's BRI Commitment by Sectors (2013 - 2024) and total investment amount*** [15]

CONCLUSION

Given the fact that every crisis also gives rise to new opportunities related to the restart of the initiative (BRI Reboot), in the process of resumption, attempts have been made to overcome the weaknesses that have arisen during the past period, adding new development guidelines related to sustainability, the green economy, etc. The objective factors also include the subjective one related to the decentralization of port management in China, the introduction of "green" shipping corridors. (GSC [16]), initiated by the Clydebank Declaration in 2021 (COP26[17]), the digitalization and decarbonization of the maritime industry (Green Shipping Challenge, 2022[18]), which require additional regulations, a centralized information network, and significant financial resources.

15 China Belt and Road Initiative (BRI) Investment Report 2024 – Green Finance & Development Center

16 Source: https://globalmaritimeforum.org/green-corridors/

17 Source: https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration

18 Source: Green Shipping Challenge

Also, the BRI's timber trade component, while providing economic development opportunities through infrastructure for many participating nations, brings significant risks of accelerating deforestation, requiring robust environmental governance to be truly sustainable.

REFERENCES (alphabetical order)

1. Alamoush, A.S., Ballini, F., Ölçer, A.I., 2021. Ports, maritime transport, and industry: The immediate impact of COVID-19 and the way forward. Maritime Technology and Research, 4, 250092.
2. Buckley, P.J., 2020. China's Belt and Road Initiative and the COVID-19 crisis. Journal of International Business Policy 3, 311–314.
3. Cariou, P., Notteboom, T., 2022. Implications of COVID-19 on the US container port distribution system: import cargo routing by Walmart and Nike. International Journal of Logistics Research and Applications 1–20. https://doi.org/10.1080/13675567.2022.2088708
4. China News Service., 2023. ASEAN annual goods enter the western region of China along the new land-sea corridor in the west (in Chinese). https://www.chinanews.com/cj/2023/0106/9929520.shtml (Accessed 6th January 2023).
5. Lee, P.T.-W., Hu, Z.-H., Lee, S., Feng, X., Notteboom, T., 2022. Strategic locations for logistics distribution centers along the Belt and Road: Explorative analysis and research agenda. Transport Policy 116, 24-47.
6. Lambovska, M. R. (2018). Control on teams: A model and empirical evidence from Bulgaria. Serbian Journal of Management, 13(2), 311–322. https://doi.org/10.5937/sjm13-14633
7. Angelova-Stanimirova, A. (2025). Essential Components of Management Control Systems in the Forestry-Based Sector. WoodEMA 2025 - Wood For The Future: Integrating Sustainability Across Industries, Proceedings of Scientific Papers, 279–284.

Authors address:
Antoaneta Kirova, Professor, Doctor of economic sciences, Department "Transport Economy and Accounting", Faculty of Transport Management, Todor Kableshkov Transport University, toni.kirova@gmail.com
Daniela Todorova, Professor, PhD, Department "Transport Economy and Accounting", Faculty of Transport Management, Todor Kableshkov Transport University, dtodorova@vtu.bg
Krassimir Krastanov, Professor, PhD, Faculty of Engineering and Construction Technologies in Transport, Department of "Hoisting and Transport and Construction Machinery and Systems", Todor Kableshkov Transport University, kkrastanov@vtu.bg
Dimitar Todorov, Master of Economics, PhD student, Department "Transport Economy and Accounting", Faculty of Transport Management, Todor Kableshkov Transport University, todorov.exante@gmail.com

CHAPTER G
POLICY, LEGAL FRAMEWORK, ESG AND REPORTING

TARIFF AND NON-TARIFF REGULATION OF WOOD EXPORT AND IMPORT IN UKRAINE AND THE EU

Serhii Kostornoi, Oksana Tulai, Rostyslav Yatsukh

Abstract: This article examines the current mechanisms of tariff and non-tariff regulation governing the export and import of timber between Ukraine and the European Union. The study aims to analyze the legal framework, economic impact, and environmental implications of existing trade barriers and incentives.

The research utilizes a comparative analysis of Ukrainian national legislation and EU regulations. It evaluates the effectiveness of fiscal tools versus administrative restrictions.

The analysis reveals a significant divergence in regulatory approaches: while Ukraine relies heavily on protective measures like the log export moratorium, the EU focuses on sustainability and "deforestation-free" supply chains through mandatory due diligence. The article highlights that the future of bilateral trade depends less on duty rates and more on the digitalization of timber tracking and compliance with international environmental standards.

The results provide insights for policymakers to harmonize Ukrainian forestry standards with EU requirements, potentially resolving long-standing trade disputes and fostering a transparent timber market.

Keywords: wood export, timber trade, tariff regulation, non-tariff barriers, log export moratorium, sustainability, Ukraine-EU Association Agreement

1. INTRODUCTION

Global market integration and the climate crisis have shifted the paradigm of international natural resource trade, placing the timber industry under stringent regulatory oversight. For Ukraine, managing timber flows is strategically vital. Under martial law and energy crises, the state must balance domestic defense and infrastructure needs with maintaining the export positions of woodworkers, while preventing forest ecosystem depletion. Consequently, analyzing tariff and non-tariff instruments is critical to building a resilient economic policy.

Ukraine's EU pre-accession negotiations require full alignment with the Acquis Communautaire. Forestry has long been a contentious bilateral trade issue, highlighted by the past arbitration over Ukraine's raw timber export moratorium. Access to the EU internal market now extends beyond eliminating duties and quotas; it demands a full transition to European standards. Non-tariff mechanisms—specifically digitized timber tracking, transparent auctions, and absolute verification of legal origin—now dictate trade access.

Furthermore, trade policy is heavily driven by the environmental agenda. The European Green Deal has shifted focus from traditional protectionism to climate neutrality and biodiversity preservation, underscored by the European Deforestation Regulation (EUDR) taking effect at the end of 2026. Environmental mandates, such as mandatory forest plot geolocation and rigorous due diligence supply chain controls, are becoming core non-tariff requirements. For Ukraine, this requires urgent modernization of its forest management system but offers a unique opportunity to become a reliable, "green" partner guaranteeing the ecological integrity of its exports.

2. TARIFF AND NON-TARIFF REGULATION OF WOOD EXPORT FROM UKRAINE

Ukraine's contemporary timber export framework relies heavily on non-tariff methods (prohibitions, quotas, licensing, digital tracking) rather than conventional tariffs. This approach aims to protect the domestic processing market, secure wartime energy needs, and align supply chains with international transparency standards.

2.1. Legal Framework: From Moratorium to Zero Quotas

The cornerstone of non-tariff regulation was established by Law No. 2860-IV, which introduced a 10-year moratorium on unprocessed timber exports (effective from 2015 for non-pine species; 2017 for pine). Although this moratorium expired in autumn 2025, wartime infrastructure damage and domestic shortages prompted the state to restructure these limits.

The government transitioned to an export licensing mechanism with zero-volume quotas, officially extended until December 31, 2026. This applies to logs, commercial wood, chips, shavings, and specific fuelwood. International legal justification rests on GATT 1994 Articles XI:2(a) (critical shortages), XX(g) (resource protection), and XXI (security exceptions).

2.2. Non-Tariff Regulation: Certification and Traceability

With raw wood exports restricted, businesses focus on processed timber (lumber, veneer, finished goods). Shipments require a mandatory Certificate of Origin to prevent the illegal export of unverified lumber.

Issuance is fully digitized via the Unified State Electronic Timber Accounting System (EAS), managed by SE "Forests of Ukraine" and overseen by the State Forest Resources Agency. Every exported batch features a digital trail linking the product to a legitimate logging site and a licensed exchange receipt.

2.3. Tariff Regulation and Export Duties

Because raw timber exports are banned, export duties play a secondary role, applying only to permitted categories. Under the Customs Tariff of Ukraine (Group 44) and the EU Association Agreement, duties on most finished wood products and lumber to the EU stand at 0%, incentivizing high-value domestic processing. Duties are retained only on select waste or non-scarce materials sent outside the EU.

2.4. Statistical Indicators of Wood Foreign Trade

Despite wartime bottlenecks, Group 44 products maintain a highly positive trade balance. State Customs and Statistics Service data for the first half of 2025 show:

- Export Value & Balance: Reached USD 830.4 million (14% growth year-on-year). Exports exceeded imports seven-fold, netting a USD 714.5 million capital inflow (4.1% of total Ukrainian exports).
- Volumes & Species: Ukraine exported 1.42 million tons of timber products (up 6% from 2024). Processed exports were dominated by Pine (68.6%), Spruce (19%), and Oak (6.6%).
- Markets & Fuelwood: Poland, Romania, and Germany remain the top EU buyers. Permitted fuelwood exports reached 1.089 million tons (USD 131.17 million) in 2024, and 894 thousand tons (USD 136 million) in the first 10 months of 2025, indicating rising unit values.

The active zero-quota regime entirely blocks raw wood exports through 2026. Monetary export growth stems solely from value-added goods, confirming the efficiency of non-tariff protectionism in driving domestic manufacturing.

3. TARIFF AND NON-TARIFF REGULATION OF WOOD IMPORT INTO UKRAINE

3.1. Tariff Regulation of Imports: Duties and Taxes

Import tariffs (Group 44 UKT ZED) align with the Customs Tariff of Ukraine, WTO rules, and free trade agreements:

- EU Association Agreement & DCFTA: A 0% duty rate applies to most Group 44 items from the EU, covering scarce raw wood, lumber, veneer, MDF/HDF, plywood, and joinery.
- Most-Favored-Nation (MFN) Status: For other WTO members without FTAs, import duties remain low:
  - Unprocessed wood, fuelwood, charcoal: 0%;
  - Lumber and longitudinally sawn wood: 0% to 2%;
  - Veneer sheets and peeled wood: 2–5%;
  - Builder's joinery, carpentry, and containers: 5–10%.
- Internal Taxation: All imported timber is subject to a standard 20% Value Added Tax (VAT) based on its customs value converted into national currency, including any applicable duties.

3.2. Non-Tariff Regulation of Imports

Non-tariff measures focus on biosecurity and supply chain transparency rather than economic protectionism:

- Phytosanitary Control: Under the Law of Ukraine "On Plant Quarantine," all timber imports (logs, fuelwood, packaging) require a Phytosanitary Certificate from the exporting country and must pass visual and laboratory inspections for quarantine pests.
- State Border Control: Pursuant to Cabinet Resolution No. 1030, timber clearance requires a positive electronic assessment by Derzhprodspozhyvsluzhba via the "Single Window for International Trade" platform.
- Radiological Monitoring: Shipments undergo mandatory verification for radioactive contamination, especially if originating from high-risk industrial or disaster zones.
- Electronic Accounting System (EAS) Integration: Imported raw or primary-processed timber must be registered in the national EAS platform. This allows Ukrainian manufacturers using imported inputs to verify full supply chain legality for subsequent exports to the EU.

3.3. Volume and Structure of Imports

Timber imports are modest since domestic forest reserves meet most of Ukraine's internal demand. According to the State Customs Service, during the first half of 2025:

- The total import value of Group 44 products was USD 115.9 million.
- Imports consisted mostly of specialized raw materials and high-tech commodities lacking domestic substitutes: polymer-coated panels (MDF/chipboard), paper, cardboard, architectural components, and exotic hardwoods.
- The primary geographic sources were the EU (Poland, Germany, Romania) and Asian nations (for veneers).

In summary, Ukraine maintains a maximum facilitation regime with 0% duties for European partners, shifting the regulatory focus entirely to non-tariff instruments that safeguard environmental and phytosanitary integrity.

4. REGULATION OF WOOD EXPORT AND IMPORT IN THE EU

The EU is a premier global consumer and trader of forest products. While its tariff policy liberalizes trade to supply raw materials, its non-tariff regulation is undergoing a major overhaul. Aligned with the European Green Deal, this framework shifts timber trade from mere commercial exchange to a primary climate tool.

4.1. Non-Tariff Regulation: Paradigm Shift from EUTR to EUDR

The old EUTR No. 995/2010 framework, focused on verifying legal timber origin, is being replaced by the far stricter European Deforestation Regulation (EUDR, Regulation (EU) 2025/2650).

- Timelines: The EUDR becomes legally binding for large operators on December 30, 2026, and for MSMEs on June 30, 2027.
- Core Bans: Products cannot enter, leave, or circulate in the EU market unless they are:
  - "Deforestation-free" (sourced from land not deforested or degraded after December 31, 2020);
  - Produced legally under the country of origin's laws;
  - Covered by a validated Due Diligence Statement.
- Mandatory Geolocation: Importers must provide exact GPS coordinates or land polygons (for plots over 4 hectares) and the production time for every timber batch. This ensures 100% traceability and prevents blending with unverified wood.

4.2. The Three-Stage Due Diligence System

Market operators bear strict liability and must apply a three-tier evaluation system:

- Information Gathering: Collecting data on volume, suppliers, origin, legal compliance, and GPS coordinates.
- Risk Assessment: Evaluating the risk of illegal or deforestation-linked wood entering the chain using an EU three-tier benchmarking system (low, standard, high risk). High-risk origins trigger increased customs inspections.
- Risk Mitigation: Taking proactive steps (independent audits, digital certifications) to neutralize any non-negligible risk.

Non-compliance triggers severe penalties, including fines up to 4% of an operator's annual EU turnover, product confiscation, and exclusion from public procurement.

4.3. Phytosanitary and Customs Oversight

Traditional biosecurity measures operate alongside the EUDR:

- Phytosanitary Certification: Under Regulation 2016/2031, imports of raw logs and lumber from non-EU states (like Ukraine) undergo strict monitoring for quarantine pests.
- Wooden Packaging: All pallets, crates, and dunnage must bear international ISPM 15 markings (heat treatment/вeapor fumigation).

4.4. Tariff Regulation of Exports and Imports within the EU

The EU's tariff structure facilitates raw material entry while protecting finished-goods manufacturers:

- Import Duties (TARIC): Raw logs and primary lumber (Group 44) carry a 0% duty. Processed goods (joinery, furniture, plywood) from nations without free trade pacts face duties of 2% to 10%.
- Preferential Regimes: Under the DCFTA and autonomous measures, all Group 44 imports from Ukraine enter at 0% duty.
- Export Duties: In line with WTO rules, the EU levies no export duties on timber. Internal resource outflows are instead controlled via logging permits and environmental allocations.

Ultimately, the fiscal tariff component has been marginalized; non-tariff barriers now dictate market access. The implementation of the EUDR at the end of 2026 effectively bans any timber that lacks a digital passport and verified coordinates of origin.

5. CONCLUSIONS

General Findings

- Dominance of Non-Tariff Mechanisms: Under the DCFTA, tariffs between Ukraine and the EU are completely eliminated (0%), shifting market regulation entirely to environmental criteria, supply chain traceability, and biosecurity protocols.
- Legalization of Trade Restrictions: Implementing export licensing with zero-volume quotas until December 31, 2026, allows Ukraine to protect its domestic market while remaining compliant with WTO and EU legal boundaries.
- The EUDR Imperative: The European Deforestation Regulation (EUDR), launching December 30, 2026, conditions EU market access on precise, digitized GPS coordinates of the exact timber harvest sites.

Avenues for Advancing Ukrainian Legislation

- Reforming Law No. 2860-IV: Transitioning from a mechanical export moratorium to ecology-driven monitoring that aligns with international free trade principles.
- Elevating EAS Legal Status: Formally anchoring the mandatory use of the electronic timber accounting system (EAS) in federal law and increasing penalties for fraudulent geospatial reporting.
- Incentivizing Value-Added Processing: Introducing targeted VAT and import duty exemptions on high-tech woodworking machinery to upgrade domestic plants.

Harmonization Roadmap with EU Requirements (Priorities until End-2026)

- Digital Geolocation Infrastructure: Deploying high-precision GNSS/GIS equipment within SE "Forests of Ukraine" to map all logging zones as digitized geographic polygons.
- System Architecture Integration: Ensuring technical interoperability between Ukraine's EAS platform and the EU's central Information System for automated Due Diligence Statements.
- National Certification Alignment: Aligning national FSC and PEFC criteria with EUDR baselines to help Ukraine attain "low-risk" status and simplify customs checks.
- Private Sector Support: Establishing advisory hubs to assist small and medium-sized enterprises (SMEs) in navigating new EU sustainability mandates.

In summary, digitalization, precision geospatial data, and verified legality represent the new "green passport". Without it, Ukrainian forestry exports face a total block from the European market beginning late 2026.

REFERENCES

1. Customs Tariff of Ukraine. URL: https://zakon.rada.gov.ua/laws/show/2697-20#Text
2. EU Customs Tariff (TARIC). URL: https://taxation-customs.ec.europa.eu/customs/common-customs-tariff-cct/tariff-classification-goods/eu-customs-tariff-taric_en
3. Kostornoi S., Yatsukh O., Tsap V., Demchenko I., Zakharova N., Klymenko M., Labenko O., Baranovska V., Daniel Z., Tomaszewska-Górecka W. (2021) Tax Burden of Agricultural Enterprises in Ukraine. Agricultural Engineering. 2021. 25(1). P. 157-169 URL: https://sciendo.com/it/article/10.2478/agriceng-2021-0013
4. Law of Ukraine "On the Specifics of State Regulation of the Activities of Subjects of Entrepreneurial Activity Related to the Realization and Export of Timber" No. 2860-IV. URL: https://zakon.rada.gov.ua/laws/show/2860-15#Text
5. Regulation on Deforestation-free Products. URL: https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en
6. State Statistics Service of Ukraine. URL: https://stat.gov.ua
7. Tsap, V., Tulai, O., & Yatsukh, O. (2025). Ensuring the export potential of Ukraine's forestry sector under conditions of sustainable development. In Wood for the Future: Integrating Sustainability Across Industries. Proceedings of Scientific Papers 2025 (pp. 145–151).
8. Yatsukh, O., Zhuravlova, I., Tsap, V. (2025). Digital platforms for the financial and economic support of forestry enterprises: the experience of ukraine. Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025. URL: https://www.woodema.org/proceedings/WoodEMA_2025_proceedings.pdf

Authors address:
Kostornoi S., PhD [1]; Tulai O., doctor of economics [2]; Yatsukh R., PhD Student, [3].
[1] Department of Finance, Accounting and Taxation, Dmytro Motornyi, Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
[2] Department of International Relations and Diplomacy, West Ukrainian National University, Ternopil, Ukraine.
[3] PhD Student West Ukrainian National University, Ternopil, Ukraine
*Corresponding author: serhii.kostornoi@tsatu.edu.ua

INFORMATION ASYMMETRY OR SIGNAL AMBIGUITY? SUSTAINABILITY AND MARKET INTERPRETATION IN WOOD PRODUCT MARKETS

Tsvetelina Simeonova

Abstract: Wood product markets within the bioeconomy are increasingly influenced by sustainability-related information, which appears to play a more significant and complex role than in many other bio-based sectors. In contrast to relatively standardized products such as biofuels or biochemicals, wood-based products are inherently heterogeneous, with their characteristics and value closely tied to origin, processing, and end-use. As a result, sustainability attributes are not only more visible, but also more difficult to define and compare in a consistent manner.

Against this background, the paper considers whether the resulting market conditions can be adequately described in terms of classical information asymmetry, or whether they reflect a different type of imperfection. Focusing on commonly used sustainability signals, such as certification schemes, carbon footprint indicators, and lifecycle-based assessments, it suggests that the coexistence of multiple, non-aligned approaches does not simply create information gaps, but introduces a degree of interpretative uncertainty.

Compared to other bioeconomy markets, where sustainability is more often embedded in standardized product characteristics and plays a limited role in differentiation, wood product markets appear to depend more heavily on diverse and context-specific signals. This has implications for how products are compared, how prices are formed, and how sustainability claims are perceived. The paper therefore argues that these structural features need to be taken into account when analysing the development of wood product markets within the broader bioeconomy.

Keywords: information asymmetry; information plurality; signal ambiguity; sustainability assessment; wood product markets.

1. INTRODUCTION

Markets increasingly rely on sustainability-related information to evaluate products, support purchasing decisions and reduce uncertainty about environmental performance. Within the bioeconomy, environmental attributes have evolved from regulatory requirements into economically relevant product characteristics influencing competitiveness, procurement and investment decisions (Christensen et al., 2021; Gillan et al., 2021). Information has therefore become an integral component of market exchange rather than merely a means of communication.

Wood product markets represent a distinctive case within this broader context. Unlike relatively standardised bio-based products, wood products differ substantially in terms of raw material origin, forest management, processing technologies and end-use applications. Their environmental performance cannot be represented by a single indicator but is communicated through multiple sustainability assessment systems, including forest certification, Environmental Product Declarations (EPDs), Life Cycle Assessment (LCA), carbon footprint indicators and ESG disclosures (Low et al., 2023; Zhelyazkova, 2020). Consequently,

sustainability attributes are not only more visible but also more difficult to compare consistently than in many other bio-based markets.

Information economics traditionally explains market uncertainty through information asymmetry, whereby relevant information is unavailable or unevenly distributed among market participants (Akerlof, 1970). Certification and disclosure mechanisms reduce such informational deficits by making otherwise unobservable product characteristics visible (Christensen et al., 2021; Spence, 1973). In contemporary wood product markets, however, uncertainty may persist despite extensive sustainability disclosure because different sustainability assessment systems evaluate distinct dimensions of environmental performance. Hence, the analytical challenge therefore extends beyond information availability to determining how multiple legitimate sustainability signals should be interpreted.

Against this background, the paper addresses the following research questions:

RQ1: Can sustainability-related market conditions in wood product markets be adequately explained through the traditional concept of information asymmetry (IA)?

RQ2: Do these market conditions require a different analytical perspective based on the concept of signal ambiguity (SA)?

To address these questions, the paper adopts a deductive conceptual approach. The research draws on the literature on information economics and sustainability assessment to compare two informational conditions: **informational scarcity and information plurality**. Their analytical implications are examined in the context of wood product markets, allowing the development of a conceptual framework for selecting the analytical perspective most appropriate to each informational condition.

2. INFORMATIONAL CONDITIONS AND ANALYTICAL PERSPECTIVES

Information economics explains market uncertainty through **information asymmetry**, which arises when relevant knowledge is unavailable or unevenly distributed among market participants (Akerlof, 1970). Under such conditions, buyers and other stakeholders cannot adequately evaluate product characteristics because the information required for informed decision-making remains inaccessible. Disclosure and signalling mechanisms thus reduce uncertainty by improving information availability (Spence, 1973; Stiglitz, 2000).

This perspective has been widely applied to sustainability-related markets, where many environmental characteristics represent credence attributes that cannot be directly verified even after purchase. Certification, sustainability reporting and third-party verification reduce informational disadvantages by making these characteristics observable (Christensen et al., 2021).

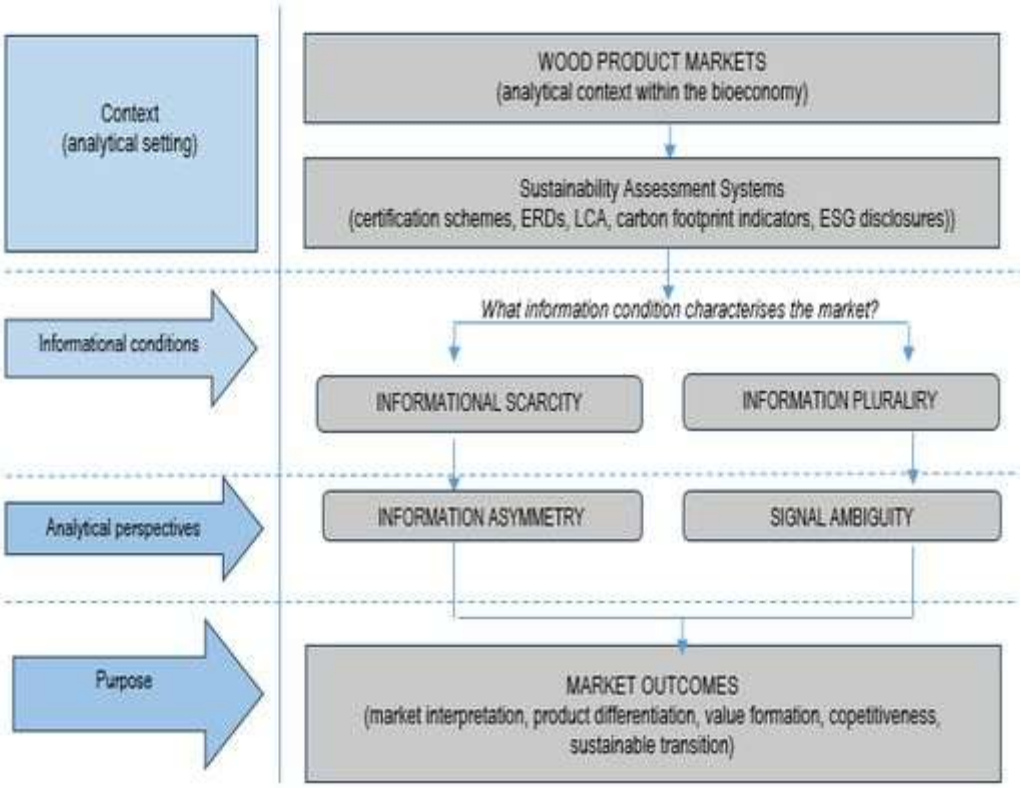
The expansion of sustainability assessment systems has, however, changed the informational environment. As the volume and diversity of sustainability information have increased, market uncertainty no longer depends solely on information availability but also on the interpretation of multiple legitimate sustainability assessments (Low et al., 2023).

For the purposes of this study, **information plurality** is defined as an informational condition in which multiple legitimate sustainability assessment systems coexist while evaluating different sustainability dimensions. Unlike **informational scarcity**, where uncertainty originates from missing or unevenly distributed information, information plurality arises because complementary assessments provide different, but equally legitimate, perspectives on environmental performance.

This distinction provides the conceptual basis for the analytical framework developed in this paper. **Information asymmetry** remains appropriate where uncertainty originates from informational scarcity. **Signal ambiguity**, by contrast, explains situations in which uncertainty persists despite extensive information because market participants must interpret and compare multiple legitimate sustainability signals.

Figure 1 summarises the relationship between these informational conditions and their corresponding analytical perspectives.

Figure 1. Analytical Framework for Choosing Between Information Asymmetry and Signal Ambiguity



Source: Author's conceptual framework.

The framework establishes the analytical basis for the subsequent examination of wood product markets.

3. SUSTAINABILITY SIGNALS AND INFORMATION PLURALITY IN WOOD PRODUCT MARKETS

Information plurality becomes analytically relevant when multiple sustainability assessment systems provide complementary rather than interchangeable evidence. Wood product markets represent a particularly suitable context for examining this condition because environmental performance is communicated through several established assessment systems addressing

different sustainability dimensions. Consequently, extensive sustainability disclosure does not necessarily produce directly comparable evaluations.

Table 1 demonstrates that environmental assessment frameworks do not present competing measurements of the same characteristic, but instead offer supplementary evidence addressing different ecological and developmental dimensions. Hence, no single assessment can provide a comprehensive evaluation of a wood product's sustainability performance.

As a result, market participants must interpret various legitimate sustainability signals as opposed to rely on a single indicator. Under these conditions, market uncertainty originates not from insufficient information but from information plurality, establishing the analytical conditions under which signal ambiguity becomes applicable.

Table 1. Why Sustainability Assessment Systems Generate Information Plurality

Sustainability assessment system	Main question answered	Level of assessment	Limitation for market comparison	Contribution to information plurality
FSC/ PEFC	Was the wood responsibly sourced?	Forest/ chain of custody	Does not evaluate the environmental performance of the final product	Adds a sourcing signal that cannot substitute for product-level assessment
Environmental Product Declaration (EPD)	What is the product's environmental profile?	Product	Does not assess forest governance or corporate conduct	Adds product-specific data that cannot substitute for sourcing or firm-level signals
Life Cycle Assessment (LCA)	What impacts occur across the life cycle?	Product life cycle	Depends on methodological choices and system boundaries	Adds life-cycle evidence that may not be directly comparable across cases
Carbon footprint	What are the greenhouse gas emissions?	Climate impact	Captures only one environmental dimension	Adds a climate-specific signal that cannot represent overall performance
ESG disclosure	How does the organisation perform on ESG criteria?	Firm/ organisation	Does not describe the environmental profile of individual products	Adds a corporate-level signal that cannot substitute for product-level evidence

Source: Author's compilation based on Christensen et al. (2021), Low et al. (2023), and Pirc Barčić (2023).

4. SELECTING THE APPROPRIATE ANALYTICAL PERSPECTIVE

The preceding analysis demonstrates that IA and SA should not be treated as competing explanations of market uncertainty. Their applicability depends on the underlying informational condition.

IA remains appropriate where uncertainty originates from informational scarcity where information is unavailable or unevenly distributed among market participants, and greater transparency reduces informational disadvantages (Akerlof, 1970; Spence, 1973). By contrast, SA becomes applicable where multiple legitimate sustainability assessment systems coexist,

and the central analytical challenge is no longer obtaining additional information but interpreting and comparing complementary sustainability evidence.

Table 2 shows that the distinction proposed in this paper is conditional rather than theoretical. IA explains uncertainty arising from informational scarcity, whereas SA is more appropriate where uncertainty results from information plurality. Selecting the analytical perspective according to the prevailing informational environment thus providing a more precise basis for analysing market behaviour in wood product markets.

Table 2. Selecting the Appropriate Analytical Framework According to the Informational Condition

Analytical criterion	Information Asymmetry (IA)	Signal Ambiguity (SA)
Informational condition	Information is unavailable, incomplete or unevenly distributed	Multiple legitimate sustainability assessment systems coexist
Source of market uncertainty	Information deficit	Information plurality
Central analytical problem	Obtaining reliable information	Interpreting and comparing available information
Role of sustainability reporting	Discloses previously hidden product attributes	Provides complementary assessments of different sustainability dimensions
Appropriate framework	Information asymmetry	Signal ambiguity

Source: Author's conceptual framework.

5. MANAGERIAL AND POLICY IMPLICATIONS

The proposed distinction has practical implications for firms, market intermediaries and policymakers operating in wood product markets. As sustainability assessment systems continue to expand, decision-making increasingly depends on interpreting supplementary sustainability information as opposed to obtaining additional information.

For firms, this means that certification, EPDs, LCA, carbon footprint indicators and ESG disclosures should be communicated as complementary rather than interchangeable sources of evidence, reducing the risk of misleading product comparisons (Atanasov, 2025).

The framework also has implications for procurement and investment decisions. Because different assessment systems support distinct evaluation objectives, decision quality depends on interpreting supplementary evidence instead of expanding sustainability disclosure alone (Gillan et al., 2021; Low et al., 2023).

From a policy perspective, greater transparency remains essential for reducing informational scarcity, but information plurality requires improved comparability, methodological consistency and interoperability across sustainability assessment systems (Christensen et al., 2021; Low et al., 2023).

Although the proposed distinction may also inform other sustainability-oriented sectors, its principal contribution lies in explaining the distinctive informational environment of wood products, where multiple complementary assessment systems shape consumer interpretation, product differentiation, and value formation.

6. CONCLUDING REMARKS

This paper examined whether sustainability-related market conditions in contemporary wood product markets can be adequately explained through the traditional concept of information asymmetry. The analysis demonstrates that the appropriate analytical perspective depends on the informational condition under investigation.

Where uncertainty results from informational scarcity, IA remains the appropriate analytical perspective. Where multiple legitimate sustainability assessment systems provide supplementary instead of interchangeable evidence, uncertainty reflects information plurality and is more appropriately analysed through SA.

The principal contribution of the paper is the contrast between informational scarcity and information plurality as alternative informational conditions requiring different analytical perspectives. This distinction provides a more precise basis for analysing market interpretation, product differentiation and value formation in wood product markets.

Future research should examine how information plurality influences purchasing decisions, supplier selection and price formation, while exploring the applicability of the proposed framework across other bioeconomy sectors.

REFERENCES

1. Akerlof, G.A. (1970). *The Market for Lemons: Quality Uncertainty and the Market Mechanism*. The Quarterly Journal of Economics, 84(3), 488–500.
2. Atanasov, A. (2025). *Integrating Sustainability Information Through Value Chain Disclosures: Insights from the Wood-Based Industries*. In: *Proceedings of the 18th International Scientific Conference WoodEMA 2025*. WoodEMA.
3. Christensen, H.B., Hail, L. & Leuz, C. (2021). *Mandatory CSR and Sustainability Reporting: Economic Analysis and Literature Review*. Review of Accounting Studies, 26(3), 1176–1248.
4. Gillan, S.L., Koch, A. & Starks, L.T. (2021). *Firms and Social Responsibility: A Review of ESG and CSR Research in Corporate Finance*. Journal of Corporate Finance, vol. 66 (C).
5. Low, M., Samkin, G. & Li, Y. (2023). *Corporate Reporting on the Sustainable Development Goals: A Structured Literature Review and Research Agenda*. Journal of Accounting Literature, 52, 1–25.
6. Pirc Barčić, A. (2023). *Contribution and Importance of Wood-Based Sector towards Carbon Neutrality and Bioeconomy*. In: *Current Trends and Challenges for Forest-Based Sector: Carbon Neutrality and Bioeconomy*. WoodEMA, 17–21.
7. Spence, M. (1973). *Job Market Signaling*. The Quarterly Journal of Economics, 87(3), 355–374.
8. Stiglitz, J.E. (2000). *The Contributions of the Economics of Information to Twentieth Century Economics*. The Quarterly Journal of Economics, 115(4), 1441–1478.
9. Zhelyazkova, V. (2020). *Environmental Reporting: Principles and Main Challenges*. Ecology & Safety, 14, 1–8.

Authors address:
Simeonova, T.
Economic Research Institute at the Bulgarian Academy of Sciences
ts.simeonova@iki.bas.bg

BEYOND COMPLIANCE: SUSTAINABILITY REPORTING AS A COMPETITIVE TOOL FOR WOOD PRODUCT COMPANIES IN THE EMERGING BIOECONOMY

Atanas Atanasov, Rumyana Marinova

Abstract: This paper examines sustainability reporting as a strategic management tool rather than a purely compliance-driven obligation, with particular reference to wood product companies operating within the bioeconomy. As expectations for transparency intensify across value chains, firms in the wood sector are increasingly required to communicate credible information on environmental, social, and governance performance. In this context, sustainability reporting may serve not only to satisfy external requirements but also to strengthen competitive positioning in evolving wood product markets.
The paper explores the extent to which sustainability reporting can contribute to market differentiation, stakeholder confidence, reputational capital, and responsiveness to changing buyer and supply-chain expectations. Particular emphasis is placed on reporting dimensions of direct relevance to the sector, including responsible sourcing, traceability, carbon-related performance, circular material use, and resource efficiency. At the same time, the analysis addresses key implementation challenges, such as limited reporting capabilities, insufficient data integration, fragmented organizational processes, and uncertainty regarding the conversion of sustainability performance into tangible market benefits.
The paper argues that, when embedded in strategic decision-making, sustainability reporting can function as a mechanism for value creation and competitive advantage, thereby supporting the broader development of transparent, resilient, and innovation-driven wood product markets within the bioeconomy.
Keywords: sustainability reporting, ESG reporting, wood product companies, emerging bioeconomy

1. INTRODUCTION

The past decade in corporate reporting has been marked by a shift toward a more comprehensive understanding of business performance, risks, and value creation by combining traditional financial indicators with sustainability-related and non-financial information. ESG reporting has evolved from a voluntary managerial practice into a central element of EU regulatory requirements and market logic, aimed at improving corporate transparency, comparability, and competitiveness. The adoption of the Corporate Sustainability Reporting Directive (CSRD), the development of the European Sustainability Reporting Standards (ESRS), the standards of the International Sustainability Standards Board (ISSB), and the growing integration of ESG criteria into investment decisions and supply-chain requirements indicate a qualitative change in the institutionalization of sustainability within the business environment. In this context, sustainability reporting, understood as systematic, verifiable, and comparable disclosure of information on ESG topics, can no longer be viewed only as a tool for regulatory compliance. Theoretical perspectives such as legitimacy theory, stakeholder theory, and the resource-based view suggest that credible sustainability disclosure may function as a strategic resource by generating reputational capital, strengthening stakeholder trust, and supporting differentiation in a competitive environment (Hummel & Schlick, 2016; Lai,

Melloni & Stacchezzini, 2017). At the same time, the growing importance of the bioeconomy as a framework for transforming production systems toward low-carbon and circular models creates specific opportunities for companies working with biological resources, such as wood product companies. For these firms, sustainability reporting becomes a way to communicate their contribution to sustainable development not only as a response to regulatory pressure, but also as a potential source of competitive advantage in markets increasingly sensitive to transparency and credibility.

The aim of this paper is to examine to what extent and under what conditions sustainability reporting can function as a mechanism for value creation and competitive advantage for wood product companies operating within the emerging bioeconomy. The central research question is: How can the integration of sustainability reporting into the strategic management of wood-processing enterprises support their competitive positioning? The main thesis is that sustainability reporting may strengthen competitiveness in wood-based enterprises by making their contribution to the circular bioeconomy visible, measurable, and credible.

Methodologically, the paper is conceptual and theoretical. It is based on a narrative review of contemporary scientific literature and current regulatory developments in sustainability reporting and the emerging bioeconomy field. The study does not aim to empirically test causal relationships, but to derive an analytical framework for understanding when sustainability reporting can serve as a tool for value creation and competitive advantage for wood product companies.

2. CONTEMPORARY SUSTAINABILITY REPORTING AS A COMPETITIVE TOOL

From a regulatory perspective, the Non-Financial Reporting Directive (NFRD) marked the first step toward mandatory non-financial disclosure, later expanded by the Corporate Sustainability Reporting Directive (CSRD) through standardized KPIs and improved comparability and verifiability. The GRI framework, ISSB standards, and IIRC principles complement this environment, and the CSRD/ESRS framework is particularly significant for wood product companies, aiming to standardize sustainability disclosures across the EU (Hummel & Jobst, 2024). This evolution has shifted the debate from *whether* companies should report to *how* they can do so in a way that creates strategic value. Although the Omnibus I package (2025) narrowed the scope of mandatory reporting and reduced administrative burden, a voluntary reporting standard (VS) was introduced for companies outside the mandatory scope. Hockmann & Thomsen (2026) argue that mandatory reporting increases transparency without reducing competitiveness, while voluntary reporting is growing as companies increasingly treat it as a strategic tool rather than a regulatory burden; wood product companies that integrate CSRD/ESRS requirements into governance may achieve greater market access and stakeholder trust (Hristov & Searcy, 2025).

A 2024 PwC global survey found that 45% of executives reporting under the CSRD view it as a competitive advantage - ranked below risk mitigation and stakeholder engagement, but above financial categories such as revenue growth or access to capital, reflecting the more abstract, long-term nature of this benefit (PwC, 2024). Beyond legal compliance, the CSRD encourages companies to embed sustainability into strategy, governance, and business models; Barker (2025) frames corporate sustainability reporting as an emerging field examining how disclosure standards create a "theory of change" that shapes corporate behaviour.

For wood product companies, reporting responds to multiple stakeholder pressures - customers demanding certified inputs, investors requiring ESG data, regulators expecting compliance, and supply-chain partners requiring traceability - thereby reducing information asymmetry where sourcing, resource efficiency, and circularity claims cannot otherwise be verified. This can support reputational capital and market access: firms reporting reliable data on sourcing, emissions, circularity, and certification may be better positioned in export markets, green procurement, and ESG-sensitive financing, though the effect depends on the report's credibility and materiality, since generic ESG statements cannot create lasting advantage without operational evidence. Rusanen et al. (2024) add an important caveat: sustainable value creation in the forest sector remains dominated by its economic dimension, with environmental and social dimensions still requiring more empirical attention — underscoring the need for reporting systems that demonstrate broader ecological and social value, not only financial or reputational gain.

Sustainability reporting strengthens competitiveness when it translates actual sustainability capabilities into credible market signals, supporting differentiation, reducing information asymmetry, and improving access to finance, but creates competitive value only when embedded in strategy and linked to measurable performance.

3. SUSTAINABILITY REPORTING AND THE BIOECONOMY

In wood-based businesses, sustainability reporting becomes a competitive tool when it translates contributions to the circular bioeconomy - such as renewable materials, carbon storage, circular design, and resource efficiency - into credible information for markets, regulators, investors, and supply-chain partners. Wood-processing enterprises occupy a specific position in the bioeconomy and circular economy because they use a renewable biological resource that can substitute materials with a high carbon footprint (Toppinen et al., 2017). At the same time, the sector faces growing scrutiny regarding raw material origin and the verifiability of sustainability claims. The EU Deforestation Regulation (EU, 2025), together with traceability criteria in public procurement and corporate purchasing policies, requires companies to move from declarative to verifiable and systematically managed sustainability reporting.

Wood product markets are closely linked to the circular bioeconomy because wood is a renewable resource, a material input, a carbon-storing product, and a substitute for fossil-based or more carbon-intensive materials. Hassegawa et al. (2022) argue that wood-based products can contribute to climate mitigation through substitution and carbon storage, but these effects must be assessed at product, market, country, and global levels. Therefore, companies cannot rely only on general claims that wood is “green” or “renewable”; they need measurable evidence of sustainability performance. Since these benefits depend on technologies, raw materials, recycling, and market conditions, high-quality and reliable reporting becomes a potential source of competitive advantage.

The circular bioeconomy perspective expands reporting beyond raw-material renewability. Aggestam and Giurca (2022) show that applying circular bioeconomy principles in wood-based value chains requires new business models, inter-firm cooperation, technological innovation, and better tools for assessing circularity. They also stress that circularity does not automatically imply sustainability or economic viability (Aggestam & Giurca, 2022). In practical terms, companies should report not only that they use wood, but also how

they manage sourcing, residues, recycling, cascading use, product lifespan, and end-of-life recovery.

Recent research links sustainability reporting directly to circular economy assessment in forestry companies. Panori et al. (2024) developed a scoring framework based on sustainability reports from 20 leading forestry companies and used it to classify firms according to their circular economy practices. Their findings show that sustainability reports can provide structured evidence of circular economy implementation, while many firms remain at early stages of adoption. They also find a statistically significant positive correlation between circular business practices and business success, measured by revenue growth (Panori et al., 2024). Thus, sustainability reporting can serve not only communication purposes, but also benchmarking and circular bioeconomy performance assessment.

Subsector-specific literature further clarifies reporting priorities. In wood-based composite panels, Garcia et al. (2024) identify opportunities related to underutilized wood sources, logging residues, fire-damaged wood, post-consumer wood, lightweight and multifunctional panels, and bio-based materials, but also challenges such as recycling post-consumer MDF, hazardous chemicals in adhesives, fire retardants and coatings, and the need for more circular manufacturing systems (Garcia et al., 2024). In the furniture sector, Kucuk and Buehlmann (2026) identify sustainable design, supply-chain management, sustainability strategies, and environmental management as key themes (Kucuk & Buehlmann, 2026). Georgieva and Tsakova (2025) add that regulatory sandboxes allow firms to test biomaterials, bio-based composites, biodegradable coatings, and other innovations, which can support bioeconomy innovation and data collection for CSRD reporting (Georgieva & Tsakova, 2025).

Taken together, the link between wood product markets and the bioeconomy is both strategic and critical. Strategically, sustainability reporting enables wood-based enterprises to position themselves within a low-carbon, circular, and bio-based economy, supporting differentiation, export competitiveness, access to green construction and furniture markets, ESG financing, and public procurement. Critically, however, the literature warns that bioeconomy claims require verification. Wood-based products are not automatically sustainable; their environmental value depends on forest management, biodiversity impacts, transportation, processing technologies, product lifespan, recycling options, substitution effects, and end-of-life management (Aggestam & Giurca, 2022; Hassegawa et al., 2022; Panori et al., 2024). A circular bioeconomy in the wood sector is therefore possible but complex, requiring new business models, industrial symbiosis, supply-chain coordination, and consideration of energy and transport impacts (Aggestam & Giurca, 2022).

The relationship between reporting quality and outcomes such as market access, export performance, access to finance, innovation capacity, or price premiums remains under-explored, especially for SMEs, which dominate many wood product markets but often lack resources for complex reporting systems (Appiah-Kubi et al., 2024). Competitiveness also requires consideration of costs. Hassegawa et al. (2022) note that the climate and market potential of wood products depend on technologies, policies, consumer perceptions, and competition for raw materials, all of which require investment. Sustainability reporting also requires time, human resources, reliable data systems, and new technologies, although these investments may bring benefits such as access to green finance, lower loan costs, and broader market opportunities.

As Hyytiä (2022) argues, sustainable development, the bioeconomy, and the circular economy create new competitive advantages for the forestry sector, driven by certification,

innovation, green policies, and strategic value-chain management. Sustainability reporting transforms these drivers into demonstrable advantage by making sustainability visible, measurable, and verifiable. Reporting becomes a competitive tool for wood product companies when it is based on substantive sustainability capabilities, uses sector-specific indicators (sourcing, traceability, certification, emissions, circularity, life-cycle impacts), and translates bioeconomy contributions into credible, decision-useful information. Under these conditions, reporting moves beyond compliance and becomes a strategic mechanism for competitive value creation.

4. CONCLUSION

This paper examines whether sustainability reporting can function beyond regulatory compliance as a mechanism for competitive advantage for wood-processing enterprises in the emerging bioeconomy. The analyzed literature confirms that this relationship is conditional: reporting creates value only when it reflects actual sustainability capabilities and translates the company's contribution to the bioeconomy into reliable and verifiable information. In this way, reporting reduces information asymmetry between enterprises and stakeholders, who cannot directly verify the origin of raw materials, resource efficiency, or product circularity. Therefore, sustainability reporting can support access to green financing, public procurement, and supply chains with traceability requirements, but only when sustainability is integrated into the business model rather than added as a formal compliance exercise. Thus, for wood product companies, reporting becomes a competitive tool when it moves from minimal disclosure to credible, value-chain-based communication that supports innovation, trust, and strategic positioning. For managers, especially in SMEs, the value of reporting lies not in its volume, but in its integration into real management processes.

REFERENCES

1. Aggestam, F., & Giurca, A. (2022). Implementing Circular-Bioeconomy Principles across Two Value Chains of the Wood-Based Sector: A Conceptual Approach. Land, 11(11), 2037. https://doi.org/10.3390/land11112037
2. Appiah-Kubi, E., Koranteng, F. O., Dura, C., Mihăilă, A., Drigă, I., & Preda, A. (2024). Green financing and sustainability reporting among SMEs: The role of pro-environmental behavior and digitization. Journal of Cleaner Production, 478, 143939.
3. Barker, R. (2025). Corporate sustainability reporting. Journal of Accounting and Public Policy, 49, 107280. https://doi.org/10.1016/j.jaccpubpol.2024.107280
4. European Union. (2025). Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation (consolidated version 26.12.2025).
5. Garcia, R., Calvez, I., Koubaa, A., Landry, V., & Cloutier, A. (2024). Sustainability, circularity, and innovation in wood based panel manufacturing in the 2020s: Opportunities and challenges. Current Forestry Reports, 10, 420–441. https://doi.org/10.1007/s40725-024-00229-1
6. Georgieva, D. V., & Tsakova, I. (2025). Regulatory sandboxes in the furniture industry: Challenges and opportunities. WoodEMA 2025 Proceedings: Wood for the Future –

Integrating Sustainability Across Industries, Ohrid, September 17th-19th 2025, WoodEMA, 3-11.
7. Hassegawa, M., Van Brusselen, J., Cramm, M., & Verkerk, P. J. (2022). Wood-Based Products in the Circular Bioeconomy: Status and Opportunities towards Environmental Sustainability. Land, 11(12), 2131. https://doi.org/10.3390/land11122131
8. Hockmann, M., and M. Thomsen. 2026. "From Compliance to Competitive (Dis)Advantage? The Transformation of Corporate Sustainability Reporting." Strategic Change 1–17. https://doi.org/10.1002/jsc.70073
9. Hristov I, Searcy C. (2025), Integrating sustainability with corporate governance: a framework to implement the corporate sustainability reporting directive through a balanced scorecard. Management Decision, Vol. 63 No. 2 pp. 443–46.
10. Hummel, K., & Jobst, D. (2024). An Overview of Corporate Sustainability Reporting Legislation in the European Union. Accounting in Europe, 21(3), 320–355.
11. Hummel, K., & Schlick, C. (2016). The relationship between sustainability performance and sustainability disclosure – Reconciling voluntary disclosure theory and legitimacy theory. Journal of Accounting and Public Policy, 35(5), 455–476.
12. Hyytiä, A. (2022). Sustainable Development - International Framework - Overview and Analysis in the Context of Forests and Forest Products - Competitiveness and Policy. Forest Products Journal, 72(s1), 1–4. https://doi.org/10.13073/FPJ-D-20-00053
13. Kucuk, E., & Buehlmann, U. (2026). Sustainability and the Furniture Industry: A Comprehensive Synthesis. BioResources, 21(1), 2669–2709. Retrieved from: https://ojs.bioresources.com/index.php/BRJ/article/view/25176
14. Lai, A., Melloni, G., & Stacchezzini, R. (2017). What does materiality mean to integrated reporting preparers? An empirical exploration. Meditari Accountancy Research, 25(4), 533-553, https://doi.org/10.1108/MEDAR-02-2017-0113
15. Panori, D., Papaspyropoulos, K. G., & Nikolaou, I. E. (2024). A forest companies typology regarding their contribution to circular economy: a sustainability reporting-based analysis. Discover Sustainability, 5(1). https://doi.org/10.1007/s43621-024-00304-4
16. PwC. (2024, June 13). PwC's Global CSRD Survey 2024: The promise and reality of CSRD reporting. https://www.pwc.com/gx/en/issues/esg/global-csrd-survey.html
17. Rusanen, K., Hujala, T., & Pykäläinen, J. (2024). Research approaches to sustainable forest-based value creation: A literature review. Forest Policy and Economics, 163, 103222. https://doi.org/10.1016/j.forpol.2024.103222
18. Toppinen, A. M. K., Korhonen, J. E., Hurmekoski, E., & Hansen, E. (2017). What makes a European forest based bioeconomy competitive? In G. Winkel (Ed.), Towards a sustainable European forest based bioeconomy: Assessment and the way forward (pp. 101–107). European Forest Institute. Available at: https://helda.helsinki.fi/server/api/core/bitstreams/146e490b-84a0-41de-a8b5-607e6075c5bd/content

Authors address:
Atanasov, Atanas[1]; Marinova, Rumyana[2]
[1,2] Department of Accounting, University of Economics - Varna, Varna, Bulgaria
*Corresponding author: atanasov_at@ue-varna.bg

IMPLEMENTATION OF GREEN SKILLS IN THE ACCOUNTING REPORTING AND TAX TREATMENT OF RESIDUAL MATERIALS FROM FURNITURE PRODUCTION

Nikolay Katsarski

Abstract:
The worldwide sustainability mandate has transformed manufacturing processes, particularly in furniture production, where wood processing by-products pose substantial economic and environmental challenges. This research examines the incorporation of green competencies—including sustainable practices, waste minimization techniques, and circular economy principles—into the accounting and taxation of these residual materials. Traditional accounting standards generally classify such materials as production costs or waste, overlooking opportunities for value recovery via recycling and reuse, which could mitigate environmental harm and financial burdens.
Keywords: green skills, waste management, STEM accounting

INTRODUCTION

The furniture industry is a dynamic sector in which micro, small, and medium-sized enterprises form the backbone of production. Within the European Union, manufacturers have a solid international reputation, keeping pace with new trends and technologies while preserving their cultural and historical heritage. This enables the workforce to adapt to new green skills, leading to improved qualifications and added value in this industry. The contribution of the furniture industry lies in the fact that it provides approximately 1 million jobs across 130,000 companies, which generate an annual turnover of approximately 96 billion euros. This places EU companies among the global leaders in setting trends in the sector, accounting for about 12% of all designs registered with the European Union Intellectual Property Office. Most impressively, the EU dominates the high-end furniture market, accounting for nearly two out of every three high-end products sold worldwide.(European Commsion, 2026)

The main aim of the research is to develop and test a theoretical methodology for assessing whether the implementation of green skills improves the accounting reporting and tax treatment of residual materials from furniture production and whether this creates financial, environmental, organisational and reporting value.

The study can be structured around the following research questions:

- How are leftover materials from furniture production currently classified and accounted for in the accounting system?
- How can “green” skills improve the valuation, recognition, and reporting of scrap materials?
- How would “green” skills affect the tax treatment of residual materials? This includes processes related to the allocation of costs to newly created products, waste management, VAT reporting, and opportunities for tax relief.
- What are the financial and non-financial implications of creating a new business model through the management of “green” skills aimed to create value?

