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Li Fengting, Zhong Shilu*[1]

Application Methods of Digital Twin Technology in Quality Control and Management of Customised Furniture

Metode primjene tehnologije digitalnih blizanaca u kontroli i upravljanju kvalitetom namještaja po mjeri

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ABSTRACT • *Digital twin technology enables intelligent manufacturing and supports digital transformation. However, its use in customised furniture quality control is limited, due to issues such as inefficient traceability, slow response times, and predictive barriers. To address the fragmented quality management across stages, this study introduces a comprehensive framework that extends digital twins beyond workshops to the entire product lifecycle – design, warehousing, production, and after-sales. Adopting a design science research approach, we have developed a digital twin model for workshop quality control and a full lifecycle management approach, focused on three key pillars: lifecycle quality data management, high-fidelity virtual simulation, and real-virtual interaction. It thereby establishes a pathway to improve the accuracy and efficiency of quality control, which can lower costs, shorten delivery cycles, and accelerate digital transformation for furniture enterprises.*

KEYWORDS: *digital twin; quality control; customised furniture; smart manufacturing*

SAŽETAK • *Tehnologija digitalnih blizanaca omogućuje inteligentnu proizvodnju i podržava digitalnu transformaciju. Međutim, njezina je primjena u kontroli kvalitete namještaja po mjeri ograničena zbog problema kao što su neučinkovita sljedivost, sporo vrijeme odziva i prediktivne barijere. Kako bi se riješio problem fragmentiranog upravljanja kvalitetom u svim fazama, ova studija donosi sveobuhvatan okvir koji proširuje primjenu tehnologije digitalnih blizanaca izvan radionice, na cijeli životni ciklus proizvoda – dizajn, skladištenje, proizvodnju i postprodaju. Usvajajući pristup istraživanja znanosti o dizajnu, razvili smo model digitalnih blizanaca za kontrolu kvalitete u radionici, uz praćenje cjeloživotnog ciklusa proizvoda. Model je usmjeren na tri ključna stupa: upravljanje podatcima o kvaliteti životnog ciklusa namještaja po mjeri, na virtualnu simulaciju visoke vjernosti i na interakciju stvarno – virtualno. Time se uspostavlja put za poboljšanje točnosti i učinkovitosti kontrole kvalitete, što može smanjiti troškove, skratiti cikluse isporuke i ubrzati digitalnu transformaciju poduzeća koja se bave izradom namještaja.*

KLJUČNE RIJEČI: *digitalni blizanci; kontrola kvalitete; namještaj po mjeri; pametna proizvodnja*

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1 INTRODUCTION
1. UVOD

The advent of intelligent manufacturing has prompted furniture enterprises to adopt a distinctive Chinese approach. This approach features a large-scale, customised panel furniture intelligent manufacturing system and model (Xiong *et al*., 2022). This initiative enhances design, production, management, and service in furniture manufacturing. It has also improved furniture product quality control and gradually eliminated deficiencies in traditional processes. Instead of relying on the earlier 'extensive and family style quality management' model (Xiong *et al*., 2017), enterprises now use quality management information technology, digital quality tools, and greater efficiency to improve customised furniture board quality and control (Fang *et al*., 2020). However, as flexible production increases, key quality control processes become more complex. Real-time and predictive quality control are still suboptimal, making traceability, assessment, and avoiding later quality problems difficult. Therefore, state-of-the-art technology in intelligent manufacturing is essential to enable upgrades and comprehensively enhance quality control for customised furniture.

The concept of a Digital Twin (DT) can be traced back to the "mirror space model" proposed by Professor Michael Grieves in 2003 (Grieves and Vickers, 2016). NASA and the Air Force later used this concept for design, maintenance, and prediction (Shafto *et al*., 2010). A DT is a digital replica, synchronised in real time, of the state and behaviour of a physical entity. This replica is created by digitally mapping the entity elements. The concept integrates multiple physical domains, uses a multi-scale approach, incorporates surrealism, and employs dynamic probability to simulate real-world entities (Zhuang *et al*., 2017). DT possess five functions: mapping reality, dynamic updating, scene reproduction, autonomous thinking, and decision-making guidance. They support product design, process planning, equipment maintenance, quality control, and workshop construction. In recent years, DT have attracted more attention in intelligent manufacturing and have become a major focus for enterprises pursuing digital transformation.

This study aims to address the existing gap between DT technology and the quality control requirements of customised furniture production. The specific objectives are to: (1) propose a comprehensive application framework extending DT technology from the workshop to the full product lifecycle; (2) identify and analyse key technological enablers supporting this framework; and (3) establish a methodological foundation for intelligent, data-driven quality management. The overall goal is to deliver a systematic reference for both academic research and industrial implementation, thereby advancing the digital transformation of furniture manufacturing.