According to the rised questions the following hypotheses can be tested:

H1: The implementation of “green” skills improves waste classification by distinguishing between waste, reusable materials, recyclable materials, by-products, and secondary raw materials.

H2: The use of "green" skills enhances the quality of accounting reporting by introducing separate accounts, better valuation methods, and more reliable documentation for residual materials, and implementing new teaching approach based on comnination between accounting and STEM education.

H3: "Green" skills contribute to more accurate tax treatment by improving the documentation, classification, and tax treatment of residual materials.

H4: "Green" skills create positive financial value by optimizing costs, managing residual materials, using resources efficiently, adapting to regulatory requirements, and reporting on sustainability. From the perspective of non-financial information, the company's reputation is of direct relevance to its financial performance.

METHODOLOGY

The study applies a mixed-methods research design to assess how the implementation of green skills influences the accounting reporting, tax treatment and value creation related to residual materials from furniture production. It combines document analysis, material-flow analysis, cost-benefit analysis, focusing on materials such as wood offcuts, sawdust, wood chips, veneer residues, MDF residues and packaging materials, which may be classified as waste, reusable inputs, recyclable materials, by-products, secondary raw materials or saleable residual outputs. Green skills are operationalised through a Green Skills Implementation Index covering technical, accounting, tax, analytical and strategic competences, assessed by examining whether employees can identify residual material streams, classify them correctly, connect physical and monetary data, apply appropriate accounting and tax treatment, and use this information for circular economy decisions. The impact is measured through improvements in accounting quality, tax accuracy, sustainability reporting, material circularity and financial value creation, including separate recognition and valuation of residual materials, correct VAT and tax documentation, reduced disposal costs, revenue from sale of residues, savings from internal reuse, lower compliance risks and improved reporting of resource use and circular economy practices. Thus, green skills are treated not merely as training or awareness, but as practical professional competences that enhance accounting systems, tax compliance, sustainability reporting and circular value creation in furniture.

LITERATURE REVIEW

Existing green accounting frameworks frequently suffer from a lack of standardization, which complicates the translation of environmental impacts into financial metrics (Albu et al., 2025, p. 832; González & Peña-Vinces, 2022, p. 9520). Specifically, the difficulty in quantifying environmental and social externalities remains a primary barrier, as researchers struggle to establish consistent measurement standards across heterogeneous industries (Lisnawati et al., 2024, p. 61). Furthermore, traditional accounting systems often fail to bridge the gap between financial performance and circular value chains, leaving stakeholders with fragmented insights into the economic benefits of waste reduction (Aureli et al., 2023, p. 292). In the furniture sector, current tax treatments often categorize residual materials solely as disposal expenses, failing to leverage the Natural Resource-Based View to identify these as potentially recoverable resources (Hasan et al., 2024, p. 3). To address these limitations, scholars emphasize that professionals must expand their expertise to include the evaluation of alternative production strategies and the implementation of robust performance management systems that align with circular objectives (Jinga et al., 2024, p. 11). Integrating such skill sets facilitates the

operationalization of the circular economy by transitioning from traditional linear reporting toward advanced frameworks like Material Flow Cost Accounting (Kokubu et al., 2023, p. 2787), (Jesse et al., 2023, p. 22). By accurately tracing material and energy losses through these integrated processes, organizations can overcome the persistent failure to assign environmental costs to specific production activities (Mukwarami & Poll, 2024, p. 719).

1. Green skills implementation model

The Green Skills Implementation Index (GSII) is a quantitative approach designed to measure how effectively an organization operationalizes sustainable practices across five core dimensions: **technical** (material recovery and circular economy knowledge), **accounting** (measuring and reporting residual materials), **tax** (assessing tax treatments and compliance), **analytical** (evaluating physical and monetary data), and **strategic** (leveraging sustainability for business value creation). Each dimension is evaluated on a maturity scale from 0 (no evidence of skill) to 5 (fully integrated into management decisions), with the final GSI score calculated as the unweighted average of the five dimensions to provide a comprehensive snapshot of green skill integration. The approach presented in table 1 Green skills implementation index is developed by the aouthor using AI tool including presented five dimensions above.

Table 1 Green skills implementation index

Dimension	Description	Example indicators
Technical green skills	Knowledge of waste hierarchy, recycling, circular economy and material recovery	Ability to classify residual materials by type, origin and further use
Accounting green skills	Ability to recognise, measure and report residual materials correctly	Separate accounts for waste, by-products, recyclable materials and secondary raw materials
Tax green skills	Ability to assess tax treatment of residual materials	Correct VAT treatment, documentation of sales, deductibility of costs, tax compliance
Analytical green skills	Ability to collect and analyse physical and monetary data	Material-flow analysis, cost-benefit analysis, waste-cost calculation
Strategic green skills	Ability to use residual materials for business value creation	Internal reuse, external sale, circular partnerships, sustainability reporting

Each dimension may be scored from 0 to 5:

The total Green Skills Implementation Index can be calculated as:

GSI = (TGS + AGS + TXGS + ANGS + SGS) / 5

TGS = technical green skills score; AGS = accounting green skills score; TXGS = tax green skills score; ANGS = analytical green skills score; SGS = strategic green skills score.

The formula give a change for analisysing the score like: 0 No evidence of the skill; 1 Basic awareness only; 2 Partial knowledge, not applied systematically; 3 - Applied in selected processes; 4 Applied systematically and documented; 5 Fully integrated into accounting, tax, reporting and management decisions

Assessing the implementation of green skills creates the conditions for a detailed analysis of the potential opportunities for their added value in the sector. Furthermore, they create

opportunities for the creation of new jobs and the retraining of vulnerable groups in society. This assessment also makes it possible to determine the level of green transformation.

2. Shaping the furniture production by implementing new business model using accounting reporting and tax treatment of residual materials.

The use of a new business model to create value through the implementation of approaches focused on the use of residual materials, effective materials management, and the creation and application of appropriate regulatory frameworks to stimulate these processes form the basis for a more in-depth analysis. Currently, IAS 2 Inventories is used. It is not sufficient to cover the new trends driving the green transition. For this reason, there is a growing need to implement green accounting practices. The accounting assessment examines whether "green" skills improve the accounting treatment of residual materials. Accounting information must identify residual materials, verify that they are correctly classified, determine their value, and specify how they should be sold and reported.

In order to organize accounting information properly, accounting accounts must be presented analytically, such as:

- reusable materials;
- recyclable materials;
- by-products;
- secondary raw materials;
- hazardous or non-hazardous waste;
- materials for disposal.

Table 2: Presents an assessment of the quality of accounting practices related to the reporting of residual materials. This table can be used as a checklist for recognition of the materials.

Table 2 Table 2: Criteria for recognizing residual materials in accounting

Criterion	Score 0	Score 1	Score 2
Identification of residual materials	Not identified	Partly identified	Fully mapped
Separate accounting	No separate accounts	Partial analytical accounts	Full separate tracking
Valuation	No valuation	Estimated valuation	Systematic valuation
Documentation	Weak documentation	Partial documentation	Complete documentation
Reporting	Not reported	Internally reported	Internally and externally reported

However, this list is not sufficient for assessing and measuring this type of material. The environmental assessment measures whether "green" skills lead to better use of waste materials. It is based on the logic of material flows, comparing the total volume of waste materials generated with the volume of those that have been reused, sold, recycled, recovered, or disposed of, as well as the value they have generated. Table 3 presents indicators that can be used to assess the relationship between "green" skills, improvements in accounting, and the need for a new approach to teaching accounting through the use of science, technology, engineering, and mathematics.

Table 3 Inciators for assesing residual materials:

Indicator	Formula
Residual material generation rate	Residual materials generated / Total raw materials used
Reuse rate	Residual materials reused internally / Total residual materials
Recycling rate	Residual materials recycled / Total residual materials
Sale rate	Residual materials sold / Total residual materials
Disposal rate	Residual materials disposed / Total residual materials
Circular use rate	Reused + sold + recycled residual materials / Total residual materials
Waste reduction rate	Waste before implementation − waste after implementation / Waste before implementation

These indicators should be measured before and after the implementation of green skills. A positive impact is present when the circular use rate increases and the disposal rate decreases.

RESULTS AND DISCUSSION

The results of the study indicate that the scope of International Accounting Standard 2 Inventory needs to be expanded, with an emphasis on residual materials and/or their reuse. Serious discussions should be held regarding the regulatory framework, particularly with regard to the treatment of expenses and the reporting of value-added tax. Tax incentives and funding for new business models would help improve the business environment.

CONCLUSION

This research demonstrates that the integration of green skills is fundamental to transforming traditional accounting from a purely administrative function into a strategic tool for circular value creation (Burger et al., 2018, p. 256; Maclean, 2012, p. 286).By synthesizing sustainability accounting with material-flow monitoring, firms can bridge the gap between sustainability reporting and actual operational efficiency, thereby enhancing both transparency and financial performance. This study contributes to the development of the field of residual materials and their utilization by establishing a new business model that combines new techniques for assessing both “green” skills and waste management. However, to achieve this, we need a comprehensive adaptation of tax regulations at both the national and international levels.

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REFERENCES

Albu, C. N., Balsarı, Ç. K., Bašić, M., Lazarevska, Z. B., Damijan, S., Dečman, N., Dionisijev, I., Grzybek, O., Guse, R., Filipović, A. L., oguz, mustafa, Perica, I., Tekavčić, M., Turuianu, E., & Milutinovic, S. V. (2025). Educating Accountants with a Sustainability-Oriented Professional Identity in Central and Eastern Europe. Amfiteatru Economic, 27(70), 830–830. https://doi.org/10.24818/ea/2025/70/830

Aureli, S., Foschi, E., & Paletta, A. (2023). Management accounting for a circular economy: current limits and avenue for a dialogic approach. Accounting Auditing & Accountability Journal/Accounting, Auditing & Accountability Journal, 38(9), 291–319. https://doi.org/10.1108/aaaj-04-2022-5766

Burger, M., Stavropoulos, S., Ramkumar, S., Dufourmont, J., & Oort, F. van. (2018). The heterogeneous skill-base of circular economy employment. Research Policy, 48(1), 248–261. https://doi.org/10.1016/j.respol.2018.08.015

European commsion. (2026, July 10). https://single-market-economy.ec.europa.eu/sectors/raw-materials/related-industries/forest-based-industries/furniture-industry_en

González, C. C., & Peña-Vinces, J. C. (2022). A framework for a green accounting system-exploratory study in a developing country context, Colombia. Environment Development and Sustainability, 25(9), 9517–9541. https://doi.org/10.1007/s10668-022-02445-w

Hasan, S. A. S., Waghule, S. N., Koliby, I. S. A., Al-Bukhrani, M. A., Haifi, M. M. A., & Hasan, M. B. (2024). Innovating for sustainability: the role of environmental management accounting in driving environmental performance. Discover Sustainability, 5(1). https://doi.org/10.1007/s43621-024-00389-x

Jesse, F. F., Antonini, C., & Luque-Vílchez, M. (2023). A circularity accounting network: CO2 measurement along supply chains using machine learning. Revista de Contabilidad, 26, 21–33. https://doi.org/10.6018/rcsar.564901

Jinga, G., Dumitru, M., Glăvan, E.-M., & Radu, G. (2024). Eco-efficiency measures in the leather industry. An educational case. Accounting and Management Information Systems, 23(2). https://doi.org/10.24818/jamis.2024.02004

Kokubu, K., Kitada, H., Nishitani, K., & Shinohara, A. (2023). How material flow cost accounting contributes to the SDGs through improving management decision-making. Journal of Material Cycles and Waste Management, 25(5), 2783–2793. https://doi.org/10.1007/s10163-023-01696-7

Lisnawati, L., Aryati, T., & Gunawan, J. (2024). Implementation of digital innovation on sustainability performance: the moderating role of green accounting in the industrial sector. The Scientific Issues of Ternopil Volodymyr Hnatiuk National Pedagogical University Series Pedagogy, 1, 59–68. https://doi.org/10.15587/1729-4061.2024.298639

Maclean, R. (2012). Skills Development for Inclusive and Sustainable Growth in Developing Asia-Pacific. In Technical and vocational education and training. Springer International Publishing. https://doi.org/10.1007/978-94-007-5937-4

Mukwarami, S., & Poll, H. M. van der. (2024). Critical environmental management accounting practices influencing service delivery of growing cities in a developing economy: a review and conceptual framework. Environment Systems & Decisions, 44(3), 710–739. https://doi.org/10.1007/s10669-023-09960-9

Vásquez, J., Aguirre, S., Puertas, E., Bruno, G., Priarone, P. C., & Settineri, L. (2021). A sustainability maturity model for micro, small and medium-sized enterprises (MSMEs) based on a data analytics evaluation approach. Journal of Cleaner Production, 311, 127692–127692. https://doi.org/10.1016/j.jclepro.2021.127692

Authors address:
Nikolay Katsarski[1];
[1] Department Finance and accounting, Faculty of Economics and Business administration, Sofia University St. Kliment Ohirdski, Sofia, Bulgaria
*Corresponding author: address@address.com

ESG COMMUNICATION VERSUS SILENT SUSTAINABILITY: DETERMINANTS OF VOLUNTARY DISCLOSURE AND PERCEIVED COMPETITIVE BENEFITS IN THE SLOVAK FOREST-BASED INDUSTRY

Lucia Dzianová, Michal Dzian, Hubert Paluš

Abstract: This paper examines the strategic tension between ESG communication and silent sustainability in the Slovak wood-based industry, focusing on the determinants of voluntary ESG disclosure and its competitive implications.
The study adopts an exploratory approach combining survey data and preliminary qualitative insights from expert interviews with secondary sources, including academic literature, policy frameworks, and sustainability reports. The analysis highlights key determinants of ESG disclosure, particularly firm size, ownership structure, certification schemes (e.g., FSC/PEFC), and increasing institutional and market pressures.
Preliminary findings suggest that firms facing stronger stakeholder expectations firms are more likely to engage in active ESG communication due to stakeholder expectations and reputational benefits, whereas resource-constrained firms tend to adopt silent sustainability strategies due to resource constraints and concerns about greenwashing. ESG communication appears to contribute to competitive advantage through enhanced credibility, trust, and market positioning, although its effectiveness depends on the consistency and verifiability of disclosed information.
The paper contributes to understanding sustainability communication strategies in the forest-based sector and offers implications for balancing transparency and strategic positioning.
Keywords: ESG disclosure, silent sustainability, greenhushing, forest-based industry, competitive advantage

1. INTRODUCTION

The modern corporate landscape is undergoing a fundamental shift from purely financial reporting to a holistic framework of non-financial disclosure (NFD). This transition is driven by increased stakeholder awareness and global commitments to sustainable development, which demand transparency regarding a company's ecological and social footprints (Saini et al., 2022). In environmentally sensitive sectors such as the forest-based industry, reporting on Environmental, Social, and Governance (ESG) factors has become a strategic necessity to maintain investor trust and secure a "social license to operate" (Alsayegh et al., 2020).

Within the Slovak wood-based sector, however, a significant research problem exists in the form of "strategic tension" between active ESG communication and silent sustainability. While some organizations aggressively market their green credentials, others perform sustainably but choose to remain silent, a phenomenon known as greenhushing (Font et al., 2017). This deliberate under-communication is often motivated by the fear of being accused of greenwashing, the perceived high cost of reporting, or the view that sustainability is simply "business as usual" that does not require external promotion (Boiral et al., 2025).

The aim of this paper is to examine the specific determinants that drive voluntary ESG disclosure among Slovak forestry firms and to evaluate how these choices impact their competitive positioning.

Voluntary disclosure serves as a critical signaling mechanism that reduces information asymmetry between management and external stakeholders, potentially enhancing market credibility (Connelly et al., 2011). Understanding these drivers, such as firm size and institutional pressures, is essential for transitioning from fragmented reporting toward the integrated sustainability models required by modern transparent markets (Carnini Pulino et al., 2022).

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

The academic literature distinguishes between several corporate stances based on the alignment of environmental performance and communication intensity. While greenwashing involves misleading or deceptive claims by firms with low actual performance (Nyilasy et al., 2014), a counter-phenomenon known as greenhushing (or silent sustainability) has emerged. Greenhushing is defined as the deliberate under-communication or withholding of information about high pro-environmental performance.

Theoretical frameworks categorize firms into four archetypes based on this performance-communication matrix

1. Vocal Green (Transparent Companies): Firms with high performance and high communication.

2. Greenwashing (Opaque Companies): Firms with low performance and high communication.

3. Silent Brown (Dark Companies): Firms with low performance and low communication.

4.Silent Sustainability (Translucent Companies): Firms with high performance that intentionally under-communicate their efforts.

Determinants of Voluntary ESG Disclosure The decision to engage in voluntary ESG reporting is driven by several firm-level and institutional factors. Firm size remains a primary determinant; larger multinational corporations typically possess the specialized resources required for complex reporting frameworks and are more susceptible to institutional pressures. In contrast, small and medium-sized enterprises (SMEs) often lack these resources and may perceive reporting as a bureaucratic burden with uncertain competitive returns (Carnini Pulino et al., 2022).

Certification schemes, such as FSC or PEFC, serve as critical signals of quality and legitimacy in the forest-based sector. However, some firms adopt a strategy of "signaling without signals," where they hold certifications but choose not to market them (Heras-Saizarbitoria et al., 2020). This behavior often stems from "moral muteness," where managers view sustainable practices as "business as usual" and consider their promotion for marketing purposes to be opportunistic or potentially hypocritical (Carlos & Lewis, 2018).

Understanding the determinants of voluntary disclosure provides an essential foundation for analyzing why firms invest in ESG reporting despite the associated operating costs (Galati et al., 2017). The decision to disclose information is not merely a passive response to external pressures but a strategic tool for achieving competitive benefits that play a key role in the wood processing sector (Chowdhury et al., 2023).

In the forest-based industry, voluntary ESG disclosure and certifications (e.g., FSC/PEFC) act primarily as signaling mechanisms that mitigate information asymmetry between management and outsiders, thereby strengthening corporate reputation and market credibility (Connelly et al., 2011; Galati et al., 2017). Key perceived advantages include establishing new business relationships and a subsequent increase in sales volumes, particularly in environmentally sensitive markets (Galati et al., 2017; Nor Suryani et al., 2011).

Although the direct impact on premium prices is often minimal compared to expectations, transparency reinforces stakeholder trust and helps maintain the "social license to operate" (Halalisan et al., 2013). This is consistent with previous regional research in the Slovak wood-based sector, which highlighted that while chain-of-custody certification serves as an essential tool for demonstrating environmental responsibility, its direct capacity to generate price premiums remains limited (Paluš et al., 2017). Furthermore, the reporting process can lead to improved internal process management and the implementation of more rigorous forest management models (Moore et al., 2012; Rametsteiner & Simula, 2003).

3. MATERIALS AND METHODS

The study combined data from a questionnaire survey of 72 firms operating in the Slovak forest-based and wood-processing industry with seven semi-structured interviews conducted in January 2025. The survey data were analysed using frequencies and percentages, while the interviews were examined through focused thematic analysis. The analysis addressed ESG-related activities, external communication, reasons for communication silence, disclosure determinants and perceived competitive benefits. Due to the small purposive sample, the findings are exploratory and are not statistically generalisable.

The study was guided by two research questions:

RQ1: To what extent do firms implement ESG-relevant activities without communicating them externally?

RQ2: What factors influence voluntary ESG disclosure, and what competitive benefits do firms associate with such communication?

4. RESULTS

Explicit ESG communication remains limited in the analysed Slovak forest-based industry. Only 22.2% of respondents reported that their firms disclose environmental or social information, whereas 51.4% reported no external disclosure. Nevertheless, 97.3% of non-disclosing firms implemented at least one ESG-relevant activity, including energy and material efficiency, waste management, responsible sourcing, working conditions or responsible business conduct. Moreover, 56.8% of non-disclosing firms held PEFC or FSC certification. These findings demonstrate a clear practice–communication gap and provide strong evidence of silent sustainability: many firms undertake verifiable sustainability activities without systematically communicating them.

Table 1. Distribution of firms by ESG communication status

Communication status	%
Explicit ESG disclosure	22.2%
No ESG disclosure	51.4%
Respondent not aware of disclosure	15.3%
Indirect or other forms of communication	11.1%

Table 2. Evidence of silent sustainability among non-disclosing firms

Indicator	%
At least one ESG-relevant activity	97.3%
PEFC/FSC certification	56.8%

The interviews confirmed that sustainability activities were often embedded in ordinary business operations but were not formally recognised or communicated as ESG. As one respondent stated, “We carry out activities that fall under the ESG agenda, but we do not report them” (R1). Participants referred particularly to efficient raw-material use, waste reduction, recycling, renewable energy and responsible sourcing. Some activities were primarily motivated by economic benefits, such as lower energy and material costs, rather than by an explicit ESG strategy. Silent sustainability therefore appeared to result not only from a deliberate communication choice, but also from firms implementing relevant practices without identifying them as ESG.

The findings indicate that voluntary disclosure is influenced mainly by internal communication capacity, stakeholder pressure and the availability of verifiable information. Half of the respondents reported no internal ESG communication, while 51.4% had not received external requests for ESG-related data. Interview participants indicated that communication became more relevant when customers or supply-chain partners requested environmental information. Certification and operational data supported the credibility of disclosed claims, although certification alone did not lead firms to communicate their sustainability performance.

Administrative complexity, limited internal expertise and the costs of data collection, consulting and auditing were identified as the main communication barriers. Interviewees also expressed concerns about increasing costs, bureaucratic requirements and the risk of making claims that could be perceived as greenwashing. These factors suggest that communication silence is frequently caused by insufficient resources and reporting capacity rather than by an intention to conceal sustainability performance.

The main perceived competitive benefits of ESG communication were enhanced credibility, customer trust, reputation and market positioning. Interviewees particularly emphasised the value of demonstrating responsible wood sourcing, efficient resource use, circularity and the carbon benefits of wood-based products. However, the study did not identify direct measurable effects on sales, prices or profitability. The competitive benefits should therefore be interpreted primarily as reputational and relational advantages.

4. DISCUSSION

The findings reveal a profound "silent sustainability" paradox (greenhushing) in the Slovak forest-based industry, characterized by a significant gap between real ESG performance and public disclosure. While 97.3% of firms implement sustainability measures, only 22.2% choose to communicate them. This identifies the sector as a cluster of "translucent companies",high performers that maintain a low communication profile (Baldassarre & Campo, 2016). Such silence is primarily driven by perceiving communication as a reputational risk, particularly regarding greenwashing accusations, prohibitive administrative costs, and a lack of specialized expertise (Boiral et al., 2025). Additionally, many managers exhibit "moral muteness," viewing sustainable practices as standard "business as usual" that requires no external promotion (Font et al., 2017). However, this strategy results in a lost competitive advantage, as voluntary disclosure is a vital signaling mechanism for reducing information asymmetry and building stakeholder trust (Connelly et al., 2011). Ultimately, Slovak wood-processing firms must bridge this gap to secure their "social license to operate" and transform silent sustainability into a tangible market benefit (Alsayegh et al., 2020).

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REFERENCES

1. Alsayegh, M. F., Rahman, R. A., & Homayoun, S. (2020). Corporate economic, environmental, and social sustainability performance transformation through ESG disclosure. Sustainability, 12(9), 3910. https://doi.org/10.3390/su12093910
2. Baldassarre, F., & Campo, R. (2016). Sustainability as a marketing tool: To be or to appear to be? Business Horizons, 59(4), 421–429. https://doi.org/10.1016/j.bushor.2016.03.005
3. Boiral, O., Brotherton, M. C., Talbot, D., & Guillaumie, L. (2025). Avoiding corporate greenwashing? Sustainability silence narratives in the agri-food industry. Business Ethics, the Environment & Responsibility. https://doi.org/10.1111/beer.12847
1. Carlos, W. C., & Lewis, B. W. (2018). Strategic silence: Withholding certification status as a hypocrisy avoidance tactic. Administrative Science Quarterly, 63(1), 130–169. https://doi.org/10.1177/0001839217694803
2. Carnini Pulino, S., Ciaburri, M., Magnanelli, B. S., & Nasta, L. (2022). Does ESG disclosure influence firm performance? Sustainability, 14(13), 7595. https://doi.org/10.3390/su1413759
3. Chowdhury, M. A. A., Rahman, M. M., Dey, M., Moudud-Ul-Huq, S., & Hossain, S. A. (2023). Perceived Pressures and Motivations for Environmental Disclosures: Role of Certification. SAGE Open, 13(4)
4. Connelly, B. L., Certo, S. T., Ireland, R. D., & Reutzel, C. R. (2011). Signaling theory: A review and assessment. Journal of Management, 37(1), 39–67

5. Font, X., Elgammal, I., & Lamond, I. (2017). Greenhushing: The deliberate under communicating of sustainability practices by tourism businesses. Journal of Sustainable Tourism, 25(7), 1007–1023. https://doi.org/10.1080/09669582.2016.1158829
6. Galati, A., Gianguzzi, G., Tinervia, S., Crescimanno, M., & Veca, D. L. M. (2017). Motivations, adoption and impact of voluntary environmental certification in the Italian Forest based industry: The case of the FSC standard. Forest Policy and Economics, 83, 169–176
7. Halalisan, A. F., Marinchescu, M., Popa, B., & Abrudan, I. V. (2013). Chain of custody certification in Romania: profile and perceptions of FSC certified companies. International Forestry Review, 15(3), 305–314
8. Heras-Saizarbitoria, I., Boiral, O., Allur, E., & García, M. (2020). Communicating environmental management certification: Signaling without signals? Business Strategy and the Environment, 29(2), 422–431. https://doi.org/10.1002/bse.2374
9. Moore, S. E., Cubbage, F., & Eicheldinger, C. (2012). Impacts of Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI) Forest Certification in North America. Journal of Forestry, 110(2), 79–88
10. Nor Suryani, A. G., Mohd Shahwahid, H. O., Ahmad Fauzi, P., Alias, R., & Vlosky, R. P. (2011). Assessment of chain–of–custody certification costs for Sawnwood manufacturers in peninsular Malaysia. Journal of Tropical Forest Science, 23(2), 159–165
11. Nyilasy, G., Gangadharbatla, H., & Paladino, A. (2014). Perceived greenwashing: The interactive effects of green advertising and corporate environmental performance on consumer reactions. Journal of Business Ethics, 125(4), 693–707. https://doi.org/10.1007/s10551-013-1944-3
12. Paluš, H., Parobek, J., Dudík, R., & Šupín, M. (2017). Assessment of Chain-of-Custody Certification in the Czech and Slovak Republic. Sustainability, 9(10), 1898. https://doi.org/10.3390/su9101898
13. Rametsteiner, E., & Simula, M. (2003). Forest certification—an instrument to promote sustainable forest management? Journal of Environmental Management, 67(1), 87–98
14. Saini, N., Singhania, M., Hasan, M., Yadav, M. P., & Abedin, M. Z. (2022). Non-financial disclosures and sustainable development: A scientometric analysis. Journal of Cleaner Production, 381, 135173. https://doi.org/10.1016/j.jclepro.2022.135173

Authors address:
Dzianová, L.[1]; Dzian, M.[2]; Paluš, H.[3]
[1] The Department of Marketing, Trade and World Forestry, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia
*Corresponding author: xdzianova@is.tuzvo.sk

FISCAL TRANSPARENCY: ESG REPORTING AND TAX COMPLIANCE IN THE FOREST SECTOR

Zhelyo Zhelev

Abstract: The report examines the interplay among fiscal transparency, ESG reporting, and tax compliance in the forest sector, an important component of the bioeconomy. In the context of sustainable development and regulatory pressures, forest-based companies are facing increasing demands for both non-financial reporting and tax transparency. The study examines the role of ESG frameworks as a tool to enhance accountability and mitigate tax risks and fraud. It analyses how insufficient fiscal transparency can constrain sustainable practices and lead to imbalances in wood products markets. It examines the regulatory environment, including European policies and international guidelines, as well as the challenges associated with the fragmentation of the legal framework. The report highlights the importance of digitalisation and integrated reporting systems as means of improving tax control and traceability in supply chains. It presents key tax risks in the sector and their implications for companies' ESG assessments.
Keywords: fiscal transparency, ESG Governance, tax risk management, forest bioeconomy

1. INTRODUCTION

The transition to a sustainable bioeconomy places the forest sector among the strategic sectors that combine economic growth, efficient use of natural resources and contribution to climate neutrality goals. Along with the environmental and social aspects of sustainable development, the quality of corporate governance, measured by the degree of transparency, accountability and compliance with applicable regulatory requirements, is gaining increasing importance (Kostova, 2025). In this context, fiscal transparency is being established as an essential component of ESG governance, as companies' tax behaviour is increasingly perceived as an indicator of their corporate responsibility, sustainability, and long-term reliability (Chen, Song, & Gao, 2023). The enhanced requirements of the European regulatory framework on corporate sustainability, combined with the growing expectations of investors, public institutions, and other stakeholders, make tax compliance a factor that complements the understanding of how to fulfil legal obligations and is integrated into the overall corporate governance system (European Commission, 2022). It is particularly important in the forest sector, which is characterised by complex supply chains, high traceability requirements for raw materials and the need for effective management of regulatory and tax risks (Pirc Barčić, Tafro, Obranković, & Jelačić, 2025). In this regard, this report aims to analyse the interrelationships among fiscal transparency, ESG reporting, and tax compliance, highlighting their roles in enhancing sustainability, competitiveness, and public trust in forest-based enterprises.

2. ESG ACCOUNTABILITY AND FISCAL TRANSPARENCY AS ELEMENTS OF SUSTAINABLE MANAGEMENT IN THE FOREST SECTOR

In recent years, the concept of sustainable corporate governance has become a key factor determining the competitiveness and long-term viability of enterprises. The model for assessing corporate performance, based primarily on financial results, has gradually evolved into an integrated approach that includes environmental, social, and governance aspects of the activity. It is in this context that ESG reporting has established itself as a leading tool for assessing enterprises' ability to advance sustainability. Along with environmental indicators that dominate public discussion, the governance component, including corporate ethics, internal control, risk management, transparency, and the tax behavior of organizations, is gaining importance (Mitroulia, Chytis, Kitsantas, Skordoulis, & Kalantonis, 2025).

The development of the ESG concept has led to a rethinking of the role of tax policy in the corporate governance system. According to Thiart (2023), companies with higher levels of ESG performance also demonstrate greater tax transparency, which helps increase the trust of investors and other stakeholders. The author emphasizes that although tax transparency is not yet an independent component in most ESG rating models, it is increasingly perceived as a manifestation of good corporate governance and a responsible attitude towards society. The trend is also reflected in the development of the European regulatory framework. The adopted on Corporate Sustainability Reporting Directive (European Commission, 2022) significantly expands the scope of non-financial reporting by introducing the principle of dual materiality. (Table 1).

Figure 1. Interrelationship between ESG reporting, fiscal transparency and sustainable management in the forest sector

According to this principle, companies should assess both the impact of their activities on society and the environment, and the impact of sustainability factors on their financial situation. Although the European Sustainability Reporting Standards (ESRS) do not contain a separate standard dedicated to tax transparency, tax policy, tax risk management, and tax strategy can be essential elements within the management activities that impact sustainable development and decision-making processes. Forestry companies operate in an environment characterized

by high levels of regulatory requirements, the need for traceability of wood, international supply chains and increased public attention to the sustainable use of natural resources. As a result, stakeholders are now assessing not only the environmental performance of companies but also their corporate behavior, including how they manage their tax liabilities, mitigate tax risks, and ensure transparent information disclosure. Tax policy is gradually becoming an element of corporate reputation, as aggressive tax planning is increasingly perceived as a contradiction of the principles of sustainable development and as posing significant reputational risk. (Marques, Montenegro, & Bras, 2024).

The contemporary literature supports the understanding that fiscal transparency should not be viewed solely as an obligation to disclose tax information but as a process that integrates corporate strategy, risk management, and the organization's ethical principles (Krasteva-Hristova & Moneva). The voluntary publication of tax strategies, tax risk management policies, indicators of total tax contribution, and information on relations with tax administrations is seen as a tool to reduce information asymmetry between enterprises and stakeholders. Recent empirical research shows that the disclosure of detailed tax information is associated with lower information asymmetry in capital markets and higher investor confidence (Brożek, Kożuch, Wieruszewski, Ankudo-Jankowska, & Adamowicz, 2025).

The forest sector plays a significant role in implementing the objectives of the European Green Deal, the circular economy, and decarbonization policies. It is why sustainable management can no longer be limited to environmental indicators alone, but should also include transparency in financial and tax processes. Fiscal transparency helps limit the risk of tax abuse, increases the effectiveness of corporate governance, and creates the conditions for building trust among enterprises, state institutions, investors, and society. It should therefore be considered an integral part of the ESG management component and as a factor that supports the sustainable development and competitiveness of enterprises in the forest sector.

3. TAX COMPLIANCE AND TAX RISK MANAGEMENT IN FORESTRY ENTERPRISES

In modern scientific literature, tax compliance is viewed not only as the fulfilment of legally established tax obligations, but as a comprehensive management process, including the identification, assessment and control of tax risks, the development of internal mechanisms for the prevention of violations and the formation of an organisational culture based on legality and corporate ethics and sustainable management (Gribnau, 2024). This approach is particularly relevant for enterprises in the forestry sector, whose activities involve cross-border trade, diverse supply chains, and heightened public interest in the legality of business activity. In the context of ESG reporting, tax compliance is gradually becoming an indicator of management quality. An increasing number of investors, financial institutions and rating agencies accept that an enterprise's tax policy reflects its ethical standards and its attitude towards society.

The specificity of the forestry sector entails several tax risks, arising from both the peculiarities of business activity and the dynamically changing regulatory environment. Among the most significant risks are the incorrect treatment of timber transactions for value-added tax purposes, inaccurate documentation of intra-community supplies and exports, incorrect determination of the place of performance in international transactions, and risks related to transfer pricing within international corporate groups (Table 1).

Table 1. Main tax risks in forestry companies and their impact on ESG management

Tax risk	Nature of the risk	Impact on ESG (Governance)	Mitigation approaches
Risk in VAT taxation	Incorrect application of the regime for intra-community supplies, exports and timber supplies	Financial sanctions, impaired transparency, reduced trust	Automated VAT control, electronic documentation, internal checks
Insufficient traceability of the origin of timber	Inconsistency between tax documents and evidence of legal origin	Reputational risk and risk of non-compliance with ESG policies	Integrated traceability systems, digital registers
Transfer pricing	Transactions between related enterprises in international trade	Tax adjustments, regulatory risk, negative impact on Governance	Transfer pricing documentation, market price analysis
Insufficient tax transparency	Lack of publicly disclosed tax strategy and information on tax risk	Reduced trust of investors and stakeholders	Voluntary tax reports transparency, ESG disclosures
Tax fraud and involvement in risky supply chains	Use of fictitious suppliers, VAT fraud or document violations	Significant legal and reputational risk	Verification of counterparties, internal control systems, risk analysis
Insufficient internal tax control	Lack of procedures for identifying and managing tax risks	Weaknesses in corporate governance	Building a Tax Control Framework, internal audit and monitoring

Recent developments in the European regulatory framework have emphasised integrated risk management. In this context, tax risk should be considered part of the overall corporate governance system, not a separate function of the finance department. Such an approach implies the participation of senior management in determining the tax strategy, building an effective internal control system and monitoring tax processes (Figure 2).

Figure 2. Model of the relationship between tax risk and ESG performance of forestry companies

Digitalisation has a significant impact on tax compliance processes (Antov, Zhelev, Kostova, & Zheleva, 2026). The use of electronic invoices, automated tax reporting systems, big data analytics, and supply chain tracking technologies creates opportunities to significantly reduce the administrative burden and limit the risk of tax fraud (Zhelev, 2024). For forest-based enterprises, such technologies have dual significance: on the one hand, they help prove the legal origin of wood; on the other, they provide reliable tax documentation and greater transparency in financial transactions. Companies that implement a transparent tax strategy, publish information on tax risk management and maintain constructive relations with tax administrations demonstrate a higher degree of institutional responsibility and resilience. In this sense, tax compliance should be seen as a strategic tool for value creation, not just a means of avoiding sanctions.

4. CONCLUSION

The modern concept of ESG management implies an integrated approach in which environmental, social and governance aspects are considered as interrelated elements of corporate sustainability. In this context, fiscal transparency is increasingly significant as an indicator of the quality of corporate governance and of enterprises' ability to build trust among investors, government institutions, and other stakeholders. The analysis shows that tax compliance should be considered not only as the fulfilment of legally established obligations, but also as a strategic tool for managing tax risks, limiting reputational losses, and increasing the sustainability of enterprises.

The study confirms a close relationship between fiscal transparency and the governance component of ESG, as transparent tax practices, effective tax risk management, and the implementation of tax compliance policies contribute to increased corporate accountability, reduced information asymmetry, and strengthened public trust. The proposed conceptual link between tax transparency, tax risk management and sustainable corporate governance broadens the approach to taxation. It outlines opportunities to integrate tax strategy into the overall ESG policies of forest sector enterprises.

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REFERENCES

1. Antov, M., Zhelev, Z., Kostova, S. & Zheleva, A. (2026). Digital Transformation and Administrative Harmonization Under the New EU Customs Reform: The Case of Post-Clearance Control in Bulgaria. Administrative Sciences, 16(3), pp. 1-22. https://doi.org/10.3390/admsci16030127
2. Brożek, J., Kożuch, A., Wieruszewski, M., Ankudo-Jankowska, A., & Adamowicz, K. (2025). Environmental, Social, and Governance (ESG) Clustering of EU Forest

Policies in the Context of the 2030 New Forest Strategy. Sustainability, 17(17), pp. 1-18. https://doi.org/10.3390/su17177925
3. Chen, S., Song, Y., & Gao, P. (2023). Environmental, social, and governance (ESG) performance and financial outcomes: Analyzing the impact of ESG on financial performance. Journal of environmental management, 345. https://doi.org/10.1016/j.jenvman.2023.118829
4. European Commission, Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 as regards corporate sustainability reporting (CSRD) (2022).
5. Gribnau, H. (2024). Sustainable tax governance: a shared responsibility. eJournal of Tax Research, 22(3), pp. 492-517. Retrieved from https://www.proquest.com/scholarly-journals/sustainable-tax-governance-shared-responsibility/docview/3234036284/se-2
6. Kostova, S. (2025). Key indicators for assessing double materiality in the wood industry. In Z. Meloska & M. M. Janakieska (Ed.), WoodEMA -Wood Future: Integr. Sustain. Across Ind., Proc. Sci. Pap. (pp. 477-482). Ohrid: WoodEMA.
7. Krasteva-Hristova, R., & Moneva, I. Digitalization, ESG Reporting, and Circular Economy: Accounting Challenges for Women-Led SMEs. World, 7(6), pp. 1-25. https://doi.org/10.3390/world7060091
8. Marques, M., Montenegro, T. M. & Bras, F. A. (2024). Tax Avoidance and Corporate Social Responsibility: A Meta-Analysis. Journal of the American Taxation Association, 46(1), pp. 137-156. https://doi.org/10.2308/JATA-2022-026
9. Mitroulia, M., Chytis, E., Kitsantas, T., Skordoulis, M. & Kalantonis, P. (2025). ESG Strategy and Tax Avoidance: Insights from a Meta-Regression Analysis. Journal of Risk and Financial Management, 18(9), pp. 1-34. https://doi.org/10.3390/jrfm18090503
10. Pirc Barčić, A., Tafro, A., Obranković, J. & Jelačić, D. (2025). Innovation Activity in Wood-Based Industry–European Union and Croatian Perspective. Wood for the Future: Integrating Sustainability Across Industries, (pp. 243-251). Ohrid: WoodEMA.
11. Thiart, C. (2023). The correlation between environmental, social and governance ratings and the transparency in Johannesburg Stock Exchange companies' tax practices. South African Journal of Economic and Management Sciences, 26(1).
12. Zhelev, Z. (2024). Application of AI to minimize information risk in tax control: Evidence from Bulgaria. Edelweiss Applied Science and Technology, 8(6), pp. 5066-5074. https://doi.org/10.55214/25768484.v8i6.3112

Authors address:
Zhelev, Zhelyo[1]
[1] Department of Control and Analysis Economic Activities, Faculty of Economic Accounting, D. A. Tsenov Academy of Economics, Svishtov, Bulgaria
*Corresponding author: zh.zhelev@uni-svishtov.bg

THE IMPACT OF THE CEFTA AGREEMENT ON WOOD FURNITURE EXPORT OF THE REPUBLIC OF NORTH MACEDONIA

Ivana Antovska, Zivka Meloska, Ana Marija Stamenkovska, Katerina Antovska

Abstract: The Central European Free Trade Agreement (CEFTA) is an important instrument for promoting trade between the countries of the region, including the Republic of North Macedonia. This paper analyzes the impact and benefits of CEFTA on furniture exports, as an important industrial branch in the national economy. Data on the largest importers of Macedonian furniture and exports to CEFTA member countries in the first five years after its signing and the last five years are analyzed. The first part of this paper analyzes data on furniture exports from North Macedonia in 6 categories: office furniture, kitchen furniture, bedroom furniture, living and dining furniture, shop furniture and other furniture. The second part analyzes data on total furniture exports, which show that Macedonian furniture manufacturers have managed to increase their competitiveness, primarily through improving quality, optimizing production processes and adapting to the requirements of foreign markets.
Keywords: CEFTA, wood furniture, export

1. INTRODUCTION

The existing crisis, technology innovation and competition demands from the furniture manufacturing enterprises continuous improvement of production technologies, product quality, implement international quality standards, and increase operational efficiency. The Central European Free Trade Agreement (CEFTA) has created significant opportunities for the wood furniture industry in the Republic of North Macedonia by providing preferential access to regional markets of approximately 20 million consumers, and promoting economic cooperation among member economies. As a free trade agreement, CEFTA eliminates customs duties on most industrial products, including wood furniture, and reduces non-tariff barriers, making it easier for manufacturers to expand their exports.

The integration and implementation of CEFTA agreement offers to the Macedonian wood furniture industry many opportunities. The export of furniture to member economies without paying customs duties results with reducing export costs and improving price competitiveness. Domestic furniture industry dominated by SMEs, CEFTA provides opportunities to expand beyond Macedonian small market. The agreement facilitates cooperation among manufacturers, suppliers, and distributors across CEFTA economies. Companies can source raw materials and components more efficiently. Also, membership makes North Macedonia more attractive to foreign investors seeking a production base with preferential access to CEFTA markets and the European Union.

Beside the numerous advantages, Macedonian furniture manufacturers also face several challenges. To cope with strong competition from producers in other CEFTA parties, Macedonian furniture manufacturers need to have continuous investment in technology and innovation. Also need to be compliance with increasingly demanding international quality, environmental, and sustainability standards.

2. HISTORY OF CEFTA

Central European Free Trade Agreement (CEFTA) aims at enhancing trade in goods and services, seeks to eliminate trade barriers between the Parties and attract investment to the region through fair, stable and predictable trade rules. The original CEFTA was signed in 21 December 1992, in Krakow, Poland, by Visegrad Group countries. CEFTA is based on the free trade principles of the EU and also of the World Trade Organization (WTO).

Macedonia was the last country to accede to the original CEFTA. The period between August and December2006, the Agreement had four members. Membership in CEFTA is a process that helps and accelerates membership in the EU with the main function of creating a free market between EU candidate countries and potential candidates' countries. That's why Bulgaria and Romania left CEFTA by the end of 2006, due to their membership of the European Union. In December 2006 CEFTA2006 expanded to include Albania, Bosnia and Herzegovina, Croatia, Kosovo, North Macedonia, Moldova, Montenegro, and Serbia.

Tabel 1. CEFTA memberships during the years

Members	Joined	Left
Poland, Czech Republic, Hungary, Slovakia	21 December 1992 (signed) 1 March 1993 (entry into force)	30 April 2004
Slovenia	1996	
Romania	1997	31 December 2006
Bulgaria	1999	
Croatia	2003	30 June 2013
Macedonia	2000/2006	
Albania, BiH, Kosovo, Moldova, Montenegro, Serbia	2007	

3. THE RESEARCH METHODOLOGY

This paper analyzes the export of furniture from the Republic of North Macedonia to CEFTA 2006 countries in the period 2005-2010 and 2020-2025. By comparing the first years of CEFTA 2006 membership and the lasts, aims to demonstrate the development of the Macedonian furniture industry. The research methodology was quantitative and used the preliminary export data from State Statistical Office of the Republic od Macedonia for the period 2005-2010 and the customs of North Macedonia for the period 2020-2025. The value of exports is presented in EUR, using mathematical and statistical methods.

4. RESULTS AND DISCUSSION

4.1. Wood furniture export from Republic of North Macedonia to CEFTA 2006 countries for the period 2020-2025

According to the preliminary export data from the custom of North Macedonia for the period 2020 to 2025, the total export of wood furniture from North Macedonia was 1.774.568.081EUR (Mean 295.761.347EUR per year). The export to the CEFTA 2006 member countries for the same period was 59.241.437EUR (only 3% from the total export of wood furniture from North Macedonia).

Table 2 presents the distribution of North Macedonia's wood furniture exports by product category to the main CEFTA markets. During the observed period, the total value of exports amounted to EUR 59.24 million, with significant differences among destination countries.

Table 2. Export of wood furniture by categories from the Republic of North Macedonia to CEFTA 2006 countries in the period 2020-2025

	Office furniture	Kitchen furniture	Bedroom furniture	Living and Dining	Shop furniture	Other furniture	Total export EUR	Mean
Albania	20.205	6.201	298.977	216.771	22.186	5.199.898	5.764.238	960.706
BIH	251	0	526.434	1.458.661	6.017	5.066.517	7.057.880	1.176.313
Serbia	68.135	15.548	1.898.969	13.626.076	365.205	12.617.977	28.591.910	4.765.318
Montenegro	649	0	1.365.988	2.159.457	10.253	2.890.706	6.427.053	1.071.176
Kosovo	285.945	15.951	1.067.906	2.779.971	488.050	6.759.177	11.397.000	1.899.500
Moldova	0					3.356	3.356	559
Total	375.185	37.700	5.158.274	20.240.936	891.711	32.537.631	59.241.437	

According to this data, most important market is Serbia, accounting for EUR 28.59 million (Mean 4.76milion per year) or approximately 48.3% of total exports. The largest share of exports consisted of living and dining room furniture. Minor impact of Macedonian wood industry has export to Moldova. These results are influenced by infrastructure connectivity and distance. The second most important export market was Kosovo, with exports totaling EUR 11.40 million (Mean 1.9milion per year), representing approximately 19.2% of total exports. Similar to Serbia, exports were concentrated in other furniture (EUR 6.76 million) and living and dining furniture (EUR 2.78 million), while bedroom furniture also contributed significantly (EUR 1.07 million).

Figure 1. Export of wood furniture to CEFTA 2006 countries in the period 2020-2025

When analyzing exports by product category, other furniture represented the largest category overall, reaching EUR 32.54 million, or approximately 54.9% of total exports. This was followed by living and dining furniture, with exports of EUR 20.24 million (34.2%), and bedroom furniture, totaling EUR 5.16 million (8.7%). In contrast, exports of shop furniture (EUR 891,711), office furniture (EUR 375,185), and kitchen furniture (EUR 37,700) accounted for only a small proportion of total exports.

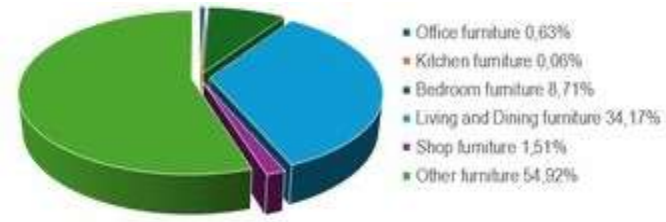

Figure 2. Export of wood furniture to CEFTA 2006 by categories in the period 2020-2025

Overall, the results indicate that Macedonian wood furniture exports within the CEFTA region are highly concentrated in a limited number of markets, particularly Serbia and Kosovo, which together account for more than two-thirds of total exports. These findings suggest that the competitive advantage of the Macedonian wood furniture industry lies primarily in the production of residential furniture – living and dining furniture. The tradition and culture of furnishing kitchens, offices, and retail spaces indicate that custom-made furniture is generally preferred. In contrast, mass-produced furniture is purchased less frequently for these types of furnishings.

4.2. Comparative Analysis of Wood Furniture Exports from North Macedonia to CEFTA Countries: 2005–2010 versus 2020–2025

To assess the impact of North Macedonia's membership in CEFTA, a comparison was made between two periods: 2005–2010 and 2020–2025. Table 3 presents the export data for these two periods, categorized by furniture type. A marked decline is observed in the first three furniture categories (office, kitchen and bedroom), while the increase recorded in the next two categories Living and dining furniture and shop furniture) is relatively modest. The most significant growth is evident in the final category, which primarily comprises furniture manufactured in the industrial development zones for export to the European market.

Table 3. Export of wood furniture by categories from the Republic of North Macedonia to CEFTA 2006 countries in the period 2005-2010 vs 2020-2025

	Office furniture	Kitchen furniture	Bedroom furniture	Living and Dining	Shop furniture	Other furniture	Total export EUR	Mean
Total 2005-10	1.214.946	1.812.700	8.097.653	19.802.143	867.878	3.274.069	33.032.805	5.505.468
Total 2020-25	375.185	37.700	5.158.274	20.240.936	891.711	32.537.631	59.241.437	9.873.573
	-69%	**-98%**	**-36%**	**2%**	**3%**	**894%**	**79%**	

A second comparison in Tabel 4, was conducted between the two study periods for the main destination countries of North Macedonia's furniture exports. The results indicate the strongest export growth in European Union member states that were not members of CEFTA. In contrast, exports to Croatia, which was a CEFTA member until its accession to the European Union in 2013, have remained relatively stagnant. It is very similar situation with export to Greece also.

Table 4. Export of wood furniture from the Republic of North Macedonia to main countries in the period 2005-2010 vs 2020-2025

	Croatia	Serbia	Slovenia	Kosovo	BIH	Montenegro	Germany	Netherlands
Total 2005-2010	9.430.902	7.815.574	3.567.383	2.071.279	1.263.290	779.923	570.293	354.389
Total 2020-2025	14.721.239	28.591.910	30.820.009	11.397.000	7.057.880	6.427.053	489.384.965	16.627.538
	56%	266%	764%	450%	459%	724%	85713%	4592%

Table 5 compares the two study periods across furniture export categories for Serbia and Croatia, the two Balkan countries to which Macedonia exports the largest volume of furniture. A common trend is the substantial decline in exports in the first two furniture categories (office and kitchen furniture) for both markets. However, the fourth and fifth categories (living and dining furniture and shop furniture) exhibit contrasting patterns. Exports to Serbia in the Living and Dining Furniture category increased by 365%, whereas exports to Croatia in the same category declined by 61%. Conversely, in the Shop Furniture category, exports to Serbia decreased by 27%, while exports to Croatia increased dramatically by 700%. Second common trend is increasing in last category (other furniture) for almost same percent.

Table 5. Export of wood furniture from the Republic of North Macedonia to two countries from Balkan, in the period 2005-2010 vs 2020-2025

	Period	Office furniture	Kitchen furniture	Bedroom furniture	Living and Dining furniture	Shop furniture	Other furniture	Total export EUR
Serbia	2005-2013	235.204	335.670	5.296.161	2.929.847	500.000	961.319	10.258.201
	2020-2025	68.135	15.548	1.898.969	13.626.076	365.205	12.617.977	28.591.910
		-71%	**-95%**	**-64%**	**365%**	**-27%**	**1213%**	179%
Croatia	2005-2013	408.126	1.399.486	2.961.108	7.730.446	14.082	618.749	13.131.997
	2020-2025	78.138	61.156	3.355.355	3.006.594	112.715	8.107.281	14.721.239
		-81%	**-96%**	**13%**	**-61%**	**700%**	**1210%**	12%

5. CONCLUSION

CEFTA 2006 represents a significant milestone in strengthening trade cooperation and economic integration among the member economies of Southeast Europe. Through the gradual liberalization of trade, customs duties on furniture products traded within the CEFTA region were eliminated in 2009. Through the liberalization of trade, customs duties on furniture products traded within the CEFTA region were eliminated in 2009. The findings indicate that tariff liberalization alone was not the only driver of export growth. Improvements in product quality, production efficiency, foreign investment, and stronger integration into European supply chains also contributed significantly to the international competitiveness of Macedonian furniture manufacturers. Also, membership makes North Macedonia more attractive to foreign investors seeking a production base with preferential access to CEFTA markets and the European Union. The full potential of the Macedonian wood furniture industry is expected to be realized upon North Macedonia's accession to the European

Union, as access to the EU Single Market will provide new opportunities for export growth, investment, and enhanced competitiveness.

REFERENCES

1. Petrovska, I.; Meloska, Z.; Efremov, K.; Postolov K.; (2016): *CEFTA agreement and opportunities for wood furniture export of the Republic of Macedonia.* In: Drvna industrija, 63, pp. 43-51.
2. Petkovska Mirchevska, T.; Petkovska, T.; Majstoroska, J.; Stanceva Gigov, I., (2011*): The Influence of the NonPrice Factors of Competitiveness on the Advancement of the Export Offer of the Republic of Macedonia within CEFTA, International Conference Regional Trade Integration in South East Europe: Benefits and Challenges*, Skopje, Republic of Macedonia. December 2011.
3. Shumanska, M. S., (2014): *Technological development of wood industry enterprises of the Republic of Macedonia, Wood, Design & Technology,* 3 (1)
4. ***: "CEFTA Secretariat" (2014) http://www.cefta.int/ (Accessed March. 15, 2026)
5. ***: Agreement on the amendment of and accession to the original Central European Free Trade Agreement, Official Gazette of the Republic of Macedonia 69/2007

Authors address:
Antovska, Ivana[1]; Meloska, Zivka; Stamenkovska, Ana Marija[3]; Antovska, Katerina[4]
[1 2 3] Faculty of Design and Technologies of Furniture and Interior, Ss.Cyril and Methodius University, Skopje, Republic of North Macedonia
[4] Iustinianus Primus Faculty of law, Ss.Cyril and Methodius University, Skopje, Republic of North Macedonia

*Corresponding author: antovska@fdtme.ukim.edu.mk

TAX INCENTIVES FOR THE DEVELOPMENT OF FOREST BIOECONOMY: EU EXPERIENCE AND OPPORTUNITIES FOR UKRAINE IN THE CONTEXT OF GLOBAL DIGITALIZATION

Volodymyr Tsap, Olena Yatsukh, Volodymyr Borkovych

Abstract: The article examines tax incentives for the development of the forest bioeconomy under conditions of transition to a sustainable economy, digital transformation, and increasing environmental challenges. The role of tax instruments as an essential component of public financial policy aimed at ensuring sustainable forest management, biodiversity conservation, and the formation of bioeconomic value chains is substantiated. The importance of the screening of national legislation and its harmonization with the European Union acquis in the field of environmental and tax policy is emphasized. Particular attention is paid to the theoretical foundations of forest bioeconomy development and the role of tax incentives within an environmentally oriented economic regulation system. The experience of European Union countries in applying tax benefits, environmental taxation, and innovation support in the wood-processing industry, bioenergy sector, and wood product markets is analyzed.

The current taxation system of Ukraine's forestry sector is assessed in terms of its impact on business activity, investment attractiveness, and bioeconomy development. Special emphasis is placed on the use of digital technologies, data analytics, and artificial intelligence as innovative tools for improving tax administration efficiency, enhancing transparency and accountability of financial flows, and strengthening environmental monitoring. The study substantiates directions for improving Ukraine's tax policy based on European experience, including the promotion of innovation, development of green energy, support for bioeconomic value chains and wood product markets, implementation of environmental tax instruments, and ensuring the sustainable development of the forest bioeconomy.

Keywords forest bioeconomy; tax incentives; tax regulation; digital transformation; legislative harmonisation; European Union; ESG; bioenergy; tax administration; sustainable development.

1. INTRODUCTION

The transition towards a sustainable economy, the implementation of the European Green Deal, and the digital transformation of public administration have strengthened the strategic role of the forest bioeconomy in promoting sustainable economic development. In the European Union, the forest sector is supported through integrated financial, tax, and investment instruments that encourage environmentally responsible production, bioenergy, innovation, and digitalization.

For Ukraine, the development of an effective system of tax incentives has become increasingly important in the context of European integration and the harmonization of national legislation with European Union law. Although legislative harmonization is progressing, the current taxation system of the forest sector remains primarily fiscal, while the potential of tax incentives to stimulate investment, digitalization, and environmental modernization remains underutilized. At the same time, limited attention has been paid to the adaptation of European tax instruments to the specific conditions of Ukraine's forest sector and to the role of digital technologies in improving tax administration.

The aim of this study is to examine the role of tax incentives in the development of the forest bioeconomy, analyze the experience of the European Union, assess the current tax regulation framework in Ukraine's forest sector, and propose strategic directions for improving tax incentives in the context of digital transformation.

2. TAX INCENTIVES FOR THE FOREST BIOECONOMY: EU EXPERIENCE

The forest bioeconomy is a key component of sustainable development, integrating economic, environmental, and social objectives through the efficient use of renewable forest resources. Tax incentives represent one of the most effective policy instruments for promoting investment, technological innovation, environmentally responsible production, and the long-term competitiveness of forest sector enterprises. In the European Union, tax incentives form an integral part of the European Green Deal, the EU Forest Strategy for 2030, and the broader bioeconomy policy framework. They include investment tax credits, accelerated depreciation, environmental tax reliefs, and fiscal support for renewable biomass and circular economy initiatives. Table 1 summarizes the principal tax incentives currently applied in European Union member states to support the development of the forest bioeconomy.

Table 1. Tax incentives supporting the development of the forest bioeconomy: experience of European Union member states

Country	Tax incentive	Eligible activity	Expected economic impact
Finland	Accelerated depreciation	Investment in wood-processing equipment	Increased investment and labor productivity
Sweden	Tax reliefs	Biofuels	Reduction of CO_2 emissions
Austria	Investment tax credit	Innovative technologies and timber construction	Modernization of production facilities
Germany	Tax reliefs	Renewable energy and ESG projects	Promotion of the green economy
Estonia	Environmental tax incentives	Environmental investments	Digitalization and environmental modernization

The analysis presented in table 1 shows that European Union member states use tax policy not only to generate public revenue but also as a strategic instrument for supporting the forest bioeconomy. Tax incentives primarily promote investment, environmental modernization, bioenergy, and digital transformation, thereby enhancing resource efficiency and the competitiveness of forest-based industries. This experience provides an important reference for Ukraine in the ongoing harmonization of its tax legislation with European Union law and the development of a modern tax incentive framework for the forest sector.

3. RESEARCH RESULTS

3.1. Tax regulation of Ukraine's forest sector

Tax regulation is one of the key instruments of state policy influencing the development of the forest sector, as it determines the level of the tax burden, the investment attractiveness of enterprises, and their opportunities for sustainable growth. In the context of European integration, assessing the actual tax burden borne by forestry enterprises has become particularly important, as it enables the evaluation of the effectiveness of the current taxation system and provides a basis for identifying directions for its further improvement. To this end, an analysis of the average tax payment indicators for enterprises operating in Ukraine's forest sector was conducted using data provided by the State Tax Service of Ukraine. The results of the analysis are presented in figure 1.

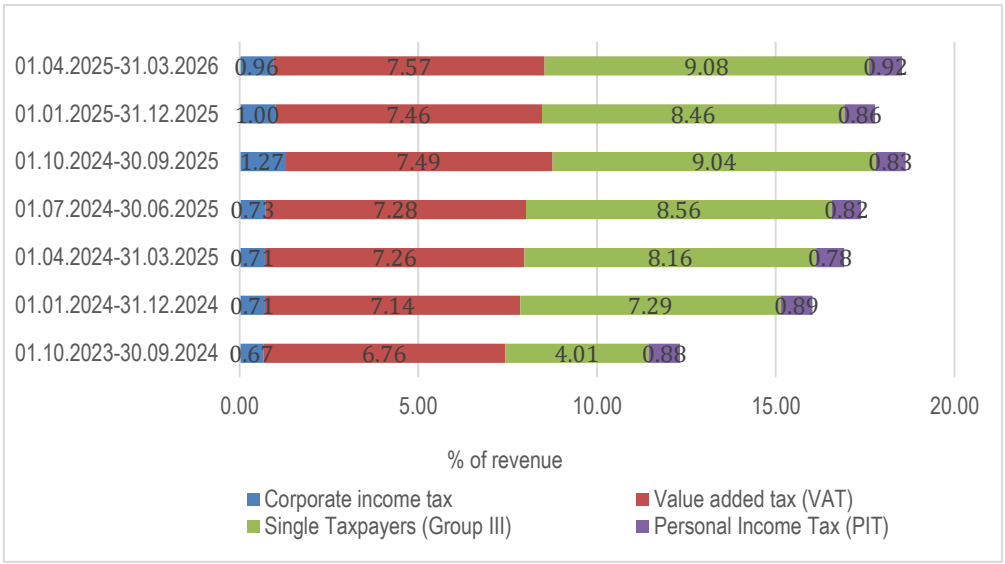

Fig. 1. Structure of the average tax burden of enterprises in Ukraine's forest sector, 2023–2026 (% of revenue).

Figure 1 presents the structure of the tax burden in Ukraine's forest sector by major tax categories. Throughout the study period, value added tax remained the largest tax component, exceeding 7% of enterprise revenue. The tax burden of group III single taxpayers showed an upward trend, whereas corporate income tax and personal income tax remained relatively stable. These findings indicate the absence of targeted tax incentives to support the forest bioeconomy.

The results also show that Ukraine's current tax system remains primarily fiscal, with limited capacity to stimulate investment, bioenergy, digitalization, and environmental modernization. A comparison with tax support mechanisms applied in the European Union provides a basis for identifying priorities for improving Ukraine's tax policy (table 2).

Table 2. Comparative assessment of tax incentives for the development of the forest bioeconomy in Ukraine and the European Union

Tax incentive	Ukraine	EU	Expected impact on forest bioeconomy development
Investment tax credit	–	+	Stimulation of investment activity
Accelerated depreciation	Partial	+	Technological modernization of enterprises
Tax incentives for bioenergy	–	+	Promotion of renewable energy development
ESG-related tax incentives	–	+	Enhancement of investment attractiveness
Tax incentives for digitalization	–	+	Acceleration of the sector's digital transformation
Tax incentives for the circular economy	–	+	Increased utilization of secondary raw materials

Unlike the European Union, where tax incentives are a key instrument for supporting the green transition and sustainable development, Ukraine has introduced only a limited range of such measures. Investment tax credits, bioenergy incentives, ESG-related tax benefits, and tax support for digital modernization remain largely absent. Consequently, aligning Ukraine's tax legislation with European approaches is essential for strengthening the competitiveness of the forest sector and advancing the forest bioeconomy.

In this context, the harmonization of Ukraine's tax legislation with European Union law should extend beyond the transposition of legal acts to include the development of a modern tax incentive framework that promotes sustainable investment, digitalization, and innovation.

3.2. Harmonization of Ukraine's tax legislation with European Union law

Ukraine's European integration process is accompanied by the gradual harmonization of national legislation with European Union law, encompassing not only technical regulation and environmental policy but also financial and tax mechanisms supporting sustainable development. For the forest sector, this process is of particular importance, as the implementation of European requirements directly affects the taxation system, the investment attractiveness of enterprises, public support mechanisms, and the development of forest bioeconomy markets. In this context, a key priority is the adaptation of Ukraine's tax policy to contemporary European instruments designed to promote the green transition, digitalization, and environmental responsibility.

Table 3. Key areas for harmonizing Ukraine's tax legislation with European Union law to support the development of the forest bioeconomy

EU policy	Key requirements	Current status in Ukraine	Expected economic impact
European Green Deal	Sustainable use of natural resources	Legislative harmonization is underway	Access to financing under the EU Green Investment Plan (over EUR 1 trillion by 2030)
EU Forest Strategy for 2030	Sustainable forest management and restoration	Partial implementation	Expanded access to EAFRD programmes (EUR 95.5 billion)
Regulation (EU) 2023/1115 (EUDR)	Traceability of timber origin	Digital monitoring and traceability systems are being introduced	Continued access to the EU market, which accounts for more than 60% of Ukraine's timber exports
EU Taxonomy	Green investment criteria	Initial stage of legislative adaptation	Attraction of ESG investments and financing through InvestEU (EUR 26.2 billion in guarantees)
Corporate Sustainability Reporting Directive	Corporate ESG reporting	Gradual adaptation of national legislation	Improved investment attractiveness and broader access to international capital

The harmonization of Ukraine's tax legislation with European Union law requires more than the transposition of legal acts; it also demands a modern tax incentive framework that supports investment, digitalization, ESG initiatives, and innovation in the forest sector. These measures are expected to strengthen the sector's competitiveness and accelerate its integration into the European economic area.

Their effectiveness, however, will depend on the implementation of modern tax support mechanisms, highlighting the need for strategic improvements to tax incentives in the context of digital transformation.

3.3. Prospective directions for improving tax Incentives in the forest bioeconomy

The digital transformation of the economy and Ukraine's integration into the European economic area require a modern approach to tax regulation in the forest sector. Tax incentives should serve not only a fiscal function but also promote innovation, digitalization, and investment in the forest bioeconomy. Based on the study findings, a digital framework integrating artificial intelligence, advanced information technologies, and digital tax administration is proposed to support the implementation of tax incentives (table 4).

Table 4. Digital framework for Implementing tax incentives in Ukraine's forest bioeconomy

Digital transformation area	Digital tool	Application	Expected tax and financial impact
Automated tax administration	Artificial Intelligence	Tax incentive risk assessment	Reduced misuse of tax incentives and improved tax compliance
Timber traceability	Blockchain	Timber supply chain monitoring	Lower shadow timber trade, broader tax base, higher budget revenues
Forest resource monitoring	GIS, satellite data	Monitoring of logging and forest restoration	More effective tax control and environmental monitoring
Tax incentive evaluation	Big Data	Assessment of tax incentive performance	Better tax policy and more efficient use of public funds
Digital tax administration	e-Tax, electronic timber tracking	Administration and monitoring of tax incentives	Lower administrative costs and greater transparency

The proposed framework adopts a phased approach to implementing digital technologies, combining electronic timber tracking, artificial intelligence, Big Data analytics, and integration with European digital platforms to improve the administration and monitoring of tax incentives.

Its implementation is expected to enhance the transparency of tax administration, strengthen public support for forest sector enterprises, stimulate investment, and accelerate the harmonization of Ukraine's tax legislation with European Union law. The proposed framework provides a methodological basis for developing a modern system of tax incentives for the forest bioeconomy in the digital era.

4.DISCUSSION AND CONCLUSIONS

The findings of this study confirm that the current tax regulation framework governing Ukraine's forest sector remains primarily fiscal in nature and makes limited use of tax incentives as an instrument for promoting the forest bioeconomy. In contrast to the European Union, where tax policy constitutes an integral component of sustainable development, the green transition, and innovation support, Ukraine has only a limited range of sector-specific tax incentives, and their application remains fragmented.

The study demonstrates that the harmonization of Ukraine's tax legislation with European Union law should extend beyond the transposition of EU legal acts and encompass the development of a modern tax incentive framework designed to stimulate investment, bioenergy, digitalization, ESG-oriented projects, and the environmental modernization of forest sector enterprises. Furthermore, the results indicate that digital technologies-including artificial intelligence, Big Data, blockchain, geographic information systems (GIS), and electronic tax

administration-can play a pivotal role in improving the transparency of tax incentives, strengthening tax control, and reducing tax risks.

REFERENCES

1. State Agency of Forest Resources of Ukraine. (2025). *Public Report of the Head of the State Agency of Forest Resources of Ukraine for 2024*. Kyiv. Available at: https://forest.gov.ua/

2. State Tax Service of Ukraine. (2025). *Industry Analytics: Average Tax Payment Indicators by Type of Economic Activity***.** Territory of High Tax Compliance. Available at: https://tpd.tax.gov.ua/analytics

3. European Commission. (2021). *Communication from the Commission: New EU Forest Strategy for 2030* (COM(2021) 572 final). Brussels. Available at: https://environment.ec.europa.eu/

4. European Commission. (2026). *The European Green Deal* (COM(2019) 640 final). Brussels. Available at: https://commission.europa.eu/

5. Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation (EUDR). *Official Journal of the European Union*, L150, 9.6.2023. Available at: https://eur-lex.europa.eu/

6. Eurostat. (2025). *Forestry, forestry products and ecosystem services statistics*. Luxembourg: Publications Office of the European Union. Available at: https://ec.europa.eu/eurostat

7. Organisation for Economic Co-operation and Development (OECD). (2023). *Tax Policy Reforms 2023: OECD and Selected Partner Economies*. Paris: OECD Publishing. Available at: https://www.oecd.org/tax/tax-policy/

8. Yatsukh, O., Zhuravlova, I., Tsap, V. (2025). Digital platforms for the financial and economic support of forestry enterprises: the experience of ukraine. *Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers 2025.* URL: https://www.woodema.org/proceedings/WoodEMA_2025_proceedings.pdf

9. Tsap, V., Tulai, O., Yatsuh, R. (2025) Ensuring the export potential of ukraine's forestry sector under conditions of sustainable development. Wood for the future: integrating sustainability across industries Proceedings of Scientific Papers p. 145-151 https://www.scopus.com/pages/publications/105019046697?origin=resultslist

10. Mostovenko O.,Tsap V., Borkovych V., Rudyk N., Nykonenko V. (2025) Assessment of the risks of using smart contracts in cryptocurrency transactions on domestic capital markets. Journal of Theoretical and Applied Information Technology, 103(20), 8581–8593 https://www.jatit.org/volumes/Vol103No20/24Vol103No20.pdf

Tsap V., PhD 1; Yatsukh O., doctor of economics 2; Borkovych V. PhD Student, 3.
1. Department of Finance, Accounting and Taxation, Dmytro Motornyi, Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
2. Head Department of Finance, Accounting and Taxation Dmytro Motornyi Tavria State Agrotechnological University, Ukraine.
3. Dmytro Motornyi, Tavria State Agrotechnological University, Zaporizhzhia, Ukraine
Corresponding author: tzapvd@gmail.com

DOUBLE MATERIALITY IN THE WOOD-BASED SECTOR: EVIDENCE ON EARLY ESRS IMPLEMENTATION

Eleonora Stancheva-Todorova

Abstract: The Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS) make double materiality the entry point for determining sustainability impacts, risks and opportunities. This paper examines how double materiality is applied in the wood-based sector, where forestry, fibre-based materials, packaging, paper and wood products connect climate change, biodiversity, circularity, water use and value-chain impacts. Building on an ESRS-aligned sustainability reporting quality framework, the study applies directed qualitative content analysis to financial year 2024 disclosures of five European companies: Stora Enso, UPM-Kymmene, Metsä Board, Holmen and Billerud. The analysis assesses four dimensions: distinction between impact and financial materiality, integration of both perspectives, methodological transparency and linkage to strategy and risk management. The cases differ in maturity. Stora Enso and UPM offer the clearest evidence of integrated double materiality assessment; Billerud and Metsä Board show solid first-year CSRD/ESRS implementation; and Holmen remains a relevant transitional ESRS-inspired case. Overall, the central issue is not how many topics are disclosed, but how clearly companies explain the materiality process, value-chain impacts and assurance-ready data.
Keywords: double materiality, ESRS, CSRD, sustainability reporting quality, wood-based sector, bioeconomy

1. INTRODUCTION

The Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS) have changed sustainability reporting in the EU from a largely voluntary practice into a standardized and assurance-oriented reporting obligation. Under this framework, companies determine the sustainability information to be reported through a double materiality assessment (DMA), covering both impacts on people and the environment and sustainability-related financial risks and opportunities (European Commission, 2023; European Parliament and Council, 2022). EFRAG guidance further emphasizes that material impacts, risks and opportunities may arise not only from own operations but also from upstream and downstream value chains (EFRAG, 2024).

The wood-based sector provides a relevant sectoral context for examining early ESRS implementation because it combines low-carbon and circularity opportunities with significant environmental dependencies. Fibre-based products and wooden construction materials may support material substitution, but the underlying business models remain closely linked to forests, land use, water resources, supplier controls and biodiversity management. This makes the connection between impact and financial materiality particularly visible.

Against this background, the paper examines how selected European wood-based companies operationalize double materiality in their financial year 2024 (FY2024) sustainability disclosures. The analysis focuses on three issues: the structure of DMA, differences in

implementation maturity, and sector-specific challenges in linking double materiality with ESRS reporting quality.

2. BACKGROUND AND ANALYTICAL FRAMEWORK

Under ESRS, double materiality is more than a filter for reportable topics. It organizes the identification and assessment of impacts, risks and opportunities (IROs), their connection with strategy and risk management, and the explanation of the process through ESRS 2 disclosures. ESMA identifies materiality assessment as the starting point for sustainability reporting and emphasizes detailed disclosure on the process itself (ESMA, 2024). This is not merely a technical classification exercise: DMA requires evidence, judgement, governance and documentation, particularly where impacts, accountability and reporting boundaries interact (Accountancy Europe, 2024; Mezzanotte, 2023).

The analysis builds on the ESRS-aligned sustainability reporting quality framework developed in Stancheva-Todorova (2026), where reporting quality is linked to strategic alignment, governance and internal control, IROs, metrics and targets, value-chain transparency, double materiality and assurance readiness. In this paper, the framework is applied through four observable DMA characteristics: separation of impact and financial materiality, integration of the two perspectives, methodological transparency and strategic linkage. This focus is particularly relevant for the wood-based sector, where raw material sourcing, forest management, fibre origin, supplier practices and downstream product use may all affect the materiality assessment.

3. RESEARCH DESIGN AND METHODOLOGY

The study uses an exploratory multiple-case design and directed qualitative content analysis. The sample was selected based on four criteria: operation in forestry, wood products, pulp, paper, board or fibre-based packaging; European reporting context; availability of FY2024 annual, sustainability or integrated reports; and disclosure of CSRD/ESRS alignment or explicit preparation for ESRS.

The final sample includes Stora Enso, UPM-Kymmene, Metsä Board, Holmen and Billerud. Stora Enso and UPM represent large, diversified forest-based and biomaterials groups; Metsä Board and Billerud represent fibre-based board, paper and packaging materials; and Holmen represents forest, wood products, board, paper and renewable energy. The sample captures several segments of the wood-based value chain while remaining suitable for exploratory comparison, as summarized in Table 1.

Table 1. Selected companies and reporting evidence

Company	Sector relevance	FY2024 reporting evidence
Stora Enso	Renewable packaging, biomaterials, wood products, forest assets	ESRS sustainability statement with limited assurance (Stora Enso, 2025)

UPM-Kymmene	Forest, pulp, paper, biomaterials and advanced materials	CSRD/ESRS-based sustainability statement; DMA-based material topics (UPM-Kymmene, 2025)
Metsä Board	Fresh fibre paperboards, white kraft liners and market pulp	CSRD/ESRS Sustainability Statement; updated DMA, value-chain IRO coverage and limited assurance (Metsä Board, 2025)
Holmen	Forest, wood products, board, paper and renewable energy	GRI-based Sustainability Report, structured with reference to ESRS and ESRS-inspired DMA (Holmen, 2025)
Billerud	Paper and fibre-based packaging materials	FY2024 CSRD/ESRS sustainability statement; value-chain coverage (Billerud, 2025)

After defining the sample, each company was assessed across four DMA dimensions: distinction between impact and financial materiality; integration in one DMA/IRO process; methodological transparency (process, criteria, stakeholder input and thresholds); and linkage to strategy, governance and risk management. Each dimension was scored from 1 to 3: 1 = limited or implicit evidence; 2 = partial but identifiable evidence; 3 = clear, explicit and integrated evidence. Total scores range from 4 to 12. Coding used explicit evidence from ESRS 2 disclosures, materiality sections, IRO descriptions, value-chain boundaries, stakeholder engagement, governance, risk management and assurance statements. Scores structure the comparison; maturity labels are interpretive, not company-reported.

4. RESULTS

The cases show movement toward ESRS-aligned DMA, although disclosure quality varies. Stora Enso and UPM are the most mature: their reports link DMA to sustainability statements, assurance evidence, renewable materials, forest-based value creation and risk management (Stora Enso, 2025; UPM-Kymmene, 2025). Billerud also provides strong first-year evidence: its FY2024 sustainability statement is prepared in accordance with CSRD and ESRS, and its DMA covers own operations and the upstream and downstream value chain (Billerud, 2025).

Metsä Board provides strong sector-specific evidence through a CSRD/ESRS Sustainability Statement with an annually updated DMA linked to a risk management process based on the COSO Enterprise Risk Management (ERM) framework. Its assessment covers own operations, the upstream and downstream value chain and other parties affected by the company's operations. It identifies material environmental topics across E1, E3, E4 and E5, including climate change, water, biodiversity and ecosystems, and resource use and circular economy (Metsä Board, 2025). Holmen's 2024 report is best treated as a transitional ESRS-inspired case: sustainability reporting is GRI-based, but its structure follows ESRS reporting areas and the materiality assessment is updated as ESRS-inspired DMA, rather than a full FY2024 CSRD/ESRS sustainability statement (Holmen, 2025).

Across the sample, the strongest disclosures present double materiality as an integrated assessment of IROs, not merely as a materiality matrix. Less detailed or more transitional disclosures are still useful, but they often provide less information about thresholds, stakeholder

input, weighting of impact versus financial criteria and the extent to which value-chain data were verified. This confirms that implementation maturity cannot be assessed only from the existence of an ESRS or DMA section.

The sectoral pattern is also clear. Climate change is consistently prominent, but in this sector it cannot be separated from biodiversity, circularity and forest-related value-chain impacts. Climate transition opportunities from renewable and recyclable materials may coexist with biodiversity risks, land-use pressures or supply-chain due diligence challenges. Reporting quality therefore depends on whether companies present these matters as connected IROs rather than as isolated disclosure topics. Table 2 summarizes the resulting maturity scores and sector-specific ESRS evidence for each company.

Table 2. Double materiality maturity and sector-specific ESRS evidence

Company	Score	DMA maturity and evidence	Sector-specific ESRS relevance	Pattern
Stora Enso	12	ESRS sustainability statement; advanced DMA architecture; limited assurance; selected reasonable assurance evidence	Forestry, renewable packaging, biomaterials, wood products, E1/E4/E5	Advanced
UPM	11	CSRD-based statement; DMA-identified ESRS topics; strong strategy and resource-use links	Forest-based value creation, climate, resource use, circularity, bio-based materials	Advanced
Billerud	10	First-year CSRD/ESRS statement; DMA covers own operations and value chain	Fibre-based packaging, wood supply, biodiversity, supplier controls, E1/E4/E5, G1	Strong
Metsä Board	10	CSRD/ESRS statement; DMA linked to COSO ERM-based risk management	E1/E3/E4/E5: climate, water, biodiversity, resource use and circularity	Intermediate-Strong
Holmen	8	ESRS-inspired DMA; not full FY2024 ESRS reporting	Forest cycle and biodiversity; transitional ESRS reporting	Transitional

The comparison in Table 2 points to three patterns. Mature ESRS implementation treats DMA as a process for identifying IROs and linking them to strategy and risk management, rather than as a topic list. The strongest wood-based cases connect climate change with biodiversity, water, circularity, resource use and supplier traceability. At the same time, the visibility of thresholds, weighting logic and stakeholder input remains uneven across the sample.

5. DISCUSSION

Viewed through the ESRS-aligned reporting quality framework, the wood-based sector illustrates why double materiality is difficult to operationalize. The sector's climate contribution is often framed positively through renewable materials and product substitution. Yet this

positive narrative has to be assessed alongside biodiversity impacts, land-use pressures, water issues, certification, sourcing and supplier data quality. Companies therefore need transparent boundaries and assumptions when assessing impacts across forests, mills, suppliers, customers and end-of-life pathways. The comparison suggests that DMA is beginning to move from a disclosure exercise toward a governance process. The remaining weakness is not the absence of materiality sections, but the uneven visibility of assumptions, thresholds and stakeholder input.

This finding is consistent with previous cross-sector evidence on FY2024 ESRS disclosures. The wood-based sector makes the issue particularly visible: broad disclosure is not the same as mature double materiality implementation. What matters is whether the report explains how impact and financial perspectives were connected and how the assessment affects strategy, risk management and assurance readiness. Forest origin, certification, raw material traceability, biodiversity exposure and downstream product use all add to the credibility challenge of DMA in this sector.

The findings also support a more balanced view of the sector's bioeconomy narrative. Wood-based companies can credibly present themselves as part of circular and low-carbon transitions only if claims about renewable materials are accompanied by transparent discussion of environmental dependencies and trade-offs. Future reporting cycles should therefore provide clearer thresholds and scoring logic, stronger explanation of stakeholder input, and deeper linkage between material IROs, targets, capital allocation, risk management and assurance procedures.

6. CONCLUSION

Taken together, the cases show how double materiality is being translated into FY2024 reporting practice in the wood-based sector. All selected companies address the principle, but they do so with different levels of depth, transparency and methodological detail. Stora Enso and UPM show the strongest evidence of integrated and transparent DMA practices; Billerud and Metsä Board provide strong first-year CSRD/ESRS evidence, although with somewhat less detailed presentation than the leading cases; Holmen represents a relevant but more transitional ESRS-inspired case.

The paper contributes empirically by examining a criteria-based sample of European companies from a sector highly relevant for the bioeconomy, circularity, biodiversity and climate transition. Conceptually, it applies the double materiality component of an ESRS-aligned sustainability reporting quality framework and shows that DMA can function as a practical indicator of reporting quality.

The study is limited by its small sample, reliance on publicly available reports and the transitional character of FY2024 reporting. Future research could extend the sample or examine whether FY2025 disclosures provide more transparent evidence on thresholds, stakeholder engagement, internal controls and assurance over DMA. For reporting practice, the main implication is that double materiality should be treated as a recurring management and reporting process rather than a one-off compliance exercise.

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REFERENCES

1. Accountancy Europe. (2024): ESRS Perspectives: Materiality Assessment. https://accountancyeurope.eu/publications/esrs-perspectives-materiality-assessment/
2. Billerud. (2025): Annual and Sustainability Report 2024. https://www.billerud.com/globalassets/cision/documents/2025/20250327-billeruds-annual-and-sustainability-report-2024-en-0-5016394.pdf
3. EFRAG. (2024): EFRAG IG 1: Materiality Assessment Implementation Guidance. https://www.efrag.org/sites/default/files/sites/webpublishing/SiteAssets/IG%201%20Materiality%20Assessment_final.pdf
4. ESMA. (2024): European Common Enforcement Priorities for 2024 Corporate Reporting. https://www.esma.europa.eu/sites/default/files/2024-10/ESMA32-193237008-8369_2024_ECEP_Statement.pdf
5. European Commission. (2023): Commission Delegated Regulation (EU) 2023/2772 as regards sustainability reporting standards. https://eur-lex.europa.eu/eli/reg_del/2023/2772/oj/eng
6. European Parliament and Council. (2022): Directive (EU) 2022/2464 as regards corporate sustainability reporting. https://eur-lex.europa.eu/eli/dir/2022/2464/oj/eng
7. Holmen. (2025): Annual Report 2024 including Sustainability Report. https://www.holmen.com/en/Newsroom/press/news/Annual-Report-2024/
8. Metsä Board. (2025): Annual Review 2024. https://www.metsagroup.com/globalassets/metsa-board/documents/investors/annual-report/2024/metsa-board-annual-review-2024.pdf
9. Mezzanotte, F.E. (2023): Corporate sustainability reporting: double materiality, impacts, and legal risk. Journal of Corporate Law Studies 23(2): 633–663. DOI: 10.1080/14735970.2024.2319058
10. Stancheva-Todorova, E. (2026): Sustainability reporting quality in the era of CSRD and ESRS: A critical review and conceptual framework. Forthcoming conference paper.
11. Stora Enso. (2025): Annual Report 2024. https://www.storaenso.com/-/media/documents/download-center/documents/annual-reports/2024/storaenso_annual_report_2024.pdf
12. UPM-Kymmene. (2025): Annual Report 2024. https://www.upm.com/siteassets/investors/reports-and-presentations/2024/upm-annual-report-2024.pdf

Author address:
Stancheva-Todorova, E.
Department of Finance and Accounting, Faculty of Economics and Business Administration, Sofia University “St. Kliment Ohridski”, Sofia, Bulgaria
e_stancheva@feb.uni-sofia.bg

AUDIT-BASED APPROACHES TO FOREST INDUSTRY VALUE CHAINS FOR SUSTAINABLE MANAGEMENT

Silviya Kostova

Abstract: The publication examines the role of auditing procedures as a tool for sustainable management of forest-based value chains. In the context of the bio-economic transition, rising traceability requirements and regulatory pressure, the management of forest resources increasingly requires integrated control, covering not only timber harvesting but also the subsequent stages of transportation, processing, and the sale of timber products. The report examines the forest-based value chain as a system of interconnected activities, in which auditing can perform verification, prevention, traceability, and management feedback functions. The study is based on an analysis of the scientific literature, official statistical data and regulatory and institutional sources. Particular attention is paid to data on forest area, timber harvesting, control activities, certification mechanisms, due diligence and chain of custody requirements. It is argued that certification and independent third-party auditing increase transparency and sustainability, but at the same time remain limited by the sample nature of inspections, differences in procedures and incomplete integration between the individual links of the chain. Therefore, auditing procedures can be seen not only as a compliance tool but also as a mechanism for coordination and sustainable management across the entire value chain. An analytical framework for applying an audit approach links the resource base, production flows and traceability requirements in the forest sector.
Keywords: forest industry value chains; audit procedures; sustainable management

1. INTRODUCTION

The forest-based value chain is an integrated system of interconnected activities in which a wood resource sequentially passes through forest management, harvesting, transportation, and primary and secondary processing, culminating in the production of end products. In the transformation of the bioeconomy, the sustainable management of this chain is increasingly seen as the ability to demonstrate its legal origin and traceability at every stage of its movement.

Modern scientific research shows that traceability is becoming a key element of the management of forest-based value chains. According to Mensah, sustainable wood product chains are based on integrated information flows, certification mechanisms and digital tracking systems that reduce the risk of illegal logging and increase market transparency (Mensah, et al., 2025). Similarly, Fripp assume that traceability is no longer just a technical tool, but a mechanism for proving sustainable origin and for managing risk in supply chains (Fripp, et al., 2023).

These conclusions are also reflected in the Chain of Custody (CoC) systems, which ensure the continuous traceability of wood from the forest to the end user. From an audit perspective, critical points do not coincide with the organizational boundaries of enterprises, but with the transitions between the individual stages of the chain. The most significant risks arise when wood moves through forestry, logging, transport and processing, including discrepancies between authorized and actual harvested quantities, loss of traceability, mixing of certified and uncertified wood and insufficient reliability of primary evidence. Therefore, the subject of the audit should not be the individual business transaction, but the complex information flow along the value chain.

2. TRACEABILITY-BASED AUDIT POINTS ALONG THE FOREST INDUSTRY VALUE CHAIN

Traceability is a fundamental principle for ensuring transparency, legality, and sustainability across forest industry value chains. It allows for continuous tracking of the movement of wood resources - from forest management and harvesting to transportation, processing and sale of final products. In this context, audit procedures should be aimed at identifying the critical control points where the most significant risks related to the origin of wood, the reliability of reporting information and compliance with sustainable management requirements are formed. The analysis of the resource base and wood flows in Bulgaria provides an empirical basis for assessing these risks and substantiating the need for an integrated audit approach grounded in traceability throughout the value chain.

The value chain in the forest industry should be viewed as a sequence of interconnected activities in which the value of the wood resource is formed and transformed from forestry to the final product. From an audit perspective, the transitions between the individual stages of use planning, extraction, transportation, storage, primary processing, secondary processing and sale are of particular importance. It is in these transitions that the most significant risks arise, related to the origin of the wood, the accuracy of the reported quantities, the mixing of materials and the demonstration of compliance with the requirements for sustainable management.

Data for Bulgaria show a stable resource base (Figure 1.). The total forest area increases from 4269 thousand ha in 2021 to 4283 thousand ha in 2024, and the afforested forest area increases from 3921 thousand ha to 3939 thousand ha over the same period. It shows that sustainable management cannot be assessed solely by the size of the forest area, but must be analyzed by how the wood resource is used, tracked, and controlled along the value chain.

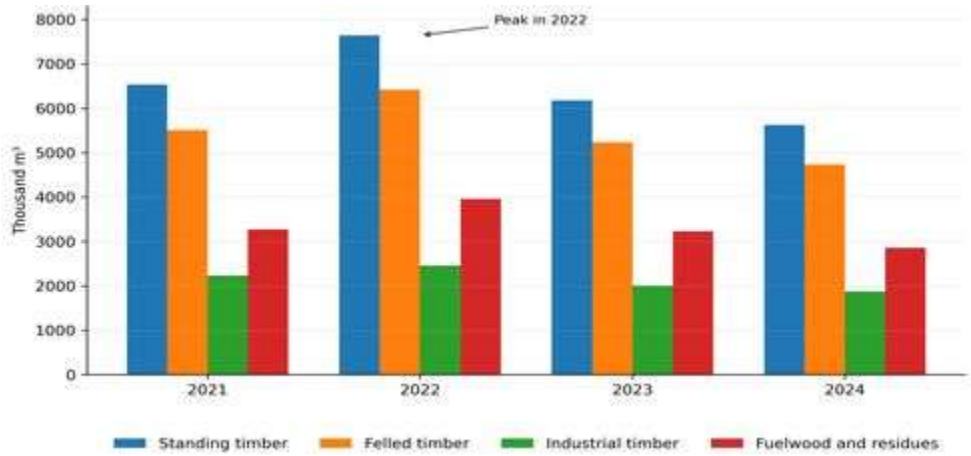

Figure 1. Timber Harvest in Bulgaria (2021–2024) Source: National Statistical Institute (2025); Executive Forest Agency (2024).

The data on harvested wood indicate a significant flow of resources to subsequent stages of processing. In 2024, the harvested wood in the standing state was 5626 thousand dense cubic meters, and in the lying state - 4736 thousand dense cubic meters. Construction wood is

1873 thousand dense cubic meters, and wood and sawdust - 2861 thousand dense cubic meters. These data outline the material basis of the value chain and show why audit procedures should cover not only the initial harvest, but also the subsequent movement of wood.

The IAG's control activity further confirms the importance of the audit approach. In 2024, 646,682 inspections were carried out, including 133,479 inspections of timber harvesting sites and 174,733 inspections of vehicles. Under the due diligence regime, 795 operators and 395 traders were inspected, and 83 operators lacked a due diligence system. These data show that the critical control points coincide with the main transitions in the value chain: harvesting, transport, trade, and proof of legal origin. The first analytical step in the report is therefore to map the value chain from an audit perspective. It means identifying not only the stages of value creation, but also the evidence through which the sustainable and legal movement of timber can be confirmed. In this sense, the audit becomes a tool for connecting the resource base, production flows and traceability requirements.

The results show that Bulgaria has a relatively stable resource base, while the control resource is mainly concentrated on the stages of harvesting and transportation. It confirms that the highest audit risk arises during the movement of wood between the individual links of the value chain, where the main requirements for traceability, proof of origin and compliance with the principles of sustainable management are formed. In summary, the resource base and timber flows in Bulgaria show that sustainable management of the forest industry should not be assessed solely by the availability of forest resources or the volume of harvest. More importantly, the system's ability to provide a reliable link between planning, harvesting, transport and subsequent processing is of greater importance. The link forms the core of the audit approach to the value chain. Therefore, critical control points should be identified where material and information flows are transferred, as it is during these transitions that the main risks to the legality, traceability, and sustainable management of the timber resource arise.

2. AUDITING PRACTICES AND TRACEABILITY MECHANISMS IN VALUE CHAIN MANAGEMENT

The audit and traceability mechanisms show a clear shift from compliance-oriented controls to a risk-based model of value chain management. The primary function of internal audit is to provide an independent assessment of management systems, risk management and internal controls, thereby contributing to the creation of organizational value (Stäuble, Nogueron, Knorr-Evans, & Schneider, 2023). Similarly, the views due diligence systems as a continuous process of identifying, assessing and mitigating risk within supply chains, rather than a one-off compliance check (Zhang, et al., 2025). The approach is further developed in (European Parliament, 2023), which requires operators to demonstrate the legal origin of timber through reliable, verifiable evidence based on risk assessment and full traceability of material flows. The development of international certification schemes also confirms this transformation. The introduction of the FSC Regulatory Module and the updated PEFC Due Diligence procedures show that voluntary certification is gradually being integrated with European regulatory requirements and is becoming a tool to support audit procedures. the effectiveness of certification mechanisms does not depend solely on the existence of a certificate, but on their ability to provide reliable traceability and verifiable evidence of sustainable management (Dröge, Verbist, Maertens, & Muys, 2024). The other authors (Berning & Sotirov, 2023) add that the new European regulatory framework is reshaping corporate responsibility by

emphasizing preventive risk management and transparency across the entire value chain. In this context, audit procedures should be seen as an integrating mechanism that links risk management, traceability and sustainability into a single forest industry management system (Figure 2.).

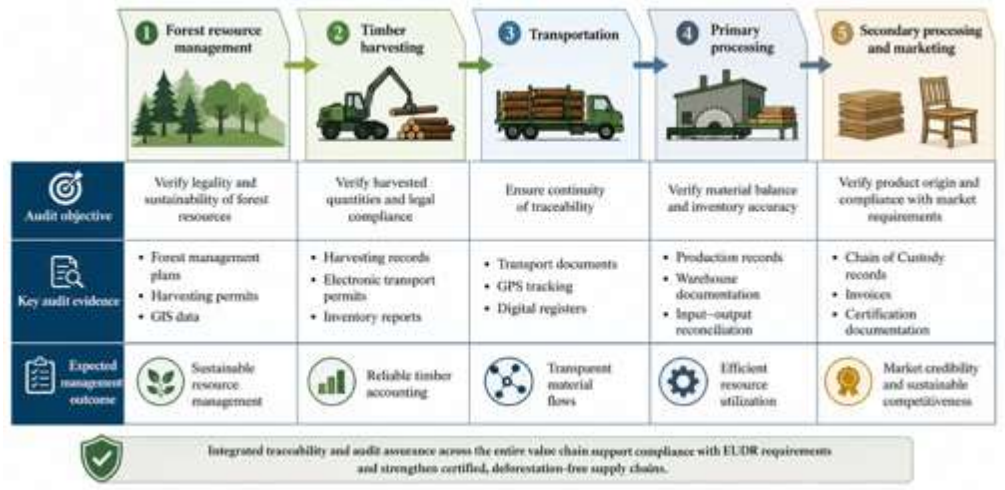

Figure 2. Integrated Audit Framework for Forest Industry Value Chains

The proposed analytical framework shows that the effectiveness of audit procedures depends on their integration into all stages of the value chain from forest resource management to the realization of final products. Traceability, risk-based auditing and reliable audit evidence form an interconnected system that supports not only the establishment of compliance with regulatory requirements, but also the sustainable management of material and information flows. In this sense, the audit approach is established as a tool for increasing transparency, limiting risk and creating added value along the entire value chain in the forest industry.

3. ANALYTICAL FRAMEWORK FOR APPLYING AN AUDIT APPROACH TO SUSTAINABLE MANAGEMENT OF THE FOREST INDUSTRY VALUE CHAIN

The analysis of the value chain and existing traceability mechanisms shows that the effectiveness of audit procedures depends not only on the implementation of individual control activities, but also on their integration into a single management system. Therefore, this study proposes an analytical framework that connects material flows, information flows and audit evidence into a common model for sustainable management (Zhelev, 2025).

The proposed framework is based on three interrelated elements. The first covers the resource base of the chain - forest resources, planning of use and harvest. The second includes the processes of transportation, processing, and sale of wood products, during which added value is created. The third integrates audit procedures by checking traceability, risk assessment, compliance with regulatory requirements and the reliability of information flows. In this way, the audit performs not only a control but also a management function, providing an independent assessment of the functioning of the entire value chain.

The proposed model aligns with the modern risk-based approach to auditing, which focus on individual business operations, the integrated audit approach allows for the assessment of the interrelationships among the origin of wood, material flow movements, internal control systems, and the reliability of reporting information (Papradanova, Kostova, & Vechev, 2025). It creates an opportunity for the timely identification of risks, reduces information inconsistencies, and increases transparency across the entire value chain.

The proposed framework systematises audit procedures along the main stages of the forest industry value chain, linking audit objectives, required evidence and expected management results into a single analytical system. In contrast to the traditional approach, in which audit activities are considered as independent checks of individual processes, the current model assumes that the reliability of management depends on the continuity of traceability between all links in the Chain - from the management of forest resources to the sale of final products. Thus, the subject of the audit is not only the legality of individual operations, but also the quality of the information links between them.The logic of the model aligns with the modern concept of risk-based auditing and the principles of due diligence. What these approaches have in common is the understanding that sustainable management of the value chain cannot be guaranteed solely through administrative controls or certification mechanisms, but requires an integrated system of traceable evidence that enables timely identification and management of risk. Audit procedures should therefore be seen as a strategic tool that ensures transparency, increases the reliability of management information and supports the sustainable functioning of the value chain in the forest industry.

The proposed analytical framework expands the traditional understanding of auditing as a tool for ex-post control, positioning it as an element of strategic value chain management (Kostova & Zhelev, 2026). By integrating resource information, production flows, and audit evidence, the prerequisites for higher transparency, more reliable risk assessment, and more effective sustainability management are created. The practical application of the model would assist both forest industry enterprises and control authorities in building systems that comply with modern European requirements for traceability, corporate governance and sustainable development.In summary, audit procedures should be seen as an integrating mechanism that connects the individual links of the value chain through verifiable evidence and reliable information. It is this function that transforms auditing from a tool for establishing compliance into a tool for creating value and sustainable management of the forest industry. In conclusion, the study confirms that sustainable management of value chains in the forest industry requires integrating traceability, risk management, and independent audit procedures. The analysis shows that the most significant risks arise at the transitions between the individual stages of the chain; therefore, an effective audit should cover not only compliance with regulatory requirements, but also the reliability of information and material flows.

The proposed analytical framework considers audit procedures as a tool for sustainable management, connecting the resource base, production processes, and traceability mechanisms within a single model. Its implementation would help increase transparency, risk management and compliance with European sustainability requirements, while creating prerequisites for more effective management of value chains in the forest industry.

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REFERENCES

1. Berning, L., & Sotirov, M. (2023). *Hardening corporate accountability in commodity supply chains under the European Union Deforestation Regulation*. 17(4), 870-890. https://doi.org/10.1111/rego.12540
2. Dröge, S., Verbist, B., Maertens, M., & Muys, B. (2024). *Do voluntary sustainability standards reduce primary forest loss? A global analysis for food commodities*. Agriculture, Ecosystems & Environment, 374, 1-10. https://doi.org/10.1016/j.agee.2024.109158
3. European Parliament. (31.05.2023 r.). Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation. https://eur-lex.europa.eu/eli/reg/2023/1115/oj/eng
4. Fripp, E., Gorman, J., Schneider, T., Smith, S., Paul, J., Neeff, T., & Zosel-Harper, A. (2023). Traceability and transparency in supply chains for agricultural and forest commodities: A review of success factors and enabling conditions to improve resource use and reduce forest loss. Washington, DC: World Resources Institute http://doi.org/10.46830/wrirpt.22.00156
5. Kostova, S., & Zhelev, Z. (2026). Artificial Intelligence for Enhancing the Information Flow in Financial Control Activities. International Conference on Digital Technologies and Applications. 1641, pp. 59-69. Cham: Springer. https://doi.org/10.1007/978-3-032-06061-7_5
6. Mensah, P., Pimenta, S., de Melo, R., Amponsah, J., Tuo, G., Chakurah, I., Medeiros, P. (2025). The Global Supply Chain of Wood Products: A Literature Review. Forests, 16(7), 1-41. https://doi:10.3390/f16071036
7. Papradanova, D., Kostova, S., & Vechev, V. (2025). Sustanability Reporting in Bulgaria. An Overview of Reporting Practices in Bulgarian Companis. От Corporate Sustainability Reporting in Central and Eastern European Companies (p. 330). Routledge. https://doi:10.4324/9781003451884-4
8. Stäuble, T., Nogueron, R., Knorr-Evans, M., & Schneider, T. (2023). Timber traceability: a diagnostic tool for practitioners and policymakers. https://doi.org/10.46830/wrirpt.21.00067
9. Zhang, B., Feng, Y., Zhou, X., Lai, D., Zhong, H., Ting, Y., Xie, J. (2025). Dynamic mechanical behaviour and life cycle assessment of rubberised solid waste-based geopolymer concrete. Journal of Cleaner Production, 1-19. https://doi:10.1016/j.jclepro.2025.145247
10. Zhelev, Z. (2025). Green taxes as a tool for sustainable development in the forest industry: approaches and impacts. WOOD FOR THE FUTURE: INTEGRATING (pp. 457-463). Ohrid: WoodEMA, i.a. – International Association for Economics and Management in wood. Retrieved from https://www.woodema.org/proceedings/WoodEMA_2025_proceedings.pdf

Authors address:
Kostova, Silviya[1]
[1]Department of Control and Analysis Economic Activities, Faculty of Economic Accounting, D. A. Tsenov Academy of Economics, Svishtov, Bulgaria
*Corresponding author: s.kostova@uni-svishtov.bg

REGULATORY FRAMEWORK FOR PLACING WOOD PRODUCTS ON THE EUROPEAN UNION MARKET

Slavica Petrović, Aleksandra Lazarević, Miljan Kalem

Abstract: The placing of wood products on the European Union market is governed by a comprehensive regulatory framework that defines the safety and compliance requirements that these products must meet. In this context, the subject of this paper is selected European Union regulations governing this area. Particular attention is given to Regulation (EU) 2023/988 on general product safety, while Regulation (EU) 2025/2509 on toy safety, Regulation (EU) 2025/40 on packaging and packaging waste, and Regulation (EU) 2024/3110 on construction products are addressed to a lesser extent. The aim of this research is to identify the most important requirements imposed on producers of certain categories of wood products when placing their products on the EU market. Special focus is placed on the requirements laid down in Regulation (EU) 2023/988 that apply to producers from third countries, i.e. non-EU Member States, including the Republic of Serbia.
Keywords: EU, requirements, market, regulation, wood products.

1. INTRODUCTION

Regulation (EU) 2023/988[19], which replaced Directive 2001/95/EC[20], is the primary general legal act governing the safety of products placed on the EU market. The Regulation is of a general nature and applies to new, used, repaired and processed consumer products produced in the EU or in third countries. It does not apply to products that need to be repaired or reprocessed before being placed on the EU market.

In the case of the wood industry, Regulation 2023/988 applies in its entirety only to wood products that are not covered by specific Union harmonisation regulations.[21] In cases where products are subject to special regulations, Regulation 2023/988 applies in so far as it relates

19 Regulation (EU) 2023/988 of the European Parliament and of the Council of 10 May 2023 on general product safety, amending Regulation (EU) No 1025/2012 of the European Parliament and of the Council and Directive (EU) 2020/1828 of the European Parliament and of the Council, and repealing Directive 2001/95/EC of the European Parliament and of the Council and Council Directive 87/357/EEC. OJ L 135, 23.5.2023, pp. 1–51.

20 Directive 2001/95/EC of the European Parliament and of the Council of 3 December 2001 on general product safety. OJ L 11, 15.1.2002, pp. 4–17.

21 The list of harmonized Union legislation is set out in Annex I to Regulation (EU) 2019/1020 of the European Parliament and of the Council of 20 June 2019 on market surveillance and compliance of products and amending Directive 2004/42/EC and Regulations (EC) No 765/2008 and (EU) No 305/2011. OJ L 169, 25.6.2019, pp. 1–44). Although the Annex to the Regulation still references superseded directives, under the principle of legislative continuity it shall be deemed to apply to the new legislation analysed in this paper, until the Annex is updated.

to general safety requirements not prescribed by special regulations. In the wood industry sector, special regulations apply to construction products (Regulation 2024/3110[22]), wooden toys (Regulation 2025/2509[23]) and wooden packaging (Regulation 2025/40[24]). However, it should be noted that the Regulation on packaging and packaging waste does not regulate the safety of products, but prescribes the requirements for the sustainability, composition, labelling and management of packaging during its life cycle. Furniture and wood products containing electrical components, when placed on the EU market, must meet the requirements prescribed by the Low Voltage Directive 2014/35/EU[25] and the Electromagnetic Compatibility Directive 2014/30/EU [26].

2. METHODOLOGY

The methodological approach used in the research is based on the application of methods of analysis and synthesis of relevant EU regulations governing the placing of wood products on the market. The research was conducted with the aim of identifying the most important requirements that manufacturers should meet when placing their wood products on the EU market. In this regard, special attention has been paid to product safety requirements. The analysis covers the applicable EU regulations governing the placing of wood products on the EU market.

3. RESULTS AND DISCUSSION

This chapter analyses the requirements of selected regulations that manufacturers need to meet when placing their wood products on the EU market.