2 LITERATURE REVIEW
2. PREGLED LITERATURE

This section reviews literature in three areas: (1) an overview of DT technology in manufacturing enterprises; (2) its evolving application in the furniture industry; and (3) persistent gaps in quality control of customised furniture.

2.1 Overview of DT technology in manufacturing
2.1. Pregled tehnologije digitalnih blizanaca u proizvodnji

DT technology is a key strategy for the intelligent transformation of manufacturing. It connects physical and virtual domains and enables easy data transmission and sharing. The shared data include quantitative and qualitative data about materials and manufacturing processes, historical data, environmental data, and crucial real-time data (Singh *et al*., 2021). DT technology allows simulation, monitoring, diagnosis, prediction, and control of a product in the real world. It builds strong collaboration throughout the product lifecycle, boosting innovation in enterprises (Wu *et al*., 2020).

In manufacturing, the implementation of DT technology has advanced across multiple tiers, encompassing equipment, production lines, and the enterprise level. The following four key areas primarily manifest as follows: real-time monitoring and predictive maintenance; production process simulation and optimisation; product design and virtual testing; and full lifecycle management. It permeates the entire design, production, and operational maintenance process, gradually shifting from isolated technological breakthroughs to the construction of fully integrated, collaborative twin systems (Wang, 2025). This enhances transparency, flexibility, and sustainability across all stages of the product lifecycle, fostering effective collaboration between phases – from virtual design and prototyping to production planning, predictive maintenance, and after-sales service – thus propelling the intelligent innovation and upgrading of manufacturing. Consequently, DT technology signifies a paradigm shift from traditional experience-driven operational models to proactive, intelligent management approaches.

2.2 Application of DT in furniture industry
2.2. Primjena tehnologije digitalnih blizanaca u proizvodnji namještaja

DT technology is widely used in manufacturing for its transparency, predictability, and flexibility. The furniture industry, known for customised and flexible production, is a key area for DT exploration. This technology helps furniture makers address challenges such as integrating workshop information, identifying object flow, and intelligent scheduling (*Xiong et al*., 2024).

Most research on DT technology in the furniture industry focuses on the DT workshop. This model, based on DT technology, aims to optimise production and control. The DT workshop includes the workshop entity, virtual model, twin data, and service system. Compared to virtual and digital workshops, the DT workshop combines their advantages. It enables real interaction between the physical and virtual workshop (Li and Wu, 2023). The DT workshop also monitors and optimises workshop production lines, inspects product quality, and maintains equipment.

The concept of "Furniture Digital Twin Shopfloor (FDTS)" was first introduced by Ouyang *et al.* (2022) They developed a five-dimensional FDTS architecture and a "digital life form" model. They also described implementation steps and main technical areas for FDTS.

Wu and Zhu (2023) integrated the informatisation of customised panel furniture production with the DT shop floor. This integration aimed to address specific manufacturing challenges. They proposed five key dimensions for the DT shop-floor: physical, virtual, DT service, twin data, and data transmission. This five-dimensional model was created to solve information challenges in metal furniture production.

Bai (2023) developed a DT workshop model for a metal-furniture production line. This model was based on the prevailing DT framework and integrated the distinctive characteristics of metal furniture manufacturing. Xie (2024) developed a DT model and a virtual commissioning system. This system enables virtual commissioning, optimises production paths, and supports capacity planning. Its use has improved production efficiency, market responsiveness, and control over the production cycle.

Guo *et al* (2025) highlighted that integrating a DT system into the veneer defect repair production line facilitates data analysis and modelling. This enables optimisation of the repair line design by adjusting production parameters and improving equipment and processes, thereby increasing efficiency and reducing wear and tear on the production line.

The DT workshop for furniture, driven by DT technology, has taken shape, indicating the direction for implementing the DT system in the furniture industry. However, extant DT research primarily focuses on the general manufacturing industry and lacks adaptation to the dynamic production scenarios of customised furniture (Yan *et al*, 2021). Such scenarios include dynamic scheduling, process optimisation, quality inspection, equipment failure prediction, and packaging and transportation in various aspects.