3.1. Obligations of the Manufacturer under Regulation (EU) 2023/988 on General Product Safety

22 Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011. OJ L 2024/3110, 18.12.2024

23 Regulation (EU) 2025/2509 of the European Parliament and of the Council of 26 November 2025 on the safety of toys and repealing Directive 2009/48/EC. OJ L, 2025/2509, 12.12.2025

24 Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. OJ L, 2025/40, 22.1.2025.

25 Directive 94/9/EC of the European Parliament and the Council of 23 March 1994 on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres (OJ L 100, 19.4.1994, p. 1). OJ L 96, 29.3.2014, pp. 357–374.

26 Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility. OJ L 96, 29.3.2014, pp. 79–106.

According to Article 9 (2) of Regulation (EU) 2023/988, the manufacturer should carry out an assessment of the safety risks of the product and prepare technical documentation before placing the product on the EU market. The technical documentation should contain "at least a general description of the product and its essential characteristics relevant to the assessment of its safety" (Article 9 (2) of Regulation 2023/988). For wood products, these characteristics include stability, load-bearing capacity, resistance, structural design, etc. The regulation does not specify how the manufacturer should demonstrate these characteristics in the technical documentation. The technical documentation of more structurally complex products must contain an analysis of the potential risks and the measures applied to eliminate or mitigate them, including test reports, as well as a list of all relevant European standards or parts thereof applied to meet the general product safety requirement (Article 9, paragraph 2 of Regulation 2023/988).

The manufacturer begins the risk assessment at the stage of designing the product and selecting the materials for its production. Risks identified at this stage should be eliminated or reduced by the application of appropriate measures. Depending on the product, its characteristics may be evaluated after manufacture in accordance with the requirements of the relevant standards. The risk remaining after the application of all risk mitigation measures, including information and warnings to users, is called residual risk (ISO 12100). This risk cannot be completely eliminated, but it is acceptable if the product complies with the general product safety requirement and is acceptable for the market.

Regulation 2023/988 does not prescribe a methodology for risk assessment, but manufacturers may use the methodology prescribed by Regulation (EU) 2024/3173[27], which is primarily intended for market surveillance authorities. According to this methodology, four levels of damage severity are distinguished, namely life-threatening (4), serious injury (3), moderate injury (2) and minor injury (1), while the probability of damage is classified into eight classes. Combining the severity level and the probability of occurrence yields the level of risk that the product may cause. The Regulation defines four levels of risk: serious (S), high (H), medium (M) and low (L) (Table 1).

27 Commission Delegated Regulation (EU) 2024/3173 of 27 August 2024 supplementing Regulation (EU) 2023/988 supplementing Regulation (EU) 2023/988 of the European Parliament and of the Council with regard to rules on access to and operation of the Safety Gate Rapid Alert System, information to be entered in that System, notification requirements and the criteria for assessment of the level of risk. OJ L, 2024/3173, 13.12.2024.

Table 1: Probability and severity of damage occurring during the foreseeable life of the product

Probability of damage occurring during the foreseeable life of the product		Severity of damage			
		1	2	3	4
High	> 50%	H	S	S	S
	> 1/10	M	S	S	S
	> 1/100	M	S	S	S
	> 1/1000	L	H	S	S
	> 1/10	L	M	H	S
	> 1/100	L	L	M	H
	> 1/1000	L	L	L	M
Low	< 1/1 000 000	L	L	L	L

Source: Regulation (EU) 2024/3173

Regulation 2023/988 stipulates that the manufacturer must have up-to-date technical documentation, keep it and make it available to market surveillance authorities for a period of ten years after the product has been placed on the market. Regulation 2023/988 does not require CE marking of products or the issuing of an EU Declaration of Conformity.

Products placed on the EU market should be clearly labelled, with a view to easy identification and monitoring in the distribution chain. The labelling of products placed on the EU market by a non-EU producer is explained in more detail in the 2022 Blue Guide on the Application of EU Product Rules (pp. 58–59). According to Article 16 of Regulation 2023/988, products from non-EU countries can be placed on the EU market only if there is a responsible person for them for products placed on the EU market. The responsible person may be a manufacturer established in the Union, an importer (when the manufacturer is not established in the Union), an authorised representative or a fulfilment service provider[28] (Regulation 2019/1020).

3.2. Obligations of the manufacturer under Regulation (EU) 2025/2509 on the safety of toys

Regulation (EU) 2025/2509 on the safety of toys, replacing Directive 2009/48/EC, applies to toys for children up to 14 years of age. Before placing the toy on the market, the manufacturer must carry out a conformity assessment, draw up technical documentation and an EU Declaration of Conformity, affix the CE marking and produce a digital product passport. Toys placed on the EU market must be safe to use and meet specific safety requirements. Special requirements relate to physical and mechanical properties, flammability, chemical, electrical and hygienic properties, as well as radioactivity. Annex II lists limit values for certain chemical elements, substances that toys must not contain, restrictions on the presence of odorous

28 "fulfillment service provider means any natural or legal person offering, in the course of commercial activity, at least two of the following services: warehousing, packaging, addressing and dispatching, without having ownership of the products involved, excluding postal services, parcel delivery services and any other postal services or freight transport services" (Regulation 2023/988).

allergens, as well as labelling obligations. The content of the technical documentation is prescribed in detail in Annex V.

Regulation 2025/2509 explicitly refers to certain provisions of Regulation 2023/988, namely Articles 19-21 relating to the obligations of economic operators in the case of distance selling, Article 22 on online sales, Articles 25-27 on the Safety Gate system and Articles 33-39 relating to the right to information and legal remedies.

3.3. Obligations of the Manufacturer under Regulation (EU) 2025/40 on Packaging and Packaging Waste

Regulation (EU) 2025/40 on packaging and packaging waste, which replaced Directive 94/62/EC, applies to all types of packaging. Before placing the packaging on the market, the manufacturer is obliged to carry out internal production control in order to assess the conformity of production with the relevant requirements, as well as to draw up the technical documentation and the EU Declaration of Conformity. The technical documentation should include a description of the packaging and its purpose, design and production drawings, descriptions and explanations of the drawings, materials used, harmonised standards used and test reports (Annex VII). The content of the EU Declaration of Conformity, issued by the manufacturer under its own responsibility, is given in Annex VIII. The regulation prescribes the requirements for the recyclability of packaging that manufacturers must meet by 2030 and 2035, respectively. The manufacturer is obliged to register in the national register of the Member State in which they place the packaging or packaged products on the market for the first time, or in which they unpack packaged products that are not intended for final consumption. Manufacturers are subject to extended producer responsibility when they make the packaging and packaged products available on the market of a Member State for the first time, or when the products are unpacked on the territory of that State and are not intended for end use. Unlike Regulation 2025/2509, Regulation (EU) 2025/40 on packaging and packaging waste does not contain explicit references to the provisions of Regulation 2023/988.

3.4. Obligations of manufacturers under Regulation (EU) 2024/3110 on construction products

Regulation (EU) 2024/3110 on construction products replaced Regulation (EU) No 305/2011. According to Article 22 of Regulation 2024/3110, when placing a product on the market, the manufacturer should determine and identify the product, prepare technical documentation, draw up a Declaration of Performance and Conformity of the product and affix the CE marking. In addition, the manufacturer is obliged to provide information about the product, draw up an instruction manual and provide information about the safety of the product (Annex IV). The technical documentation, the content of which is prescribed by Article 22, paragraph 3, represents the basis for the preparation of the Declaration of Performance and Conformity. According to Article 14, a Declaration is not required for individual products or products made to order. The content of the Declaration is set out in detail in Annex V of the Regulation. Regulation (EU) 2024/3110 introduced a digital passport for products, and Article 76 prescribes its content. The categories of construction products referred to in Regulation (EU) 2024/3110 are listed in Annex VII. Regulation (EU) 2024/3110 does not contain explicit references to the provisions defined by Regulation (EU) 2023/988.

4. CONCLUSION

The regulations analysed in the paper are part of the new EU regulatory framework, as they have all been adopted during the past three years. Regulation (EU) 2023/988 constitutes the primary legal act governing the safety of consumer products placed on the EU market. An explicit reference to certain provisions of Regulation 2023/988 exists only in the Regulation on toys, while the Regulations on construction products and on packaging contain no direct reference. Article 16 of Regulation (EU) 2023/988 stipulates that products covered by the Regulation and coming from third countries cannot be placed on the EU market without a responsible person established in the territory of the EU. Other analysed regulations do not contain such an article, but the definitions of the importer and the authorised representative state that they must be established in the territory of the EU. All analysed regulations clearly define the requirements that manufacturers must meet when placing their products on the EU market.

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REFERENCES

1. ***: Commission Delegated Regulation (EU) 2024/3173 of 27 August 2024 supplementing Regulation (EU) 2023/988 supplementing Regulation (EU) 2023/988 of the European Parliament and of the Council with regard to rules on access to and operation of the Safety Gate Rapid Alert System, information to be entered in that System, notification requirements and the criteria for assessment of the level of risk. OJ L, 2024/3173, 13.12.2024. https://eur-lex.europa.eu/eli/reg_del/2024/3173/oj/eng
2. ***: European Commission (2022). The 'Blue Guide' on the implementation of EU product rules 2022. OJ C 247, 29.6.2022, pp. 1–152. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2022.247.01.0001.01.ENG&toc=OJ%3AC%3A2022%3A247%3AFULL
3. ***: ISO standard 12100 (2010): Safety of machinery – General principles for design – Risk assessment and risk reduction
4. ***: Regulation (EU) 2019/1020 of the European Parliament and of the Council of 20 June 2019 on market surveillance and compliance of products and amending Directive 2004/42/EC and Regulations (EC) No 765/2008 and (EU) No 305/2011. OJ L 169, 25.6.2019, pp. 1–44. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1020.
5. ***: Regulation (EU) 2023/988 of the European Parliament and of the Council of 10 May 2023 on general product safety, amending Regulation (EU) No 1025/2012 of the European Parliament and of the Council and Directive (EU) 2020/1828 of the European Parliament and the Council, and repealing Directive 2001/95/EC of the European Parliament and of the Council and Council Directive 87/357/EEC. OJ L 135, 23.5.2023, pp. 1–51. https://eur-lex.europa.eu/eli/reg/2023/988/oj/eng

6. ***: Regulation (EU) 2025/2509 of the European Parliament and of the Council of 26 November 2025 on the safety of toys and repealing Directive 2009/48/EC. OJ L, 2025/2509, 12.12.2025. https://eur-lex.europa.eu/eli/reg/2025/2509/oj/eng
7. ***: Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. OJ L, 2025/40, 22.1.2025. Available at: https://eur-lex.europa.eu/eli/reg/2025/40/oj/eng.
8. ***: Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011. OJ L 2024/3110, 18.12.2024. https://eur-lex.europa.eu/eli/reg/2024/3110/oj/eng

Authors address:
Petrović, S.[1]; Lazarević, A.[1]; Kalem, M.[1]
[1] Department of Wood Science and Technology, University of Belgrade - Faculty of Forestry, Belgrade, Serbia
*Corresponding author: slavica.petrovic@sfb.bg.ac.rs

CHAPTER H
WOOD IN ARCHITECTURE, DESIGN AND INTERIOR

THE ROLE OF TIMBER IN BIOPHILIC DESIGN PATTERNS

Marija Miloshevska Janakieska

Abstract: The biophilic design is focused on the connection between humans and nature within the built environment, and it contributes to improved well-being, comfort, health and productivity, which is proved scientifically. The natural materials can contribute to the biophilic design, and among them, wood holds a unique position due to its sensory, aesthetic, and environmental qualities. This paper explores the role of wood as an architectural material and how it contributes to biophilic design practices, how it strengthens the connection of the people with nature, through different biophilic design patterns.
At the beginning of the paper, a brief overview of biophilic design is provided, including the positive effects of wood in architecture, not just from sustainable and environmental point of view, but also as part of the biophilic design. Following this overview, the study examines how timber contributes to different biophilic design patterns, including visual and non-visual connections with nature, material connection with nature, and connection with natural systems. The role of timber is discussed across different architectural applications such as structural elements, facades, urban equipment, and interior spaces, supported by selected architectural examples. The aim of the paper is to emphasize the importance of wood as a construction material and to point out its benefits beyond the traditional way of thinking. Wood is a material that provides sensory experiences for the building users and strengthens the human-nature relationship in contemporary architecture, which is truly important nowadays.

Keywords: Wood, Biophilic Design, Patterns, Timber Architecture, Natural Materials

1. INTRODUCTION

People are spending most of their time indoors, in closed spaces. Even when they go outside, it isn't usually in a natural setting, but built environment with high-rise concrete buildings, artificial materials, wide streets filled with cars, which impacts negatively on people's health and well-being. The modern way of life has contributed to disconnection with nature, which has been a focus in numerous studies lately. There are studies that show that people that are disconnected from nature show dissatisfaction with their lives, depression and illness [Barrable et al., 2022].
Architects and designers are trying to find a solution to this problem and to investigate how the design can return that connection between humans and nature. The design that is focused on emphasizing the bond between humans and nature is called biophilic design. Studies have shown that biophilic design improves the health of the users, their productivity, positivity and well-being. The paper by S. H. Hung and C. Y. Chang reviews scientific evidence showing that biophilic-designed environments improve human health and well-being by reducing stress, enhancing cognitive performance, and supporting psychological restoration through increased connection with nature [Hung & Chang, 2021].

The application of natural materials in architectural design is one of the best ways to achieve biophilic design and improve the connection between the users of the designed space and nature, allowing them to feel the positive aspects. This study is focused on exploring the role of wood in supporting biophilic design through selected biophilic design patterns and different architectural applications. The methodology is based on literature review, analyses of biophilic patterns and examination of case studies.

2. BIOPHILIC DESIGN: CONCEPT AND PRINCIPLES

Biophilia refers to humanity's innate biological connection with nature and the natural tendency to affiliate with other forms of life. Building on this concept, biophilic design represents an approach to shaping the built environment by incorporating nature-inspired elements and principles, guided either by intuitive appreciation of nature or by scientific evidence demonstrating measurable biological and psychological benefits [Ryan & Browning, 2020]. Besides improving health and productivity, biophilic design can also generate measurable economic value, as nature-integrated workplaces are associated with increased employee efficiency, reduced absenteeism, higher job satisfaction, and lower operational costs, ultimately providing financial benefits for organizations [Barnaby et al., 2023].

According to Terrapin Bright Green in 14 Patterns of Biophilic Design, biophilic design patterns represent a set of design strategies derived from nature that can be integrated into the built environment to support human health and well-being. These patterns include direction connections with nature, such as natural light, vegetation, and water; and indirect connections with nature, such as natural forms and materials, design that mimic natural environments. With this, biophilic design reduces stress, improves well-being, and enhances overall user experience in the architectural designs [Browning et al., 2014].

3. WOOD AS A BIOPHILIC MATERIAL

Wood is one of the oldest construction materials used since prehistoric times. Besides its numerous construction and environmental benefits, wood holds a high position in achieving biophilic design. Wood has many characteristics that support biophilia.

Firstly, wood is naturally renewable material, which is not related just to biophilic design, but also to sustainable construction practices. Secondly, wood has visual qualities, such as natural color variations, distinctive grain patterns, and a sense of warmth, which contributes to aesthetically pleasing environments that remind us of nature. In addition, wood offers important tactile experiences, including pleasant texture and comfortable surface feel, which influences positively on the senses. The wood regulates the humidity in the interior space. It has a specific natural scent, and it can provide acoustic comfort.

Together, these attributes contribute to positive psychological responses, including feelings of warmth, relaxation, and well-being. Thus, contemporary architectural trends are focusing on timber application and the use of engineered wood products as key elements in creating healthier, biophilic, and sustainable built environment.

4. CASE STUDIES

4.1. Timber as Structural Material

Mjøstårnet Building in Brumunddal, Norway (Figure 1) has a height of 85.4m, and it is one of the tallest timber buildings in the world. The main structure of the building is a frame made from glulam columns and beams. The slabs are made from Cross Laminated Timber (CLT). This structure demonstrates how EWPs can replace conventional materials such as steel and concrete, even in high-rise buildings.
The biggest biophilic pattern used here is the exposed timber structure which creates visual connection, but also involvement of the other senses. The natural wood surfaces are creating warmth, comfort and human-scale perception. Moreover, the wood is locally sourced from the surrounding, so it emphasizes the strong connection with the context.

Figure 1: Mjøstårnet Building in Brumunddal, Norway
*[*https://www.archdaily.com/934374/mjostarnet-the-tower-of-lake-mjosa-voll-arkitekter]

4.2. Timber in Interior Design (Decorative and Sensory Use)

SunnyHills at Minami-Aoyama in Tokyo, Japan is a building designed by the architect Kengo Kuma (Figure 2). The structure is complex wooden lattice made from cedar, and it is clearly visible in the interior. The wood is used as a structural material, but at the same time serves to create atmosphere, texture, and spatial experience. The structural lattice filters the light and creates patterns of shadow, enhancing the sensory perception as part of the biophilic patterns. In this building we can see the strong visual connection with nature, but also sense the non-visual connection, through the tactile experience with the exposed wood surfaces. The furniture inside is also made from wood which strongly compliments the overall aesthetic of the structural lattice.

Figure 2: SunnyHills at Minami-Aoyama in Tokyo, Japan [https://www.archdaily.com/484981/sunnyhills-at-minami-aoyama-kengo-kuma-and-associates]

4.3. Timber in the Urban Context / Urban Equipment

The Metropol Parasol in Seville, Spain, designed by Jürgen Mayer H. is one of the largest wooden structures in the world located in a public urban square. The structure is made from laminated timber panels with protective coatings. This structure serves as urban infrastructure, providing shade, public spaces, walkways, and viewpoints. Nowadays, it is also perceived as a landmark.

In terms of biophilic design, it introduces a large natural material presence within a dense urban environment, creates a comfortable microclimate and shaded public space, and encourages interaction between people, architecture, and the surrounding urban ecosystem.

Figure 3: Metropol Parasol in Seville, Spain [https://www.archdaily.com/201961/metropol-parasol-j-mayer-h-arup]

5. BIOPHILIC DESIGN PATTERNS AND THE ROLE OF WOOD

The patterns in the biophilic design are used to create a framework for integration of nature in the built environment to support human well-being. Wood is highly efficient material within this framework, as it contributes to visual, sensory, material and temporal experiences at the same time. There are several patterns where the role of the timber is highlighted strengthening the human-nature connection.

The first one is the visual connection with nature which refers to the perception of natural elements through sight. Wood supports this pattern through its natural appearance such as visible grain, color, variation and organic texture. Exposed timber surfaces emphasize the presence of natural materials in the architectural design, allowing the users to visually connect with nature even in closed spaces.

The second pattern is the non-visual connection with nature which is equally important where the users are experiencing nature through the other senses such as touch, smell,

and sound. Wood has pleasant tactile qualities, warm surface, and natural texture. In addition, timber may emit subtle natural scents which contribute to this pattern. With the acoustic comfort that the timber can provide, a calming spatial experience can be created.

The material connection with nature is the most obvious pattern where timber has a strong impact on. Timber is a renewable and authentic material, which strengthens the connection with nature by expressing its natural origin. Its use contrasts with synthetic materials, reinforcing a sense of authenticity and closeness to nature in architectural design.

The connection with natural systems reflects awareness of natural processes and changes over time. Wood visibly ages, developing patina and subtle variations in color and texture. These changes express the material's life cycle and environmental interaction, allowing users to perceive the passage of time and natural processes within the built environment. This can be observed in older interiors where timber is used.

Table 1. Wood Contribution to Biophilic Design Patterns

Biophilic Design Pattern	Concept	Contribution of Wood	Example
Visual Connection with Nature	Refers to visual access to natural elements using the visual senses to sense the nature	Wood provides a natural appearance through visible grain, color variation, and organic patterns. Exposed timber structures strengthen the perception of nature.	Exposed timber beams or wooden wall panels in interiors that visually emphasize natural materiality.
Non-Visual Connection with Nature	Involves sensory interactions with nature beyond sight, such as touch, smell, and sound.	Wood offers pleasant tactile qualities through its natural texture and warm surface feel. Natural timber can also emit subtle scents and contribute to acoustic comfort in interior spaces.	Wooden flooring, handrails, or furniture that users frequently touch and interact with.
Material Connection with Nature	Refers to the use of natural materials that reflect local ecology and natural processes.	As a renewable and authentic natural material, wood strengthens the material connection to nature and contrasts with synthetic materials that lack biological origin.	Interior finishes made from solid wood or engineered wood products instead of plastic laminates.
Connection with Natural Systems	Represents awareness of natural processes and cycles over time.	Wood visibly ages, develops patina, and changes slightly in color and texture, reflecting natural material life cycles.	Exterior timber cladding gradually weathers and changes appearance over time.
Complexity and Order	Describes rich sensory information that follows organized natural patterns.	The unique grain patterns of wood create visual complexity while maintaining natural order.	Layered timber structures, cross-laminated timber surfaces.

The last pattern is complexity and order which describes presence of rich, organized patterns like those that can be found in nature. Wood naturally embodies this quality through its grain patterns and structural formations. Layered timber systems and detailed joinery create visual richness while maintaining harmony, contributing to aesthetically balanced and engaging spaces.

The contribution of the wood in these five patterns is analyzed in Table 1.

6. CONCLUSION

Wood has a high role in supporting biophilic design, by contributing to multiple design patterns simultaneously. Wood affects all the senses through its visual, tactile, sensory and environmental qualities. Although it is used as a construction material with a wide range of applications, wood should be also understood as a design strategy that influences human well-being and contributes to biophilic design. As shown in the presented case-studies, wood has the capacity to create meaningful, multi-sensory interactions, which are relevant for contemporary architectural projects.

REFERENCES

1. Barnaby, J., Irouke, V. M., Odoanyanwu, N. M., Ivoke, H. I., & Nzewi, N. U. (2023). Economic benefits of biophilic design: A holistic approach to enhancing productivity and wellbeing in the workplace. *UBS Journal of Engineering, Technology and Applied Sciences, 1*(1), 1–16.
2. Barrable, A., & Booth, D. (2022). Disconnected: What can we learn from individuals with very low nature connection? *International Journal of Environmental Research and Public Health, 19*(13), 8021. https://doi.org/10.3390/ijerph19138021
3. Browning, W. D., Ryan, C. O., & Clancy, J. O. (2014). *14 patterns of biophilic design: Improving health and well-being in the built environment*. Terrapin Bright Green.
4. Hung, S. H., & Chang, C. Y. (2021). Health benefits of evidence-based biophilic-designed environments: A review. *Journal of People, Plants, and Environment, 24*(1), 1–16.
5. Kengo Kuma & Associates. (2014). *SunnyHills at Minami Aoyama*. ArchDaily. https://www.archdaily.com/484981/sunnyhills-at-minami-aoyama-kengo-kuma-and-associates
6. Meyer, K. (2012). *Metropol Parasol / J. Mayer H. + Arup*. ArchDaily. https://www.archdaily.com/201961/metropol-parasol-j-mayer-h-arup
7. Ryan, C. O., & Browning, W. D. (2020). Biophilic design. In V. Loftness (Ed.), *Sustainable built environments* (Encyclopedia of sustainability science and technology series). Springer. https://doi.org/10.1007/978-1-0716-0684-1_1034
8. Voll Arkitekter. (2020). *Mjøstårnet: The tower of Lake Mjøsa*. ArchDaily. https://www.archdaily.com/934374/mjostarnet-the-tower-of-lake-mjosa-voll-arkitekter

Authors address:
Marija Miloshevska Janakieska[1]*
[1] Department of Architecture, Faculty of Engineering, International Balkan University, Skopje, Macedonia
*Corresponding author: marija.miloshevska@ibu.edu.mk

KNOWLEDGE AND PERCEPTION OF WOOD AND ENGINEERED WOOD PRODUCTS IN ARCHITECTURAL EDUCATION: A CASE STUDY OF ARCHITECTURE STUDENTS AT IBU

Marija Miloshevska Janakieska

Abstract: Although wood and Engineered Wood Products (EWPs) are highly important in sustainable architectural practices, their integration into architectural education remains limited, especially in North Macedonia. This paper investigates the knowledge, the perception, and the education exposure of architecture students to wood and EWPs through a survey conducted at the Department of Architecture at the International Balkan University (IBU) in Skopje, North Macedonia. This survey was administrated to students at different levels of study, including bachelor, master and PhD Studies, to assess their awareness of EWPs, familiarity with specific products, the application of timber and wood-based products in students' projects, and perceived readiness to apply these materials in professional practice in future. The results show that although students have general awareness of wood-based materials, there is limited familiarity and application of EWPs, especially as structural elements as part of the structural systems in building projects. Most of the students that participated in the research stated that their knowledge is not sufficient and express a strong interest in further education on timber and EWPs, especially from practical point of view. The results of this study show that courses related to these products should be implemented more in the architectural curricula, emphasizing the necessity for more practice-oriented integration of these materials.

Keywords: Wood, Engineered Wood Products (EWPs), Architectural Education, Student Perception

1. INTRODUCTION

The application of Engineered Wood Products (EWPs) in architecture and building construction is increasing every day, due to many advantages of these products, such as structural stability, design flexibility, durability, sustainability, negative environmental impact, aesthetic quality, cost efficiency etc. (Janakieska et al. 2024; Yadav and Kumar, 2021). North Macedonia is following this trend of increased application of EWPs in the building construction. The increased use of EWPs should imply an increase at an educational level as well, especially in the universities where architecture and civil engineering are being thought. Although this might be the case in more developed countries, in North Macedonia the situation is slightly different. This paper is focused on a case study where the opinion of architecture students at the Department of Architecture, Faculty of Engineering, at International Balkan University (IBU) is analyzed. The aim of the study is to determine their knowledge of EWPs during their studies. The main aim of this study is to research the students' knowledge of EWPs during their studies at IBU, based on collected data, and to identify the possible directions for future development of the education and curriculum within the Department of Architecture.

2. METHODOLOGY

The methodology of this research is based on a survey questionnaire that was distributed among participants architetcure students across all level of studies at the Department of Architecture, Faculty of Engineering, at International Balkan University (IBU). The aim was to gather responses on architetcural education about EWPs. Data were collected using an online survey administered via SurveyPlanet (https://surveyplanet.com/), a web-based platform that allows researchers to create, distribute, and manage surveys. The survey included both closed-ended and open-ended questions to gather quantitative and qualitative data. Participants accessed the survey through a unique link, ensuring anonymity and ease of participation. Responses were automatically compiled and exported for further statistical analysis.

The questionnaire was divided into several parts. The first part consisted of questions related to the gender and the level of studies. The second part consisted of questions connected to the familiarity of the respondedts to EWPs with a focus on specific EWPs, while the third part was related to their application in their projects on which they are working on during the studies within the architectural courses. The last part of the questions was related to students' suggestions on what was missing in the curriculum and what would they want to learn to feel more prepared in future, esepcially for more practical application. A total of 71 valid responses were received.

3. RESULTS AND DISCUSSION

According to the survey, 34% of the respondents were male and 66% were female. The respondents came from all levels of studies, bachelor, master's and PhD studies. First-year students were not included in the sample, since their academic program is centered on foundational coursework. They have not yet undertaken specialized courses related to building materials, including those addressing EWPs, and therefore may lack sufficient subject-specific knowledge to provide informed responses. All respondents were students from the Department of Architecture at IBU.

The familiarity of EWPs among the students is high (72% of the students have heard of EWPs), as shown in Figure 1.

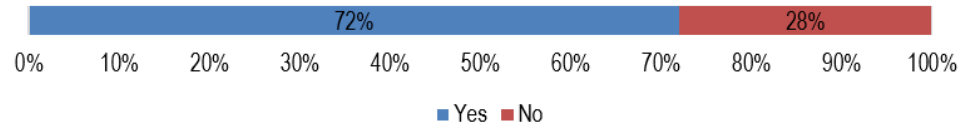

Figure 1. Respondent familiarity with EWPs

Respondents were asked to identify which EWPs they were most familiar with from a list provided. The list included photos of the products. The possible selection products are listed in Table 1. The cells reflecting a familiarity percentage higher than 60% are colored grey. In general, the overall familiarity with EWPs is relatively high among the students.

Table 1. Respondent familiarity with specific EWPs

	GLT Glulam-glued laminated timber	CLT Cross-laminated timber	PSL Parallel strand lumber	LSL Laminated strand lumber	SWP Solid wood panel	LVL Laminated veneer lumber	PW Plywood	LDF/MDF Low/medium/ high-density fiberboard	VP Veneered particle board	PB Particle board	OSB Oriented strand board	LS Light sandwich panel
Yes	45	44	15	12	40	16	43	37	8	9	13	23
	63%	62%	21%	17%	56%	23%	61%	52%	11%	13%	18%	32%

The most common EWPs familiarity among the students are GLT, CLT, PW, SWP and LDF/MDF/HDF – over 40% respondents note familiarity with these products. GLT is ranked higher, followed by CLT (Table 2).

Table 2. Respondent familiarity with Top 5 Ranked EWPs

	GLT	CLT	PSL	LSL	SWP	LVL	PW	LDF/MDF/HDF	VP	PB	OSB	LS
ranks	1	2	8	10	4	7	3	5	12	11	9	6

A total of 89% of the respondents stated that they had learned about timber and EWPs during their studies, indicating a high level of theoretical exposure. However, despite this educational background, 31% reported that they had not applied EWPs in their design projects. Among those who had used EWPs, the majority incorporated them as interior decorative elements (51%), followed closely by façade elements (49%). Their use as structural components was significantly lower (39%), as shown in Figure 2. This distribution suggests that, although students are familiar with EWPs, they tend to associate them primarily with non-structural applications. The choice for structural materials in architectural projects remain predominatly reinforced concrete, followed by steel, reflecting the common practices in North Macedonia, presented in the study of Janakieska and Kitek Kuzman, 2025.

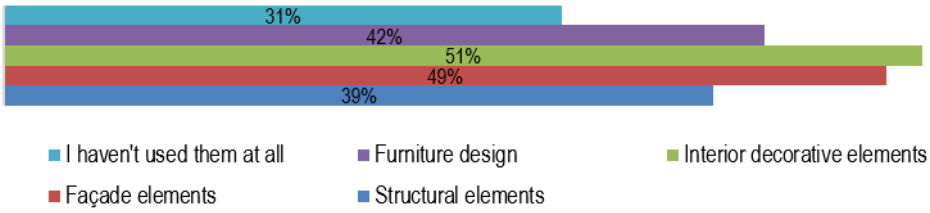

Figure 2. Respondent application of EWPs in their projects within architectural courses

The respondednts were asked if the knowledge gained during their studies is sufficient for pratctical application of wood and EWPs. 45% answered positivly, 38% answered partially, and 17% answered negativly (Figure 3).

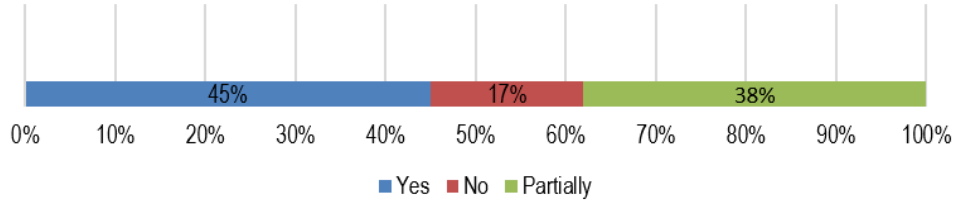

Figure 3: Sufficiency of the knowledge gained at university about wood and EWPs for practical application

56% of the participants in the survey answered that they would like to learn more about EWPs during their studies. The last question of the survey was related to perceived gaps in the curriculum related to wood end EWPs. The majority of the answers were related to concerns about the lack of practical and hands-on experience. The need for workshops, model-making, factory and production companies visit, field trips, and construction site visits were emphasized as crucial in the learning process. While many of the students acknowledged that the theoretical content is provided, they expressed the need for practical exposure to timber construction, which is a problem since there are not many construction sites where timber is used in North Macedonia. This can be partially solved with presentations of contemporary case studies from more developed countries.

A second theme that was pointed out by the respondents was the lack of technical knowledge, especially related to structural analyses, details, fire performance, moisture, durability and other technical issues related to EWPs. Several responses suggested that EWPs should be treated with the same level of depth as reinforced concrete or steel courses.

In addition, some answers mentioned the sustainability aspect of EWPs. Although briefly it is learned within the course Sustainable Architecture, the students expressed interest in deeper knowledge on this topic.

A smaller group of respondents pointed to institutional and regional influences, noting that wood is not widely used in North Macedonia. Some students reported limited encouragement from instructors to apply timber in projects, often due to perceptions of cost or regional construction practices.

Finally, a minority of respondents stated that nothing is missing from the curriculum or that their current knowledge is sufficient.

Overall, the findings suggest that while theoretical knowledge of wood and EWPs is present within the curriculum, students perceive a significant gap in practical application, technical depth, and integration of contemporary sustainable timber practices.

4. CONCLUSIONS

The study is focused on the knowledge, perception, and educational exposure to wood and EWPs among students from the Department of Architecture at International Balkan University (IBU) in Skopje, North Macedonia. The results show important information about timber and EWPs within architectural education in the local context.

From the responses we can conclude that students have a relatively high level of awareness of EWPs, since the majority of the respondents (72%) answered that they are

familiar with EWPs. Familiarity with specific products such as glulam (GLT), cross-laminated timber (CLT), plywood, and solid wood panels was also notable. These findings suggest that timber-related topics are present in the curriculum at a theoretical level.

However, the practical application of EWPs in student projects remains limited. Although most students have been exposed to the topic academically, 31% reported that they had not used EWPs in their projects.

Students' self-assessment of their preparedness further reinforces this conclusion. While 45% consider their knowledge sufficient for practical application, a substantial proportion (38%) perceive it as only partially sufficient, and 17% consider it insufficient. Moreover, more than half of the respondents (56%) expressed a desire for additional education on wood and EWPs.

Based on the results, it can be concluded that there is a serious lack of practical, hands-on experience, including workshops, site visits, real-life case studies, and project-based integration. Moreover, the need for technical knowledge is also emphasized, especially regarding detailing, durability, fire and moisture resistance. The need for sustainability related topics is also mentioned.

An additional contextual factor identified by respondents is the limited use of timber in professional practice in North Macedonia, where reinforced concrete and steel remain dominant structural materials. This professional reality appears to influence both teaching approaches and student design decisions, potentially limiting experimentation with timber systems.

Overall, the findings suggest that while wood and EWPs are introduced within the architectural curriculum at IBU, their integration remains predominantly theoretical and insufficiently practice oriented.

Future curriculum development should consider the introduction of dedicated or expanded courses on timber and EWPs, increased project-based learning, collaboration with industry, laboratory experimentation, and exposure to contemporary mass-timber case studies. Strengthening the educational foundation in this field may contribute not only to improved student competence but also to a gradual shift in professional practice toward more sustainable material choices in North Macedonia.

Further research on this topic can focus on similar analyses in the other universities in our country who offer study programs in architecture, so that the results can be compared. It would be beneficial if these results could be compared with similar results from more developed countries where EWPs are more commonly used. Comparison of the curriculum, and implementation of wood related courses which are offered in foreign universities would be also beneficial.

REFERENCES

1. Janakieska, M. M., Kuzman, M. K., & Sandberg, D. (2024, May 31). Engineered wood products in modern architecture: Pioneering the future of architecture with wood. TOPER DOOEL Skopje.
2. Janakieska, M. M., Kuzman, M. K. (2025, September). Architectural perspectives on wood reuse within circular construction in North Macedonia. In 18th International Scientific

Conference WoodEMA 2025: Wood for the future: Integrating sustainability across industries (pp. 45–50).
3. SurveyPlanet. (n.d.). Online survey platform. Retrieved March 4, 2026, from https://surveyplanet.com/
4. Yadav, R., & Kumar, J. (2021, August 30). Engineered wood products as a sustainable construction material: A review. IntechOpen. https://doi.org/10.5772/intechopen.99597

Authors address:
Marija Miloshevska Janakieska[1]*
[1] Department of Architecture, Faculty of Engineering, International Balkan University, Skopje, Macedonia
*Corresponding author: marija.miloshevska@ibu.edu.mk

WHY DO MUSEUMS RARELY USE WOOD IN THEIR ARCHITECTURE

Arbresha Ibrahimi

Abstract: Museums, being one of the most complex typologies of institutional architecture, specialising in the conservation, protection, and exhibition of cultural heritage, require the integration of architectural, constructive, and environmental solutions that guarantee the sustainability of the conditions for the conservation of museum artefacts. According to statistics, out of a total of 104,000 museums worldwide, only 10% of them employ the use of wood as a building material, with 3-4% employing it as a structural material, 2-3% employing it for facade solutions, and 4-5% employing it for interior solutions. Despite the fact that the material is considered to be one of the most sustainable building materials for the environment, the use of wood in museum architecture is still limited, mainly because of the high standards that need to be met by the building, particularly regarding the microclimatic conditions, safety, stability of temperatures, relative humidity, controlled air circulation, filtration of pollutants, solar radiation, artificial lighting, and high standards of fire resistance. These parameters are critical to the conservation of sensitive materials like art pieces, textiles, paper documents, and other organic artefacts. The study focuses on the potential of wood and engineered wood to satisfy the functional parameters. The parameters are compared with other wood products like cross-laminated timber (CLT), glued laminated timber (glulam), laminated veneer lumber (LVL), among others. The advantages of the new systems include better dimensional stability, predictable structural performance, and compliance with current standards for fire safety and environmental control. In conclusion, the potential of wood-based materials is explored for various museum typologies. The potential of the material is explored for integration into contemporary museum architecture.

Keywords: Museum architecture; Engineered wood products (EWPs); Museum collections; Conservation requirements; Sustainable architecture

1. INTORDUCTION

The importance of museum buildings stems from their role as symbols, centers of integration and activity, institutional entities, tools for urban planning and design, and instruments of urban imagination, making them one of the most catalytic building types within the urban, cultural, and social fabric of cities (Ibrahimi, 2024). Museums were defined by the International Council of Museums (ICOM) in 2022 as “a not-for-profit, permanent institution in the service of society that researches, collects, conserves, interprets, and exhibits tangible and intangible heritage. Open to the public, accessible and inclusive, museums foster diversity and sustainability. They operate and communicate ethically, professionally, and with the participation of communities, offering varied experiences for education, enjoyment, reflection, and knowledge sharing” (ICOM, 2022). In particular, museums play a significant role in promoting cultural and social diversity.

However, given that wood is one of the most sustainable building materials, an interest in exploring sustainability in museum architecture led to the question of whether wood is used in museums, and if so, why, and if not, why not. According to World Museum Statistics 2025 (Statista, 2025), fewer than 10% of the approximately 104,000 museums worldwide use wood

strategically in their architecture. Within this limited percentage, wood is incorporated in various ways, with approximately 3–4% of museums using it as a structural material, 2–3% employing it in façade solutions, and 4–5% integrating it into interior design applications (Statista, 2025)(Table 1). Despite being recognized as one of the most sustainable building materials (Alapieti et al., 2020), wood remains relatively underutilized in museum architecture. This raises an important question: Why is wood used in such a small proportion of museum buildings?

Table 1. Global Distribution of Museums and Estimated Strategic Use of Wood in Museum Architecture by Continent/Region (Statista, 2025)

Continent/ Region	Approximate number of museums (2025)	Estimated % using wood strategically	Notes
Europe	30000	8-10	Strong tradition of wooden architecture in some areas
North America	20000	5-8	Some use of wood in sustainable buildings and facades
Asia	25000	3-6	Mix of traditional wooden structures and modern materials
Latin America	10000	2-5	Growing interest in sustainability but less wood usage
Africa	5000	1-3	Limited use, focus on different materials
Oceania	3000	5-7	Timber usage in some cultural museums
Worldwide total	104000	< 10% (approx.)	Wood use is a niche but growing sustainable practice

2. BACKGROUND AND LITERATURE REVIEW

To answer the question, 'Why is wood used in such a small proportion of museum buildings?', this literature review examines the issue from two perspectives. The first focuses on museum architecture and the conditions that museum spaces must meet to ensure the preservation, conservation, and exhibition of collections. The second explores the role of wood in architecture, its effects on people, and the characteristics of engineered wood products (EWPs), including their architectural applications and environmental and material performance characteristics.

2.1. MUSEUM COLLECTION REQUEREMENTS

One of the primary missions of a museum is to protect objects "against destruction by man or the environment" (Johnson & Horgan, 1979, p. 27). The preservation of museum collections requires a suitable environment in every space where objects are housed. Museum objects are primarily kept in storage rooms, research spaces, and exhibition galleries. Taking into account the material characteristics of the objects, each of these spaces should be designed and managed in accordance with the temperature and humidity requirements of the museum collections, as well as the critical relative humidity thresholds identified for different materials (Johnson & Horgan, 1979) (Table 2).

Table 2. Recommended Environmental Conditions, Relative Humidity Tolerances, Lighting Limits, for Museum Collection Materials (Naredi-Rainer, 2004; Johnson & Horgan, 1979)

Museum collection material	Temp. (°C)	RH (%)	Max Light (lux)	UV Limit (µW/lm)
Paper	19–24	45–60 (optimum 45%)	50	<30 (max 75)
Stretched paper	19–24	45–60 (critical low limit 45%)	50	<30 (max 75)
Photographs, films	2–20	30–45	50	<75
Parchment, vellum	19–24	55 (stable state)	50	<30 (max 75)
Leather (dyed)	19–24	45–60	50	<30 (max 75)
Leather (undyed)	19–24	45–60	250	<30 (max 75)
Fabric (natural fibers)	15–21	45–60	50	<30 (max 75)
Bone, ivory	19–24	45–60	250	<30 (max 75)
Wood	19–24	45–60 (critical)	250	<30 (max 75)
Painted wood	19–24	45–60 (critical)	50	<30 (max 75)
Manila, sisal, feathers	19–24	45–60	50	<30 (max 75)
Plastics	19–24	Variable (material-dependent)	50	<30 (max 75)
Metals (polished)	19–24	≤30 (preferably lower)	300	<75
Stone, stoneware, porcelain	19–24	Stable conditions; RH not critical	300	<75
Glass	19–24	45–60	300	<75
Lead, pewter	19–24	Stable conditions; RH not critical	300	<75
Bronze (archaeological)	19–24	≤35 preferred	300	<75
Ceramics (archaeological)	19–24	Stable conditions; RH not critical	300	<75
Plaster, terracotta	19–24	45–60	300	<75
Low-fired earthenware	19–24	45–60	300	<75

Note: ACH (Air Changes per Hour) should be maintained at 3–5 air changes per hour. Air pollutant levels should remain low and not exceed recommended limits. Museum spaces should be protected with fire-resistant construction, early smoke detection systems, and appropriate fire-suppression systems. Objects should be stored in darkness when not on display. Light-sensitive materials, such as paper, photographs, textiles, painted wood, feathers, plastics, and dyed leather, should be exhibited only for limited periods and rotated regularly according to conservation requirements .

Based on the information provided in the tables, it can be seen that there exist different sensitivities of museum materials towards temperatures, relative humidity (RH), lux, UV, air changes per hour (ACH), air pollutant levels, and fire safety issues. Specifically, organic materials like papers, photographs, parchments, leather, fabrics, and wood are highly sensitive to factors such as shrinking, warping, hardening, cracking, and surface changes. Such materials are highly subject to biological deterioration where there exists an environment of high humidity which fosters the growth of molds. On the other hand, inorganic materials such as glass, stone, porcelain, and ceramics tend to be less sensitive to the environment. Metal objects require low relative humidity levels to prevent corrosion, while archaeological objects are best preserved in low-humidity environments that inhibit salt activation and other forms of material deterioration. These findings indicate that environmental control is one of the most critical aspects of museum building design (Naredi-Rainer, 2004; Johnson & Horgan, 1979).

In addition to the environmental requirements of museum objects, museum operations introduce further complexity through research activities, the use of materials, techniques and tools, lighting systems, ventilation, staff and visitor circulation, and display or support structures. If not carefully monitored and controlled, these factors can contribute to the deterioration of museum collections. Hence, the choice of construction materials for museums and building

finishes for both inside and outside should correspond as accurately as possible to the environment in which museum artifacts can be preserved for a long period.

2.2. WOOD IN ARCHITECTURE

In turn, wood and especially EWPs should be considered as one of the most important building materials, which include architecture from construction and joinery to furniture and urban design. The nature of timber in terms of its look, texture, and applicability affects users' behavior directly. Even if the number of empirical studies that analyze these aspects is quite limited due to their methodological flaws and lack of longitudinal studies that investigate the impact of wood on humans, it becomes clear that it has positive effects on people's well-being (Alapieti et al., 2020).

However, besides analyzing how timber affects humans psychologically, it is necessary to consider which types of EWPs can be used successfully in architecture and their applications (Gustafson, 2021; USDA Forest Products Laboratory, 2010). According to the figure, structural engineered wood products such as CLT, Glulam, LVL, and PSL are primarily used for load-bearing systems due to their high strength and dimensional stability. In contrast, panel-based products such as plywood, MDF, and HDF are widely used in interior architecture, furniture, and joinery because of their versatility and ease of processing. Composite and hybrid products, including WPC and bamboo composites, are more suitable for exterior applications and environments exposed to weathering due to their enhanced durability and resistance to environmental conditions. Overall, these different categories of engineered wood products address a broad spectrum of architectural requirements, ranging from high-performance structural systems to sustainable and aesthetically driven design solutions (Gustafson, 2021, USDA Forest Products Laboratory, 2010).

Aaside from determining the sustainable application of EWPs in structural, joinery, interior, and exterior architecture purposes, it is important to look into the following attributes of EWPs: moisture resistance, volatile organic compound emission, relative humidity resistance, ultraviolet ray resistance, and thermal insulation capability (USDA Forest Products Laboratory, 2010) (Table 3). According to the comparative analysis conducted above, considerable variance in terms of environmental properties and performance can be seen between the engineered wood products. The products such as LVL, PSL, WPC, CLT, Glulam, MPP, bamboo, cork and FRT have shown high to very high stability against moisture, high level of resistance against variations in relative humidity, as well as good thermal behaviour. On the other hand, PB, LDF, and MDF products are characterized by lower resistance to moisture and relative humidity variations. Besides, these products have shown relatively higher levels of VOCs. Veneers and mass timber products, in general, show relatively low VOC emission levels as well as high dimensional stability; however, OSB, HDF, and plywood offer rather moderate values on most of the parameters. With regard to the UV resistance, charred wood, HPLV, FRT, IBC, and WPC have shown better performance compared to fibre boards and particle boards. Thus, it can be concluded that structural engineered wood products provide better stability, durability and thermal efficiency; fibre-based and particle-based wood products are sensitive to environmental factors.

Table 3. Environmental and Material Performance Characteristics of Engineered Wood Products (Gustafson, 2021, USDA Forest Products Laboratory, 2010)

EWP Type	Moisture Stability	VOC Emissions	Resistance to RH Fluctuations	UV Resistance	Thermal Performance
Components of Sawn Timber	↔	↓↓↓	↔	↔	↑↑
Edge-Glued Panel (EGP)	↑↑	↓↓	↑↑	↔	↑↑
Glued-Laminated Timber (Glulam/GLT)	↑↑	↓↓	↑↑	↔	↑↑
Cross-Laminated Timber (CLT)	↑↑	↓↓	↑↑	↔	↑↑
Lightweight Wood Material (LWM)	↔	↓↓	↔	↔	↑↑
Fiber-Reinforced Timber (FRT)	↑↑	↓↓	↑↑	↑↑	↑↑
Plywood (PW)	↔	↓	↔	↔	↔
Mass Plywood Panel (MPP)	↑↑	↓↓	↑↑	↔	↑↑
Laminated Veneer Lumber (LVL)	↑↑↑	↓↓	↑↑↑	↔	↑↑
Laminated Veneer Product (LVP)	↑↑	↓↓	↑↑	↔	↑↑
High-Pressure Laminated Veneer (HPLV)	↑↑	↓↓	↑↑	↑↑	↔
Parallel Strand Lumber (PSL)	↑↑↑	↓↓	↑↑↑	↔	↑↑
Oriented Strand Board (OSB/WB)	↔	↔	↔	↓↓	↔
Laminated Strand Lumber (LSL)	↑↑	↓	↑↑	↔	↑↑
Particleboard (PB)	↓↓	↑↑	↓↓	↓↓	↔
Inorganic-Bonded Composite (IBC)	↑↑	↓↓↓	↑↑	↓↓	↔
Wood-Plastic Composite (WPC)	↑↑↑	↓↓↓	↑↑↑	↑↑	↔
Low-Density Fiberboard (LDF)	↓↓	↔	↓↓	↓↓	↔
Medium-Density Fiberboard (MDF)	↓↓	↑	↓↓	↓↓	↔
High-Density Fiberboard (HDF)	↔	↔	↔	↓↓	↔
I-Joist and Box-Beam	↑↑	↓↓	↑↑	↔	↑↑
Wood Sandwich Panel	↑↑	↓↓	↑↑	↔	↑↑
Flexible EWPs	↔	↓↓	↔	↔	↔
Aged Wood	↔	↓↓↓	↔	↓↓	↑↑
Charred Wood	↑↑	↓↓↓	↑↑	↑↑	↑↑
Bark EWPs	↔	↓↓	↔	↔	↔
Bamboo	↑↑	↓↓	↑↑	↔	↑↑
Cork	↑↑	↓↓↓	↑↑	↔	↑↑↑

Note: ↓↓↓ = Very Low; ↓↓ = Low; ↓ = Low–Moderate; ↔ = Moderate; ↑ = Moderate–High; ↑↑ = High; ↑↑↑ = Very High.

3. RESULTS

Compatibility evaluation between museum collection needs and the environmental performance of EWPs is illustrated in Table 4. According to the results of the evaluation, there are considerable differences between the types of EWPs concerning their ability to create and maintain proper environmental conditions for museums and the preservation of collections. Wood products which are known for high moisture stability, minimal VOCs emissions, resistance to changes in relative humidity, and good thermal properties are considered the most applicable for museums.

Table 4. Compatibility of Engineered Wood Products (EWPs) with Museum Collection Materials

EWP Type	Paper & Documents	Photographs & Films	Textiles & Leather	Wood & Painted Wood	Metals	Glass & Ceramics	Overall Museum Suitability
CLT	↑↑	↑↑	↑↑	↑↑	↑	↑↑	↑↑
Glulam	↑↑	↑↑	↑↑	↑↑	↑	↑↑	↑↑
LVL	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
PSL	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
MPP	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑
FRT	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑
LVP	↑↑	↑↑	↑↑	↑↑	↑	↑↑	↑↑
LSL	↑↑	↑	↑↑	↑↑	↔	↑↑	↑↑
HPLV	↑	↑	↑↑	↑↑	↑↑	↑↑	↑↑
WPC	↔	↔	↑↑	↑↑	↑↑	↑↑	↑↑
Bamboo	↑↑	↑↑	↑↑	↑↑	↑	↑↑	↑↑
Cork	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑
EGP	↑↑	↑↑	↑↑	↑↑	↔	↑↑	↑↑
I-Joist & Box Beam	↑↑	↑↑	↑↑	↑↑	↔	↑↑	↑↑
Wood Sandwich Panel	↑↑	↑↑	↑↑	↑↑	↔	↑↑	↑↑
Plywood	↔	↔	↔	↔	↔	↔	↔
HDF	↔	↔	↔	↔	↔	↔	↔
OSB	↔	↓	↔	↔	↓↓	↔	↔
Flexible EWPs	↔	↔	↔	↔	↔	↔	↔
Bark EWPs	↔	↔	↔	↔	↔	↔	↔
Components of Sawn Timber	↔	↔	↔	↑↑	↔	↔	↔
MDF	↓↓	↓↓	↔	↔	↓↓	↔	↓↓
LDF	↓↓	↓↓	↔	↔	↓↓	↔	↓↓
Particleboard (PB)	↓↓	↓↓	↓↓	↔	↓↓	↔	↓↓

Note: ↓↓↓ = Very Low; ↓↓ = Low; ↓ = Low–Moderate; ↔ = Moderate; ↑ = Moderate–High; ↑↑ = High; ↑↑↑ = Very High.

In terms of their suitability to accommodate museum collection requirements, LVL and PSL products prove to be the most compatible followed by CLT, Glulam, MPP, FRT, bamboo, cork, and other veneer products. These wood products ensure good dimensional stability and optimal environmental conditions that contribute to preserving paper, photographical works, textile, leather, and wooden collections of different museums. PB, MDF, and LDF possess the lowest compatibility properties due to their low moisture resistance, higher susceptibility to humidity changes, and higher VOC content. For instance, plywood, OSB, HDF, bark-based materials, and flexible EWP have intermediate compatibility levels, although they may require additional environmental management when applied within museums. As such, the study shows that modern manufactured wooden products, which include timber and veneer woods, are able to meet the demands for museum conservation, and thus can be good substitutes in museums.