2.3 Research gaps in quality control for customised furniture

2.3. Praznine u istraživanjima kontrole kvalitete namještaja po mjeri

Quality control can be defined as the process of organising and coordinating related activities to meet specific quality requirements (Wu *et al*., 2019). It is also an important competitive tool for modern furniture companies. In the context of custom furniture, quality control encompasses four critical phases: design, storage, production, and after-sales service. Poor design can result in substandard products that fail to meet quality expectations. The quality of raw materials on the incoming board directly affects the processing quality of the final product. Errors during production operations can lead to deformation, chipping, and warping. Post-sales service is vulnerable to inadequate packaging, transportation losses, and incomplete fittings, which complicates ensuring product safety (Ye *et al*., 2019). These quality issues stem from the production process, which is the primary focus of manufacturing enterprises that prioritise control (Hu *et al*., 2023).

In accordance with the provisions of the "customised furniture quality inspection and quality assessment" and other pertinent national standards, most enterprises have established a quality management system, thereby implementing a more streamlined quality inspection (Figure 1).

Currently, many furniture manufacturers still rely on traditional manufacturing models or basic information-based quality control platforms (Xiong *et al*., 2018). Only a few companies, such as the Sophia Huanggang Factory, have truly adopted intelligent inspection systems that integrate technologies like vision and artificial intelligence (Xiong *et al*., 2018). The factory has two sets of quality inspection systems: one for the surface of the plate and a set for sealing quality. By using Charge-Coupled Device (CCD) ultra-high-speed imaging technology; this enterprise ensures product quality. Although the custom furniture industry in China has implemented the aforementioned quality control systems, there are still several significant shortcomings in the quality control of custom furniture based on the "Furniture Quality Traceability System Specification" issued by the Ministry of Industry and Information Technology and industry practices, which hinder efficiency, traceability, and quality consistency. The specific issues are as follows:

1) Low efficiency in tracing quality problems: Quality information for furniture products is dispersed across multiple departments, making assigning blame more difficult. This, in turn, affects the timely detection and resolution of problems, thereby reducing the efficiency of quality traceability. In addition, there is insufficient real-time monitoring of the pro-

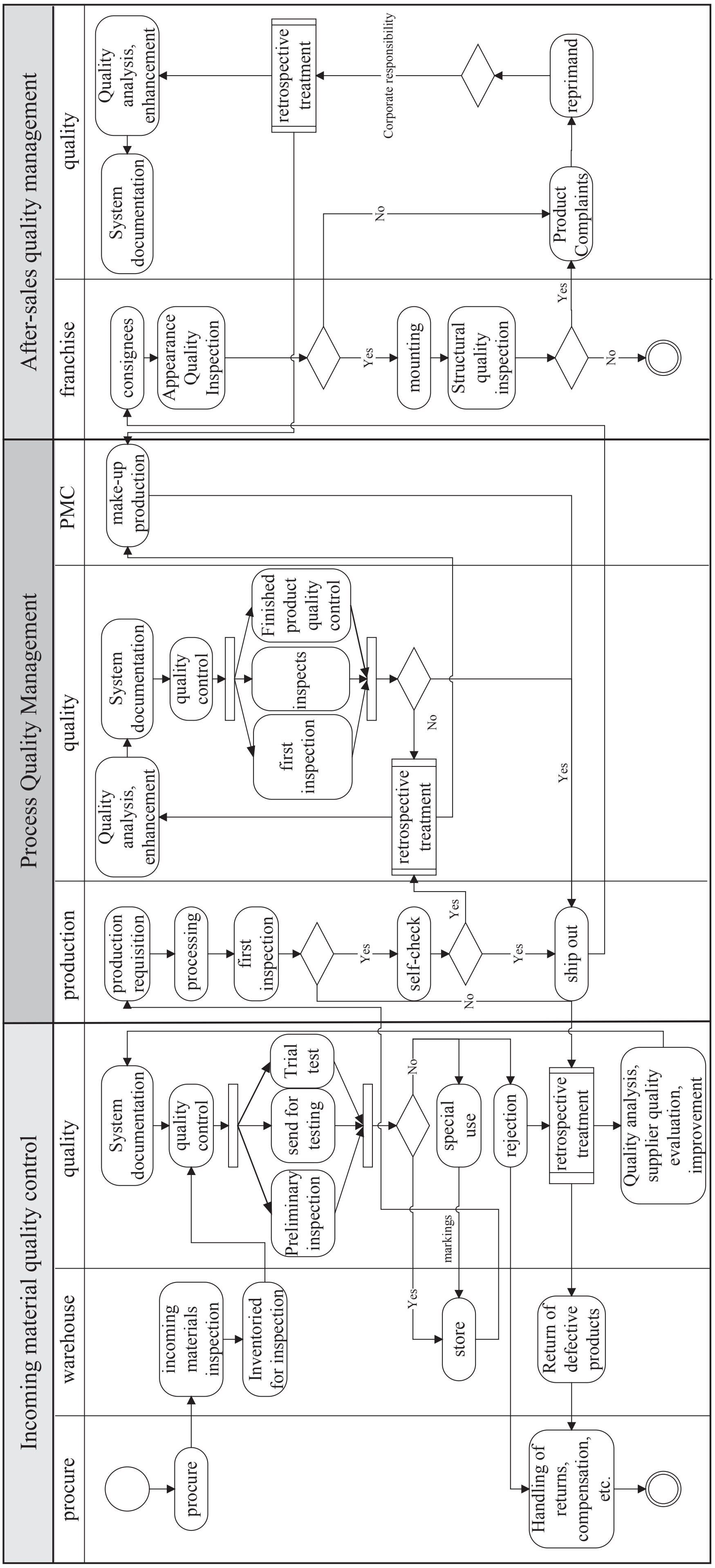

Figure 1 Customised furniture quality inspection management flowchart
Slika 1. Dijagram toka upravljanja kontrolom kvalitete namještaja po mjeri

duction process. As a result, the product production process is not transparent to quality control and is not traceable. This makes it difficult to determine the root cause of the quality problem, which, in turn, affects the efficiency of traceability.

2) Poor quality control timeliness: Throughout the life cycle of quality information acquisition technology, the methods employed are antiquated, predominantly manual record upload. This engenders an information lag, hinders managers' timely acquisition of feedback, complicates on-site problem resolution, and impedes the flow of information within the department. The degree of sharing is minimal, and the flow of information is inefficient, which adversely affects the quality of feedback transmission and, consequently, delivery and production plans (Fang, 2020).
3) Unreliable quality prediction: Enterprises must consider the six factors of "Man, Machines, Materials, Method, Environment (4M1E)" when making quality predictions (Cui *et al*., 2020). However, due to the high dimensionality, dynamics, and uncertainty of furniture product quality data (Lee *et al*., 2014), it is challenging to efficiently and reliably determine the impact of production variables on quality characteristics. This hinders the ability to support continuous quality optimisation.
4) The effect of quality improvement is not obvious: Furniture quality problems result from numerous factors, and improvement methods must address them comprehensively. However, the low efficiency of traceability hinders the effectiveness of surface improvement methods, necessitating repeated testing, which is both time-consuming and complex. This, coupled with the absence of quality assessment standards, results in a challenging situation in which the desired improvement may not be attainable.

This reveals that the core challenge in quality control for custom furniture lies in real-time monitoring and predictive control throughout its entire lifecycle. Currently, DT technology remains in its infancy for quality control applications in this sector, failing to provide a comprehensive, data-driven framework that bridges critical quality information gaps across different lifecycle stages. To address these deficiencies in existing quality control systems, this study aims to optimise production quality control processes and fill the research gap by developing an integrated DT framework and key technologies for full lifecycle quality management in custom furniture.

3 RESEARCH METHODS
3. METODE ISTRAŽIVANJA

This study adopts the design science research paradigm, following the systematic process from problem analysis to solution, aiming to develop a conceptual framework for quality control of the whole life cycle of customised furniture using DT technology, in order to solve the problem of fragmented quality control in the production of customised furniture. The study is grounded in multi-source evidence analysis, incorporating structured literature reviews, relevant national standards, technical reports, and observations of industry practices.

It proceeds through three sequential phases: First, it decomposes macro-level quality control challenges in custom furniture into four lifecycle-specific issues–design, warehousing, production, and after-sales service–and identifies stage-specific pain points using analysed evidence. Second, by aligning these pain points with DT technology core capabilities, it identifies critical intervention points and constructs key application models, establishing the logical foundation for full lifecycle quality control. Finally, it synthesises an integrated DT-driven lifecycle quality control framework, deriving the essential supporting technologies required for its implementation through both practical and theoretical reasoning.

4 RESULTS
4. REZULTATI

Based on the systematic analysis, this study has systematically developed the following core framework and key findings.

4.1 DT-driven quality control for customised furniture manufacturing workshops
4.1. Kontrola kvalitete vođena digitalnim blizancima za radionice koje proizvode namještaj po mjeri

The production workshop is the core arena for quality control. As the foundational scenario for implementing DT, we have first constructed an application model for workshop-level quality management, based on the FDTS architecture (illustrated in Figure 2).