4. CONCLUSION

In fact, the decreased use of wood as a building material for designing museum structures can be explained by problems associated with environmental stability, air pollution within the building, moisture, emission of pollutants, and specific conditions that should be met to ensure protection of the collection. Traditionally, all these factors determined the use of other, more prevalent building materials such as concrete, steel, and brick in designing museums.

However, recent advances in the engineering of wooden materials have rendered the use of wood for construction more practical to counteract the deficiencies that have been highlighted in timber. It is evident from this study that the current engineered wood materials such as LVL, PSL, CLT, Glulam, MPP, FRT, bamboo, and cork have characteristics that are quite similar to those required for the conservation of museums. These materials have dimensional stability, release fewer volatile organic compounds, moisture stability, and good thermal characteristics.This implies that such engineered wood materials can play an important role in providing optimal indoor environments for the conservation of museum collections. The implication here is that engineered wood building systems can act as suitable options for use within museums in several ways. However, there are still some aspects that should be worked on. It will be necessary to improve the level of reductions in VOCs resulting from adhesives and binders, increase moisture resistance, raise UV-resistance and environmental stability under changing climatic conditions. Research into the impact of EWP on the work of environmental control systems at museums with regard to humidity and pollutants is also required.

The issue now is not about wood's possibility of being applied in the design of museums, but about which kinds of engineered wood products are best able to meet the high requirements of a museum environment. One can see that advanced mass-timber and veneer products have great prospects in this area and can have an even greater impact on museum design in the future. Given proper technology and environmental control, the wood products could prove to be a useful tool for developing sustainable museums with high conservation standards maintained there.

REFERENCES

1. Alapieti, T., Mikkola, R., Pasanen, P. et al. The influence of wooden interior materials on indoor environment: a review. Eur. J. Wood Prod. 78, 617–634 (2020). https://doi.org/10.1007/s00107-020-01532-x
2. Statista Research Department. (2025). *Museums worldwide – statistics & facts*. Statista. https://www.statista.com/topics/7489/museums-worldwide/
3. Johnson, E. V., & Horgan, J. C. (1979). *Museum collection storage*. UNESCO.
4. Ibrahimi, A. (2024). *Muzeji kot generatorji identitete v Skopju* [Doctoral dissertation]. Repository of the University of Ljubljana. https://repozitorij.uni-lj.si/IzpisGradiva.php?lang=eng&id=155671
5. Naredi-Rainer, P. (2004). *Museum Buildings: A Design Manual.* Basel, Switzerland: Birkhauser Verlag AG.
6. Gustafson, S. R. (Ed.). (2021). *Architectural woodwork standards* (3rd ed.). Architectural Woodwork Institute.

7. USDA Forest Products Laboratory. (2010). *Wood handbook: Wood as an engineering material* (General Technical Report FPL-GTR-190). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
8. International Council of Museums. (2022, August 24). *Museum definition*. ICOM. https://icom.museum/en/resources/standards-guidelines/museum-definition/

Authors address:
Arbresha Ibrahimi[1];
[1] Department, Faculty, University, City, Country Architecture, Faculty of Engineering, International Balkan University, Skopje
*Corresponding author: arbresha.ibrahimi@ibu.edu.mk

THE IMPORTANCE OF WOODCARVING AS A COMMUNITY PROJECT IN 19TH CENTURY ARCHITECTURE.

Marko Icev

Abstract: This paper examines the importance of woodwork in the 19th century through the work of William Morris and draws a connection to Balkan woodcarving guilds. Until the late 19th century, woodcarving was a profession with serious demand, especially for interior decorations, altarpieces and everyday furniture. While industrialization changed the relationship to wood objects, forests, and work, William Morris explains that the work itself is an important element that adds to the meaning of the finished piece. In the Balkans, the main wood works of the period are panels and altarpieces done by guilds of woodcarvers - rezbari i zografi, similar to the idealized working groups in Morris's texts. Collective work organization of builders and designers in the 19th century through the example of William Morris and the rezbari shows the importance of woodcarvers in and highlights the relationship between certain traditions and 19th century architectural theory. Through historical and archival research of artifacts and literature this paper will follow Morris' argument that industrial-scale production diminished the community's relationship to the product, the forest and the whole ecosystem. The paper further argues that woodworking in the 19th century had a more holistic relationship between the material and the finished product and that relationship followed the process of work. This relationship is an important aspect of artisan woodcarving and crafts in the contemporary context because it relates the quality of the work to the process of production, which adds unique aesthetic qualities to the finished artifacts.

Keywords: William Morris, woodcarving, collective work, historic sustainable practices

1. Woodcarving the in the 19th century through William Morris

> *"To give people pleasure in the things they must perforce use, that is one great office of decoration; to give people pleasure in the things they must perforce make, that is the other use of it."*[29]

Until the mid-19th century, architecture and especially interiors had a lot of elements that were made from wood, mainly done by hand from beginning to end. From the 1830s onward industrialization changed the way that work was done from intricately hand-made unique pieces of art to mass-produced objects. This was a particularly interesting period that saw major changes in the way that the work was done.The details and the hard work that went into hand-carved furniture and decorations, was now being replaced by machinery that exploited instead of exalting the workers.

In this period William Morris (1834-1896), became one of the most forefront proponents of the idea that it was actually the work of the craftsmen that made the finished piece more valuable, instead of the machine-created piece of furniture.[30]

[29] Morris, William. *The Decorative Arts*, in *The Architect,* 18 December 1877, pp 308-12

[30] For more on the work and life of William Morris: Rodgers, David. William Morris at Home. London: Ebury Press.1996; MacCarthy, Fiona. William Morris: A Life for Our Time. London: Faber & Faber.;

This was based on the idea that machinery and industrialization were not only reshaping the way people made furniture, but it diminished the quality of their lives, because it alienated them from their labor, as well as the finished piece. With these changes the worker, who previously was engaged with every aspect of the making the work, from selecting the wood, to polishing the final piece, was now a simple machine operator who never saw the finished product. The craftsman became a replaceable day-laborer. This industrialized way of work, according to Morris was detrimental for the soul of the worker as well, and it was detrimental to nature and the community.[31] The alienation was taking away the creativity of the worker, and it was taking away the quality and uniqueness of the final piece.

> *"Now it is one of the chief uses of decoration, the chief part of its alliance with nature, that it has to sharpen our dulled senses in this matter: for this end are those wonders of intricate patterns interwoven, those strange forms invented, that men have so long delighted in: forms and intricacies that do not necessarily imitate nature, but in which the hand of the craftsman is guided to work in the way that she does, till the web, the cup, or the knife, look as natural, nay as lovely, as the green field, the river bank, or the mountain flint."*[32]

In *The Decorative Arts*, Morris explains his views that industrialization has diminished the art of the craftsmen, and has separated craft and decorations from the so-called "high arts": architecture, painting, and sculpture. Morris goes on to explain that historically all of those arts and crafts were included into one functional whole that served the entire community involved. This was important because the finished piece, like a medieval cathedral, had beauty that relied on natural forms, and on the skill of the craftsmen, and as such it provided not only aesthetic relief for the eye, but also meaningful employment of people who could make beautiful things with their hands. This was, according to Morris, one of the most, if not the most important type of self-realization one could achieve.

> *"I cannot suppose there is anybody here who would think it either a good life, or an amusing one, to sit with one's hands before one doing nothing — to live like a gentleman, as fools call it."*[33]

To work with one's hands was to Morris the true calling of the creative spirit of people, and it elevated not only the people who made the objects, the craftsmen, but the visitor and user of the space or object as well. For this to be achieved Morris found inspiration in the Middle Ages. For Morris and his collaborators the medieval period gave an example through the guilds of how work, labor and art can be organized so that the maker and the consumer can satisfied with beautiful work. The key to this idea was that the people involved in the process of making the objects – the craftsmen, were supposed to be trained in the beauty of drawings, of nature and that they need to devote time to honing their craft and skills. The objects that these craftsmen produced had more that sheer beauty, they had meaning; meaning to the maker and the consumer. This was the relationship to work, to art, to the self, that industrialization and

Donovon, Andrea Elizabeth.William Morris and the Society for the Protection of Ancient Buildings. Routledge. 2007
31 Morris, W. News From Nowhere.*1890.*
32 Morris, W. The Decorative Arts., 1877
33 ibid.

consumerism was destroying in the 19th century by mass-production, filling the homes with garbage and polluting the rivers and forests with refuse.[34]

> *Is money to be gathered? Cut down the pleasant trees among the houses, pull down ancient and venerable buildings for the money that a few square yards of London dirt will fetch, blacken rivers, hide the sun and poison the air with smoke and worse, and it's nobody's business to see to it or mend it: that is all that modern commerce, the counting-house forgetful of the workshop, will do for us herein.*[35]

Morris set out to change the world around him by filling it with beauty. He was one of the founders of the Arts and Crafts movement in England, that later spread throughout the western world. His view on design and especially wood-made objects was that they were beautiful as long as they had meaning, and meaning came from the relationship between the craftsmen, nature, and the community or the public. Morris and his collaborators created Morris and Co. to produce hand-designed and hand-made decorations, furniture and architecture, and went on to become one of the most successful design firms in history. Morris & Co. designs are extremely popular and valuable even today.

The importance of Morris and Co. for the history of architecture cannot be overstated. Morris himself, a visionary who surrounded himself with talent in his firm, set out to change the world with beauty. His goal was to educate the public on beautiful objects made by hand, and in that way instill a reverence for the work of their fellows, so that the public would insist on high-quality hand-made architecture, decorations and furniture. This goal was to be achieved by producing high-quality goods with designs inspired from nature and the medieval period, because of their simplicity and honesty to principles of function and beauty. This was also supposed to reverse the runoff of talented workers into the lumpen-proletariat that was sweeping the country.

> *These arts, I have said, are part of a great system invented for the expression of a man's delight in beauty: all peoples and times have used them; they have been the joy of free nations, and the solace of oppressed nations; religion has used and elevated them, has abused and degraded them; they are connected with all history, and are clear teachers of it; and, best of all, they are the sweeteners of human labour, both to the handicraftsman, whose life is spent in working in them, and to people in general who are influenced by the sight of them at every turn of the day's work: they make our toil happy, our rest fruitful.*[36]

Morris was a firm believer and proponent of socialism and Marxism. He was a contemporary of Marx, a friend of Kropotkin, and he clearly understood the dangers of labor alienation and the destruction that industrial processes had on the environment.[37] For Morris the beauty of nature had to be protected from the greedy destructive practices of the industrial capitalism. In fact, Morris argued that this process of mass-production, mass-consumerism was detrimental to the environment, one of the few people in the period to think so. He drew a clear connection between the destruction of nature, the forest, river and plain, by industry and the destruction of

34 Morris. News From Nowhere
[35] *Morris.The Decorative Arts.*
[36] Ibid
[37] William Morris writing archive on marxists.org:
https://www.marxists.org/archive/morris/works/index.htm

the human spirit who had to toil away in dark and polluted factories with child labor and abuses running rampant. For him the clear way out of this devastation was a return to collective labor organization, something that was present in the medieval period. The medieval guilds where all craftsmen and the community was involved into making beautiful objects for the community was the answer to the ever-worsening crisis of the human spirit under capitalism.

> *That art will make our streets as beautiful as the woods, as elevating as the mountain-sides: it will be a pleasure and a rest, and not a weight upon the spirits to come from the open country into a town; every man's house will be fair and decent, soothing to his mind and helpful to his work: all the works of man that we live amongst and handle will be in harmony with nature, will be reasonable and beautiful: yet all will be simple and inspiriting, not childish or enervating; for as nothing of beauty and splendour that man's mind and hand may compass shall be wanted from our public buildings, so in no private dwelling will there be any signs of waste, pomp, or insolence, and every man will have his share of the best.*[38]

Morris's idea that everybody deserves beautiful, well designed, hand-made objects in their home is perhaps best exemplified by the Sussex chair. A simplified and elegant design of a set of chairs and benches from oak that could find a use in any household. The slim supports of the back of the chair with simple yet clear details of geometric shapes make the chair a standout 19th century piece for its modern simplicity and functionality.

2. Woodcarving in the Balkans

During the same period of the middle of the 19th century, on the other side of the continent, in Macedonia, then a province of the Ottoman empire, woodcarving was a very important profession, done mostly by groups of highly-skilled carvers and sculptors called rezbari (woodcarvers) and zografi (painters). These groups functioned similar to the medieval guilds that Morris was idolizing in his work. They were usually comprised of several generations of the same family of craftsmen, who had to go through a years-long apprenticeship before they could call themselves craftsmen, and work on projects on their own.[39] This reliance on apprenticeship made the final work highly sought after especially in churches, and sometimes in administration buildings, as well as private homes.

These guilds in the Balkans, often called tajfi (builders guilds) or esnafi (urban craftsmen) were a remnant from previous medieval period with direct links to the 13th century and functioned more or less unchanged during this time.[40] They stood as a stronghold of handmade work in many crafts against the industrialization process, that was slow to arrive in the Ottoman empire, even in the 19th century. Partially due to tradition, partially do to historical circumstances the handmade objects of the rezbari and zografi, as well as the esnafi for household goods, in the

[38] Morris. The Decorative Arts.

[39] For more on woodcarving in Macedonia see: Kornakov, Dimitar. Makedonska Rezba. Matica. Skopje. 1994.; Kornakov, D. Rezbarskite Centri vo Makedonija. Sv. Kliment Ohridski. Skopje 1998; more in references. On the altarpieces of the 19th century see: Ivkovska, Velika, The Architecture and Painting of the Church of St. Panteleimon in Veles by Andrea Damjanov. Skopje 2022.

[40] Trajanoski, Lj. Македонската резба во сакралните објекти во периодот од XIV – XXвек. marh.mk

Balkans was a living example of guild-organization of work that can produce high-quality art by the community and for the community, something that Morris was trying to achieve with his firm.

The rezbari and zografi in the Balkans were not as politically organized in the Balkans as the rest of Europe in the medieval period. In the 18th and 19th century, where most household goods were done by the esnafi, the rezbari were mostly working on major altar pieces for churches and decorations for the few wealthy households. All of these pieces were made strictly by hand with no use of machinery, even the most rudimentary ones used by Morris. There was barely a connection to the western markets and their products, considering that Macedonia and most of the Balkans under Ottoman rule were sleepy agricultural provinces, with very small urban centers. The demand for handmade goods was something more of a necessity, rather than a conscious choice by the consumers.[41] The handmade objects provided households with high-quality objects for everyday use, while the sophisticated and meticulous altars in the churches were considered unique and special, due to the skill of the craftsmen involved, their reliance on natural and local materials such as oak and chestnut, and the beauty of the finished pieces that can only be done by hand.

One of the most famous rezbari of this period in Macedonia, Dimitar Stanishev, has been attributed as the author of many of the most famous altar pieces that survive today. He was a contemporary of Morris, and lived a life dedicated to the craft of woodcarving, creating unique and high-quality pieces of art that remain astonishing to viewers even today.[42] Stanishev, was an example of the master craftsman that Morris was trying to emulate. Stanishev was very popular and sought after in his day, creating ecclesiastical furniture with deep carved three dimensional figures in his pieces, and with a clear insistence on precision in details present in his and his apprentices work. Stanishev and his crew were even depicted in their works in small self-portraiture depicted with the chisel in hand. This is significant because for Stanishev and many other carvers in the Balkans, it was their handwork that made them famous and popular. The concepts of following the beauty of nature with their hands are present in the finished pieces. The elegant and exuberant florals that surround the altar piece, open up and frame the central scenes so that they exist in a rich context of history in a natural setting.

2. Conclusion

While Morris went on to have huge commercial success with his firm, the rezbari of the Balkans were slowly pushed to the margins as they slowly disappeared with the introduction of industrial capitalism in the late 19th and early 20th centuries through multiple wars. The carefully designed and carefully made objects from Morris and the beautiful unique woodcarvings of the zografi carry the same moral story: that working with wood by hand is a noble and worthwhile effort not just for the financial reward, but for the spiritual and aesthetic enhancement of the human soul. This was also connected to the welbeing of the forest and the ecosystem. As made obvious by the current destruction of forests worldwide and the abundance of cheap wood

[41] Tomovski, K. Makedonskite majstori-graditeli od 19ti vek. Macedonian Academy of Arts and Sciences (MANU). Skopje. 2006
[42] Kornakov, Dimitar. Kopanicarot Dimitar Stanishev. Matica makedonska. Skopje. 2009

decorations and furniture, the theses of Morris and the practices of the rezbrari needs to be taken more seriously: crafted pieces by skilled workers are better than mass produced ones for the workers, the consumers and the environment. Crafted pieces carry with them the connection between nature, human work done by hand, and aesthetic enjoyment. While Morris & Co. designs today fetch thousands of euros, and the altarpieces of the rezbari are admired for their work, it is important to remember this connection, that is was the work of the craftsmen, and their relationship to the community and nature that makes them valuable, and as such they stand the test of time.

REFERENCES (alphabetical order)

Arscott, Caroline. *William Morris and Edward Burne-Jones: Interlacings*. Yale University Press. 2008

Donovon, Andrea Elizabeth. *William Morris and the Society for the Protection of Ancient Buildings*. Routledge. 2007

Hadzieva-Aleksievska, J. Makedonskite graditeli, graditelski skoli. MANU. 1995

Ivkovska, Velika, The Architecture and Painting of the Church of St. Panteleimon in Veles by Andrea Damjanov. Skopje 2022.

Kornakov, Dimitar. Kopanicarot Dimitar Stanishev. Matica makedonska. Skopje. 2009
__. Rezbarskite Centri vo Makedonija. Sv. Kliment Ohridski. Skopje 1998
__. Graditeli i Zografi. Matica makedonska. Skopje. 2010.

MacCarthy, Fiona (2010). *William Morris: A Life for Our Time* (pbk. ed.). London: Faber & Faber.

Morris, William. The Decorative Arts, in The Architect, 18 December 1877, pp 308-12
__. News From Nowhere. Marxists.org
__. The Meaning of Socialism. 1885. Marxists.org

Serdenkovska, M. Mijacko stanbena graditelstvo. Matica makedonska. 2016.

Rodgers, David (1996). *William Morris at Home*. London: Ebury Press.

Tomovski, K. Makedonskite majstori-graditeli od 19ti vek. Macedonian Academy of Arts and Sciences (MANU). Skopje. 2006

Trajanoski, Lj. Македонската резба во сакралните објекти во периодот од XIV – XXвек.marh.mk

Authors address:
Icev, M.[1],2;
[1] Department of Architecture, Faculty of Engineering, International Balkan University, Skopje, North Macedonia.
[2] Center for Advanced and Postdoctoral Research, University of Ss. Cyril and Methodius, Skopje.
*Corresponding author: marko.icev@ibu.edu.mk

SUSTAINABLE INTERIOR DESIGN STRATEGIES IN THE HOSPITALITY SECTOR: BALANCING ENVIRONMENTAL IMPACT AND GUEST EXPERIENCE

Boryana Umnkova-Rusev, Phd

Abstract: The hospitality industry is increasingly challenged to reduce its environmental footprint while maintaining high standards of comfort and aesthetic appeal. Current trends in interior design following natural materials use are supporting hotel businesses in their effort of improving the sustainable acceptability of the customers. This research explores sustainable practices in the interior design of hotels, focusing on the integration of eco-friendly materials, energy-efficient systems, and adaptive design strategies. Through a combination of case study analysis, literature review, and interviews among hotel experts, the study examines how design decisions—such as the use of low-impact materials, modular furnishings, and biophilic elements—can contribute to both environmental sustainability and enhanced guest experience. The findings highlight that sustainable interior design is not only a technical or environmental concern but also a critical component of brand identity and customer satisfaction in contemporary hospitality. This paper proposes a framework for designers that aligns sustainability goals with functional and experiential design, offering practical guidelines for implementation in new and existing hotel projects.
Keywords: sustainable design, hotels, guests, experience

1. Introduction

The Hospitality industry plays an important role in advancing social, economic, and environmental pillars. According to Booking Holding Sustainability Report (2025) 68% of the travelers' express willingness to travel more sustainable, however the uncertainty in the options provided and the criteria of measuring sustainable standards is limited and inconsistent, which leads to uncertainty in the traveler. These uncertainties reflect in the still low level of willingness of the consumers to pay 10% and more for sustainable hotel accommodation (Statista, 2024). Essential tools to fight this challenge are documented institutional signals like Travelife, Ecostars or Green Key, third partey sertify organisations validating the dedication of the company in its efforts and mission toward sustainable strategigal development. The findings presented here constitute the first phase of a multi-dimensional investigation into the Sustainable practices in hospitality within the Bulgarian mass tourism market. This research is situated within a larger effort to map the transition of large-scale resort complexes from traditional operational models toward sustainable innovation.In the context of the current paper the methodology approach is designed to bridge the "say-do gap"—the discrepancy between travelers' stated intentions and their actual booking behaviors—by analyzing authentic, post-stay evaluations rather than prompted survey responses.

2. Theoretical Framework & Literature Review

2.1. Dimensions of Sustainable Interior Design

The selection of natural, renewable, and low-impact materials has become a critical component of brand identity and guest satisfaction in contemporary hospitality (Baah et al., 2025; Safeer

et al., 2025). According to Signaling Theory, when sustainable efforts are embedded in the physical design—using wood, stone, or natural fibers—they serve as tangible quality signals (Pinthong et al., 2026). These help to reduce consumer uncertainty and lower skepticism regarding "greenwashing," as guests perceive the material choices as a sincere and genuine expression of the company's beliefs (Safeer et al., 2025). The integration of natural materials directly addresses the Health Value domain, which is identified as the most significant driver for modern sustainable consumption (Baah et al., 2025). The use of indoor greenery as a natural design element acts as a restorative stimulus (S) in the Stimulus-Organism-Response (S-O-R) framework (Lee et al., 2026). Eye-tracking research confirms that natural features capture visual attention significantly longer than built elements, elevating emotional pleasure and enhancing the guest's perception of the hotel's sustainable performance (Lee et al., 2026). Modular furnishings support a circular economy by enabling hotels to easily repair, replace, or repurpose individual components rather than discarding entire units. This shift toward durable rather than disposable products is a core dimension of the Sustainable Hospitality and Tourism Consumption Value (SHTCV) scale (Baah et al., 2025). By combining natural materials that signal authenticity and health with modular furnishings that offer operational flexibility, hospitality designers can bridge the "say-do gap." This approach transforms sustainability from a technical requirement into a critical component of the guest experience and brand differentiation.

2.2.The Trust Mechanism

The Trust Mechanism in the sustainable hospitality sector is a complex psychological and strategic process designed to overcome information asymmetry—the gap where guests cannot fully evaluate a hotel's environmental performance before their stay (Pinthong et al.,2026; Safeer et al.,2025). The Stimulus-Organism-Response (SOR) framework explains how the physical and technological environment of a hotel influences guest behavior (Safeer et al., 2025). In this model, sustainable design features serve as environmental stimuli (S) that trigger internal psychological changes (O), leading to a final behavioral response (R) (Pinthong et al., 2026). The research by Lee et al. (2026) provides a groundbreaking empirical basis for utilizing indoor greenery as a strategic design tool in hospitality, particularly within the luxury segment. It demonstrates, that greenery significantly increased pleasure and perceived sustainable performance, which positively affected hotel image and mediated the relationship between greenery and willingness to pay more. Research utilizing eye-tracking technology proves that greenery captures guest attention significantly longer than artificial elements, functioning as a primary stimulus for all subsequent evaluations (Lee et al., 2026). Since many sustainable operations (like energy efficiency) are invisible, hotels use quality signals, such as natural materials and interior greenery elements to communicate their ethical integrity (Hoang-Tran & Duong, 2026; Pinthong et al., 2026). In an era of high consumer skepticism, hotels utilize third-party certifications like Travelife to overcome information asymmetry—the gap between a hotel's green claims and the guest's ability to verify them (Safeer et al., 2025; Hoang-Tran & Duong, 2026). These certifications serve as "quality signals" that reduce the perceived risk of greenwashing (Pinthong et al., 2026; Safeer et al., 2025). The Travelife Standard (Version 3.1) establishes rigorous criteria that hotels must meet to achieve "sustainable acceptability" among travelers. These requirements are with high impact on the guest experience, because while their presence is expected, their absence can lead to significant guest dissatisfaction (Pinthong et al., 2026). Travelife requires properties to conduct annual performance reviews of energy, water, and waste. Specifically, according to standards manual (Version 3.1) at least 80% of all

areas must utilize low-energy lighting, and maximum water flow is restricted in showers (10l/min) and basins (5l/min) to ensure resource conservation without compromising the high standards of comfort expected by guests. Properties are mandated to prioritize natural, renewable, and locally sourced materials [Travelife Standard]. This aligns with the trend toward modular furnishings and low-impact material use, which enhances brand identity and contributes to a healthy lodging environment (Baah et al., 2025).

2.3. The Value Domain (SHTCV Scale)

According to the research by Baah et al. (2025), the Sustainable Hospitality and Tourism Consumption Value (SHTCV) scale consists of the following six components that constitute the value derived from sustainable consumption: health; quality and price, emotional, epistemic, environmental and social value. The most critical driver for modern guests is health value, referring to an individual's assessment of a hotel's capability to improve their well-being through non-toxic environments and designs that improve air quality (Baah et al., 2025). The integration of natural materials specifically satisfies this value by providing restorative service scapes (Lee et al., 2026). The technical implications of sustainable practices, such as photovoltaic panels, energy saving systems, and water saving systems are statistically main features integrated in eco-friendly hotels according to residents in Italy in 2024 (Statista, 2025). Even though furniture made with eco-friendly materials is only with 15% and bio architecture is only with 9% represented in the same research, theoretically following SHTCV scale it has the strongest impact on guests value creation and experience. In addition to that perceived green CSR and CSR authenticity only lead to repeat visit intentions if they first strengthen the hotel's credibility in the mind of the guest (Safeer et al., 2025). And finally the SHTCV scale are prioritized differently based on national culture, as cultural origin dictates a guest's specific eco-sensitivity and baseline expectations (Baah et al., 2025; Berezan et al., 2013; Hansen et al., 2024)

3. Methodology

This study employs a two-phase sequential mixed-methods design to examine the alignment between sustainable design and guest experience. Phase 1 utilized a combined qualitative and quantitative content analysis of 775 user reviews from Booking.com to identify spontaneous eco-awareness and "zones of friction". To provide institutional depth and validate these findings, Phase 2 involved qualitative fieldwork through semi-structured interviews with the marketing leadership responsible for the certified hotel sample (Pitakaso et al., 2025). For the purposes of analyzing consumer perceptions, this study utilizes a combined qualitative and quantitative content analysis of secondary, user-generated digital data (User-Generated Content - UGC) extracted from Booking.com. The selection of this approach is based on the fact that online platform reviews reflect real-world user experiences and authentic post-stay attitudes immediately following the visit (Çetinkaya et al., 2026; Ledro et al., 2025). By analyzing spontaneous mentions of sustainability, the study captures the true "sustainable acceptability" of green innovations without the prompting bias inherent in traditional questionnaires (Manthé et al., 2025). To ensure maximum objectivity a purposive sampling method was deployed (Baah et al., 2025). The selected hotels are located exclusively within the Golden Sands resort territory in Bulgaria. The sampling criteria included only those properties with active "Certified Sustainability" badge on Booking.com—proving a rigorous audit by an independent third-party certification body recognized by the Global Sustainable Tourism Council (GSTC), such as

Travelife or Green Key and an aggregate guest rating score of ≥ 8.0 ("Very Good" / "Superb") on the platform to ensure a high baseline of service quality.
Out of a macro-universe of 84 hotels available for booking during the period of August 1st–6th, 2026 in the period of research 15-25th June 2026, 54 properties maintained a high rating score, whereas only 8 properties were officially certified for sustainability. The content analysis specifically tracks the positive and negative attitudes of guests across all 8 of these certified hotels, comprising a total of 775 processed comment entries for year 2025. These reviews were coded into four operational dimensions of sustainability (Travelife, 2021; Yi et al., 2018): D1: Circular Economy Elements: (e.g., plastic elimination, bulk dispensers, refillable systems), D2: Energy and Climate Efficiency: (e.g., smart HVAC sensors, lighting deactivation, resource-saving laundry loops), D3: Sustainable Sourcing: (e.g., local/organic food, food waste management in all-inclusive buffets). D4: Institutional Signaling: (e.g., the visibility and perceived value of the eco-badge and certifications). For the purposes of the interpretation thematic and content analysis was conducted. To convert qualitative text into quantifiable metrics, two specific indices were applied: Eco-Visibility Index (EVI) and Eco-Friction Score (Index of Eco-Dissatisfaction).

4. Discussion of findings

At this stage The Eco-Visibility Index (EVI) is as a quantitative metric developed within the primary research to measure the level of spontaneous environmental awareness among hotel guests demonstrates. The current findings, derived from the content analysis of 775 user reviews across eight certified hotels, serve as the empirical baseline for the project. By analyzing spontaneous mentions of green practices, this phase objectively quantifies the Global Eco-Indifference Index (90.45%) and the 3:1 ratio of eco-dissatisfaction. Within the active segment that did mention sustainability, over 70% of reviews were negative. This "3:1 ratio of eco-dissatisfaction" occurs when green initiatives are perceived as compromises to personal comfort (Table 1.). These metrics are critical for the broader research aim of identifying the specific "friction points" where environmental operations clash with guest comfort in high-density mass tourism environments. Measuring indifference is critical for identifying the "say-do gap"—the discrepancy between travelers who claim to want sustainable options in surveys and those who actually notice or prioritize them in a real-world setting. The index provides a real-world contrast to traditional surveys where a high percentage of travelers (e.g., 68% in the Booking Holdings 2025 report) declare an interest in sustainability. The fact that 701 out of 775 guests remained completely silent regarding green badges or certifications proves that, for the vast majority of the mass market, sustainability is a "background factor" rather than a primary driver of the guest experience. Or at least not for the individual guests booked through the platform an All Inclusive hotel in a mass tourism destination, as Golden Sands, Bulgaria. Out of the 775 guest reviews, 53% are Romanians (412), 22% Bulgarians (165), 8% Germans (62), 6% from Poland (43), 4% from the UK (28), 2% from Czech Republic, 2% Hungary (17) and other containing 3% of the sample. This data isolates a clear geo-cultural division, as seen in Table 1. Western and Central Europeans function as the primary drivers of Eco-Support (+), while the Regional Balkan markets generate the vast majority of Eco-Dissatisfaction (-) due to different cultural definitions of premium holiday value. These findings compliment a recent research by Statista (2024), claiming that 20% of the German and 23 % of the British traveler will pay more than 10% for sustainable hotels in Europe.

Table 1. GEO-CULTURAL BEHAVIORAL PATTERNS

Nationality / Origin	Active Segment	Eco-Support (+) Rate	Eco-Dissatisfaction (-) Rate	Review coding operational dimensions of sustainability
Romania	42	7.14% (3)	88.10% (37)	Displays intense pushback against portions and bulk hardware. Generates sharp text complaints when green limits breach luxury comfort zones (D1, D2, D3)
Germany	11	63.64% (7)	36.36% (4)	Actively reviews and validates building engineering, praising thermodynamic structural insulation but penalizing unheated pool networks (D2)
United Kingdom	6	83.33% (5)	16.67% (1)	Highly receptive to visible sustainable sourcing; explicitly praises plant-based and carbon-neutral protein buffet display setups (D3)
Bulgaria	6	0.00% (0)	33.33% (2)	Exhibits low spontaneous green tracking (93%+ indifference). The small active subset focuses on reporting operational staff service lapses (D2).
Hungary	5	0.00% (0)	100.00% (5)	Highly sensitive to indoor environmental degradation; issues severe score penalties for trapped moisture and stale bathroom air (D2)
Czech Republic	4	75.00% (3)	25.00% (1)	Strongly supports active on-site rules and staff interventions to clear abandoned towels and stop sunbed resource hoarding (D4).
Poland	2	0.00% (0)	50.00% (1)	Focuses closely on tracking seasonal heating stability, air circulation loops, and the atmospheric quality of spa relaxation spaces (D2).
GRAND TOTALS	74	24.32% (18)	70.27% (52)	

The data presented in Table 1: Geo-Cultural Behavioral Patterns provides empirical evidence of how nationality acts as a primary moderator for sustainable acceptability in the mass tourism sector. It quantifies the "say-do gap" across different markets, confirming that cultural origin dictates a guest's specific eco-sensitivity and which green practices transition from being a background factor to a source of motivation. This fully compliments the expert opinion of the marketing leadership responsible for the certified hotel sample, who outlines that “valid sustainable certification as Travelife or Greenkey has terned into a value proposal and bargain power in the field of allotment negotiations with big international tour operators”. Confirmed by Fang, & Zaman (2025) with outlining the high value of eco labeling for marketing purposes. As in Bulgaria, Germany with 1 018 269 tourist (7% of all for year 2025) has been a traditional emitting market for seasonal mass leisure tourists, the sustainable certification and as part of it the sustainable interior design, is an important element in the hotel management strategy and brand identity. Guests associate natural surfaces and non-toxic finishes with a "healthy lodging environment," which is a necessary condition for forming positive attitudes and behavioral loyalty (Baah et al., 2025; Pinthong et al., 2026). And even though after the pandemic years the travellers from Romania are more dominant in the arrivals numbers (2 622 595, 19% of arrivals for 2025) we can see that they exhibit intense pushback when sustainability is perceived to breach "luxury comfort zones" (Indicators D1, D2, D3), but are highly appretiative according to the hotel expert, when experiencing high luxury features such as natural materials high end furniture and compliments, such as reusable branded waterbottles as a present from the hotel. Adaptive design strategies, including the use of modular furnishings, is mentioned from the expert as a posibility for the hotels to “align environmental sustainability with high standards of comfort and aesthetic appeal:”

In conclusion, this research demonstrates that sustainable interior design in premium hospitality must transition from invisible, restrictive resource reductions toward visible, high-quality experiential assets that actively strengthen brand identity and protect guest comfort. The empirical findings validate that while technical eco-protocols often trigger significant customer diferences across regional markets, strategic interior choices such as premium co-branded hardware and dedicated plant-based spatial layouts successfully bridge the consumer "say-do gap".

REFERENCES

1. Baah, N. G., Kim, S. S., & Han, H. (2025). Development and validation of a multidimensional sustainable hospitality and tourism consumption value (SHTCV) scale. International Journal of Hospitality Management, 126, 104077. https://doi.org/10.1016/j.ijhm.2024.104077
2. Berezan, O., Raab, C., Yoo, M., & Love, C. (2013). Sustainable hotel practices and nationality: The impact on guest satisfaction and guest intention to return. International Journal of Hospitality Management, 34, 227–233. https://doi.org/10.1016/j.ijhm.2013.03.010
3. Çetinkaya, A., Dondurucu, Z. B., Çağlayan, S., Cılızoğlu, G. Y., & Kuşay, Y. (2026). Hotel guests' perceptions of sustainable tourism practices within the framework of cue utilization theory. Sustainability, 18(2), 1113
4. Fang, L., & Zaman, U. (2025). Sustainable consumer-brand relationship: The role of sustainable marketing in shaping room booking intentions in green hospitality services. Acta Psychologica, 258, 105197. https://doi.org/10.1016/j.actpsy.2025.105197
5. Hoang-Tran, K.-N., & Duong, N.-H. (2026). [Predicting green behavior through personal innovativeness and metaverse engagement]. Cleaner and Responsible Consumption, 21, 100401. https://doi.org/10.1016/j.clrc.2026.10040
6. Ledro, C., Nosella, A., & Vinelli, A. (2025). Leveraging artificial intelligence for sustainable customer relationship management. Journal of Cleaner Production, 535, 147142. https://doi.org/10.1016/j.jclepro.2025.147142
7. Lee, J., Kim, M., & Lee, E. (2026). Greening hospitality: How indoor greenery and visual attention shape guest experience and sustainability perception in luxury hotels. International Journal of Hospitality Management, 135, 104616. https://doi.org/10.1016/j.ijhm.2026.104616
8. Manthé, E., Morrongiello, C., Bonnefoy-Claudet, L., Bezançon, M., & Bilgihan, A. (2025). Do hotels' green efforts lead guests to adopt sustainable behaviors? Mediating roles of perceived motives, gratitude, and green trust. International Journal of Hospitality Management, 131, 104302. https://doi.org/10.1016/j.ijhm.2025.104302
9. Pinthong, C., Inprasertkul, T., Rattanopas, C., Fakfare, P., Han, H., & Chua, B. L. (2026). Spa social responsibility as a quality signal: Building customer loyalty through ethical and sustainable practices. International Journal of Hospitality Management, 133, 104485. https://doi.org/10.1016/j.ijhm.2025.104485
10. Pitakaso, R., Golinska-Dawson, P., Luesak, P., Srichok, T., & Khonjun, S. (2025). Embracing open innovation in hospitality management: Leveraging AI-driven dynamic scheduling systems for complex resource optimization and enhanced guest satisfaction. Journal of Open Innovation: Technology, Market, and Complexity, 11, 100487. https://doi.org/10.1016/j.joitmc.2025.100487
11. Safeer, A. A., Abrar, M., & Qing, W. (2025). Navigating corporate social responsibility and customer behavior in sustainable hospitality: Role of credibility, environmental concerns, and green brand image. Acta Psychologica, 261, 105794. https://doi.org/10.1016/j.actpsy.2025.105794
12. **Reports**

Booking Holdings. (2025). Sustainability report 2025. https://www.bookingholdings.com/wp-content/uploads/2026/04/Booking-Holdings_2025-Sustainability-Report.pdf
Statista. (2024). Willingness to pay more for sustainable hotels in Europe 2024, by country
Statista. (2025). Main features of eco-friendly hotels according to Italians 2024
Statista. (2025). Main features of eco-friendly hotels according to Italians 2024
Travelife. (2021). Travelife accommodation certification standard, version 3.1. https://travelife.org/wp-content/uploads/Travelife-Accommodation-Standard-V3.1.pdf

Authors address:
First author: Umnikova-Rusev, Boryana
[1] Department of Tourism, Varna University of Management, Varna, Bulgaria
*Corresponding author: boryana.unikova@vum.bg

TIMBER AS A MEDIATOR BETWEEN THE HISTORIC FABRIC AND NEW RESIDENTIAL INHABITATION

Jasna Grujoska-Kuneska

Abstract: Adaptive reuse has emerged as a vital strategy for extending the lifespan of historic buildings, while accommodating contemporary uses. It requires careful mediation between old and new, preserving the building's material and spatial character. In the recent decades timber has emerged as an effective material for heritage interventions due to its capacity to support both reversible and sustainable practices with minimal impact on the original fabric. This paper explores three European case studies where diverse categories of historic buildings have been transformed into living spaces, including Astley Castle (England), The Mill (Scotland) and Tas's Church (Spain). Across these case studies, timber emerges as a versatile mediator between historic fabric and new residential inhabitation, ranging from independent internal structure, through spatial creator to atmospheric tool. The findings highlight the potential of timber across different building typologies in creating warmth and functional living spaces, while having minimal impact on the original material and authenticity of the buildings.
Keywords: timber as mediator**,** historic buildings, adaptive reuse, residential conversion, material dialogue

1. INTRODUCTION

The practice of adaptive reuse involves transforming existing structures to accommodate new contemporary functions, as a way to extend their lifespan, (Vafaie et al., 2023). Changing social conditions and urban transformation have affected many historic buildings to lose their primary function and even remain neglected or deteriorate. Integration of new function within historic buildings, particularly residential, represents an effective strategy for the building to remain vital and active, since it provides continuous occupation of the space and regular maintenance. The adaptive reuse of historic buildings stands between conservation and sustainable development. Beyond the physical fabric, it preserves the values and authenticity of the buildings, providing continuity between past and present. Moreover, transforming buildings instead of demolishing and building anew, supports resource efficiency (reduces demolition waste, conserve resources) and minimize overall environmental impact, (Hu & Świerzawski, 2024).

Within the contemporary adaptive reuse practice, timber has emerged as an important material, due to its exceptional versatility, natural character and reversibility. This paper explores the potential of timber to transform different historic buildings into contemporary living environments. It considers the potential of timber across several criteria: spatial strategy, structural role, relationship with historic masonry, visual expression and reversibility.

2. PROPERTIES AND PERFORMANCE OF TIMBER

Wood is often regarded as sustainable material, associated with its potential for renewability, recyclability, carbon storage capacity, etc. Beyond its environmental benefits, wood demonstrates favourable structural properties, such as high strength-to-weight ratio, elasticity, and good compression strength (depending on the loadings). Wooden elements can

achieve same volume as equivalent concrete elements, while having only 1/5 of the weight. Its lightweight nature is especially suitable in the adaptive reuse practices, since it allows reversible interventions which reduce the impact on the original materials, (Asdrubali et al., 2017). The low thermal conductivity of wood, which ranges from 0,042 to 0,18 W/m^{2}K, enables creation of elements with small thickness but relatively high thermal resistance. This is especially suitable for residential buildings since it limits the heat loss and improve overall energy performance of the building, providing stable indoor temperatures, (Asdrubali et al., 2017).Some studies highlight the potential of timber in creating pleasant indoor environments and having positive psychological effect on the occupants, which is especially important in residential buildings, as people spend a significant amount of time in them. These features are often associated with feelings of warmth and comfort that enhance the mood of the occupants, (Alapieti et al., 2020).

3. CASE STUDIES

3.1. Astley Castle (England)

The mediaeval Astley Castle is located in the rural countryside setting within North Warwickshire and once was a home of an aristocratic English family. It has layered historical background - originally built in 12th century with substantial expansions in 15th, 17th and 19th century. In 1970s devastating fire significantly damaged the building and left it partially deteriorated, and the following years of neglect and vandalism transformed it into ruin on a verge of collapsing. After an architectural competition to restore the occupancy of the castle, in 2012 it was transformed into contemporary holiday home, figure 1. The accommodation involved two-storey residence with four bedrooms and two bathrooms in the lower level and a continuous living space with kitchen and dining area on the 1st floor. Initially, the ruin was cleared, consolidated and stabilized using almost invisible technique of anchor system. New building materials, brickwork and concrete, were used to provide structural support and infill all the gaps in the original structure, (The Landmark Trust, 2014) (Pamela Buxton, 2013).

Figure 1. Adaptive reuse transformation of Astley Castle, (James Taylor-Foster, 2013)

Laminated timber was used for the construction of the roof and slabs allowing large spans without imposing significant structural weight to the existing structure. The spatial definition of the interior was done using birch plywood partitions, and oak was used for the construction of stairs and window's frames, (Pamela Buxton, 2013).

3.2. Tas's Church (Spain)

Tas's church is a small-scale Renaissance building located in the rural area of Las Barrietas, in the Basque Country near Bilbao. During late 18th century the church undergone significant alteration in neoclassical style, in form of height modification and additions. The

adaptive transformation started in 2019 and at this stage the church was abandoned with collapsed roof in its interior. Since the existing structure (masonry walls) was in a good state of preservation, the focus was to initially reinforce the bell tower and the dome. New programme adapts to the original structure, with its high ceilings - the main triple-height space contains living area, dining area and kitchen in the apse; a master bedroom is situated on the first mezzanine level with an office space positioned above; a small spare bedroom is situated in upper part of the church, within its tower, figure 2.

Timber is the main material used during the transformation of the church, visible only from the inside. Its implementation goes beyond the role of a roof structure but also contributes to arrange the new residential program by creating platforms, circulation and even furniture, (Garmendia Cordero Arquitectos, 2020)(Tas's Church/Garmendia Cordero Arquitectos, 2020).

Figure 2. Adaptive reuse transformation of Tas's Church, (Garmendia Cordero Arquitectos, 2020)

3.3. The Mill (Scotland)

The Mill is a historic farm building situated within the rural landscape of the Scottish Borders, near the town of Biggar. The building most probably dates from the 19th century and after the end of its use was left neglected for a certain period, existing as a ruined threshing mill. In 2014 it was transformed into rural holiday home, figure 3. At this stage the building has preserved stone envelope; the roof and floors were in a very poor condition without possibility to repair. The adaptation involved retaining the historic masonry envelope and insertion of a new structure within. Original walls were consolidated and repaired using local stones and re-pointed using lime-mortar. Due to lack of cross walls and necessity to improve lateral stability of the building, steel portal frames and cross bracing were subtly added.

The elongated shape of the building enabled linear arrangement of the new residential program and wide panoramic views towards the natural surroundings. The inserted volume comprises two levels, having kitchen, dining room, bathroom, utility and a bedroom on the ground floor and three bedrooms and 2 bathrooms on the 1st floor. The living area is positioned above the dining hall, elevated for just a half level, which creates flow between the areas, (The Mill /WT Architecture, 2015) (WT Architecture, 2014).

The project involved insertion of a new timber structure, clad in black stained timber. Inner surfaces of the walls are clad in construction grade spruce plywood. Wood is also found in the interior, for the construction of the stairs and certain floors made of pine boards (The Mill /WT Architecture, 2015).

Figure 3. Adaptive reuse transformation of the Mill, (The Mill / WT Architecture, 2015)

4. COMPARATIVE ANALYSIS OF THE SELECTED CASE STUDIES

The selected case studies present various types of historic buildings, including medieval castle, small renaissance church and 19th century mill, all transformed into contemporary living spaces. Although timber remains primary material within the interventions, each project demonstrates its unique capacity in the adaptive reuse process, figure 4.

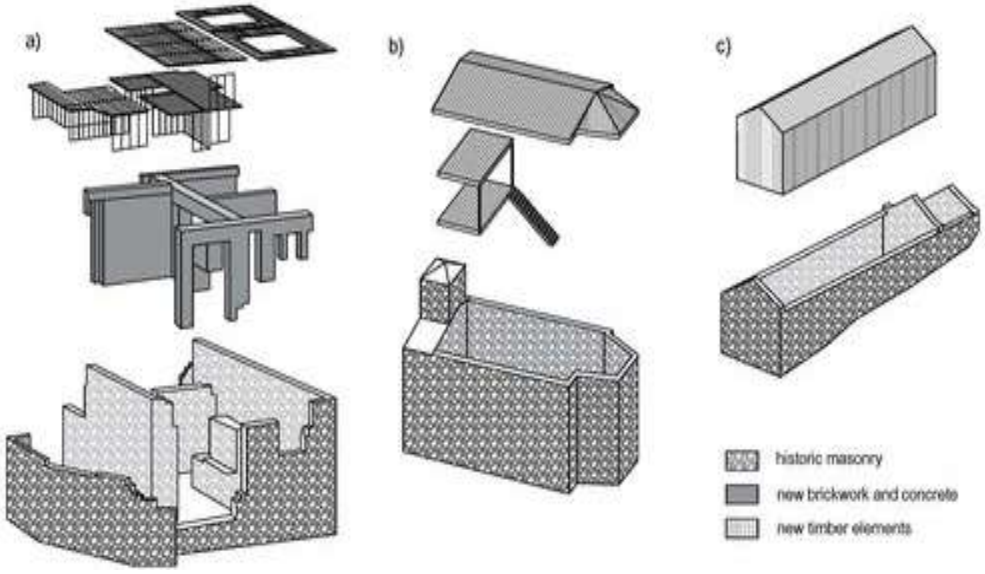

Figure 4. The role of timber during adaptive transformation, a) Astley Castle, b) Tas's Church, c) The Mill, (Pamela Buxton, 2013) (The Mill / WT Architecture, 2015)

In the case of Astley Castle timber do not have a primary structural role, but rather acts like secondary intervention, shaping the new residence programme – the roof, staircase and room partitions. Timber elements are relatively independent, connecting to the historic masonry only where necessary, like in the case of the new stained pine roof, which due to the massive 7m spans in the living room was built using laminated timber. The use of this material enables more lightweight solutions, compared to other alternatives like concrete or masonry, reducing additional loads on the existing structure. This minimalistic approach is aligned with the principles of reversibility often related to adaptive reuse of heritage buildings, (Australia

ICOMOS, 2013). Timber creates clear distinction between old and new, however the selected colour pallet is carefully matched with the existing one which creates subtle chromatic dialogue.

At Tas's Church timber have both structural and spatial function. Existing masonry structure is not entirely isolated from the new timber insertions, instead, at certain points act as a support of the intervention. However, where possible, like in the case of the wooden staircases, the structure remains detached, respecting the original structure. Integration of the residential programme within the building, in combination with the timber, was performed in the most sensitive and discreet way, preserving church's identity. The creative design of the wooden ceiling resembles the one of a cathedral, and the wooden frame which form the two separate floors occupies only the corner of the building. Despite the minimal alteration, the implementation of timber has meaningful impact – deliver atmospheric qualities and domestic scale to the space, enhancing the residential comfort.

The Mill shows a distinctive approach. Unlike previous case studies, where timber elements partially rely on the historic masonry and use this structure as a starting point for the new residential program, this project establishes the concept of "house within a house". It interprets the ruin as outer shell for the new inserted timber volume, which is entirely independent from the shell. This concept enables greater reversibility, without compromising original building structure, in future. Additionally, the low thermal conductivity of wood, makes it an effective natural insulating material, improving the overall energy efficiency of the new living spaces. When seen from outside, the intervention is subtle and the selected timber material allow for the masonry to remain dominant in the landscape. On the inside, the dominancy of the wooden textures contributes for the creation of more natural, pleasant and warm living conditions. A summary of the findings is presented in table 1.

Table 1. Timber contribution

Astley Castle	**Tas's Church**	**The Mill**
	Spatial strategy	
Integration- new elements complement existing fabric	Integration- new elements complement existing fabric	Insertion- new volume placed within historic envelope
	Structural role	
Secondary structural role	Primary structural role	Primary structural role
	Relationship with historic masonry	
Partially connected	Partially connected	Independent
	Visual expression	
Contrast old-new with subtle chromatic dialogue	Harmonious relationship, preserving church's identity	Timber remains subordinate to the historic masonry
	Degree of reversibility	
Moderate	Moderate	High

* Degree of reversibility:
High: Intervention can be removed with negligible impact on original (historic) fabric
Moderate: Intervention is partially removable with minor impact on original (historic) fabric
Low: Intervention is difficult to remove, with substantial impact on original (historic) fabric

5. CONCLUSION

This paper outlines the role of timber in transforming different typologies of historic structures into contemporary residential spaces. The selected case studies analyse the impact of timber in context of several parameters: spatial strategy, structural role, relationship with historic masonry, visual expression and reversibility, which are essential in

Within these projects timber acts as a mediator between historic fabric and new residential programme, ranging from integrated additions to independent spatial system and atmospheric tool. Its lightweight properties reduce the additional load on the existing masonry, suitable to the historic context. The interventions respect and minimize the contact to the existing masonry, connecting only where necessary. In the case of the Mill the strategy goes beyond this approach, by creating entirely independent timber volume, which enhance the potential for reversibility, aligning with the heritage preservation strategies. The warmth and natural appearance of wood bring domestic atmosphere into the new living spaces, contrasting the old rough masonry, especially evident in the case of Tas's Church. While there is a clear distinction between old and new materials, the presence of timber does not impose itself over the existing structure, but harmonizes with, or even remains deliberately subordinate, like in the case of the Mill.

REFERENCES

1. Alapieti, T., Mikkola, R., Pasanen, P., & Salonen, H. (2020). The influence of wooden interior materials on indoor environment: a review. European Journal of Wood and Wood Products, 78(4), 617–634. https://doi.org/10.1007/s00107-020-01532-x
2. Asdrubali, F., Ferracuti, B., Lombardi, L., Guattari, C., Evangelisti, L., & Grazieschi, G. (2017). A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications. Building and Environment, 114, 307–332. https://doi.org/10.1016/j.buildenv.2016.12.033
3. Garmendia Cordero Arquitectos. (2020). Tas's Church. Archello. https://archello.com/project/tass-church
4. Hu, M., & Świerzawski, J. (2024). Assessing the environmental benefits of adaptive reuse in historical buildings. A case study of a life cycle assessment approach. Sustainable Environment, 10(1). https://doi.org/10.1080/27658511.2024.2375439
5. James Taylor-Foster. (2013). Critical Round-Up: Stirling Prize 2013. ArchDaily. https://www.archdaily.com/434184/critical-round-up-stirling-prize-2013?ad_campaign=normal-tag
6. Pamela Buxton. (2013). How they Kept the Keep. RIBA Journal ((RIBAJ). https://www.ribaj.com/buildings/how-they-kept-the-keep
7. The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance (2013).
8. The Landmark Trust. (2014). Astley Castle: History Album Volume II: Conservation & Conversion.
9. The Mill / WT Architecture. (2015). ArchDaily. https://www.archdaily.com/623555/the-mill-wt-architecture
10. Vafaie, F., Remøy, H., & Gruis, V. (2023). Adaptive reuse of heritage buildings; a systematic literature review of success factors. Habitat International, 142, 102926. https://doi.org/10.1016/j.habitatint.2023.102926
11. WT Architecture. (2014). The Mill, Scottish Borders. Architizer. https://architizer.com/projects/the-mill-scottish-borders/

IN(OUT)SIDE: WOOD AS A MEDIATOR OF STRUCTURE AND EXPERIENCE IN CONTEMPORARY EXHIBITION ARCHITECTURE

Harika Shehabi

Abstract: The paper examines how wood functions in contemporary exhibition design as both a structural and an atmospheric element. Starting from an interest in investigating form and space in traditional pyramids, the project proposes an absolute clash in understanding what a pyramid is supposed to be. Much like in a traditional pyramid, the Inverted Pyramid evokes the familiar triangular shape. The idea is a permanent pyramid structure to house Egyptian finds currently scattered across the Venetian lagoon and on the island of San Lazzaro degli Armeni, designed to be located within the historic garden of Palazzo Ca' Zenobio. This research examines how a large wooden pyramid can provide a cohesive spatial experience by serving as a mediator among historical narratives, such as Egyptian, Armenian, and Venetian. The project investigates the tectonic, material, and interior attributes of wood using a design-based technique, emphasising its ability to create intimacy, continuity, and diffused light within a mathematically rigorous shape. By reinterpreting the pyramid typology in wood, a more tangible and pleasant space condition is proposed, challenging its conventional association with monumentality. The study makes the case that well-designed wooden buildings can serve as experiential and contextual interfaces, changing exhibition spaces and connecting the past and present.