This model aims to facilitate real-time data collection, analysis, and prediction within the production boundary. In this application model, quality information from the physical workshop is collected in real time. This includes:
- product quality information: size, shape, material and quality standard, etc;
- production process information: process flow information, process control information, and production progress information, etc.;
- equipment information: operation status, maintenance records, and failure statistics, etc;
- environment information: temperature, humidity, cleanliness, etc;

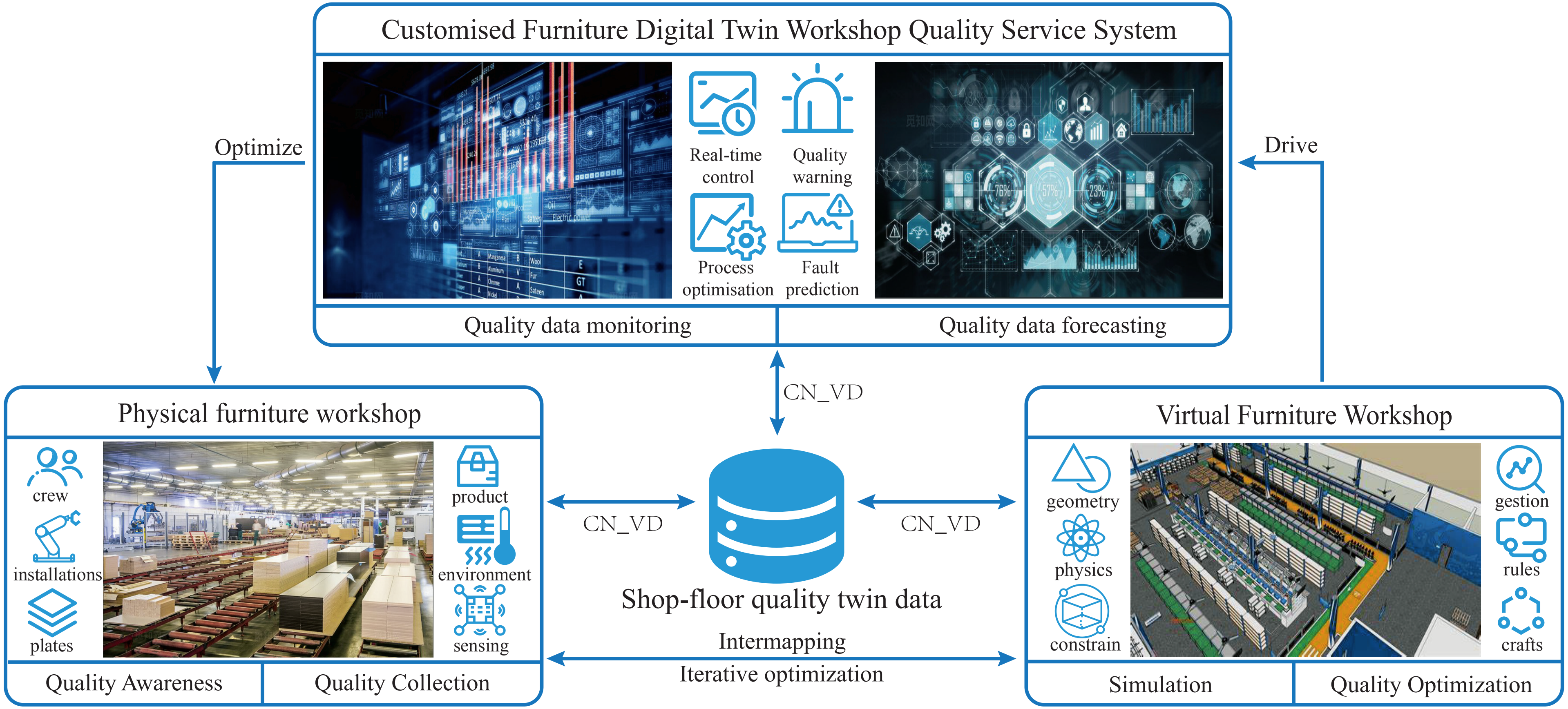

Figure 2 DT application model for quality control in customised furniture production workshop
Slika 2. Model primjene tehnologije digitalnih blizanaca za kontrolu kvalitete u radionici za proizvodnju namještaja po mjeri

- personnel information: location and status, etc, uploaded and stored as workshop quality twin data.

The virtual workshop realises simulation by analysing and predicting the workshop quality twin data and mapping it to the physical workshop; and the workshop quality service system is driven by the quality twin data output from the physical workshop and the virtual workshop to realise real-time management and control, process optimization, quality early warning, and fault prediction. The physical workshop, virtual workshop, and workshop quality service system are closely connected through the workshop quality twin data, which serves as the driver to support the iterative operation of production process quality information management, product quality control, and optimisation among the three.