Keywords: Venice, exhibition, transparent, ancient, structure

1. INTRODUCTION

One of the biggest issues facing architectural practice and heritage preservation today is the incorporation of modern architectural interventions into historical contexts. By providing the rational usage of traditional materials with new construction techniques and spatial experiences that both respect the cultural significance of heritage and meet modern architectural needs, contemporary design increasingly seeks to engage in dialogue with existing contexts rather than merely replicating historical forms.

Wood is now used by architects to investigate sustainability, recyclability, craftsmanship, and sensory experience in addition to its structural qualities. Architecture is characterized by its tectonic expression, or the interaction of material, structure, and experience, in addition to its form. In this situation, wood can express both atmospheric aspects and structural strength, making architecture more than just a visual phenomenon (Frampton, K., 1995). The outcome of precisely planned interactions between material, light, proportion, and environment is known as architectural mood. These viewpoints show that the choice of materials affects how architecture is viewed, experienced, and remembered in ways that go beyond technical issues. As a result, wood can be viewed as a mediator between users, location, and historical context in addition to being a building material. Wood, beyond being merely a building material, becomes an architectural language that blends the physical characteristics of a space with the sensory experiences of its users. Architecture can be understood not only through sight, but also through the body, memory, and mood created by the materials themselves.

The structure, which was designed to resemble a modern wooden pyramid, will display the Description de l'Égypte, the monumental publication that details Napoleon's expedition in Egypt and is kept in the Armenian Monastery on the island of San Lazzaro degli Armeni in the Venetian lagoon. The idea establishes a respectful dialogue with the Venetian surroundings by reinterpreting the pyramid as an abstract spatial device that frames movement, light, and perception, rather than rebuilding an ancient Egyptian monument.

The title "In (Out) side" captures the main point of this study. The proposal is characterized by the unclad designed wooden framework that supports both reception and continuity, as well as the threshold that unites the internal and external spaces. A bridge is created by the wooden structure, the garden and pavilion-like exhibition area, historical background, modern intervention, exhibition and landscape, permanence and transience. Through these changes, architecture ceases to be a historical artifact and instead becomes an experience that changes throughout time.

2. WOOD AND FORM AS A CONTEMPORARY INTERPRETATION

2.1. Wood

According to Vittorio Gregotti, architecture is essentially an act of change: an intentional engagement with place, history, and material that transforms the existing condition. Architecture starts with a landscape already influenced by cultural, social, and physical connotations, rather than an empty surface. In this way, a modern intervention in a historic setting ought to offer a fresh perspective on the past rather than trying to replicate it. The architectural act turns into a conversation between change and continuity (Gregotti, V. 1985).

Timber reflects a distinct relationship with time, unlike materials whose character is frequently associated with weight and permanence. This substance reveals growth, assembly, and transformation. Its structural connections, joints, and grains are still visible, enabling the construction process to be incorporated into the architectural experience. However, the primary focus of our discussion and investigation is how we can revive a type of structure that has left its mark using a different, sustainable material and a creative construction method.

Francesco Venezia's architectural approach, which examines the connection between material sensitivity, historical context, and architectural innovation, is intimately associated with this notion (Venezia, F.,1944). According to Venezia, materials are both intellectually and physically present; they are active contributors to the meaning-making process rather than neutral resources. Without replicating the past, architecture can create continuity between various historical times through meticulous building and attention to detail. *(Figure 1)*

Figure 1. Francesco Venezia • "Mostrum" - Pompeii and Europe 1748-1943- Pompei (Naples). *Source: https://maimoniblog.blogspot.com/2015/06/il-monstrum-di-pompei-un-allestimento.html*

The exhibition space becomes more than just a place to display objects; it becomes a tool that influences movement, focus, and interpretation. The visitor can perceive the architecture not as a background element, but as an active participant in the exhibition narrative, thanks to its structural clarity, material warmth, and ability to filter light. The inviting feeling of wood draws the visitor into a labyrinth, ultimately leading them to a bright garden at the end. It can also be described as an innovative projection and experience of ancient geometric forms. In this situation, wood acts as a bridge between the temporality of modern intervention and the permanence of legacy. Instead of trying to compete with historical resources, it adds a new temporal dimension based on experience, transformation, and adaptability.

2.2. Form and Pyramid

The symbolic aspect of architecture also helps to explain the connection between shape and memory. According to Étienne-Louis Boullée, geometry can convey significance beyond practical necessity in architectural form, which serves as a conduit for thoughts and feelings. His interest in the pyramid and other pure geometric volumes shows how architectural forms may function as symbols that go beyond their actual construction (Boullée, É. L. 1953). As a result, the pyramid is more than just a shape; it is also a cultural symbol of wisdom, permanence, and collective memory. *(Figure 2,3)*

Figure 2,3. Étienne-Louis Boullée • Progetto di cenotafio per Turenne. Source: https://denniscooperblog.com/etienne-louis-boullees-unbuildable-tombs-2/

However, rather than reproducing its original meaning, the modern reading of such a form necessitates a transformation. Instead of attempting to replicate an Egyptian monument, the wooden pyramid suggested for Ca' Zenobio makes use of the pyramid's metaphorical significance to create a new connection between the item, display, and location. The pyramid's meaning is changed from an object of permanence to a place of interaction by using timber to transform the towering image into a transient and immersive structure. As they have significance beyond their original purpose, some architectural forms endure across time. They become pieces of the collective imagination that are constantly reinterpreted by various generations. One such characteristic of the pyramid as an archetypal form is that it simultaneously belongs to history, imagination, and architectural memory (Rossi, A., 1982).

3. CASE STUDY: THE WOODEN PYRAMID AT CA'ZENOBIO

3.1. Historical Context

Ca' Zenobio Palace is an excellent example of late Baroque architecture, situated in the Dorsoduro district of Venice and designed by Antonio Gasparri at the end of the 17th century for the wealthy Greek noble Zenobio family. The Palace was later converted into the Moorat-Raphael Armenian College. This modification added a new cultural layer instead of eliminating the palace's aristocratic status, enabling it to serve as a hub for scholarship, education, and cross-cultural interaction in Venice. In addition, the Ca' Zenobio Palace consists of a main

building with a magnificent ballroom, decorated interiors with stuccos and frescoes by well-known artists, a courtyard with a Neoclassical loggia, and an exceptional Romantic private garden whose size is astounding when compared to similar Venetian structures. Its garden, which is located between the imposing palace and the city outside, serves as a threshold, a place that is neither wholly natural nor wholly constructed, but rather one that encourages reflection and transition. *(Figure 4)*

Figure 4. The location of Ca ' Zenobio Palace on a map. *Source: Google Maps*

But in parallel, when you look beyond the Dorsoduro district to the Venetian lagoon, the dialogue of the site continues in San Lazzaro degli Armeni. This island also belongs to the Armenian community, and languages, manuscripts, archaeology, and scientific knowledge were gathered, translated, conserved, and shared at San Lazzaro. Napoleon recognized the monastery's significance as a scientific academy as well as a monastic life and exempted it from the closure of religious establishments in 1810. In this regard, Description de l'Égypte is more than just a historical work. This massive work, which was created between 1809 and 1829 in the wake of Napoleon's Egyptian war, is among the first contemporary attempts to methodically record the monuments, landscapes, flora, animals, and culture of ancient Egypt. Another level of interpretation is added by its inclusion in the Armenian collections at San Lazzaro, which guarantees that information from Egypt traveled through France and was conserved in an Armenian intellectual establishment in Venice. As a result, the voyage of the book mirrors the history of Venice, a city founded on ongoing cultural exchange rather than a single identity. *(Figure 5)*

Figure 5. Some pages from Description de l'Égypte, the main artefacts shown in the wooden pyramid. *Source: Archive of San Lazzaro*

3.2. Design and Spatial Experience

The placement of the pyramid from Ca' Zenobion's ballroom, its connection to the garden gallery, and the fact that the pyramid is not obscured by wooden panels but rather the wooden truss is visible in its unadulterated state were all crucial components for us. As in the case of the ancient Egyptian pyramids, we thus eliminated all the panels, leaving only the exhibition

area hidden and revealing the wooden truss and the calculated structure. A stunning, huge, constructivist wooden truss is visible from the outside. Our goal was to create an entry with axes that were inspired by the palace, deliver an experience, and end it in the direction of the gallery. *(Figure 6,7)*

The imposing solid holds a spirit of timelessness and eternity, being made to last forever as a memorial of the greatness of the Ancient Egyptian society. How the internal spaces are shaped seems to have a lesser importance, and often these spaces are even created to be purposefully confusing, having a complex web of maze-like corridors and false entrances. In an ephemeral pyramid like the one proposed, the understanding of time plays an important role in the design conception. Without the purpose of eternity, the intent of a pyramid becomes fragile, as if it could be made of air. When this notion is added to an analysis of void and volume, a new pyramid is born. In this case, the structural form becomes the architectural form, and the void excavated from the solid form is revealed, becoming the most important piece of the composition. Detaching the interior volume from the exterior structure, the only element connecting these two parts is the base, a grounding system that holds the arrangement together. *(Figure 8,9)*

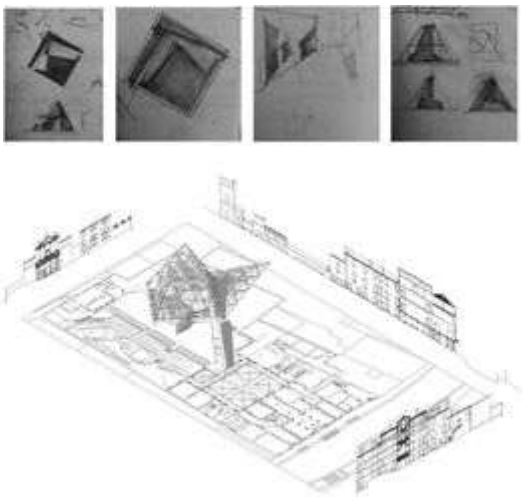

Figure 6,7. The development and the site organization of the pyramid.

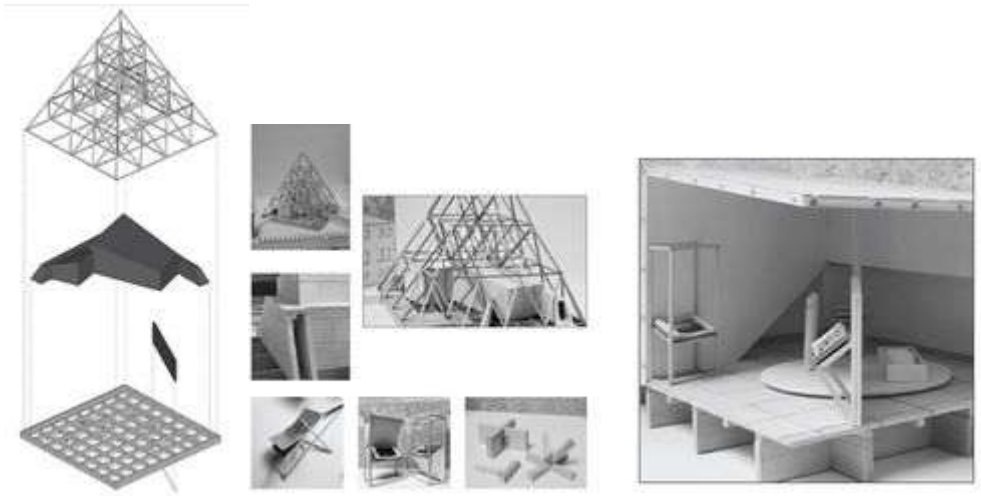

Figure 8,9. Layers and the final models.

4. DISCUSSION AND CONCLUSION

A discussion between Ca' Zenobio, the Armenian Monastery of San Lazzaro, and Description de l'Égypte shows how authentic architectural depiction may bridge historical narratives and civilizations. As a result, the pyramid is viewed as an architectural archetype whose meaning is modified by material and context rather than as an archaeological reconstruction. Lightness, sustainability, and tectonic openness take the place of the monumentality of the wood-built building, enabling the intervention to stay modern while honoring the historical identity of its surroundings. Building on the *'Biennale'* history of Venice, the goal is to conserve the island's Baroque and Neoclassical fabric, almost as an exhibition element, and portray the story of the ancient Egyptian pyramids in a way that would not be startling to tourists. Wood proves to be more than just a structural remedy. It turns into the medium by which architecture negotiates the relationships between interior and outside, object and visitor, and permanence and temporality. The architectural space itself can take part in the exhibition narrative because of its natural nature and evident construction, which translate structure into experience.
As a result, the concept of In(Out)Side transcends the pyramid's actual boundaries. In this way, the project makes the case that the ability of materials and construction to foster fresh conversations with the past may be more important for the future of exhibition architecture in heritage contexts than formal copy. By acting as a mediator in this conversation, wood's sensory capabilities show how architecture may both maintain and re-experience cultural memory.

Acknowledgements: My profound appreciation goes out to my friends and colleagues, *Bello Baros Alice Carolina, Smajić Edin, and Štulanović Maida*, who worked with me on the design of the pyramid and creative exhibition area project described in this study. Their inventiveness, commitment, and sharing of ideas made the design process an interesting, inspiring, and enriching experience. I am incredibly appreciative of the conversations, ideas, and experiences that were exchanged and helped to define the project.

REFERENCES

Books

1. Ambrogio, C., Rinaldi Vito M. *'L'Architettura delle Piramidi Menfite'* Genoa: Tipografia Canessa, Genoa, 1965.
2. Gregotti, V. *'Inside Architecture'* New York: Cambridge: The Graham Foundation / MIT Press Series in Contemporary Architectural Discourse, Cambridge, 1985.
3. Pallasmaa, J. '*The eyes of the skin*: Architecture and the Senses'. Hoboken: John Wiley & Sons, New Jersey, 2012.
4. Petrie, F. *'The Pyramids and Temples of Gizeh'*, London: Histories and Mysteries of Man Ltd, London, 1990.
5. Ralston, S. J. *'The Great Pyramid of Jizeh'*, Ohio: Cincinnati, R. Clarke & Co., Ohio, 1871.
6. Rossi, A. *'The Architecture of the City'*, Cambridge: MIT Press, Cambridge, 1982.
7. Zenotto, F. *'Le Fabbriche e i monumenti cospicui di Venezia'*, Venezia : Nello stabilimento nazionale di G. Antonelli, a spese degli editori Giuseppe Antonelli e Luciano Basadonna, Venezia, 1858.

Articles

1. Bitter, S. & Helmut, W. *'Making ruins'*. In: Phillipe, T., Mark, T., & Margot, Y. (eds). *'Memory'*, (pp. 38–47). British Columbia: Peter Wall Institute for Advanced Studies, British Columbia, 2018.
2. Boullée, É. L. *'Architecture, Essay on Art'*. London: Academy Editions. London, 1953.
3. Frampton, K. *'Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture'*. London: MIT Press. London, 1995.
4. Utidjian, H. *'The Mekhitarist Congregation of San Lazzaro as Guardians and Propagators of the Legacies of SS Gregory of Narek and Nersēs of Klay: An Outline', Lisbon, 2025.*
5. Vujicic, L. *'Architecture of the longue durée: Vittorio Gregotti's reading of the territory of architecture '*. Architectural Research Quarterly, 2015.

Author's address:
Shehabi, H.
Department of Architecture, Faculty of Engineering, International Balkan University,
Skopje/ North Macedonia
Makedonsko Kosovska Brigada,
Skopje 1000
harika.shehabi@ibu.edu.mk
shehabiharikaa@gmail.com

PITCHED TIMBER ROOFS FROM A SUSTAINABILITY PERSPECTIVE

Dominika Košútová, Daniel Bebej, Hanna Maťová, Róbert Uhrín

Abstract: This paper addresses the environmental assessment of selected pitched roof assemblies with a timber load-bearing structure from a life cycle perspective. Four roof cladding alternatives are compared: a pitched roof with ceramic tiles, a pitched roof with concrete tiles, a pitched roof with metal roofing, and a pitched green roof. The assessment is carried out using Life Cycle Assessment (LCA) methodology in the SimaPro software environment, applying the ReCiPe 2016 method at both midpoint and endpoint levels.

The functional unit is defined as 1 m² of roof assembly under comparable technical and performance requirements. The study focuses on the identification and comparison of environmental impacts associated with the material composition and structural layers of the analysed roof systems. Particular attention is paid to impact categories related to climate change, resource use, fine particulate matter formation, land use, and water consumption.

The paper examines the extent to which the choice of roofing material and assembly composition influences the overall environmental profile of pitched roofs designed with timber supporting structures. By comparing conventional roofing materials with a vegetated roof solution, the study highlights the differences between traditional and alternative roof systems in terms of their environmental burdens.

The results provide a basis for a more objective evaluation of roof design options and contribute to a better understanding of the role of material selection in sustainable building design. The paper thus supports environmentally responsible decision-making in the design of pitched timber roof structures and offers relevant insights for research and construction practice.

Keywords: pitched timber roof; Life Cycle Assessment; ReCiPe 2016; green roof; roof covering; environmental assessment

1. INTRODUCTION

In contemporary architectural design, the roof is no longer perceived only as a protective technical layer of the building envelope. Especially in pitched timber buildings, the roof can contribute to the architectural expression, daylighting strategy and overall environmental performance of the building. In this context, the roof may be understood as the “fifth façade”, forming an exposed and visually significant part of the building envelope, similarly to vertical façades.

The need for a more objective evaluation of timber-based design solutions is also supported by previous research showing that users strongly consider fire safety, lifespan and energy efficiency, while the environmental benefits of timber construction need to be communicated more clearly through aspects such as renewability, embodied energy, production impacts and construction waste [3].

The technical performance of timber building envelopes is also strongly influenced by construction details and element connections, as demonstrated by research on wood window

installation, where the position of the window within the wall thickness affects the resulting linear thermal transmittance of the thermal bridge [4]. The concept of the fifth façade has also been linked to biophilic design, where roof surfaces are reinterpreted as green and productive spaces that integrate nature into the built environment and contribute to climate change mitigation, as well as to the health and well-being of urban areas [2]. In this context, pitched green roofs represent a relevant alternative to conventional roof coverings and require a more detailed assessment of their environmental performance.

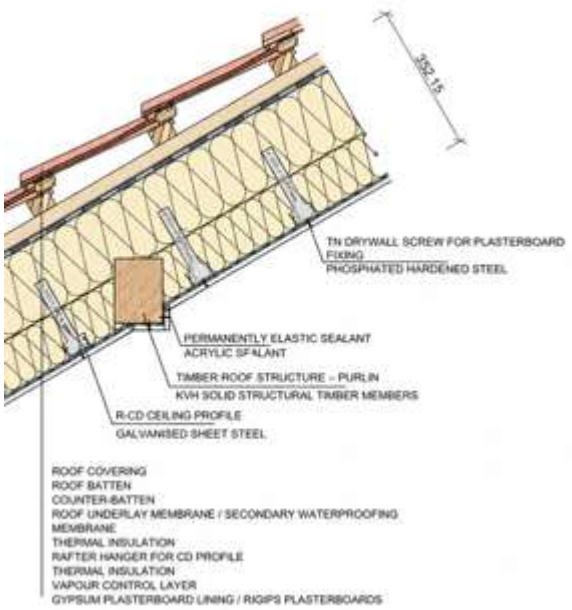

Figure 1: Conventional pitched timber roof assembly with ventilated roof covering.

2. MATERIALS AND METHODS

This section presents the materials, system boundaries and modelling procedure used for the Life Cycle Assessment of the analysed pitched timber roof assemblies. Four roof variants were evaluated under comparable functional and technical assumptions in order to identify the influence of roof covering and assembly composition on the overall environmental performance.

2.1. Description of Roof Assembly Variants

Four pitched timber roof assembly variants were analysed, representing three conventional roof coverings and one lightweight extensive green roof system (Table 1).

Table 1: Analysed variants of pitched timber roof assemblies and their main variable layers

Variant	Roof assembly type	Main variable layer
V1	Pitched timber roof with ceramic tiles	Ceramic roof covering
V2	Pitched timber roof with concrete tiles	Concrete roof covering
V3	Pitched timber roof with metal sheet roofing	Lightweight metal sheet covering
V4	Pitched timber roof with lightweight extensive green roof	Green roof build-up with substrate and sedum vegetation

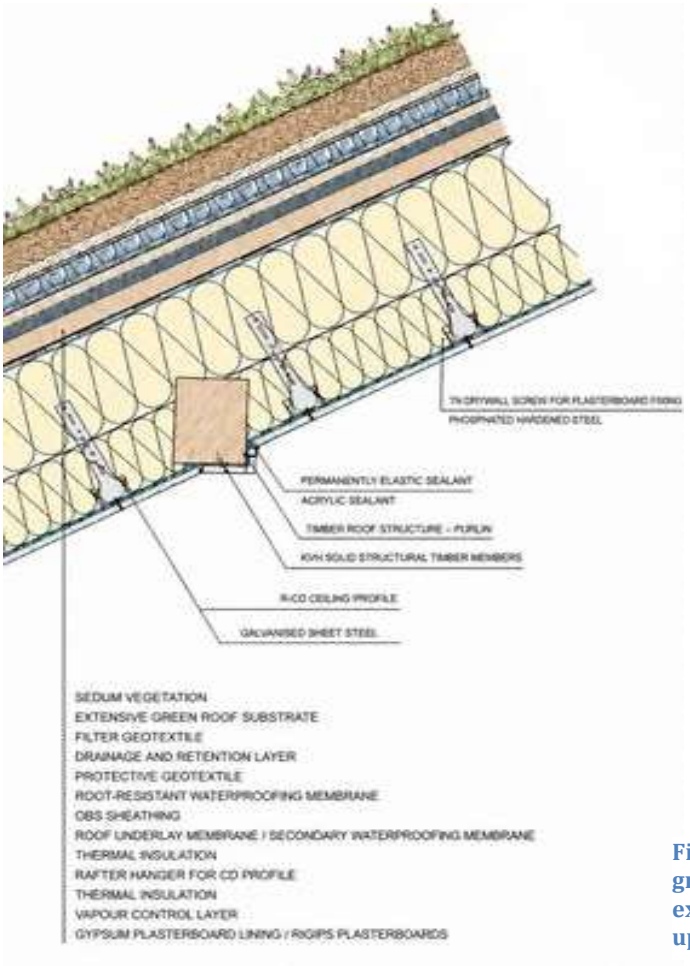

Figure 2: Pitched timber green roof assembly with an extensive vegetated build-up above the roof underlay

Variants V1–V3 share the same basic timber roof assembly and differ mainly in the roof covering material. Variant V4 replaces the conventional roof covering and supporting battens with an OSB substrate and a lightweight extensive green roof build-up, including waterproofing, geotextiles, drainage and retention layer, substrate and sedum vegetation mat.

2.2. Functional Unit and System Boundaries

The functional unit was defined as 1 m² of roof assembly measured along the roof slope. The system boundary was limited to modules A1–A3, corresponding to a cradle-to-gate assessment, including raw material supply and processing, transport of raw materials to the manufacturing process, and the production of construction materials and components. Transport to the construction site, installation, use, maintenance, replacement, and end-of-life stages were not included in the assessment. This system boundary enables a focused comparison of the embodied, material-related environmental impacts of the analysed pitched timber roof variants.

2.3. Life Cycle Inventory and Modelling in SimaPro

In the lightweight extensive green roof variant, OSB was considered as a full-area timber-based board substrate; its relevance in timber building envelopes is supported by previous research on OSB air permeability and airtightness performance [5].

Table 2: Material inventory of analysed pitched timber roof variants per 1 m² of roof area

Material group	V1 C	V2	V3	V4
External roof layer / green roof build-up	50.00	43.00	5.00	58.45–73.45
Timber-based components	13.44	13.44	13.44	20.10–23.10
Common internal layers	16.74	16.74	16.74	16.74
Total material mass [kg/m²]	80.33	73.33	35.33	95.29–113.29

Common internal layers include glass mineral wool, galvanised CD profiles and hangers, vapour control membrane and gypsum plasterboard. In V1–V3, timber-based components include rafters, battens and counter-battens; in V4, they include rafters and OSB sheathing. The green roof build-up includes waterproofing, geotextiles, drainage/retention layer, substrate and sedum vegetation.

2.4. Impact Assessment Method

The ReCiPe 2016 method was selected in order to provide a consistent life cycle impact assessment framework for the comparison of the analysed pitched roof variants. Recent research in the roofing sector has shown considerable variability in LCA methods and impact categories used for roofing materials and roofing systems, which confirms the need for a clearly defined assessment method and comparable impact categories [1].
For graphical interpretation, the results were expressed as relative values, where the maximum value within each impact category was set to 100%. Selected midpoint indicators were presented in the results in order to highlight the most relevant differences between the analysed roof variants.

3. RESULTS AND DISCUSSION

The ReCiPe 2016 Endpoint (H) characterisation results show that the environmental profile of the analysed pitched timber roof assemblies is strongly influenced by the selected roof covering and by the complexity of the roof build-up. Among the conventional variants, the concrete tile and metal sheet roofs generally achieve lower endpoint impacts than the ceramic tile roof. The metal sheet variant performs best in the global warming-related endpoint indicators and in water consumption-related damage indicators, while the concrete tile variant shows favourable results in several toxicity, eutrophication and resource-related categories. In contrast, the ceramic tile roof reaches the highest values in several endpoint categories, including fine particulate matter formation, ecotoxicity, mineral resource scarcity and water consumption-related indicators.

The lightweight extensive green roof does not achieve the lowest endpoint impacts within the A1–A3 boundary. Its additional material layers above the roof underlay membrane increase the environmental burden in categories such as fossil resource scarcity, land use, ozone formation and stratospheric ozone depletion. However, these results should be interpreted with caution, as the assessment covers only the product stage. Potential use-stage benefits of green

roofs, including stormwater retention, microclimate regulation, protection of waterproofing layers and biodiversity support, are not included in the presented comparison.

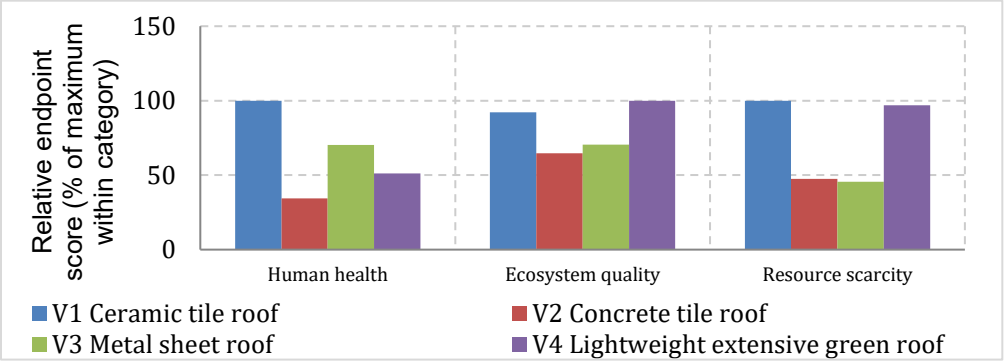

Figure 3: Relative ReCiPe 2016 Endpoint (H) damage results for the analysed pitched timber roof assemblies.

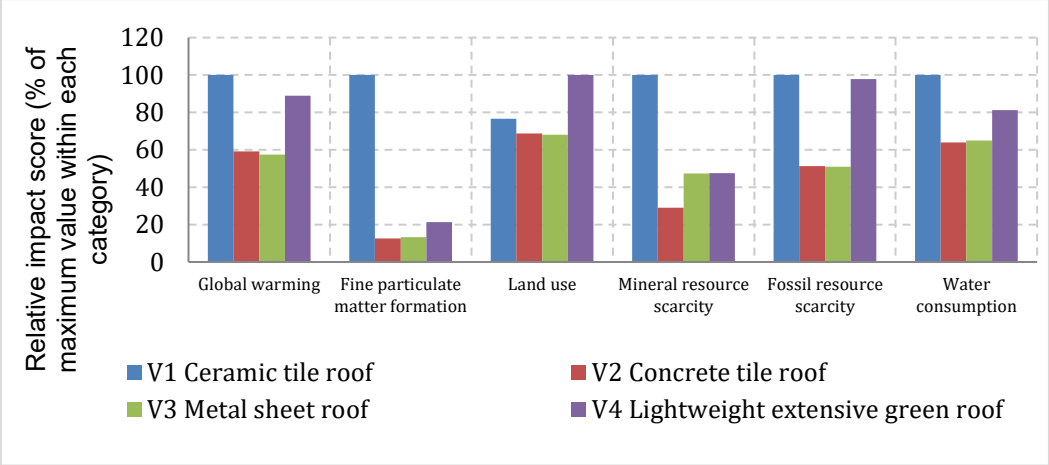

Figure 4: Relative ReCiPe 2016 Midpoint (H) impact scores for selected environmental categories of the analysed pitched timber roof assemblies.

4. CONCLUSIONS

The results confirm that the environmental profile of pitched timber roof assemblies depends not only on the type of roof covering, but also on the overall material composition of the assessed variant. Within the defined A1–A3 system boundary, the roof with concrete tiles showed the most favourable relative endpoint profile among the evaluated variants. The less favourable result of the ceramic tile roof may be mainly related to the energy intensity of its production, particularly the firing process at high temperatures. In the case of the metal sheet roof, the positive effect of its low surface mass was evident, although the production of metal materials and their surface treatments may increase impacts in selected toxicity and resource consumption categories. The higher impacts of the lightweight extensive green roof in the A1–A3 stage can be attributed to its more complex material composition, including OSB sheathing, waterproofing and separation layers, drainage layer, substrate and vegetation. Therefore, the

results cannot be generalised to the entire life cycle of the roof, as they do not include the use stage, maintenance, replacement of layers or the potential benefits of the green roof during operation. The environmental assessment of roof assemblies should therefore move beyond the selection of a single roof covering material and consider the roof as an integrated material system, with impacts distributed across all layers of the build-up, including additional construction elements integrated into the roof envelope, such as roof windows.

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REFERENCES

1. Aggarwal, C., Molleti, S., & Ghobadi, M. (2024). A comprehensive review of life cycle assessment (LCA) studies in roofing industry: current trends and future directions. *Smart Cities*, *7*(5), 2781-2801.
2. Cook, R.; Gilbert, J. (2015). The fifth façade: Designing nature into the city. *Council on Tall Buildings and Urban Habitat*, 1.26, 288.
3. Kaputa, V.; Olšiaková, M.; Maťová, H.; Drličková, E. (2019): Do preferences for wood-framed houses' attributes change over time? In: *Digitalisation and circular economy: forestry and forestry based industry implications. Proceedings of the 12th International Scientific Conference WoodEMA 2019*, pp. 161–166.
4. Nôta, R. (2022). Analysis of the thermal bridge of wood window installation position. *Acta Facultatis Xylologiae Zvolen*, 64(2), 49–56.
5. Sedlák, P.; Bednár, J.; Búryová, D. (2020): Air permeability of OSB and its influence to heating energy costs. In: Sustainability of forest-based industries in the global economy: Proceedings of Scientific Papers, WoodEMA 2020, Zagreb, pp. 279-284.

Authors address:
Košútová, D.[1], Bebej, D. [2], Maťová, H.[3], Uhrín, R.[4]
[1 2] Department of Wooden Constructions, Faculty of Wood Sciences and Technology, Technical University in Zvolen,
Slovakia
[3] Department of Marketing, Trade and World Forestry, Technical University in Zvolen, Slovakia
[4] Department of Wood Processing and Biomaterials, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague
University in Zvolen, Zvolen, Slovak Republic
*Corresponding author: buryova@tuzvo.sk

INFLUENCE OF WOOD SURFACE QUANTITY AND MATERIAL AUTHENTICITY ON USER PERCEPTION IN INTERIORS

Faton Kalisi

Abstract: Wood is increasingly used in interior spaces and often associated with improved comfort and occupants' well-being, especially in sustainable and biophilic design. However, it is still unclear if these effects are caused by the amount or the type of wood used in these spaces. This question becomes important because the impact of material authenticity versus the presence remains under researched, especially in contemporary interiors where the use of engineered and wood-like materials are very common. The aim of this study is through a controlled visual experiment to examine the influence of amount of wood surface coverage and how real the materials are in relation how good people think the setting is inside the office space. A set of realistic renderings of an office space were created, in which two factors will be changed: (1) the amount of visible wood surfaces (none, medium, and high coverage), and (2) the type of material used (solid wood, dark-stained wood, veneer/MDF panels, high-quality wood-look materials, and low quality synthetic imitations). While all the other elements such as the layout, lighting and furniture remained unchanged. Using a Likert scale questionnaire the participants will evaluate different interior scenarios. The survey will include approximately 100 participants. Visual quality, naturalness, perceived authenticity, comfort, and overall well-being will be evaluated. Through comparative statistical methods the purpose of the study is to determine whether increased wood enhances user perception and whether real wood is viewed differently than manufactured or synthetic wood-like materials. It is anticipated that the findings would provide empirical insight on how material presence and authenticity influence user perception in interior spaces, particularly when deciding between natural and wood-like materials.

Keywords: Interior design, wood surface, material authenticity, user perceptions

1. INTORDUCTION

Work interiors are more than just workspaces, they influence how users perceive comfort, well-being and atmosphere. Since, indoor environments can influence occupants' comfort, health and sleep quality, it's important to pay attention to their design (Shen et al., 2019). Therefore, material selection is not only an aesthetic choice but rather plays an fundamental role in how users perceive the quality of space.

Wood is usually associated with its ability to evoke perceptions of warmth, naturalness, and a pleasant user experience, which has attracted much attention in interior design spaces. In emperical research comparing wooden and non-wooden office interiors, Shen et al. (2019) reported that users preferred wooden office options over the concrete one, and also performed better in wooden environments on a given neurobehavioral test. Another study by Ojala et al. (2023) reported that there was less anxiety in wooden office room than in a control room, where all environmental and spatial parameters were kept constant, however other psychological effects were modest. Even though the existing studies highlight the importance of wood in interiors, these findings should not be interpreted as proof that it always produces positive effects on human experience.

This issue is closely related to the concept of biophilic design due to its connection with natural materials, which Wilson (1984) describes biophilia as people's tendency to respond to

life and life-like processes. Based on this idea, the following literature evolved into biophilic design, which studies the relationship between people and nature (Kellert et al., 2008). In this contenxt, materiality plays an important role in this topic. According to McGee and Park (2022), natural materials are among the most common biophilic qualities studied in literature and design practice.

However, most of the existing discussions occur on comparisons between wooden and nonwooden environments, and not enough attention is given to the difference between the amount of visible wood and how users perceive the authenticity of the material. This distinction is important because one space may visually appear wooden, but the material may be entirely engineered or synthetic. Therefore, the current study investigates how users' perceptions of office interiors are influenced by the amount of visible wood and the authenticity of th material. To examine these effects, photorealistic renderings and on online questionnaire survey were conducted, following an approach similar to that uesed by Xie et al. (2023).

2. BACKGROUND AND LITERATURE REVIEW

Based on the theory of biophilia and biophilic design, Wilson (1984) describes biophilia as the tendency of people to respond to life and life-like processes. This theory was later developed in the architectural context through the concept of biophilic design, which examines the ways in which buildings can be support the human connection with nature (Kellert et al., 2008). For interior spaces this connection does not include only vegetation and outside vistas, material choice also has an influence on this connection. According to McGee and Park (2022) colour, light and materiality also play an important role as part of biophilic interior design both in research and design practice.

Previous studies on this subject, have not all measured the same response to wood, which makes the findings useful but difficult to compare. Research conducted by Shen et al. (2020) focused on office interiors by examining user preference and cognitive performance; the findings showed the users preferred the wooden interior setting over a non-wooden concrete one. Ojala et al. (2023) on the other hand focused on the well-being responses in wooden office spaces, and the results showed that the level of anxiety in the participants was lower, even though other psychological outcomes were less clear. A different approach by Kumpulainen et al. (2024) measured physiological responses, well-being and sensory measures by comparing a wooden room and a resin plastered room, where the results supported the positive response to wooden rooms. The different methodological approaches are important because they demonstrate the importance of wood in interiors and that the results depend on what exactly is being measured.

Since the aim of this study is to examine the visual judgement, rendered images offer an option to control design variables. Therefore, I use a similar methodological approach, as adopted by Xie et al. (2023) where a simulated office scene was used to assess subjective impression.The renders allow to test different combinations of material finish and appearance of the same office space without changing the parameters such as lighting, furniture, layout and camera angle. With this, the users respond more to visible wood quantity and material authenticity rather than just comparing wooden and nonwooden spaces. This approach responds to a gap in existing literature, where wood in usually treated as a homogeneous category.

3. METHODOLOGY

To address the aim of this study, which is to analyze how material quantity and material authenticity influence user perception of office spaces, a set of photorealistic rendering of a same office space was produced, followed by an online survey. This method was chosen because it allowed for the comparison of different material conditions while keeping the remaining conditions of the space constant.

For this reason, a set of five office scenarios was generated (Figure 1). The office layout, furniture, lighting conditions and camera angle were kept the same, while only the intended differences were in the amount of visible wood and the type of wood. Accordingly, the render set included: a no-wood scenario, a medium natural wood scenario, a veneer/MDF scenario, a high natural wood scenario, and a synthetic wood-like scenario, which were used to evaluate both wood exposure and perceived material authenticity.

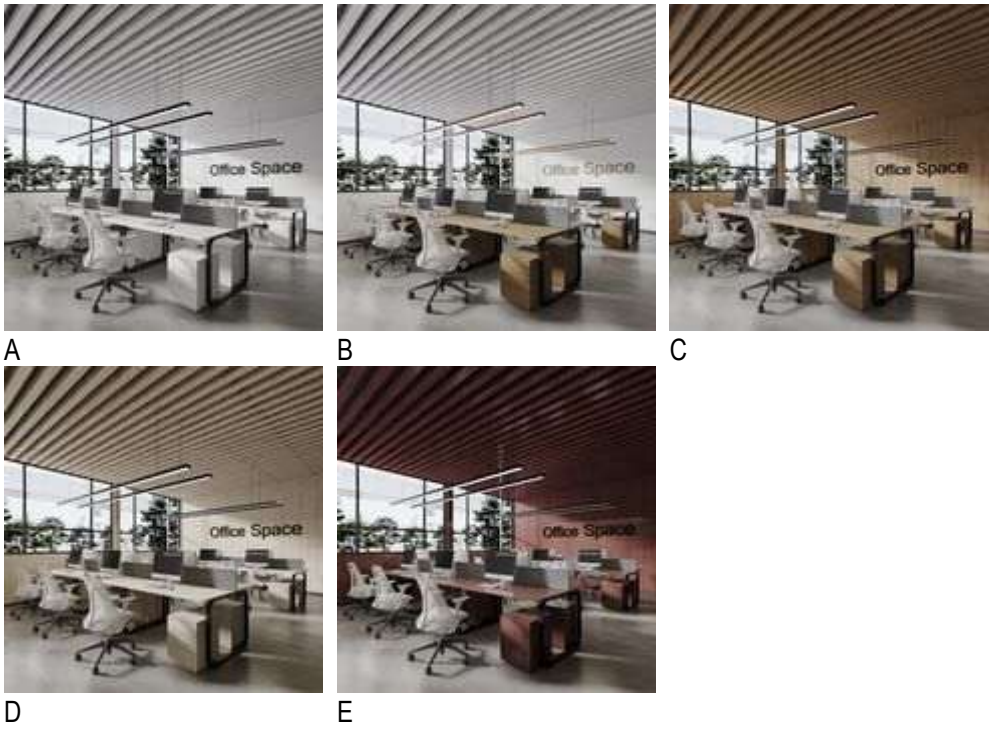

Figure 1. Interior scenarios: (a) a no-wood scenario; (b) a medium natural wood scenario; (c) a veneer/MDF scenario; (d) a high natural wood scenario; and (e) a synthetic wood-like scenario.

Data collection was conducted through an online questionnaire. Participants were shown the five interior scenarios, labelled accordingly (Interiors A-E (Figure 1)), without revealing the material conditions associated with each scenario, so that their response would not be influenced. For each image, the participants rated a series of statements using a six-point Likert scale, ranging from “strongly disagree” to “strongly agree.” The evaluations included visual pleasantness, comfort, warmth, well-being, naturalness and perceived authenticity, because these variables were directly related to the research objectives. The survey included 100 participants. Additional information was also collected from the participants prior to evaluating

the interior scene scenarios. Those information's were: general background, age category, educational or professional background, familiarity with materials, and how often do they work or studying in office environments. The survey was completely anonymous, and no personal information was collected from the participants, as it was designed solely for academic research purposes.

The collected data were analyzed by examining the average rating for each scenario and comparison between different scenarios based on the amount of visible wood and the type of material used. Participants' overall preferences will also be taken into consideration. Due to the nature of this survey, the findings only evaluate the visual responses of the participants and not the actual environmental conditions such as air quality, acoustics, thermal comfort and physiological reactions.

4. RESULTS

Of the 101 people who responded to the questionnaire, 96% agreed to participate in the study. Of this 33% belong to the 18-24 age group, 32% belong to the 25-34 age group, and 29% to the 34-44 age group. A further 9% belong to the 45 and over age group. Of the total number of respondents, 55% have a background in architecture and interior design, followed by 26% participants with a non-technical profession, and from 3 to 7% of the total number of participants, belong to professions such as, engineering - construction, design - art, business – administration, it/technology and students. More than half of the participants, i.e. 60% of them work or study in an office-like environment daily, while the others several times, 18%, occasionally 12% and the others rarely. The vast majority of respondents, i.e. 41%, reported having basic knowledge or experience with interior materials, while 32% of the total number of participants have professional knowledge and the others have no knowledge or experience with interior materials. Therefore, the response of the 28% of participants without basic knowledge of interior materials reflect primarly subjective perceptions of the five presented scenarios.

From the data collection in shown in the diagram 2 (Figure 2a), it results that scenario C dominates as the interior would you most prefer to work in with 55%, followed by scenario D with 22%, and in third place with 12%, scenario E dominates. Regarding the question of which interior appeared the most neutral, diagram 2 (Figure 2b), scenario C dominates with 65%, followed by scenario D with 24%. Similary, for the question concering perceivedd authenticity represented in the diagram 3 (Figure 2c), scenario C dominates with 47%, followed by scenario C with 22% and scenario D with 18%. Scenarios C, D, and E were chosen more often than Scenarios A and B. This can be explained by the higher quantity of wood present in these scenarios. Among them, Scenario C (veneer/MDF) was predominant and accounted for 56% of total answers. On the other hand, Scenario D (high natural wood) constituted 23% of answers, whereas Scenario E (synthetic wood-like) comprised only 15%.

Scenario C (veneer/MDF) was most most frequently identified as the most realistic and authentic interior scenario. Where the participants strongly agree that this scenario appears visually pleasant, feels natural, feels warm and welcoming, they would feel comfortable working in this kind of environment, it positively influences their well-being, and appears authentic.This finding implies that in a visual survey, perceived authenticity may depend on material's visual appearance rather than its solid wood content, which is proven by the selection of only 22% of the scenarios where high natural wood was used. In contrast, participants only slightly agreed or slightly disagreed that Scenario D appears visually pleasant, feels natural, feels warm and

welcoming, provides a comfortable working environment, positively influences their well-being, and appears authentic.Opposite to this, the synthetic wood-like situation had the poorest ratings among all scenarios on almost all evaluation factors. This is due to the diminished feeling of authenticity and naturalness that come with artificial materials. Artificial surfaces may look more uniform, repetitive, and manufactured compared to natural materials and hence do not trigger any positive feelings.

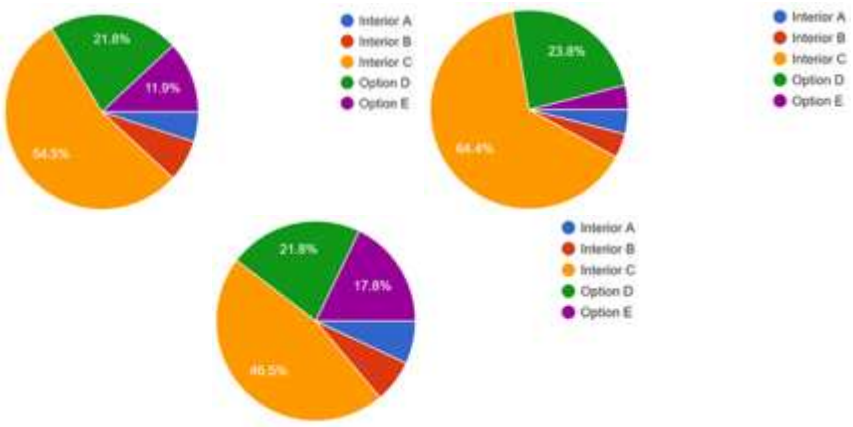

Figure 2. Survey diagrams illustrating participants' responses to: (a) Which interior would you most prefer to work in?; (b) Which interior appears the most natural?; and (c) Which interior appears the most authentic?

4. DISCUSSION

From the analyzed survey results, it is interesting to note that the dominant group of participants was aged between 18 and 44 years, with the majority having a professional or academic background. Furthermore, 60% of the participants reported working in office environments on a daily basis. The results indicate that the perception of wood quantity and attributes such as visual pleasantness, naturalness, warmth and welcoming atmosphere, comfort while working, positive influence on well-being, authenticity, and overall aesthetic appeal were particularly important to participants. The findings show that participants responded more positively to the veneer/MDF scenario. This result is important because it suggests that visual perception does not necessarily depend on the actual nature of the material. In the context of the generated images, a wood-based designed surface can be perceived as pleasant, natural, warm, and comfortable. Due to the nature of this study and its focus on visual perception, the findings should be interpreted as reactions to the appearance of the material rather than as an assessment of its actual quality.These results are consistent with previous studies showing that not only the presence of wood, but also its perceived authenticity, has a major impact on users' preferences and environmental experience. However, this study also raises the question of what constitutes the perception of naturalness in wood, suggesting that perceived authenticity may be more influential than material quality itself.

4. CONCLUSION

Though photorealistic rendering and online survey, this study examined how visible wood quality and material authenticity affect users' perception of office interior. The results show that the most preferred option was the veneer/MDF scenario and as the most natural and option, suggesting that interiors containing higher amounts of wood were perceived in a positive way compared to those with either lower or no amounts of wood at all. Among the three scenarios analysed in the study, the one with veneer/MDF was the most positively evaluated and considered preferable, natural and authentic, while the no-wood, higher amount of natural wood and synthetic wood look scenarios were lower, suggesting that the presence and visual quality plays an important role in interior perception. How ever, the study is limited to only visual evaluation and does not measure tactile experience, smell, acoustics, indoor air qutliy and physiological response. Since participants evaluated images only, the findings should be understood as visual impressions rather than full material experience and future research could compare rendered images with real material samples or physical interior settings to better understand how visual and multisensory perception differ.

REFERENCES

1. Kellert, S. R., Heerwagen, J. H., & Mador, M. L. (Eds.). (2008). Biophilic design: The theory, science, and practice of bringing buildings to life. John Wiley & Sons.
2. Kumpulainen, S., Kilpiäinen, M., Koski, J., & Pesola, A. J. (2024). Wooden interiors improve heart rate variability-derived psychophysiological well-being: An acute cross-over study. Environment and Behavior, 56(3–4), 155–178. https://doi.org/10.1177/00139165241270631
3. McGee, B., & Park, N.-K. (2022). Colour, light, and materiality: Biophilic interior design presence in research and practice. Interiority, 5(1), 27–52. https://doi.org/10.7454/in.v5i1.189
4. Shen, J., Zhang, X., & Lian, Z. (2019). Impact of wooden versus nonwooden interior designs on office workers' cognitive performance. Perceptual and Motor Skills, 127(1), 36–51. https://doi.org/10.1177/0031512519876395
5. Wilson, E. O. (1984). Biophilia. Harvard University Press.
6. Xie, J., Sawyer, A. O., Ge, S., & Li, T. (2023). Subjective impression of an office with biophilic design and blue lighting: A pilot study. Buildings, 13(1), Article 42. https://doi.org/10.3390/buildings13010042

Authors address:
Faton Kalisi[1];
[1] Architecture, Faculty of Engineering, International Balkan University, Skopje
*Corresponding author: faton.kalisi@ibu.edu.mk

INNOVATIVE TECHNOLOGIES USED IN ENERGY-EFFICIENT WOODEN CONSTRUCTION

Renata Stasiak-Betlejewska

Abstract: Energy-efficient wooden construction uses a number of advanced, often patented technologies that combine ecology with high energy efficiency (low energy demand for heating). The main areas of innovation include prefabrication, advanced insulation materials, and structural systems. This study explores innovative technologies applied in the energy-efficient wooden construction, including engineered wood products, prefabrication, BIM, AI, and renewable energy integration. The research applies Structural Equation Modelling (SEM) to analyse the relationships between technological adoption and energy performance outcomes.

Keywords: timber construction, energy efficiency, BIM, CLT, SEM, sustainability

1. INTRODUCTION

The global construction industry is responsible for a substantial share of energy consumption and greenhouse gas emissions. The need for low-carbon solutions has accelerated the development of sustainable building technologies. Timber construction has gained increasing attention due to its renewable nature, carbon sequestration capacity, and lower embodied energy compared to traditional materials. The construction industry, responsible for approximately 40 % of global carbon emissions, plays a pivotal role in environmental degradation, primarily due to its substantial resource consumption and waste generation. The adoption of sustainable building materials is a crucial measure in response to these environmental challenges. By focusing on materials that offer renewable sources, low emissions, and enhanced energy efficiency, the construction industry can significantly reduce its overall environmental impact (Isakson et al. 2018; Kuzior et al. 2026; Sandanayake 2022).

Recent research emphasizes that wood-based construction systems offer significant innovation potential across all phases of the building lifecycle, from design to demolition. In this context, the energy-efficient wooden construction integrates advanced materials and digital technologies to optimize performance and sustainability. The integration of advanced materials and digital technologies is revolutionizing timber construction across all lifecycle phases (Timber Construction Industry 2026, Sironen, 2025; Starzyk et al. 2024; Blanchet et al. 2024):

1) Key Advanced Materials:
- Mass Timber Products: Engineered wood such as Cross-Laminated Timber (CLT) and Glue-Laminated Timber (Glulam) provide structural strength that rivals traditional materials, enabling mid- and high-rise wooden architecture.
- Nanomaterials: The integration of nanocellulose and wood-foam enhances the thermal performance and biodegradability of modern timber structures.
- Smart Panels: Phase Change Materials (PCMs) impregnated directly into wood structures regulate indoor temperatures naturally by absorbing and releasing thermal energy.

2) Digital & Manufacturing Technologies:
- Prefabrication: Off-site CNC milling and laser-guided measurement systems ensure high dimensional accuracy, minimizing material waste and construction time (Construction Industry Outlook 2025/2026).
- BIM (Building Information Modelling): Digital planning allows architects and engineers to optimize resource use, ease planning complexity, and accurately simulate a building's energy performance (Zhao et al. 2025) .
- Circular Economy Tools: Technologies such as AI-driven robotic separation (e.g., Urban Machine) safely extract, clean, and recycle used timber from demolished buildings to extend the material's lifecycle.

3) Lifecycle Advantages:
- Design Phase: BIM drastically cuts material waste and allows for easy disassembly, promoting circularity.
- Construction Phase: Mass timber elements are significantly lighter than concrete, requiring shallower foundations and resulting in fewer construction site deliveries.
- Demolition Phase: Prefabricated timber components are increasingly designed for deconstruction (DfD), which preserves the wood for future reuse or recycling rather than sending it to a landfill.

Cross-border coalitions are defining the future of wood in the built environment through the Building – Breakthrough Agenda Report 2025 by the IEA (Xianli 2026).

Engineered Wood Products (EWPs) represent one of the most significant technological advancements in modern construction engineering. Unlike conventional solid timber, EWPs are manufactured by bonding wood veneers, strands, fibers, or lumber under controlled industrial conditions to produce structural materials with superior mechanical performance, dimensional stability, and durability. These products have transformed the construction industry by enabling taller, stronger, and more sustainable timber buildings while reducing environmental impacts associated with traditional construction materials such as concrete and steel (Ding et al. 2022; Yadav & Kumar, 2021; Gong, 2022).

Engineering technologies overcome these disadvantages by reorganizing wood fibers into optimized structural configurations. Modern EWPs maximize the utilization of raw materials while improving structural reliability and reducing variability. Growing demand for low-carbon construction solutions, resource efficiency, and circular economy principles has accelerated research and industrial implementation of innovative engineered wood systems. Combined with digital design tools, advanced manufacturing technologies and Building Information Modelling (BIM), engineered wood products have become a cornerstone of sustainable building practices worldwide (Zhang, 2026).

Structural Innovations in Modern Timber Engineering include: mass timber construction, hybrid timber structures, timber-concrete composite systems, modular prefabrication, innovative connection technologies, fire performance innovations and digital technologies supporting engineered wood. Mass timber refers to large prefabricated structural systems manufactured using engineered wood products and it has emerged as a primary technology for sustainable urban development. Owing to this solutions industrial prefabrication enables entire building modules to be manufactured off-site.

Digital Technologies Supporting Engineered Wood like Building Information Modeling (BIM) facilitates are following: structural optimization, clash detection, lifecycle management, construction sequencing. AI applications in Engineered Wood include: structural optimization,

predictive maintenance, defect detection, manufacturing quality control. Machine learning algorithms improve production efficiency and minimize waste. Recent patent activity reveals several dominant technological directions (Table 1).

Table 1. Technologies within Engineered Wood Products

Innovation Area	Primary Objective	Technological Impact
Cross-Laminated Timber	Structural optimization	High
Composite wood panels	Material efficiency	High
Hybrid timber systems	Increased load capacity	High
Timber-concrete composites	Structural performance	Medium–High
Smart timber panels	Digital integration	Emerging
Structural connectors	Seismic resistance	High
Automated manufacturing	Productivity improvement	High
Lightweight timber panels	Material reduction	High

The majority of patents originate from North America, Europe, Japan, and increasingly China, reflecting strong governmental support for sustainable construction technologies.
Current research trends that concern Engineered Wood include: bio-based structural adhesives, nanocellulose reinforcement, self-healing wood composites, smart timber with embedded sensors, robotic timber assembly, AI-assisted structural design, 3D printing of wood composites, moisture-resistant engineered wood, carbon-neutral manufacturing technologies. These innovations aim to further improve durability, sustainability, and structural efficiency. Future developments are expected to focus on: intelligent structural health monitoring, AI-driven optimization, fully automated prefabrication, robotic construction, carbon-negative building systems, multifunctional timber composites, bio-inspired structural materials, integration with renewable energy technologies (Kuzior et al. 2026, Potkany et al. 2018). The convergence of digital manufacturing, material science, and sustainable engineering will likely establish engineered wood as one of the dominant structural materials in twenty-first-century construction.

Author of that paper presents and explores innovative technologies applied in the energy-efficient wooden construction, including engineered wood products, prefabrication, BIM, AI, and renewable energy integration. The research applies Structural Equation Modelling (SEM) to analyse the relationships between technological adoption and energy performance outcomes.

2. RESEARCH METHODOLOGY

This study adopts a quantitative research design to examine the influence of innovative technologies on the energy performance of wooden buildings. Proposed conceptual framework assumes that the adoption of advanced technologies contributes directly and indirectly to improved energy efficiency, sustainability, and operational performance of timber construction projects. Structural Equation Modelling (SEM) was selected because it enables the simultaneous examination of multiple latent variables and causal relationships while accounting for measurement errors. Compared with traditional regression techniques, SEM provides a comprehensive assessment of direct, indirect, and mediating effects among technological and performance variables.

The conceptual model consists of six latent constructs: Engineered Wood Technologies (EWT), Prefabrication Technologies (PREF), Digital Construction Technologies (DIG), Renewable Energy Integration (REI), Energy Performance (EP), Sustainability Performance (SP).
The study employs Structural Equation Modelling (SEM) to evaluate relationships between latent constructs: Engineered Wood Technologies (EWT), Digital Technologies (DT), Energy Efficiency (EE), and Sustainability Performance (SP). Data were simulated for 250 observed applied solutions analysed in the paper.
Proposed research framework assumes that technological innovation improves the energy efficiency of wooden buildings both directly and through enhanced building performance.
Based on the literature on sustainable construction, smart buildings, and timber engineering, the following hypotheses are proposed:
H1. Engineered wood technologies positively influence energy performance.
H2. Prefabrication technologies positively influence energy performance.
H3. Digital technologies (BIM, Artificial Intelligence and IoT) positively influence energy performance.
H4. Renewable energy integration positively influences energy performance.
H5. Energy performance positively influences sustainability performance.
H6. Digital technologies positively affect the adoption of prefabrication.
H7. Engineered wood technologies positively influence renewable energy integration.
H8. Technological innovation has a significant indirect effect on sustainability performance through energy performance.
The questionnaire consists of 30 items measured using a seven-point Likert scale ranging from 1 ("strongly disagree") to 7 ("strongly agree").
Example items in the questionnaire concerns: engineered wood products improve thermal performance, prefabricated timber components reduce construction waste, BIM and AI improve energy-oriented design decisions.
Data were collected through a structured survey conducted among professionals involved in the sustainable timber construction including: architects, structural engineers, construction managers, prefabrication manufacturers, energy consultants, researchers. The target sample comprised 380 respondents, which satisfies the recommended sample size for covariance-based SEM analyses.

3. RESEARCH RESULTS AND DISCUSSION

The empirical model was analysed using SmartPLS 4 (PLS-SEM approach) due to its suitability for analysing complex models with multiple latent variables and predictive relationships. The analysis was performed in two stages.
In the research stage 1, that concerns Measurement Model Assessment, the reliability and validity of the constructs were evaluated using: Cronbach's Alpha (>0.70), Composite Reliability (CR >0.70), Average Variance Extracted (AVE >0.50), Indicator Loadings (>0.70), Variance Inflation Factor (VIF <3.3), Heterotrait–Monotrait Ratio (HTMT <0.85).
Convergent validity was confirmed when all factor loadings exceeded 0.70 and AVE values were above 0.50. Discriminant validity was assessed using both the Fornell–Larcker criterion and the HTMT ratio.

In the research stage 2 that concerns Structural Model Assessment, the structural model was evaluated using: path coefficients (β), t-statistics, p-values, coefficient of determination (R^2), predictive relevance (Q^2), effect size (f^2), standardized root mean square residual (SRMR). Statistical significance was accepted at $p < 0.05$. The structural model can be expressed as:

$$EP = \beta_1 EWT + \beta_2 PREF + \beta_3 DIG + \beta_4 REI + \varepsilon$$

$$SP = \beta_5 EP + \varepsilon$$

where:

- **EP** = Energy Performance,
- **SP** = Sustainability Performance,
- **EWT** = Engineered Wood Technologies,
- **PREF** = Prefabrication,
- **DIG** = Digital Construction Technologies,
- **REI** = Renewable Energy Integration,
- **β** = standardized path coefficients,
- **ε** = error term.

The proposed SEM model is expected to demonstrate satisfactory psychometric properties, including:

Indicator	Recommended value
Cronbach's Alpha	> 0.70
Composite Reliability	> 0.70
AVE	> 0.50
HTMT	< 0.85
SRMR	< 0.08
R^2 (Energy Performance)	> 0.50
R^2 (Sustainability Performance)	> 0.60

4. CONCLUSION

The results of the SEM analysis are expected to demonstrate that digitalisation, engineered wood technologies, and prefabrication exert significant positive effects on energy performance, while improved energy performance acts as a mediator linking technological innovation to overall sustainability performance. Presented research findings provide empirical support for the strategic adoption of advanced technologies in energy-efficient wooden construction and offer evidence-based guidance for practitioners and policymakers seeking to accelerate the transition toward low-carbon buildings.

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REFERENCES

1. Blanchet, P., Perez, C. & Cabral, M.R. (2024): *Wood Building Construction: Trends and Opportunities in Structural and Envelope Systems*. Curr. For. Rep. 10, 21–38 (2024). https://doi.org/10.1007/s40725-023-00196-z
2. Construction Industry Outlook 2025/2026, Atradius, 2025.
3. Ding, Y., Pang, Z., Lan, K., Yao, Y., Panzarasa, G., Xu, L., Hu, L. (2022). *Emerging engineered wood for building applications*. Chemical Reviews, 123(5), 1843-1888.
4. Gong, M. (Ed.). (2022). *Engineered wood products for construction*. BoD–Books on Demand.
5. Isaksson, A., Linderoth, H. (2018): *Environmental considerations in the Swedish building and construction industry: the role of costs, institutional setting, and information*, J. Housing Built Environ., 33 (2018), pp. 615-632, 10.1007/s10901-017-9588-8
6. Kuzior, A., Lobanova, A., Tulenkov, M., Karytka, V. (2026), *A Criteria-Based Model for Assessing the Social Efficiency of Agile Project Management in Production-Oriented Organizations under Crisis Conditions*. Production Engineering Archives, vol. 32, no. 3, pp. 461-472. https://doi.org/10.30657/pea.2026.32.38.
7. Potkány, M., Gejdoš, M., Debnár, M. (2018): *Sustainable Innovation Approach for Wood Quality Evaluation in Green Business*. Sustainability. https://doi.org/10.3390/su10092984
8. Sandanayake, M.S. (2022): *Environmental impacts of construction in building industry—A review of knowledge advances, gaps and future directions Knowledge*, 2 (1), 139-156, 10.3390/knowledge2010008
9. Sironen, S., Iliescu, O., Niknafs, P., Amiri, A., Rohdin, P., (2025). *Review on the potential to circulate wood-based materials in the building sector*. Environmental Research: Infrastructure and Sustainability, 5(3), 032001.
10. Starzyk, A., Rybak-Niedziółka, K., Nowysz, A., Marchwiński, J., Kozarzewska, A., Koszewska, J., Piętocha, A., Vietrova, P., Łacek, P., Donderewicz, M., Langie, K., Walasek, K., Zawada, K., Voronkova, I., Francke, B., & Podlasek, A. (2024). *New Zero-Carbon Wooden Building Concepts: A Review of Selected Criteria*. Energies, 17(17), 4502. https://doi.org/10.3390/en17174502
11. Yadav, R., & Kumar, J. (2021). *Engineered wood products as a sustainable construction material: A review*. IntechOpen.
12. Zhang, C., Behrens, P., & Myers, R. J. (2026). *Aligning circular economy and low-carbon economy for a sustainable built environment*. Cell Reports Sustainability.
13. Zhao, S., Deng, H., Cao, J., Gustaf, M., (2025): *Digital transformation of construction enterprises and carbon emission reduction: evidence from listed companies*. Front. Environ. Sci. 13:1570182. doi: 10.3389/fenvs.2025.1570182
14. *Timber Construction Industry 2026*: What Lies Ahead, January, 2026 by Werner
15. Xianli, Z. (2026), *Global Climate Policy 2026-2028: Strategic Assessment & Priority Actions for Governments, Businesses, and Investors*. http://dx.doi.org/10.2139/ssrn.6351380

Authors address:
Renata Stasiak-Betlejewska[1]
[1] Department of Production Engineering and Safety, Faculty of Management, Czestochowa University of Technology, Częstochowa, Poland

CHAPTER I
TECHNOLOGICAL INNOVATIONS IN PRODUCTION AND CONSTRUCTION

FLEXURAL PROPERTIES OF DEEP EUTETIC SOLVENT (DES) TREATED WHITE WILLOW (*Salix Alba* L.)

Dario Pervan, Miljenko Klarić, Kristina Klarić

Abstract: This study investigates the effects of two deep eutectic solvent (DES) treatments on the flexural properties of white willow (*Salix alba* L). Deep eutectic solvents have recently gained attention as environmentally friendly and cost-effective solvents for wood and woody biomass treatment, with increasing research interest due to their biodegradability and lower cost compared to ionic liquids. As DESs can modify the chemical structure of wood, particularly lignin and hemicelluloses, they also influence its mechanical properties. The aim of this work is to evaluate changes in mass and flexural properties of DES treated white willow wood. Flexural testing was conducted according to ASTM D143. White willow was selected as a fast-growing, low-density hardwood with a relatively homogeneous structure, making it suitable as a model material and supporting the valorisation of low-value hardwood resources for wider industrial use. Type 3 DES systems were used based on choline chloride as hydrogen bond acceptor and urea and lactic acid as hydrogen bond donors. The study contributes to a better understanding of how DES pretreatment affects the mechanical properties of lower-density hardwood.
Keywords: Deep eutetic solvents (DES), Flexural properties, white willow (*Salix alba* L.)

1. INTRODUCTION

Chemical wood modification technologies have attracted attention over the past decade due to the growing need for environmentally friendly processing methods. Standard chemical modification methods often involve toxic solvents and high energy consumption. Deep eutectic solvents (DES) have emerged as promising green alternatives to ionic solvents because of their biodegradability, low toxicity, low cost, and ease of preparation. DES systems comprise of two components: a hydrogen bond acceptor and a hydrogen bond donor. Their combination produces a eutectic mixture with a melting point lower than that of either component used. They often form a liquid at room temperature. Among the various agents for preparing DES, those based on choline chloride as a hydrogen bond acceptor and acids or amides as hydrogen bond donors are the most attractive due to their low cost and availability (Vanda *et al.* 2018). Recent studies have shown that DES interact effectively with lignocellulosic wood components, partially dissolving and modifying lignin and hemicellulose, which leads to changes in the chemical and structural properties of wood (Wu *et al*. 2020). Although DES have been extensively studied for biomass fractionation, delignification, and extraction processes, considerably less attention has been given to their effects on the mechanical properties of solid wood, particularly lower density wood (Alvarez-Vasco *et al.* 2016). White willow (*Salix alba* L.) is a fast growing deciduous tree with low density and a relatively homogeneous structure. Due to its rapid growth and wide distribution in Croatia, it has potential for use in value added wood products. However, its low density and modest mechanical properties often limit its industrial application (Rosso *et al*. 2013) Investigating environmentally friendly modification methods that could alter or improve

its properties may contribute to the utilisation of this wood species. In this study, two deep eutectic solvent systems based on choline chloride as the hydrogen bond acceptor and urea or lactic acid as hydrogen bond donors were used to treat white willow wood. The effects of DES treatment on mass and flexural properties were evaluated. Flexural testing was performed according to ASTM D143 to determine the influence of DES-induced chemical modifications on the bending behaviour of the treated wood. The results indicate the role and potential of DES in processing wood species of lower quality.

2. MATRIALS AND METHODS

2.1. Materials

In this study, samples of white willow lamellas were used with the following dimensions: thickness 7 mm, length 170 mm, and width 40 mm. The moisture content of the lamellas before the treatment was approximately 8 %. The mass of each specimen was around 30 g. Choline chloride (99 %) and lactic acid (90 %) were purchased from ThermoFisher, and urea (98 %) was purchased from VWR Chemicals. DES solutions were prepared by mixing choline chloride with the specified chemical in a beaker. DES based on urea (Reline) and lactic acid were both prepared using a 1:2 molar ratio. The mixture was heated to 60 °C and stirred at 200 rpm until the liquid became clear and homogeneous.

2.2. Methods

Three lamellas were used for each DES treatment. The lamellas were placed in glass containers and submerged in DES at a wood-to-DES mass ratio of 1:30. The container with the lamellas and DES was then placed in a vacuum desiccator to impregnate the samples under vacuum. The samples were kept at a vacuum pressure of -0.09 MPa and a temperature of 95 °C to remove air from the wood and increase the viscosity of the DES. After 1 hour, pressure was released and the container with DES and lamellas was placed on a heater, where the temperature of 95 °C was maintained for 5 hours. Figure 1 shows the lamellas after DES treatment.

Figure 1. White willow lamella after DES treatment with urea (left) and DES treatment with lactic acid (right)

After DES treatment, the lamellas were washed with distilled water to remove excess DES from the surface and then weighed to determine DES retention and mass change. Test specimens for gravimetric and mechanical analyses were subsequently sawn from the treated lamellas. For gravimetric analysis, specimens were dried to an absolutely dry state to determine moisture content and relative mass gain after DES treatment. Specimens intended for flexural testing were conditioned to approximately 8% moisture content using a Memmert UN 110 dryer. Flexural properties were determined according to ASTM D143 using a three-point bending test on a Schenck Trebel UPM 20 T testing machine (Figure 2). The testing procedure was adapted to the sample dimensions, with test samples sawn from each lamella to final dimensions of 170 mm × 12 mm × 7 mm. Support span of 110 mm was used for the three-point bending test.

Figure 2. Schenck Trebel UPM 20 T during testing

The results were then analyzed in SPSS Statistics (IBM) (v2025) and Excel (Microsoft) (v2019). For statistical analysis of the data, the Kruskal–Wallis test was used to determine whether significant differences existed between the sample groups.

3. RESULTS AND DISCUSSION

Results of mass change of lamellas after DES treatment is showed in Table 1. The total mass gain after DES treatment was higher for lamellas treated with the lactic acid-based DES. This was expected, as the lactic acid used for DES preparation contained a certain amount of water. In lamellas treated with the urea-based DES, the water present in the system mainly originated from the hygroscopic nature of choline chloride. The moisture content of lamellas treated with the lactic acid-based DES was 21.85 %, while lamellas treated with the urea-based DES showed a moisture content of 14.92 %.

Table 1. Mass gain of DES treated lamellas

Sample / DES treatment	Mass before treatment (g)	Mass after treatment (g)	Mass gain (%)	Moisture content after treatment (%)	Mass after drying to 8 % (g)	Relative mass gain (%)
Lactic acid based DES	30	38.5	28.33	21.85	33.5	11.7
Urea based DES	25.9	32.3	24.71	14.92	29.1	12.4

After samples were dried to 8% moisture content, the relative mass gains of the treated lamellas became similar. The results for flexural strength and modulus of elasticity are presented in Figures 1 and 2.

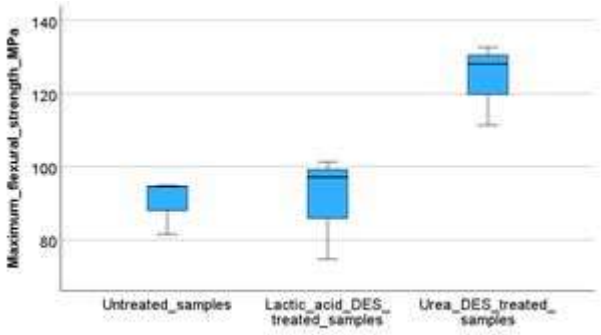


Figure 3. Flexural strength of lamella samples

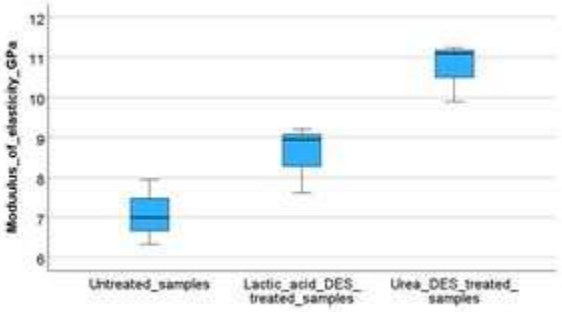


Figure 4. Modulus of elasticity of lamella samples

Both samples treated with DES showed higher flexural strength and elastic modulus. This confirms that DES treatment of wood modifies its internal chemical structure. Lamellae treated with urea-based DES achieved mean flexural strength and modulus of elasticity values of

124.03 MPa and 10.74 GPa, respectively. Samples treated with lactic acid based DES had lower flexural property values (101.36 MPa and 9.2 GPa), while the lowest values were recorded for untreated samples (94.96 MPa and 7.95 GPa). This difference can be explained by the different mechanisms through which DES influences the wood material. Lactic acid based DES, like other more acidic DESs, is more aggressive towards wood components. It primarily acts on lignin by cleaving its ether bonds and effectively dissolving it. Urea based DES does not break the strong bonds in lignin but acts more on cellulose and hemicellulose by disrupting internal hydrogen bonding in the cell wall without excessively degrading the polymer chains. It also leads to plasticisation of the wood structure (Jančíková and Jablonský. 2024). These differences in action result in varying flexural properties. As shown in Table 2, only the samples treated with urea based DES showed a statistically significant difference. Although samples treated with lactic acid based DES showed improvement compared to untreated samples, the differences were less pronounced than those observed with urea based DES.

*Table 2. Pairwise comparisons of untreated, lactic acid DES, and urea DES samples (ns – not significant ($p > 0.05$); * – significant at $p < 0.05$.)*

	Adj. p-value	Significance
Untreated vs. Lactic acid DES-treated	0.890	ns.
Untreated vs. Urea DES-treated	0.034	*
Lactic acid DES-treated vs. Urea DES-treated	0.408	ns.

4. CONCLUSION

This study investigated the potential of using deep eutectic solvents (DES) to enhance the properties of white willow (*Salix alba* L.) wood. The results showed that both lamella treatments resulted in higher flexural property values, although the extent of improvement depended mainly on the type of DES used. The milder treatment (DES with urea) appears to be the more favorable option, as it results in higher flexural strength values in tested samples. The results also confirm that white willow, a low-density species with poor mechanical properties, can be improved by DES treatment. This demonstrates the potential of DES as an ecological pretreatment for enhancing mechanical properties of lower density wood species.

REFERENCES

1. Alvarez-Vasco, C.; Ma, R.; Quintero, M.; Guo, M.; Geleynse, S.; Ramasamy, K.K.; Zhang, X. (2016): Unique low-molecular-weight lignin with high purity extracted from wood by deep eutectic solvents (DES): a source of lignin for valorization. Green Chemistry 18 (19): pp. 5133-5141.

2. Jančíková, V.; Jablonský, M. (2024): Exploiting deep eutectic solvent-like mixtures for fractionation biomass, and the mechanism removal of lignin: a review. Sustainability 16 (2): 504.
3. Rosso, L.; Facciotto, G.; Bergante, S.; Vietto, L.; Nervo, G. (2013): Selection and testing of *Populus alba* and *Salix* spp. as bioenergy feedstock: preliminary results. Applied Energy 102: pp. 87-92.
4. Vanda, H.; Dai, Y.; Wilson, E.G.; Verpoorte, R.; Choi, Y.H. (2018): Green solvents from ionic liquids and deep eutectic solvents to natural deep eutectic solvents. Comptes Rendus Chimie 21 (6): pp. 628-638.
5. Wu, Y.; Yang, L.; Zhou, J.; Yang, F.; Huang, Q.; Cai, Y. (2020): Softened wood treated by deep eutectic solvents. ACS Omega 5 (35): pp. 22163-22170.
6. ***: ASTM D143 (latest revision): Standard Test Methods for Small Clear Specimens of Timber. ASTM International, West Conshohocken, PA, USA.

Authors address:

Pervan, D[1]; Klarić, M[1]; Klarić, K[2]
[1] Department of Materials Technology, Faculty of Forestry and Wood technology, University of Zagreb, Zagreb, Croatia
[2] Department of Production Organisation, Faculty of Forestry and Wood technology, University of Zagreb, Zagreb, Croatia
*Corresponding author: dpervan@sumfak.unizg.hr

INFLUENCE OF TOOL HOLDER DESIGN ON ROUGHNESS OF THE MILLED PLYWOOD SURFACE

Alen Ibrisevic, Murco Obucina, Ruzica Beljo Lucic, Goran Mihulja

Abstract: The production of special plywood products sometimes requires a milling process to cut out various component shapes. It is crucial that the machined surfaces are of relatively high quality, as subsequent sanding of curved surfaces is only feasible through long-term manual work, which is not financially viable. The design and construction of a tool holder for computer numerical control (CNC) machines are important for the stability of the wood milling process and thus for the quality of milled surfaces. This study aimed to determine the effect of different tool holder design on the roughness of the milled plywood surfaces. Different tool holders were used with a 12 mm Z2+2 finish router to mill 12 mm plywood panels. Roughness of milled surfaces was measured at two different cutting depths (3 and 6 mm). An analysis of variance (ANOVA) was performed to evaluate the effect of different tool holder design and cutting depth on surface roughness. According to the results of this study, for CNC milled plywood surfaces, it can be concluded that the tool holder design has a statistically significant effect on the surface roughness parameters R_a and R_z, at the 95% confidence level, while the effect of cutting depth is statistically significant only on the surface roughness parameter R_a, but at the 94% confidence level.
Keywords: CNC milling, tool holder, cutting depth, surface roughness, plywood

1. INTRODUCTION

The production of special plywood products sometimes requires a milling process to cut out various component shapes. It is very important to obtain machined surfaces of relatively high quality, as subsequent sanding of curved surfaces is only feasible through long-term manual work, which is not financially viable. The design and construction of a tool holder for computer numerical control (CNC) machines are important for the stability of the wood milling process and thus for the quality of milled surfaces. Various types of tool holders and elastic collets are used to fix tools on CNC machines. The most widely used are tool holders with mechanical tool clamping. The development of tool holders and collets for fixing tools has intensified in recent years. The aim of developing a new tool holder, first of all, is to ensure the accuracy of tool positioning in the chuck, i.e., the goal is to achieve ideal centering of the tool axis in relation to the chuck axis, in order to increase processing accuracy, reduce vibrations and achieve the highest quality processing. There are various special tool holders on the market that, depending on the construction, eliminate unwanted effects such as noise, vibration, and tool heating.

The aim of every production process is to obtain a product with low production costs and high-quality characteristics. For end users, surface quality is one of the most important factors affecting the perceived value and price of the final product (Iskra and Hernandez, 2009). Surface roughness depends on wood properties and processing parameters (Hazir and Koc, 2019; Gurgen et al., 2022; Ibrišević et al., 2023). Surface roughness is the main indicator of wood machining quality on CNC machines (Hazir and Koc, 2019) and depends on the feed rate, cutting depth, tool geometry, and workpiece material (Chen et al., 2012). Feed rate is one of the most important factors affecting surface roughness (Ibrišević et al., 2023). Important

factors are wood species, wood density, and moisture content (Sutcua and Karagoz, 2012), as well as the anatomical section of the wood. The most commonly used surface roughness parameters are R_a and R_z (ISO 4287:1997).
This study aimed to determine the effects of different tool holder designs on the roughness of milled plywood surfaces.

2. MATERIALS AND METHODS

Nine-layer birch (*Betula pendula)* plywood with dimensions of 1105×205×12 mm was milled using a 5-axis CNC machine center VENTURE 316 M (HOMAG GmbH, Germany). Milling was performed using a shank-type milling cutter with solid tungsten carbide (HWM) blades (Z2+2), 12 mm in diameter, produced by CMT Utensili S.p.A. (Pesaro Urbino, Italy) (Figure 1). The samples are labeled with letters indicating the tool holder type and numbers indicating the elastic collet type. The tool was mounted using 8 different tool holders produced by 5 different companies. Six tool holders are with a draw in a collet chuck, one with a heat-shrinking chuck (TER), and one with a hydro clamping chuck (HID). The tools were fixed in the holder with two types of elastic collets (ER32, ER40) produced by Metal World S.p.A (Udine, Italy). In this way 8 clamping type groups were formed (Table 1) with 10 measurements for each group (80 measurements in total). Tools were clamped using torque spanners or by cooling of termo holder. The clamping moments are recomonded by the producer of tool holders, and they are presented in Table 1.

Table 1. Tool holders, used collets, and clamping force

Label	Producer	Collet	Moment (Nm)
AKE32	Ake Knebel (Germany)	ER32	180
TER	Leuco Ledermann (Germany)	n/a	n/a
MEW40	Metal world (Italy)	ER40	196
HID	Leuco Ledermann (Germany)	n/a	5.7
SEM40	Semar (Italy)	ER40	196
LDU32	Leuco Ledermann (Germany)	ER32	130
LKR32	Leuco Ledermann (Germany)	ER32	130
KLE32	Klein tools (Italy)	ER32	130

The rotational frequency of the spindle was 18.000 rpm, and the average feed rate was 7 m/min. Cutting depths were 3 and 6 mm. The milling profile is shown in Figure 1, and its length is 1670 mm.

Figure 1. Profile of milling, milling cutter and surface roughness tester

Figure 2. Different types of tool holder: 1 – AKE32; 2 – TERMO; 3 – MEW40; 4 – HID; 5 – SEM40; 6 – LDU32; 7 – LKR32; 8 – KLE32

The milling was performed at the University of Zagreb Faculty of Forestry and Wood Technology, Croatia. The surface roughness was measured along the machined surface using the surface roughness tester shown in Figure 1 and the Dataview software. Two roughness parameters, R_a (absolute arithmetic mean) and R_z (arithmetic mean deviation of the profile), were determined in accordance with ISO 4287:1997 from the measured surface profile to evaluate the surface roughness of the samples. Measurement of surface profile and determination of surface roughness parameters were performed at the Faculty of Mechanical Engineering, University of Sarajevo, Bosnia and Herzegovina. Statistical analysis of the surface roughness results was performed using two-way ANOVA in Statistica.

3. RESULTS AND DISCUSSION

The results of the surface roughness measurements of the CNC-milled samples are presented in Tables 1 and 2, and in Figures 3 and 4. ANOVA was performed to evaluate the effects of

tool holder type and cutting depth on the surface roughness parameters R_a and R_z. Table 1 presents the effects of tool holder type and cutting depth on the measured R_a values, while Table 2 presents their effects on the measured R_z values.

Table 1. The effect of the tool holder and cutting depth on surface roughness parameter R_a

Effect	*SS*	Degr.of freedom	*MS*	*F*	*p*	Tukey test (Tool holders)
Intercept	1914.81	1	1914.81	3761.85	**0.000**	(1,3,4,5,6,7) (2,3,4,5,7,8)
Tool holder	27.17	7	3.88	7.63	**0.000**	
Cutting depth	1.87	1	1.87	3.67	0.056	
Tool holder × cutting depth	7.92	7	1.13	2.22	**0.032**	
Error	154.74	304	0.51			
Marked values are significant at $p < 0.05$						

Table 2. The effect of the tool holder and cutting depth on surface roughness parameter R_z

Effect	*SS*	Degr. of freedom	*MS*	*F*	*p*	Tukey test (Tool holders)
Intercept	57457.57	1	57457.57	3598.89	**0.000**	(1,3,4,5,6,7) (2,3,4,5,6,7,8)
Tool holder	717.60	7	102.51	6.45	**0.000**	
Cutting depth	18.22	1	18.22	1.14	0.286	
Tool holder × cutting depth	184.07	7	26.30	1.65	0.122	
Error	4853.47	304	15.97			
Marked values are significant at $p < 0.05$						

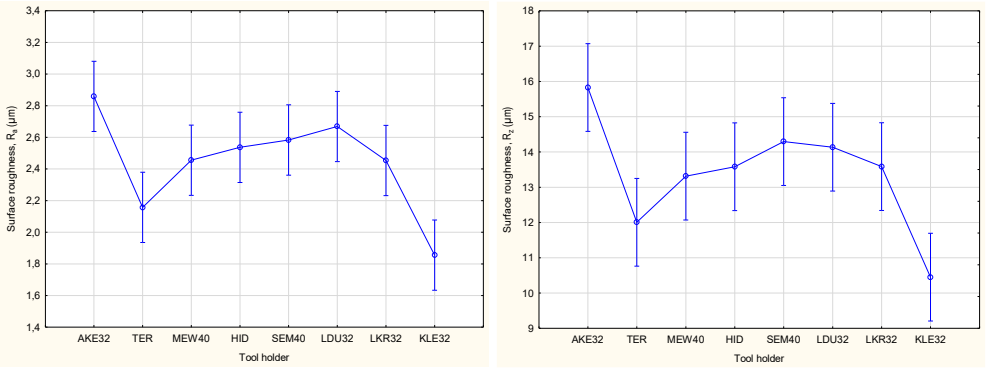


Figure 3. Arithmetic means and 95% confidence intervals of R_a (left) and R_z (right) values depending on the type of tool holder

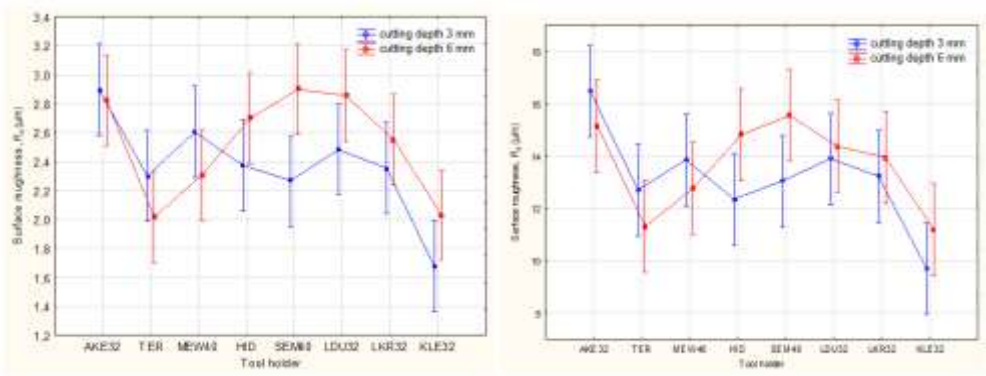


Figure 4. Arithmetic means and 95% confidence intervals of R_a (left) and R_z (right) values depending on the cutting depth and tool holder type

According to the results presented in Tables 1 and 2, increasing the cutting depth from 3 to 6 mm did not have a statistically significant effect on the surface roughness parameters R_a and R_z at the 95% confidence level. However, at the 94% confidence level, the effect on R_a was statistically significant (p = 0.056).

According to Figure 4, as the cutting depth increases, the values of Ra and Rz also increase, i.e., the surface roughness increases. This trend is observed for most holders; however, for certain holders, the surface roughness parameter Ra decreases as cutting depth increases (Figure 4).

ANOVA results show that tool holder type has a statistically significant effect on the surface roughness parameters R_a and R_z (p = 0.000). The best results of surface roughness parameters were obtained with tool holders KLE32 (Klein) and TER (Termo). According to the results of the Tukey test presented in Tables 1 and 2, there are no statistically significant differences of the obtained surface roughness parameters R_a and R_z between the tool holders KLE32 and TER.

KLE32 is a tool holder with standard mechanical tool fixing. It is a simple-construction tool holder produced by Klein (Pesaro, Italy). This tool holder uses a standard ER 32 collet. One advantage of this tool holder is its lower price compared to other tool holders. TER tool holder is a heat-shrinking chuck produced by Leuco Ledermann (Horb am Neckar, Germany). It is a specialised tool holder for precise clamping, and its use is expected to yield good machining quality. The disadvantage of this tool holder is its high price. The worst surface-roughness results were obtained with tool holder AKE, which is unexpected. The AKE tool holder is produced by Ake Knebel (Balingen, Germany). It is a very expensive tool holder, and it is expected to deliver better machining quality.

Two factorial ANOVA (Figure 4, Table 1) shows that the effect of the interaction of tool holder type and cutting depth on surface roughness parameter R_a is statistically significant. It means that the effect of cutting depth on surface roughness is different for different tool holders. According to Table 2 and Figure 4, there is no statistically significant effect of the interaction of tool holders and cutting depth on surface roughness parameter R_z, indicating that the effect of cutting depth on surface roughness is similar for all tool holders.

The effect of tool holder type on CNC-milled surface quality is greater than the effect of cutting depth, which is noticeable in the higher F values for the effect of tool holders.

4. CONCLUSION

The results of the experimental milling have shown that the type of tool holder has a significant effect on the surface quality of CNC-milled plywood. Using a tool holder with mechanical clamping produced by Klein and a tool holder with termo coupling produced by Leuco has achieved the best surface roughness results. Samples machined with Klein and Termo tool holders exhibited 15-30% lower surface roughness than samples machined using the other tool holders. In general, cutting depth did not have a statistically significant effect on surface roughness.

The presented results provide new insights into the use of tool holders. However, further research should investigate noise emission, tool temperature and tool durability to support their practical applications in CNC milling of plywood.

REFERENCES:

1. Chen, C.C.; Liu, N.M.; Chiang, K.T.; Chen, H.L. (2012): *Experimental investigation of tool vibration and surface roughness in the precision end-milling process using the singular spectrum analysis.* The International Journal of Advanced Manufacturing Technology 63: pp. 797-815.
2. Gürgen, A.; Cakmak, A.; Yildiz, S.; Malkoçoğlu, A. (2022): *Optimization of CNC operating parameters to minimize surface roughness of Pinus sylvestris using integrated artificial neural network and genetic algorithm.* Maderas Ciencia y tecnología 24 (1): pp. 1-22.
3. Hazir, E.; Koc, H. (2019): *Optimization of wood machining parameters in CNC routers: Taguchi orthogonal array based simulated angling algorithm.* Maderas Ciencia y tecnología 21 (4): pp. 493-510.
4. Ibrisevic, A.; Obucina, M.; Hajdarevic, S.; Mihulja, G.; Kitek Kuzman, M.; Busuladzic, I. (2023): *Effect of grain and cutting direction of different wood species on surface quality obtained by CNC milling.* Bulletin of the Transilvania University of Brasov Series II 16 (65): pp. 127-140.
1. Iskra, P.; Hernandez, R.E. (2009): *The influence of cutting parameters on the surface quality of routed paper birch and surface roughness prediction modeling.* Wood and Fiber Science 41 (1): pp. 28-37.
2. Sütcü, A.; Karagöz, U. (2012): *Effect of machining parameters on surface quality after face milling of MDF.* Wood research 57 (2): pp. 231-240.
3. ISO 4287:1997: Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters.

Authors address:
Ibrisevic, A.[1]; Obucina, M.; Mihulja, G.[2]; Beljo Lucic, R.[2]
[1] Department of Wood Technology, Faculty of Mechanical Engineering Sarajevo, University of Sarajevo, Sarajevo, Bosnia and Herzegovina
[2]Department of Wood Technology, University of Zagreb Faculty of Forestry and Wood Technology, Zagreb, Croatia
*Corresponding author: gmihulja@sumfak.unizg

INFLUENCE OF UVA AND UVC IRRADIATION ON THE COLOUR CHANGES OF BEECH WOOD (*Fagus sylvatica* L.)

Miljenko Klarić, Kristina Klarić, Gabrijela Dautanec, Dario Pervan

Abstract: The influence of ultraviolet (UVA and UVC) radiation on the colour changes of beech wood (*Fagus sylvatica* L.) has been investigated. Wood samples were exposed separately to UVA and UVC irradiation under controlled laboratory conditions for varying exposure durations, in order to evaluate the extent and nature of colour modification induced by different types of UV irradiation. Colour measurements were performed before and after irradiation using the CIE*L*a*b** colour system, allowing the quantification of changes in lightness (*L**), red-green axis (*a**), and yellow-blue axis (*b**). The total colour difference (Δ*E**) was calculated to assess the magnitude of visible change. Both, UVA and UVC irradiation induced measurable alterations in the surface colour of beech wood, with variations in intensity of change depending on the radiation type and exposure duration. More pronounced changes are determined in samples exposed to UVC irradiation, than in samples exposed to UVA irradiation.
Keywords: beech wood, UVA, UVB, irradiation, colour, CIE *L*a*b**

1. INTRODUCTION

Wood is a natural, renewable and visually attractive material which is widely used in different applications e.g., furniture and decorative products. Besides its mechanical properties, colour is one of the most important surface characteristics influencing the aesthetic value and market acceptance of wood products. The colour of wood depends on various factors, such as: anatomical structure, chemical composition, surface microscopic and macroscopic properties, but it can also be significantly modified by environmental factors such as solar radiation, temperature, humidity and atmospheric oxygen (Fiest and Hon, 1984).

Beech wood (*Fagus sylvatica* L.) is one of the most important European hardwood species and is commonly used in furniture, flooring, veneer and other value-added wood products (Pramreiter and Grabner, 2023). Its relatively uniform texture and light colour make it suitable for different finishing and design applications. However, wood is among others, sensitive to surface discolouration caused by exposure to ultraviolet radiation in indoor and outdoor use, and those colour changes may affect both the visual appearance and the stability of finished wood surfaces (Kúdela *et al.,* 2018).

Ultraviolet radiation is an important factor in wood surface ageing. Depending on wavelength and exposure intensity, UV radiation can initiate photochemical reactions in the main chemical components of wood, especially lignin and extractives (Pandey, 2005). UVA radiation has a longer wavelength and lower photon energy, and it reaches the Earth's surface as part of natural solar radiation. In contrast, UVC radiation has a shorter wavelength and higher photon energy, but it is almost completely absorbed by the atmosphere and normally does not reach the Earth's surface (WHO, 2016). Therefore, while UVA exposure is more relevant to natural service conditions, UVC irradiation can be useful under controlled laboratory conditions for evaluating the sensitivity of wood surfaces to high-energy ultraviolet radiation.

The aim of this study was to investigate the influence of UVA and UVC irradiation on the colour changes of beech wood (*Fagus sylvatica* L.) under controlled laboratory conditions. Special attention was given to the comparison of colour changes caused by different UV radiation types and exposure durations. The results provide insight into the photochemical sensitivity of beech wood surfaces and may contribute to a better understanding of wood colour stability during ultraviolet exposure.

2. MATERIAL AND METHODS

2.1. Material

Test samples were prepared from a kiln dried beech wood (*Fagus sylvatica* L.) element with dimensions of 80 × 12 × 2 cm (L × W × T). The samples were cut in the longitudinal direction from left to right, as shown in Figure 1. First, two 1 cm wide samples were cut for the determination of the initial moisture content (MC). They were followed by seven 5 cm wide samples intended for UV irradiation. In the middle part of the element, two additional 1 cm wide samples were cut for the determination of the initial MC. After that, six further 5 cm wide samples were prepared for UV irradiation, and finally, two 1 cm wide samples were cut from the end of the element for the determination of the initial MC. Samples with odd numbers were intended for UVC irradiation, while samples with even numbers were intended for UVA irradiation. Eight measuring points, at which colour changes were monitored, were marked on each sample. The measuring points were marked using a punch, as shown in Figure 2, rather than with pens or pencils, in order to avoid ink bleeding or graphite smearing on the measuring area, which could affect and disturb the measured colour values. The diameter of the punch ring was 20 mm.

Figure 1. Test samples (photo: Klarić M.)

Figure 2. The punch (photo: Klarić M.)

2.2. Methods

2.2.1. UVA and UVC irradiation

Irradiation of the test samples was carried out in a BS-03 irradiation chamber (Opsytec Dr. Gröbel GmbH, Ettlingen, Germany). Two separately controlled lamp groups covering different spectral ranges were used: Group 1 consists of 10 UVA lamps (irradiance 8 mW/cm^2), while Group 2 consists of 10 UVC lamps (irradiance 10 mW/cm^2). The emission spectra of the lamps are shown in Figures 3 and 4. The lamps were operated at 100 % power. During irradiation, the operating temperature inside chamber according to the chamber design was

approximately 25 °C, which should prevent thermal damage to the specimens. The chamber is characterized by high irradiation uniformity, ensuring consistent exposure conditions across the sample surface. The samples were at the same position in the chamber, during all cycles. The irradiation process was controlled using a UV-MAT Touch controller and dedicated computer software.

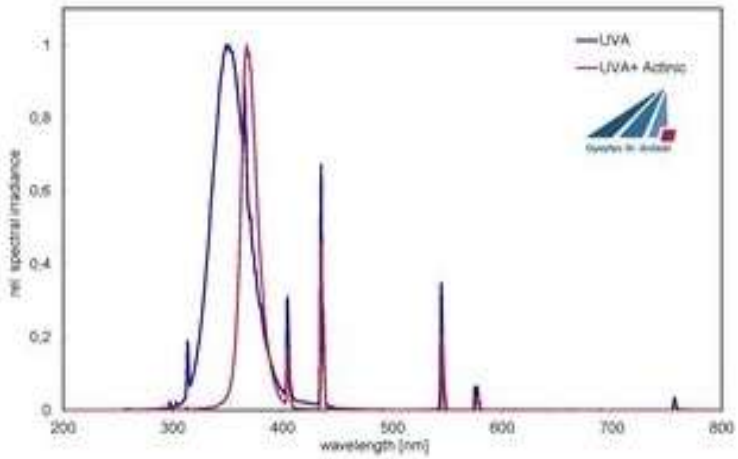


Figure 3. UVA spectra of irradiation-blue (Opsytec Dr. Gröbel, 2026)

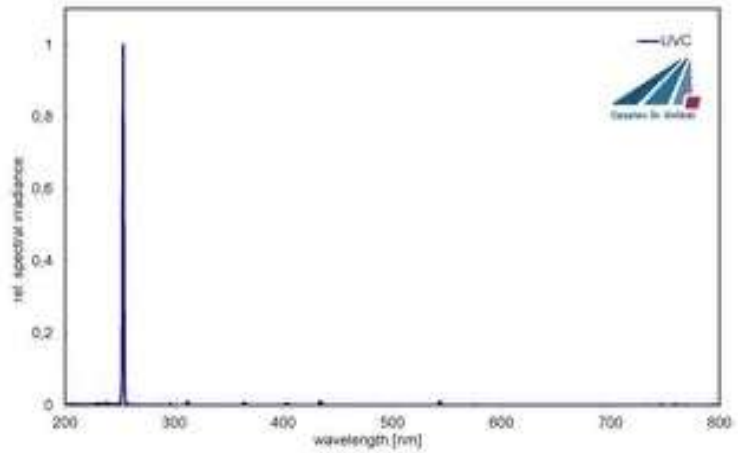


Figure 4. UVC spectra of irradiation (Opsytec Dr. Gröbel, 2026)

The same test samples were irradiated two times, with each irradiation cycle lasting 24 h. Colour was measured before irradiation and after each exposure period, *i.e.,* after 24 h and 48 h of cumulative irradiation. Colour was measured at the same previously marked measuring points on each sample throughout the experiment. Therefore, the colour difference was determined for the same surface area at each measurement interval, which enabled a more reliable evaluation of colour changes caused by irradiation.

2.2.2. Colour measurement

Colour measurements were performed using a Konica Minolta CM-700d portable spectrophotometer, according to the CIE *L*a*b** colour system. The measurement parameters were as follows: D65 standard illuminant, 8 mm aperture diameter, di:8°/de:8° measuring geometry, and 10° standard observer. Eight measuring points were marked on each test sample. Colour was measured before treatment and after each 24 h irradiation interval. Based on the measurements performed before and after irradiation, the changes in individual colour coordinates were determined: lightness difference (Δ*L**), red-green axis difference (Δ*a**) and yellow-blue axis difference (Δ*b**). In addition, the total colour difference of each sample in relation to the initial wood colour was calculated as Δ*E**. The total colour difference was calculated using Equation 1.

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

2.2.3. Initial moisture content determination

Moisture content was determined gravimetrically. The mass of six samples intended for initial MC determination was measured and then oven-dried at 103 ± 2 °C in a Memmert UF75plus drying oven until a constant mass was reached. After oven drying, the samples were cooled in a desiccator and weighed again using the same balance. A Sartorius Entris II Essential precision balance with a capacity of 6200 g and readability of 0.01 mg was used for all mass measurements. The moisture content was calculated according to Equation 2, where m_x is the mass of the sample at the time when the moisture content is determined [g], and m_0 is the mass of the oven-dry sample [g].

$$\omega = \frac{m_x - m_0}{m_0} \times 100\ [\%] \quad (2)$$

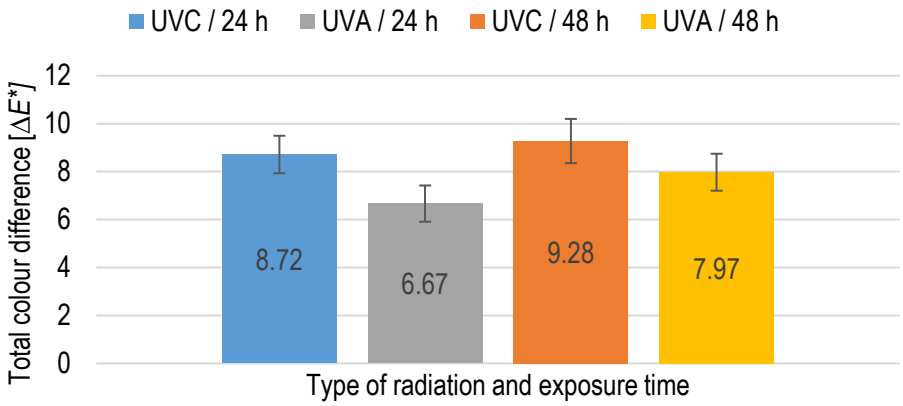
3. RESULTS AND DISCUSSION

The obtained results are presented in Table 1 and Graph 1. Table 1 shows the changes in lightness and individual colour coordinates after 24 h and 48 h of UVA and UVC irradiation. Values are presented as mean ± standard deviation of all measuring points. In addition, the total colour difference (Δ*E**) was calculated in order to evaluate the overall colour change in relation to the initial colour of untreated wood. Graph 1 values presents the total colour difference (Δ*E**) after 24 h and 48 h of irradiation for both UVA and UVC series. Error bars indicate standard deviation. The mean initial moisture content was 13.28 ± 0.25 % (mean ± standard deviation, *n* = 6).

Table 1. Colour changes of beech wood after UVA and UVC irradiation

Radiation type	Exposure time	Δ*L**	Δ*a**	Δ*b**
UVC	24 h	-3.88 ± 0.86	0.61 ± 0.36	7.74 ± 0.64
UVC	48 h	-4.37 ± 0.87	0.48 ± 0.36	8.12 ± 0.91
UVA	24 h	-3.85 ± 0.83	0.52 ± 0.35	5.38 ± 0.48
UVA	48 h	-4.31 ± 0.89	0.73 ± 0.38	6.63 ± 0.48

Graph 1. Total colour difference (ΔE) after 24 h and 48 h of irradiation*



The colour of beech wood changed noticeably after both UVA and UVC irradiation. In all treatments, the most pronounced changes were observed in the lightness coordinate *L** and the yellow-blue axis *b**. After irradiation, *L** values decreased, indicating darkening of the wood surface, while *b** values increased, indicating a shift towards a more yellow colour tone. Changes in the red-green axis *a** were less pronounced.

After 24 h of exposure, the total colour difference Δ*E** was higher for samples exposed to UVC irradiation than for those exposed to UVA irradiation. The average Δ*E** after 24 h was 8.72 for UVC-treated samples and 6.67 for UVA-treated samples. A similar trend was observed after 48 h of exposure, where the average Δ*E** increased to 9.28 for UVC irradiation and 7.97 for UVA irradiation. The higher colour change caused by UVC irradiation can be attributed to its shorter wavelength and higher photon energy (Kataoka *et al*., 2007). Although UVC radiation is normally absorbed by the atmosphere and does not reach the Earth's surface under natural conditions, its use under controlled laboratory conditions enables the evaluation of the sensitivity of wood surfaces to high energy ultraviolet radiation. In contrast, UVA radiation is more relevant to natural exposure conditions, as it reaches the Earth's surface and contributes to the ageing and colour instability of wood surfaces.

The results show that most of the colour change occurred during the first 24 h of irradiation, especially in the case of UVC exposure. Further exposure up to 48 h resulted in an additional increase in Δ*E**, but the increase was less pronounced than during the initial irradiation period. This indicates that the early stage of UV exposure is particularly important for colour modification of beech wood. This trend is in agreement with previous studies showing that wood colour changes caused by photodegradation are most intensive at the beginning of irradiation and become less pronounced with further exposure (Cirule *et al*., 2022; Dzurenda and Dudiak, 2022; Tolvaj and Faix, 1995).

3. CONCLUSION

The results of this study showed that both UVA and UVC irradiation caused noticeable colour changes on the surface of beech wood. UVC irradiation caused more pronounced colour changes on beech wood than UVA irradiation. The colour change was mainly the result of wood darkening, expressed by negative Δ*L** values, and increased yellowness, expressed by positive Δ*b** values. The highest intensity of colour change occurred during the first 24 h of exposure.