4.2 Full lifecycle quality control framework extended from DT technology
4.2. Okvir kontrole kvalitete cijeloga životnog ciklusa namještaja po mjeri proširen tehnologijom digitalnih blizanaca

To transcend the limitations of this isolated workshop model and address the lifecycle-wide challenges identified in Section 2.3, we have proposed extending DT technology to encompass the entire product journey. Building upon the workshop model, an integrated full lifecycle management framework was proposed, as illustrated in Figure 3. In the design phase, a virtual model is constructed to simulate the production and usage environment and predict potential quality problems. In the warehousing phase, the stability of material quality is predicted using historical and real-time data to optimise purchasing efficiency. In the after-sales phase, installation quality is verified using the installation twin model, which simulates the steps, tool configurations, and actual conditions.

In this comprehensive process management framework, the integration of sensors and Internet of Things (IoT) devices (e.g., Radio-Frequency Identification (RFID) for tracking board batches; force sensors for monitoring sealing pressure; and visual sensors for detecting surface imperfections) establishes a comprehensive data chain for customised furniture. This encompasses the domains of design, procurement, production, and delivery to collect real-time quality parameters at each stage.

The implementation of a DT enables dynamic quality monitoring, automatically identifying problematic links and the responsible individual when abnormalities are detected. When anomalies are triggered, the system can automatically identify the problematic links and trace them back to the responsible person. Concurrently, the system can thoroughly analyse the data to identify the root causes of defects (e.g., panel cracking and warping).

The system can construct a prediction model by integrating historical and real-time data, data to predict the risk of the process and optimise the improvement strategy. Integration of quality data from multiple sources is feasible, and through multidimensional analysis, a visual signage board can be generated to guide parameter tuning and process iterations, ensuring that quality indexes throughout the life cycle remain stable and controllable.

The quality twin data of each stage of the customised furniture entire life cycle is stored, interacted with, and updated by a dynamic data model. The support model is adaptively adjusted to meet the quality control needs at different stages of the life cycle, thereby forming a closed-loop control system. This system enables precise quality management from the source to the end of the customised furniture life cycle.

4.3 Key enabling technologies for DT-driven quality control
4.3. Ključne tehnologije za kontrolu kvalitete vođenu digitalnim blizancima

The realisation of both the workshop model and the full lifecycle framework relies on breakthroughs in three key technological pillars, which are detailed below. These enabling technologies are essential for creating a closed-loop, DT-driven quality control system.

4.3.1 Full lifecycle DT quality data management
4.3.1. Upravljanje podatcima o kvaliteti dobivenim tehnologijom digitalnih blizanaca tijekom cijeloga životnog ciklusa namještaja po mjeri

In light of the growing demand for comprehensive quality management throughout the entire lifecycle of customised furniture, the primary technological challenge is to establish a unified, data-driven platform that facilitates effective collaboration and closed-loop management of cross-stage, multidimensional quality information (illustrated in Figure 4).

This DT quality data management platform encompasses the entire life cycle of customised furniture, incorporating quality data sources, collection, processing, and feedback. The quality data source comprises three components: first, quality information spanning the entire life cycle within the physical space; second, simulation information within the virtual space; and third, interaction data between the physical entity and the virtual model. Real-time quality data are collected through equipment during the production process, such as sensors, Programmable Logic Controllers (PLCs), RFIDs, and industrial control computers (Leng *et al.*, 2022).

The selection of collection modes, such as photos, videos, text, and data, is determined by the need for high-quality data analysis across various stages

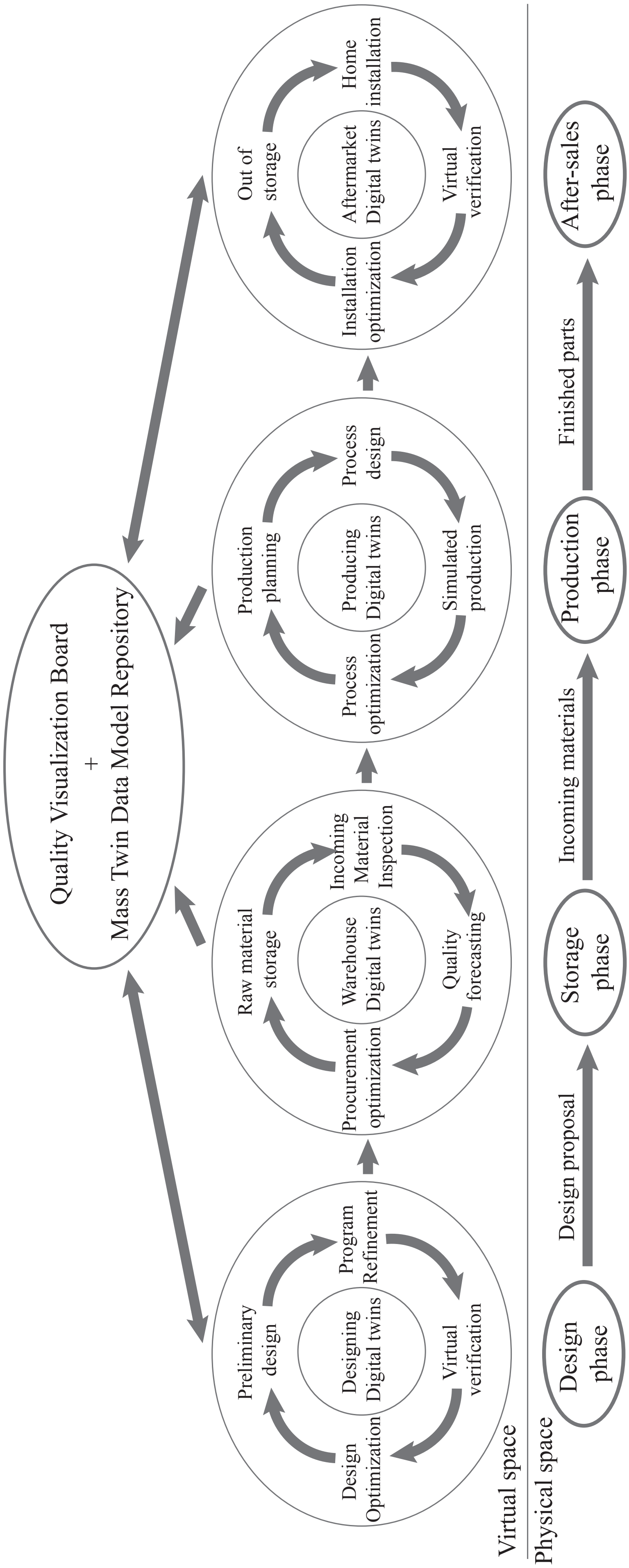

Figure 3 Full lifecycle management framework of customised furniture for DT technology
Slika 3. Okvir za upravljanje cijelim životnim ciklusom namještaja po mjeri uz pomoć tehnologije digitalnih blizanaca