Additional colour changes were observed with further exposure up to 48 hours, but their intensity was lower than during the initial exposure period. This indicates that the early phase of UV irradiation is particularly important for colour modification and surface photodegradation of beech wood. This may contribute to a better understanding of the behaviour of beech wood under UV exposure and may be useful in future research for evaluating colour stability, surface protection and finishing treatments.

REFERENCES

1. Cirule, D.; Kuka, E.; Andersone, I.; Andersons, B. (2022): Wood Discoloration Patterns Depending on the Light Source. Heritage Science 10: 158.
2. Dzurenda, L.; Dudiak, M. (2022): Colour Change of Steamed Alder Wood Caused by UV Radiation. Drvna industrija, 73 (3), 289-297.
3. Feist, W.C.; Hon, D.N.-S. (1984): Chemistry of Weathering and Protection. In: The Chemistry of Solid Wood. American Chemical Society, Washington, DC, pp. 401–451.
4. Kataoka, Y.; Kiguchi, M.; Williams, R.S.; Evans, P.D. (2007): Violet light causes photodegradation of wood beyond the zone affected by ultraviolet radiation. Holzforschung. 61 (2007): pp. 23-27.
5. Kúdela, J.; Kubovskỳ, I; Andrejko M. (2018): Impact of Different Radiation Forms on Beech Wood Discolouration. Wood Research 63 (6): pp. 923-934.
6. Pandey, K.K. (2005): A Note on the Influence of Extractives on the Photo-discoloration and Photo-degradation of Wood. Polymer Degradation and Stability 87 (2): pp. 375-379.
7. Pramreiter, M.; Grabner, M. (2023): The Utilization of European Beech Wood (Fagus sylvatica L.) in Europe. Forests 14 (7): 1419.
8. Tolvaj L.; Faix, O. (1995): Artificial Ageing of Wood Monitored by DRIFT Spectroscopy and CIE L*a*b* Color Measurements. Holzforschung 49: pp. 397-404.
9. ***: Opsytec Dr. Gröbel (2026): Spectra of irradiation chamber BS-03. Accessed online: 7 June 2026.
   URL: https://www.opsytec.com/products/irradiation-chamber/bs-03
10. ***: WHO (2016): Ultraviolet radiation. Accessed online: 7 June 2026.
    URL: https://www.who.int/health-topics/ultraviolet-radiation#tab=tab_1

Authors address:
Klarić, M.[1]; Klarić, K.[2]; Dautanec, G.[3]; Pervan, D.[1]
[1] Department for Materials Technology, Faculty of Forestry and Wood Technology, University of Zagreb, Zagreb, Republic of Croatia
[2] Department for Production Organisation, Faculty of Forestry and Wood Technology, University of Zagreb, Zagreb, Republic of Croatia
[3] Student of Faculty of Forestry and Wood Technology, University of Zagreb, Zagreb, Republic of Croatia

*Corresponding author: mklaric@sumfak.unizg.hr

TIMBER AS A STRUCTURAL MATERIAL IN THE AGE OF CONCRETE

Vesna Grujoska

Abstract: Despite the predominance of concrete in contemporary construction sector, wood is increasingly re-emerging as a viable structural material. This is largely due to its favorable properties and its capacity to combine structural performance with environmental and aesthetic benefits. This paper aims to examine the evolution of timber structures in Europe, from the beginning of 21st century to the present day, highlighting its advantages as smart and improved construction material, primarily through the development of advanced engineered wood products such as cross-laminated timber (CLT) and glued laminated timber (glulam). Additionally, technological innovations enable the possibilities for timber to be positioned as a potential smart material with advanced properties. The research is based on recent literature review and analysis of selected case studies. The findings highlight wood's advantageous properties, such as structural efficiency, sustainability and efficiency in the construction process, emphasizing the strong potential of wood in future structural practice.
Keywords: timber constructions, structural efficiency, sustainability, CLT, glulam, smart material

1. INTRODUCTION

21th century overview of construction sector can be identified by advances in technology use and sustainable and modern concept. Urbanization and environment is synergy concept that challenges the construction sector as one of the most advanced concepts especially from economical perspective.

Generally we can say that we live in era where concrete is main construction material due to its many advantages as high strength, durability, versatility, and cost-effectiveness. Diverse architectural and structural requirements can be achieved through the capability of concrete to be cast in different shapes. But the limited natural resources for production of concrete, as well as the CO_2 emission during the production of cement are drawbacks that are not in accordance with the contemporary sustainability requirements. In response to the environmental challenges associated with concrete use, timber can provide a viable alternative to concrete in structural application. As an advanced engineering product cross-laminated timber (CLT) and glued laminated timber (glulam) can satisfy the key structural requirements related to strength, stiffness, stability, durability, and safety. This enables new wave of timber construction gaining momentum in the 21st century.

If the construction sector is observed through CO_2 emission, then timber structures are considered as a storage of CO_2 contrary to concrete and steel structure which are significantly contributing to CO_2 emissions that had to go into the atmosphere, *(Horx-Strathern et al.2017)*

CLT panels are made of glued boards layered at 90 degrees between each later. With this arrangement of the boards in two ways is achieved two way spanning. The strong axis corresponds to the direction in which the majority of the layers are oriented. Glulam is

manufactured from layers of timber that are all oriented in the same direction and the use is mostly for linear elements as columns and beams.

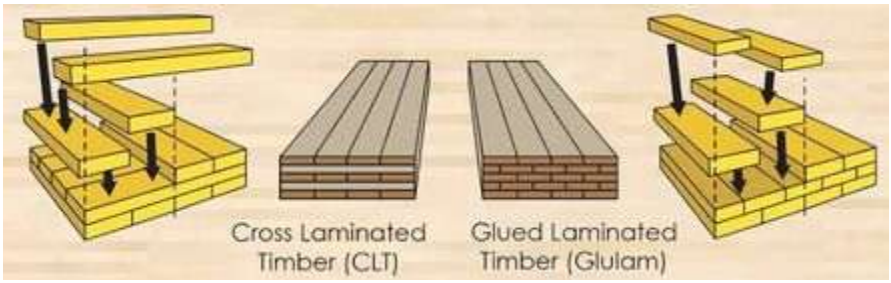


Figure 1 Structural Comparison: Cross Laminated Timber vs Glued Laminated Timber, (Brooshakian, 2016)

CLT offers a range of advantages:

- High strength in relation to the weight
- Prefabrication
- Good thermal insulation
- Fire resistance (protective layer is form after outer layer is char)
- Chemical resistance
- Flexible production
- Long-term carbon storage, (Fröbel, 2022)

According to Tran et al. (2020) building and construction materials are one of the three main factors that are affecting Indoor Air Quality (IAQ). Also use of timber helps maintain balanced indoor humidity conditions, which can prevent bacterial growth.

2. STATE-OF-THE-ART

Current century was considered as an era for high rise timber buildings all around the world. The use of large CLT panels is the main reason for growth of the timber construction industry. Timber in the construction sector was differently appreciated over the last few decades. First, as a treating material prone to fire, timber was forbidden to be used for multi story buildings. But today's advanced version of construction timber overcomes the disadvantages which were stopping the massive use of timber for multi story structures.

Växjö, Sweden, is known as Europe's first modern wooden city. The city Växjö declared to be completely fossil-free in energy supply by year 2050. Wood processing industry is present in this part of Sweden therefore, it is highly advantageous to utilize this potential. From 2006-2009 in this area were built multiple eight-story timber buildings (CLS structures with some stud-and-rail parts as dividing walls between apartments), (Johansson & Schauerte, 2015).

First wooden tennis arena that fill the standards for passive house was also built in this region in 2012. The arena features a structural system comprising load-bearing glulam columns and beams, *(Johansson & Schauerte, 2015).*

Cenni di Cambiamento is a timber complex in Milan Italy completed in 2013. This complex consist of four towers of nine stories connected with two story buildings constructed with CLT and built in just 18 months, *(Rossi, n.d.).*

Figure 2. Cenni di Cambiamento, (Rossi, n.d.).

The Treet building, Bergen, Norway is considered as a remarkable 14 story timber building constructed using CLT panels, along with glulam columns and beams. Strength, durability and sustainability are the main reason why timber is part of this high-rise building. Capture and long-term storage of carbon dioxide (CO_2) exceed the CO_2 emission during the construction process, so this building is considered as carbon-negative structure. This structure is definitely a representation of innovative use of timber and consciousness for the environment, *(Ibrahim & Labaran, 2024).*

In the heart of a city of London, in a dense urban domination by concrete and steel construction, **Black and White building** represent one more environmental friendly structure with modern architectural look. This seven-story building represent tallest office building in central London. Combination of a beech LVL (laminated veneer lumber) frame with CLT slabs and core. To get maximum achievement in sustainability but also in modern design, a glazed curtain wall façade was used, while solar protection is provided through a secondary façade system consisting of vertical timber louvers. The arrangement of the louvers was a parametric model that simulates the movement of the sun, (TU Delft, 2024), (Waugh Thistleton Architects, n.d. - b).

Based on the structural capacity and sustainability, timber is considered as a practical choice in nowadays construction.

3. CASE STUDY OF CHARACTERISTIC HIGH-RISE TIMBER STRUCTURES IN EUROPE, FROM THE BEGINNING OF 21ST CENTURY TO THE PRESENT DAY

Timber structures in Europe has experienced growth in height. This is a consequence of the population growth so the development of the cities were vertical rather than horizontal. The extensive use of CLT and Glulam are responsible for the position of the wooden structure in today concrete era.

At the beginning of the 21st century the new wave of timber use was driven by the enhanced sustainability requirements and CO_2 reduction in construction sector.

E3 building in Berlin (2008) represent a seven-storey timber structure constructed with glulam columns and beams and CLT timber panels for walls, and equipped with two concrete cores, (Tomei et al., 2024).

*Fig. 3 E3 building in Berlin (*EUmies Awards, n.d)

This project renders energy efficient building in order to be maximized the healthy environmental contribution. At the time of construction, the energy consumption of the building was 30% compared to conventional massive building. This project came as a refreshment after changing the regulation in Germany in 2002 for timber structures to be limited to three floor building, *(Moore 2016).* The structure is combination of concrete and timber. Stairwell is a concrete structure next to the fire wall of the neighbor building and is connected with the apartments with footbridges. The timber shell and core of the apartments is timber columns and beams structure. Into the solid timber panels of the facade is integrated the bracing of the building, *(World Construction Network., n.d.)*.

Stadthaus (also known as Murray Grove) in Hackney, London, is a nine-story building built almost entirely from CLT including its load-bearing walls, floor slabs, balcony balustrades and stair and lift cores.

*Fig. 4 a). Stadthaus (also known as Murray Grove) in Hackney, London, (*Archello. n.d.)

b). Construction process of the Stadthaus (instaling CLT panels) (Nevado, 2008)

This building was finished in a time frame in 49 weeks, fully insulated proving that is an eco-friendly and attractive replacement for concrete and steel in the dense urban housing, (*Nevado, 2008)*.

*Fig. 5 Section showing honeycomb structure, (*Waugh Thistleton Architects 2009):

In **2017, Dalston Works** was the world's largest CLT building. As a ten-story building made entirely of CLT the external, party and core walls, the floors and stairs, weighing only one-fifth as much as an equivalent concrete structure, it reduced construction deliveries by 80%.

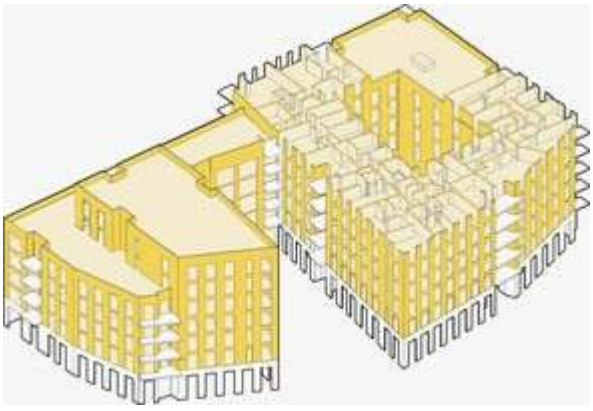


*Fig.6 Drawing showing the CLT structure (*Waugh Thistleton Architects, n.d. - a):

HoHo Wien is one of the tallest wooden high rise buildings in Europe. With 84 m high this twenty-four story building is constructed with glulam columns and CLT panels integrated into a prefabricated concrete–hybrid floor and CLT wall panels along the perimeter, *(RLP Rüdiger, n.d.)* Three towers with 84m , 57m and 40 m are part of this construction. The concrete–timber structural system is attached to the concrete core, positioned on both sides of the core in the 84 m and 40 m towers and directly connected to it in the 57 m tower.

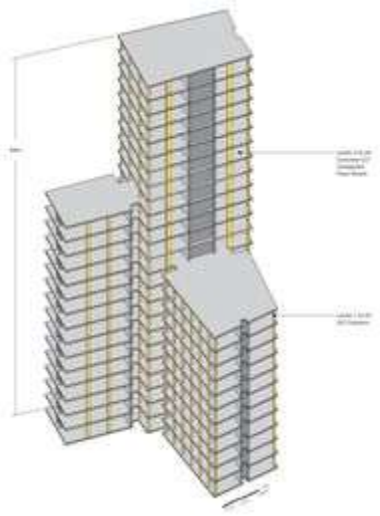


Fig.7 Isometric diagram of HoHo Wien's structural system, showing the relationship between the concrete core, shear walls, and prefabricated floor panels structure, (RLP Rüdiger, n.d)

4. RECENT INNOVATIONS AND FUTURE PROSPECTS OF TIMBER STRUCTURES

Biggest step in the massive use of timber in the concrete and steel construction sector is use of CLT and glulam. Implementation of Building Information Modeling (BIM) technologies in wood construction is highly complementary approach to modern building design and construction. Because high level of prefabrication is involved when it comes to timber structures, the use of BIM will improve construction accuracy and reduce material waste, *(Lobos et al. 2024).*

Timber structures are still in the research lanes. Wood has not yet achieved its full development. Even more improved version of this material are tested. Super strong wood is tested with self-densification strategy by resembling highly aligned wood fibers as functional units and self-densified without the need for hot pressing. Testing showed ultra high tensile strength (496.1 MPa) and flexural strength (392.7 MPa). This material undergoes uniform shrinkage within the cross-section while maintaining its longitudinal dimensions. This results shows that such a strong and yet light material can replace structural materials such as metals, *(Huang et al.* 2025).

5. CONCLUSION

The review of the timber use in the current century showed that timber is viable and sustainable structural solution to the conventional materials as concrete and steel. The new wave of timber use is a response to the advanced use of CLT and glulam which significantly improved structural performance and durability of timber buildings. Additionally timber offers lighter construction, high degree of prefabrication and significant environmental benefits through long-term carbon storage capacity.

The benefits of using timber are reflected through many remarkable multi-story buildings all over Europe. These projects demonstrate that contemporary construction can be achieved with this natural material. Concrete cannot be fully replaced by timber, but many buildings can be replaced and that is a huge environmental contribution.

Construction sector in the future need to be more timber orientated, more frequent use of hybrid timber–concrete systems. Furthermore, the increasing integration of BIM with engineered timber construction is expected to play a crucial role in the future of the industry as well as continued development of new wood products.

REFERENCES

1. Archello. (n.d.). Stadthaus, London (Murray Grove). https://archello.com/project/stadthaus
2. Brooshakian, V. (2016): Re: What are the advantages of cross laminated timber compared to glulam and solid wood? ResearchGate.
3. EUmies Awards (n.d.): e3 Berlin. EUmies Awards. URL: https://eumiesawards.com/heritageobject/e3-berlin/
4. Fröbel, J. (2022): The CLT Handbook: CLT Structures – Design and Detailing. Swedish Wood, Stockholm.
5. Horx-Strathern, O.; Varga, C.; Guntschnig, G. (2017): The Future of Timber Construction: CLT – Cross Laminated Timber. Zukunftsinstitut Österreich GmbH, Vienna.
6. Huang, D.; Li, J.; Li, S.; Hu, J.; Cao, Z.; Guo, Y.; Ding, Y.; Zhu, M.; Chen, Y. (2025): Self-densified super-strong wood. Journal of Bioresources and Bioproducts 10 (2): pp. 199–208. DOI: https://doi.org/10.1016/j.jobab.2025.03.001
7. Ibrahim, U. M.; Labaran, Y. H. (2024): Cultivating holistic approaches to sustainable construction: Insights from the real-world projects. ArtGRID – Journal of Architecture Engineering and Fine Arts 6 (1): pp. 121–150. DOI: https://doi.org/10.57165/artgrid.1382482
8. Johansson, M.; Schauerte, T. (2015): Nine-storey residential timber construction and the wood building strategy of Växjö municipality. In: Proceedings of the 21st International Holzbau-Forum IHF 2015, Garmisch-Partenkirchen, Germany, 2–4 December 2015, pp. 1–10.
9. Lobos Calquin, D.; Mata, R.; Correa, C.; Nuñez, E.; Bustamante, G.; Caicedo, N.; Blanco-Fernandez, D.; Díaz-Huenchuan, M.; Pulgar-Rubilar, P.; Roa, L. (2024): Implementation of Building Information Modeling Technologies in Wood Construction: A Review of the State of the Art from a Multidisciplinary Approach. Buildings 14 (8): 2516. DOI: https://doi.org/10.3390/buildings14082516
10. Moore, C. (2016). E3: Europe's first wooden high-rise – Detailed good practice building report. Wuppertal Institute for Climate, Environment and Energy. https://www.scribd.com/document/437372373/E3-Berlin-Final-1
11. Nevado, M. (2008): Stadthaus N1: Una torre de viviendas de 8 plantas en Londres de madera contralaminada. Infomadera. Available at: https://infomadera.net/uploads/articulos/archivo_5339_2531821.pdf
12. RLP Rüdiger Lainer + Partner (n.d.): HoHo Wien – Hybrid timber high-rise building, Seestadt Aspern, Vienna. URL: https://www.hoho-wien.at/en/hoho-vienna/
13. Rossi Prodi Associati (n.d.): Housing Sociale via Cenni (Cenni di Cambiamento), Milan. URL: https://www.rossiprodi.it/projects/housing-sociale-via-cenni/

14. Tomei, V.; Sciomenta, M.; Sandoli, A. (2024): The Use of Structural Timber in Europe: An Overview on Recent Developments. Proceedings of the 18th World Conference on Timber Engineering (WCTE 2024), Brisbane, Australia.
15. Tran, V. V.; Park, D.; Lee, Y.-C. (2020): Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality. International Journal of Environmental Research and Public Health 17 (8): pp. 2927. DOI: https://doi.org/10.3390/ijerph17082927
16. TU Delft (2024): Black and White Building (Circular Design Atlas case study). Circular Impuls Initiative, Circular Built Environment, Delft University of Technology. URL: https://filelist.tudelft.nl/BK/Onderzoek/Onderzoeksthemas/Circular_Built_Environment/Circular_Impuls_Initiative/Circular_Design_Atlas/2024_UA_Atlas_Black%20and%20White%20Building_reduced.pdf
17. Waugh Thistleton Architects (2009): Murray Grove / Stadthaus, London – 24 Murray Grove residential CLT building. URL: https://waughthistleton.com/murray-grove/
18. Waugh Thistleton Architects (n.d. - a): Dalston Works, London – 10-storey residential CLT development. URL: https://waughthistleton.com/dalston-works/
19. Waugh Thistleton Architects (n.d. - b): The Black & White Building, London. URL: https://waughthistleton.com/the-black-white-building/
20. World Construction Network. (n.d.). E3 residential building, Berlin. https://www.worldconstructionnetwork.com/projects/e3-leaf/

Authors address:
Grujoska,V[1]
[1] Civil Engineering, Faculty of Engineering, International Balkan University, Skopje, N. Macedonia

ARCHITECTURAL PROGRAMMING, CONFIGURATION AND CONSTRUCTION OF MODULAR PREFABRICATED TEMPORARY WOODEN STRUCTURES

Mirza Bašalić, Nerman Rustempašić, Murčo Obućina

Abstract: Monolithic structures made of permanent materials are built as permanent constructions, exclusively on construction land primarily designated for that purpose. On non-construction land, building is highly restricted and possible only under specific conditions and in accordance with all relevant regulations.Monolithic construction typically requires more time; its phases are often discontinuous and irregular, heavily dependent on a significant amount of manual labour, and its main disadvantage is the highly complex process of removing and recycling the used materials.On the other hand, the prefabricated construction of buildings, based on the use of configurable modular systems that rely on traditional materials such as wood, provides an optimal solution for the construction of simple temporary structures.The aim of this research is to analyse the possibilities offered by the architectural programming of temporary modular prefabricated wooden systems, which can offer mass production, simple construction, and ease of use, as well as—ultimately—the possibility of dismantling the structure, freeing the space, and restoring it to its original condition.During the research, data and results from an experimental method involving laboratory testing of characteristic wooden component samples were used to analyse their static stability. Furthermore, a theoretical analysis method was employed to process the collected data and decompose complex processes into simpler phases. The objective was to draw a final conclusion and analyse options for the construction of temporary wooden structures that, through their construction and exploitation, will not permanently destroy agricultural land, while simultaneously ensuring all necessary conditions for use.
Keywords: Architectural Programming, Temporary Structures, Prefabrication, Programmability, Composability, Modularity, Open Prefabrication Systems.

1. INTRODUCTION

The process of planning and defining an architectural work, its creation, and its integration into space differs in many ways today compared to earlier periods and traditional building construction, with a tendency toward major changes in the time to come. The modernization of construction technology, the application of new and more advanced building materials, the desires of investors or space users, the ambition of the architect-designer, and other factors have caused these changes to be highly intensive and strongly pronounced.

The primary goal of this research and the methodological approach during the preparation of this paper is to analyze an open modular prefabrication system, architectural programming, and the use of standardized individual modular components. When combined, create an appropriate configuration of a demountable prefabricated structure primarily made of timber structures.

After analyzing and selecting the appropriate modular timber component, the fabrication and load-bearing testing of the prepared structural samples were performed, followed by reading and recording the obtained results and analyzing the load-bearing capacity.

During the research and preparation of this paper, the method of theoretical analysis was utilized, whereby all collected data were analyzed, and complex processes were broken down into simpler phases. This was done to conclusion while analyzing possible options and solutions for the architectural programming of modular buildings.

Additionally, an experimental method was used to conduct laboratory testing on samples of a typical timber component made of timber, for the purpose of assessing its static stability and geometric immutability under the action of vertical and horizontal loads.

2. ARCHITECTURAL PROGRAMMING OF MODULAR SYSTEMS

The nature of a building and the very process of its creation are highly complex activities, composed of several different interdependent and interconnected phases. When discussing architecture and the creation of an architectural work, one most frequently thinks of two characteristic phases or processes associated with it. The first relates to the designer-architect, who conceptualized and planned the structure, and the second relates to the builder and entails the actual construction of the building. This division can also be found in the writings of one of the first architectural theorists and Roman historians, Marcus Vitruvius Pollio, who likewise links architecture to these two processes. “Architecture connects two aspects; the first is identified with the construction process, and the second presupposes a designer, given that the builder of a primitive hut previously had to conceive it.” (Rodrigez Ljera, 2009, str. 5).

Thus, the process of defining an architectural work consists of multiple complex phases and a series of logically interconnected and coordinated activities by which the architectural work is defined. "The four basic, standard phases in defining architectural space are: (1) preparation of the design brief and program (architectural programming); (2) architectural design; (3) construction; and (4) use and maintenance." (Bijedić, 2012, str. 82)

In professional literature, the term architectural programming is often identified and equated with the preparation of the design brief (program). While these two phases may have common points of contact, in no case do they mean the same thing.

"Architectural programming implies a completely different process compared to the phase of preparing the design brief, and most frequently represents the software-based or other generation of the structure and form of specific parts of a building or the entire building, or otherwise the process of assembling a building from a provided program of finished, prefabricated, individual compatible modules." (Bašalić, 2024, str. 46). Architectural programming – configuring a modular system implies assembling a composition from previously prepared combinable segments; more precisely, individual compatible modules are assembled, which collectively constitute and form a whole into the final product.

2.1. Configurable Modular Systems and the Process of Architectural Programming/Configuration

Today, products are generally not purchased directly from stock on the market; instead, the product is configured by adapting it to the specific requirements of each customer/buyer. This represents one of the key factors for success in the market, meaning that offering the widest possible range of product variants is essential.

"The configuration process is an activity that determines the structure of a product variant tailored to the customer's requirements, within the constraints set by the architecture of the product itself." (Pavlić, 2003, str. 33).

The advantage of serial modular production is a significantly shorter time required for building construction compared to the traditional construction of monolithic structures, as well as a significant simplification of the preparation of design documentation and, ultimately, the construction of the building itself. "Depending on the specific case, the time savings required to complete the process of defining and constructing an architectural object amount to 30–70%." (Parker, 2017, str. 17).

2.2. Construction of Temporary Structures Using Modular Components Assembled from Timber Joists

Timber is one of the oldest building materials. Due to its unique properties and advantages over other materials, it rightfully maintains a significant position in construction today. It is easy to process, lightweight, has good mechanical strength, and is resistant to compression and bending. Furthermore, it possesses good insulation properties and, when adequately protected, can offer satisfactory durability. Regarding the characteristics of timber compared to other construction materials, it is important to note that timber is up to four times lighter than concrete: "Volume mass of timber: 500–800 kg/m³, concrete: 2,400 kg/m³"(Dr. Mirsada Oruč & Dr. Raza Sunulahpašić, 2014, str. 104). Stresses in timber parallel to the grain direction, as well as the strength of the wood fibers, can be compared with the strongest construction materials used in civil engineering today. The remainder of this paper analyzes the application of identical or highly similar modular components that belong to a single system and allow for a greater number of repetitions, such as the component made of timber elements. The dimensions of the basic component "K160" are a width and length/height of 2MJ = 160 cm, and the shortened component "K80" has a width of 2MJ = 160 cm and a length/height of 1MJ = 80 cm.

3. RESULTS

3.1. Laboratory Proof Load Testing of the Basic Component "K160" Structure

At the Institute for Materials and Structures of the Faculty of Civil Engineering, University of Sarajevo, testing was conducted on a timber component with dimensions of 160 x 160 x 15 cm. The component was assembled from fir joists measuring 15x5 cm, which were connected using 2 mm thick metal connector plates and "MASTER" type self-tapping wood screws (5x50 mm and 6x100 mm). The weight of a single assembled component is 48 kg. They were transported individually on a car roof rack and prepared for testing on the Institute's premises.

3.1.1. First Horizontal Load Testing of the Wall Structure Element

The timber component was clamped in a press, leaving its entire length cantilevered, and the load was applied at the very end of the component.

The behavior of the structural element was monitored and recorded from the very beginning until the structural failure. The timber element was fixed in an "AMSLER" press with a pressure of 90 kN.

To measure displacements at characteristic locations, a high-precision Mitutoyo Metric Electronic Digital Calculation Indicator device was used, featuring a stroke of 0–60.9 mm, an allowable error of up to 2.5 µm, and a measured accuracy value of 1.1 µm. The moisture content of the structural timber was measured using an FMC/FME device (moisture meters

feuchtemessgerate Version 6.14). A press (jack) with an integrated manometer for pressure measurement was used to apply the test load. The testing results are presented in a chart and a tabular overview (Figure 1).

The component was loaded in 14 increments, during which displacement, cracking, joint relaxation, and ultimately the structural failure were recorded. As shown in the chart and table, the maximum displacement value reached 40.15 mm, while the residual displacement after unloading amounted to 27.85 mm. A crack appeared in the compression element E5 of the "K160" component at a load value of 130 bar, which corresponds to 12.38 kN. Joint relaxation occurred at a load of 90 bar, corresponding to 13.0 kN.

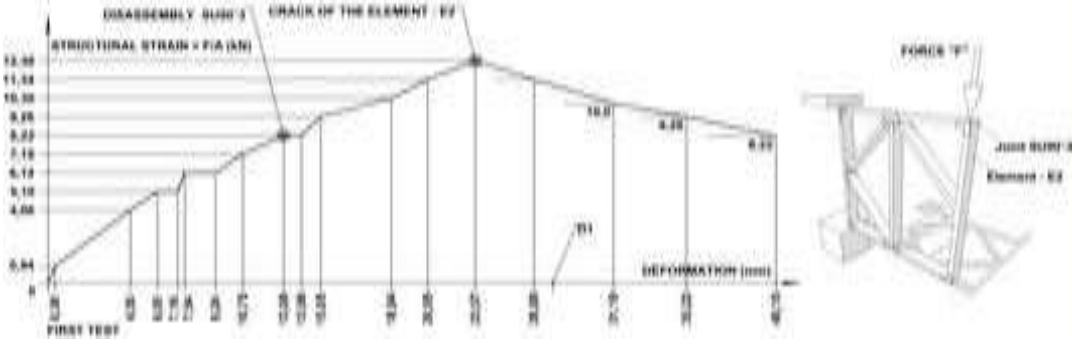


Figure 1. Graphical representation of the first test results

Following the first test, a second test was conducted on an identical component, with the addition of two "MASTER" type 6x100 mm self-tapping wood screws at joints SU90°1 and SU90°3 on the compression member. (Figure 2).

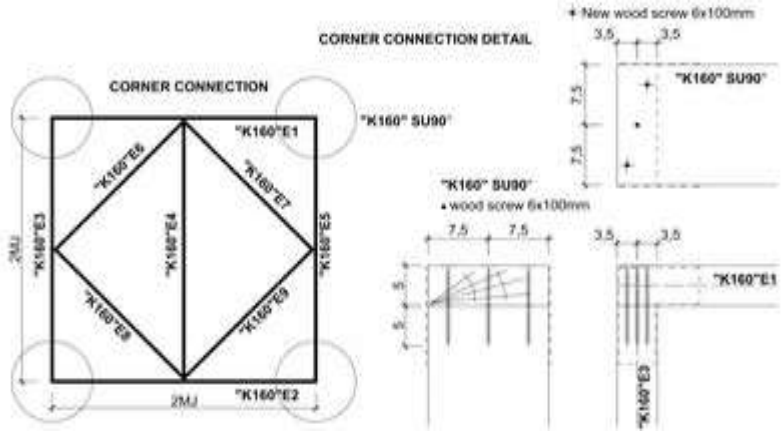


Figure 2. Additional reinforcement of the connection with two screws

The component was clamped in the press in the same manner, leaving its entire length cantilevered, and the load was applied at the very end of the component. As in the previous case, the behavior of the structural element was monitored and recorded from the very beginning until structural failure. The test results are presented in a chart and a tabular overview (Figure 3).

The component was loaded following the same procedure as the previous example, and displacement, cracking, joint relaxation, and ultimately structural failure were recorded. As shown in the chart and table, the maximum displacement value reached 46.68 mm, while the residual displacement after unloading amounted to 29.90 mm.

A crack appeared in the compression element E5 of the "K160" component at a load value of 160 bar, which corresponds to 15.50 kN.

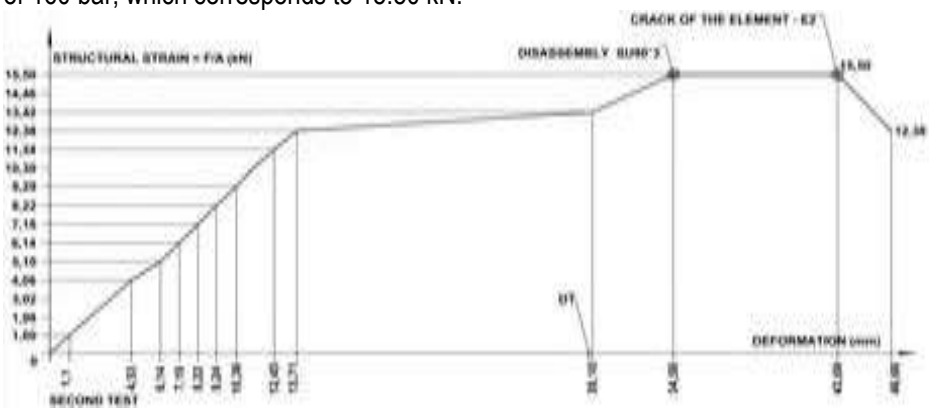


Figure 3. Graphical representation of the second test results

Based on the obtained results, it can be seen that the same element—additionally reinforced with two screws at the two corner joints that proved to be the weakest points of the component—yielded significantly better results. The recorded load value at which the crack appeared was over 25% higher in the second test, while the result regarding joint relaxation improved by over 33%.

The "K160" timber component proved to be a highly stable and durable structure under both horizontal and vertical loads. The horizontal load testing, and particularly the vertical load testing, resulted in minor structural deformations that remain well within allowable limits.

4. CONCLUSION

In the book „Arhitektura Bosne i put u savremeno“, the authors make a basic classification of buildings from the earlier period into “permanent, masonry structures made of solid materials, and transient ones made of weak and easily destructible materials.”(Grabrijan & Neidhardt, 1957, str. 268).

Today, monolithic building construction using permanent and solid materials is most commonly practiced. Compared to prefabricated construction systems, this represents a much more complex process and often carries certain disadvantages, particularly when it comes to temporary or transient structures.

The construction of buildings from solid, permanent materials takes longer; the construction phases are often intermittent and irregular, with less utilization of material and technical possibilities, and the structures are permanent, lacking the capacity for mobility or a temporary lifespan at a specific location.

Architectural programming and the construction of modular, prefabricated, temporary timber structures can offer mass production alongside simple construction, operation, and, ultimately, the ability to remove temporary, transient structures without permanently destroying non-building land.

Therefore, configurable modular prefabrication systems composed of simple elements and components that rely on traditional building materials—particularly timber—offer an optimal solution for constructing buildings that are fundamentally very simple in terms of design, production, transport, assembly, disassembly, and recycling.

REFERENCES

1. Bijedić, D. (2012). *Arhitektura holizam umjesto optimalizacije integralni pristup u arhitektonskom stvaralaštvu.* Sarajevo: Arhitektonski fakultet univerziteta u sarajevu.
2. Grabrijan, D., & Neidhardt, J. (1957). *Arhitektura bosne i put u savremeno.* Ljubljana: Državna založba Slovenije.
3. Jensen, P. (2010). *Configuration of modularised building systems.* Luleå: Luleå tekniska universitet.
1. Mirza Bašalić, (2024) Doktorska disertacija: Arhitektonsko programiranje / konfiguriranje otvorenih sistema modularne industrijske izgradnje poljoprivrednih objekata, (architectural programming / configuration of open systems for modular industrial construction of agricultural facilities) Arhitektonski fakultet Sarajevo
2. Pavlić, D. (2003). *Sustav za konfiguriranje proizvoda modularne arhitekture, Magistarski rad, ZAGREB.* Zagreb: Sveučilište u Zagrebu, Fakultet strojarstva i brodogradnje.
3. Rodrigez Ljera, R. (2009). Kratka istorija arhitekture. Sremska Mitrovica: Imprimator Tabernakl.

Mirza Bašalić [1], Faculty of Architecture, University of Sarajevo, Sarajevo, BiH, mirza.basalic@af.unsa.ba
Nerman Rustempašić [2], Faculty of Architecture, University of Sarajevo, Sarajevo, BiH, nerman.rustempasic @af.unsa.ba
Murčo Obućina[3], Mechanical Engineering Faculty, University of Sarajevo, Sarajevo, BiH, obucina@af.unsa.ba

MECHANICAL PROPERTIES OF END-TO-END GRAIN TENON AND DOWEL JOINTS

Seid Hajdarević, Ibrahim Busuladžić, Margarita Bego, Sandra Martinović

Abstract: This paper investigates the mechanical properties of end-to-end grain tenon joints and dowel joints bonded with PVA-c adhesive, compared with finger joints commonly used in solid-wood furniture manufacturing. Experimental testing and finite element analysis, employing orthotropic linear-elastic and nonlinear constitutive models, were conducted to evaluate strength, stiffness, and stress–strain responses. The results demonstrated that tenon and dowel joints exhibited much lower bending strength than finger joints of equivalent cross-sectional dimensions, while the modulus of elasticity showed no significant variation among the three joint types. Numerical analyses closely matched experimental load–displacement curves, validating the capability of the applied numerical models. Although tenon and dowel joints are less suitable for longitudinal load-bearing applications, they provide sufficient strength for use in solid wood construction.
Keywords: wood, end-to-end grain joint, tenon joint, dowel joint, finger joint, numerical analysis, strength

1. INTRODUCTION

One of the most common types of joints used in furniture design are tenon and dowel joints. These profile–adhesive joints have simple geometry, are easy to manufacture and assemble, and possess neutral aesthetic value. There are multiple variations of tenon joints, which, depending on the connection model, achieve good structural strength and load-bearing capacity. Compared to a tenon joint, a dowel joint has lower structural strength but mechanical properties suitable for moderately loaded structures.

Generally, numerous variables affect joint mechanical properties, such as wood properties, joint profile geometry, adhesive type, and joining process, while the interactions among these factors are even more complex (Ibrisevic et al. 2021). In addition to experimental analysis, numerical methods are widely employed to investigate the effects of numerous variables and to evaluate the mechanical behavior of wood joints. Besides, numerical results depend strongly on the chosen models, constitutive relations, and approximations (Martinovic et al. 2008; Hu and Liu, 2020; Hitka et al. 2026).

The problem with tenon and dowel joints in the formation of end-to-end grain joints is that their mechanical properties are significantly reduced compared to finger joints, due to the geometric complexity of the resulting beam cross section and the adhesive characteristics of the anatomical sections of the wood.

This paper presents numerical stress and strain analyses of end-to-end grain tenon, dowel, and finger joints, conducted using the finite element method with orthotropic linear-elastic and nonlinear models. Numerical results were compared with experimental results of strength and stiffness tests of this types of joints. This paper aimed to explore the mechanical properties and capabilities of the common joints in the case extend wood element length in the construction of solid wood furniture.

2. MATERIALS AND METHODS

The dimensions of the beam formed by joining wood elements with three types of end-to-end grain joints are shown in Figure 1. The physical models of the tenon joint, dowel joint, and finger end-to-end grain joints had the same beam geometry configurations as well as the same loading diagram.

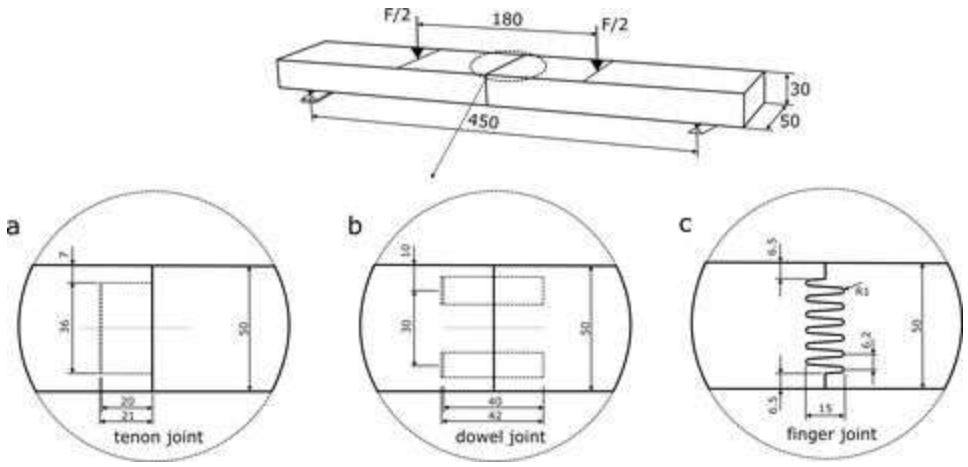


Figure 1. Physical models of the end-to-end grain joints: a) tenon joint, b) dowel joint, c) finger joint

The orthotropic wooden components and the isotropic adhesive of the three types of joints were represented in a numerical 3D nonlinear model (Figure 2), which was solved using the finite element method. Numerical simulations were performed with Abaqus software. Global coordinates were applied to define the grain direction, along with the radial and tangential cross-sectional directions of the wooden parts. A 3D hexahedral solid element was selected to construct the FE mesh. The adhesive layer, with a thickness of 0.1 mm, was connected to the surrounding elements through a TIE-type constraint.

Figure 2. Numerical models of the end-to-end grain joints: a) tenon joint, b) dowel joint, c) finger joint

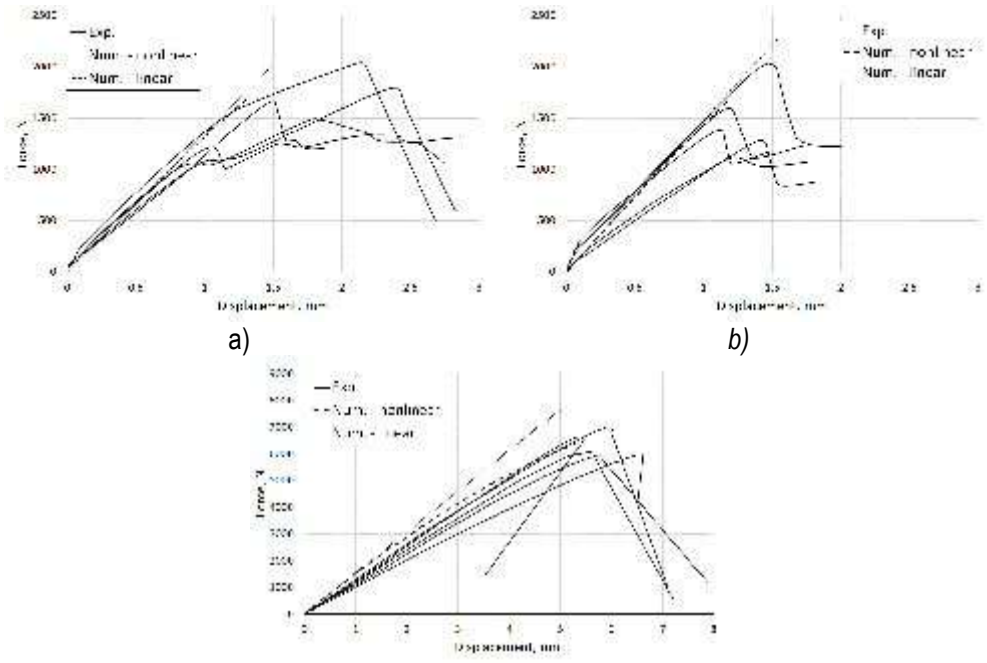
Calculations were carried out for common oak (*Quercus robur* L.) and PVAc adhesive. The elastic properties of these materials are presented in Table 1. Hill's function was applied to describe the anisotropic plastic flow of wood material beyond the yield point (Kawecki and Podgorski, 2020; Kawecki, 2021). The yield stress was determined as 62 MPa for oak wood and 10 MPa for the PVAc adhesive. The numerical results were compared with experimental data reported in studies that investigated the bending strength and modulus of elasticity of the same types of end-to-end grain joints (Hajdarevic et al., 2024).

Table 1. Elastic properties of wood (Tippner et al. 2022) and adhesive (Jain et al. 2017)

Oak wood									PVAc adhesive	
Modulus of elasticity (MPa)			Modulus of rigidity (MPa)			Poisson's ratio			Modulus of elasticity (MPa)	Poisson's ratio
E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}	E	ν
14 669	656	494	1900	2015	127	0.037	0.028	0.326	707.9	0.3

3. RESULTS

The deformation–force diagrams obtained from bending strength tests of five oak wood beam specimens with all three types of joints are shown in Figure 3.



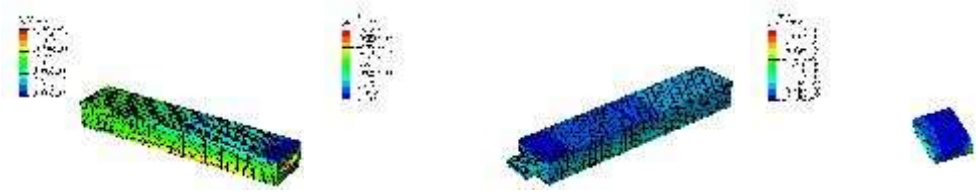
a) b)

c)

Figure 3. Force-displacement diagrams - experimental and numerical results: a) tenon joint, b) dowel joint, c) finger joint

According to the experimental results reported in studies (Hajdarević et al., 2024), the average failure load of tenon joints was 1683.4 N and that of dowel joints was 1510.1 N, corresponding to 26.3% and 23.2% of the average failure load (6390.0 N) of the finger joints, respectively. Furthermore, the average bending strength of tenon joints was 15.7 MPa (coefficient of variation, CV = 14.3%) and that of dowel joints was 13.9 MPa (CV = 18.9%), corresponding to 26.3% and 23.2% of the bending strength value (59.8 MPa; CV = 6.0%) of the finger joints, respectively. The numerical models exhibited curve patterns consistent with experimental results but showed greater stiffness, attributable to the adoption of literature values for the elastic properties of wood and adhesive and the neglect of anatomical cross sectional effects of the adhesive surface. Furthermore, the models revealed no significant difference in the modulus of elasticity between simulated joint types and indicated a proportionality limit force of approximately 1000 N for tenon and dowel joints and 2000 N for finger joints.

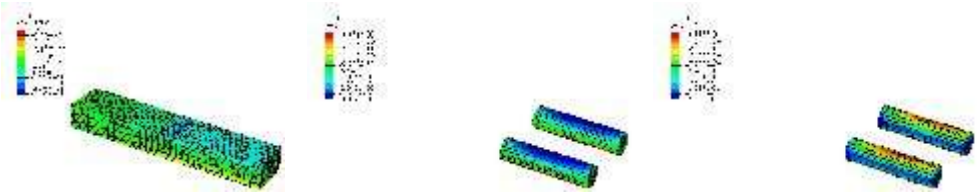
The distribution of normal stress S_{11} (the dominant stress component in beam bending) in the wooden parts of the tenon joint (Figure 4a), loaded with the average specimen failure load, reveals that the highest positive normal stress occurs in the zone where the tenon protrudes from the shoulder. This sharp contour represents a place of stress concentration exceeding the yield stress of oak wood and constitutes the initiation point of fracture. Also, the distribution of Von Mises stress in the adhesive layer (Figure 4b) indicates values exceeding the adhesive yield stress, extending across most of the adhesive surface in the beam zone subjected to tension.



a) b)

Figure 4. Tenon joint: a) normal stress S_{11} in the wooden parts of the joint, b) Von Mises stress in the adhesive layer

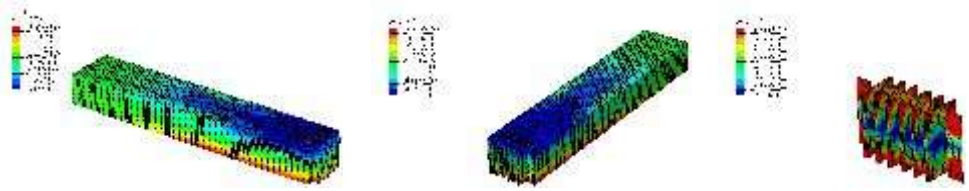
The distribution of normal stress S11 and Von Mises stress in the failure load dowel joint (Figure 5) shows that the highest values occurred in the zone of the inserted cylindrical pins. The stress in the wood did not exceed the yield stress, and loos strength in the joint adhesive surfaces could cause the dowels to be pulled out.



a) b)

Figure 5. Dowel joint: a) normal stress S_{11} in the wooden parts of the joint, b) Von Mises stress in the adhesive layer

The distribution of normal stress S_{11} in the wooden parts of the finger joint (Figure 6a), loaded with the average failure load, shows that the highest values occur in the upper and lower grains of the cross-section. These stress values remain below the yield stress of oak wood. In contrast, the Von Mises stress in the adhesive layer (Figure 6b) exceeds the adhesive yield stress in the upper and lower zones of the adhesive surface, constituting the initiation point of fracture.



a) b)

Figure 6. Finger joint: a) normal stress S_{11} in the wooden parts of the joint, b) Von Mises stress in the adhesive layer

A fracture in the wood and adhesive surfaces and pulling out of tenon and dowel parts of joints, and a gap in the end-grain surfaces of the beam in the tension zone, are typical failure modes for these types of joints (Figure 7a). A finger joint fracture develops along the adhesive surfaces and the wood, initiating at the beam edges within the finger zone (Figure 7b).

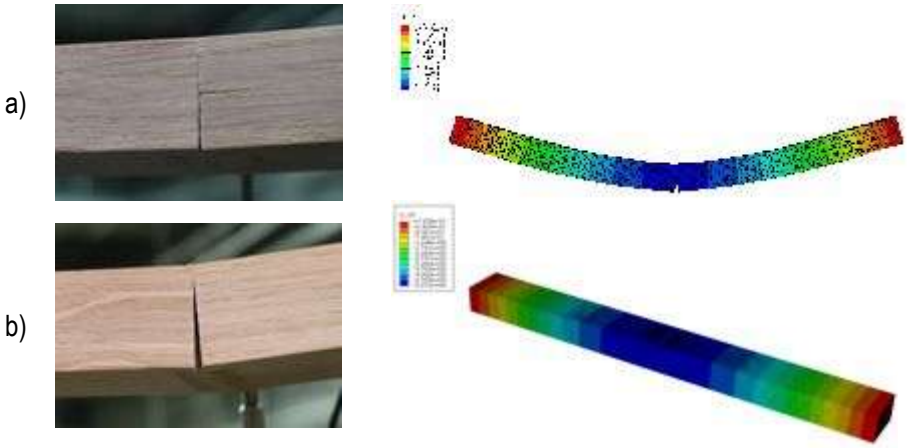


Figure 7. Characteristic patterns of the fractures and displacement U3: a) tenon joint, b) finger joint

4. CONCLUSION

This paper analyzes the bending behavior of end-to-end grain tenon and dowel joints in beams with cross-sectional geometries that reduce the moment of inertia and section modulus. Numerical results obtained using the finite element method with an orthotropic linear-elastic model and an orthotropic nonlinear model were compared with experimental results, as well as with results for end-to-end grain finger joints under the same beam configuration. Nonlinear

models showed higher stiffness, but are well aligned with experimental curves, and have the capability to describe joint mechanics. The test results, stress values, and stress distributions indicate that, due to the inability to obtain a quality adhesive layer across the cross-section, beams with tenon or dowel joints are weakened and exhibit much lower bending strength compared to finger joints.

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REFERENCES

1. Hajdarevic, S.; Busuladzic, I.; Martinovic, S.; Ibrisevic, A.; Obucina M. (2024): End-to-end grain joints in the construction of solid wood furniture. In: Proceedings of the 17th Int. Sc. Con. WoodEMA 2024. Bulgaria. May, 2024. 392-396
2. Hitka, M.; Naď. M.; Klement, I.; Sydor, M. (2026): Improving joint strength through controlled wood swelling, Wood Material Science & Engineering, 21:2, 1071-1080, DOI: 10.1080/17480272.2025.2466844
1. Hu, W.; Liu, N. (2020): Numerical and Optimal Study on Bending Moment Capacity and Stiffness of Mortise-and-Tenon Joint for Wood Products. Forests 11, no. 5: 501. https://doi.org/10.3390/f11050501
2. Ibrisevic, A.; Obucina, M.; Hajdarevic, S.; Mihulja, G. (2021): Influence of moisture content on the strength of finger joints bonded beech wood. In: Proceedings of the 32nd DAAAM International Symposium, pp.0270-0274, Vienna, Austria. DOI: 10.2507/32nd.daaam.proceedings.038
3. Jain, N.; Vinay, K. S.; Chauhan, S. (2017): A review on mechanical and water absorption properties of polyvinyl alcohol based composites/films. J Mech Behav Mater 2017; 26(5–6): 213–222. DOI: 10.1515/jmbm-2017-0027
4. Kawecki, B. (2021): Guidelines for FEM modelling of wood-CFRP beams using ABAQUS. Archives of Civil Engineering. Vol. LXVII Issue 4: pp 175-191. DOI: 10.24425/ace.2021.138493
5. Kawecki, B.; Podgórski, J. (2020): 3D Abaqus simulation of bent softwood elements. Archives of Civil Engineering. Vol. LXVI Issue 3: pp 323-337. DOI: 10.24425/ace.2020.134400
6. Martinović, D; Horman,I.; Hajdarević, S. (2008): Stress distribution in wooden corner joints. Strojarstvo, 50:193–204
7. Tippner, J.; Milch, J.; Sebera, V.; Brabec, M. (2022): Elasto-plastic material model of oak at two moisture content levels. Holzforschung 76(10): 886–896. DOI: 10.1515/hf-2022-0008

Authors address:
Hajdarević, S[1*]; Busuladžić, I[1]; Bego, M[2]; Martinović, S[1]
[1] Department of Wood Technology, Faculty of Mechanical Engineering Sarajevo, University of Sarajevo, Sarajevo, Bosnia and Herzegovina
[2] Department of Art and Restoration, University of Dubrovnik, Dubrovnik, Croatia
[*]Corresponding author: hajdarevic@mef.unsa.ba

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