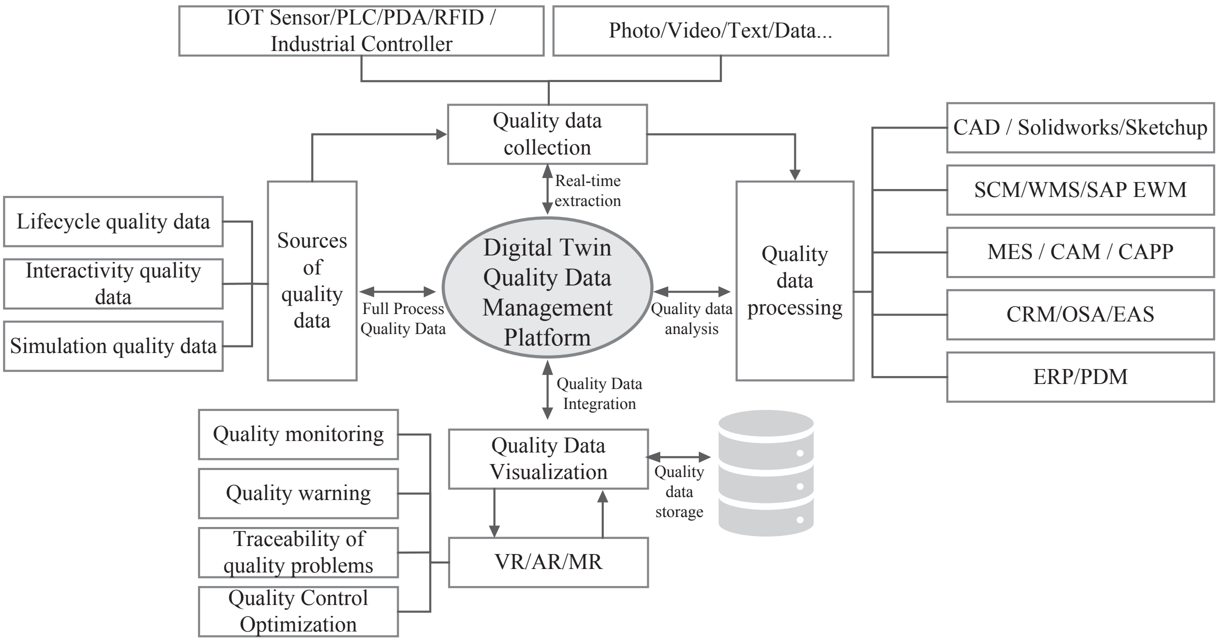

Figure 4 DT quality data management platform for the whole life cycle of customised furniture
Slika 4. Platforma za upravljanje podatcima o kvaliteti dobivenima uz pomoć tehnologije digitalnih blizanaca za cijeli životni ciklus namještaja po mjeri

(Kuo *et al*., 2022; Cao *et al*., 2021). The processing and feedback of quality data entail integrating quality information into the design process (e.g., CAD/ Solidworks/ Sketchup) and into the warehousing process. With logistics management software (e.g., SCM/ WMS/ SAP EWM), quality information in the production process with manufacturing software (e.g., MES/ CAM/CAP), after-sales process quality information and customer management and office software (such as CRM/OA/EAS) and the whole life cycle quality information and management software (such as ERP/PDM), etc., are integrated into the DT quality data management platform for analysis and processing, and through the VR/AR/MR technology to build the quality information visualization Kanban, intuitive feedback Quality data and abnormality localization.

The platform integrates the entire quality control data lifecycle, creating a closed-loop process that encompasses data collection, processing, storage, and feedback. This facilitates the end-to-end integration of quality information flow and promotes the quality control of customised furniture through an intelligent transformation from "experience-driven" to "data-driven".

4.3.2 Virtual model construction and simulation
4.3.2. Izrada i simulacija virtualnog modela

The construction of high-precision models constitutes the foundation of DT-driven quality control for the full life cycle of customised furniture (Tao *et al*., 2019). The high-precision model involved in the full life cycle of customised furniture is divided into four DT forms: design, storage, production, and after-sales (Cheng *et al*., 2021). The DT model is created vertically from six dimensions: geometry, physics, behaviour, rules, constraints, and processes. It is also created horizontally from six perspectives: Man-Machine-Material-Method-Environment-Measurement. Virtual reality mapping is also employed (Leng *et al*., 2022).

In the model construction, the material properties of the wood used are accounted for, including its physical, chemical, and mechanical properties. These properties are incorporated into the model as a critical parameter. The construction of high-precision digital models is facilitated by the utilisation of SolidWorks, Demo3D, and other three-dimensional tools. Ansys mechanical simulation is used to ensure model consistency with the physical entity. This comprehensive approach enables the mapping of furniture structure. The material properties (e.g., the hardness of the plate) and process flow (e.g., the "U"-shaped production line layout to balance the efficiency of the process) constraints on the operating range of equipment and AGV path planning (Gou *et al*., 2021) define the input and output of each process node, operation steps, and resource requirements, forming a standardised process framework.

Concurrently, integrating VR/AR technology enables the creation of a visual twin scene, thereby facilitating the dynamic display of the furniture physical state. This approach empowers users to adjust parameters in real time through an interactive interface, thereby optimising the quality prediction and improvement strategy. The integration of virtual and real linkage quality is realised throughout the entire process. Control, in the simulation, using COMSOL, Witness, and other software to build a dynamic model of the whole life cycle, by setting quality standards and testing methods, performing virtual product quality assessment, enabling real-time traceability of the root causes of production problems, and optimising and improving.

In the simulation, Witness and other software are utilised to construct a dynamic model of the entire life cycle. Quality standards and testing methods are established to evaluate the quality of virtual products. The root causes of production problems are traced in real time, and the improvement process is optimised and enhanced. Concurrently, the Simright finite element analysis tool can be used to import the furniture geometric model and define attributes to simulate the actual force and the virtual assembly process. This enables us to validate the precision of parts matching and optimise the structural design to improve quality and efficiency.

4.3.3 Real-virtual interaction technology
4.3.3. Tehnologija stvarne virtualne interakcije

The quality control of customised furniture oriented to DT technology is predicated on the realisation of equivalent expression of physical and virtual space. The establishment of bidirectional mapping between physical and virtual models focuses on multi-sensory real-time interaction, synchronised analogue simulation, and the application of 3R technology. Virtual-reality fusion collects real-time quality data, such as equipment status and production progress, in physical space via sensors, and relies on high-speed, stable, and low-latency transmission protocols to enable bidirectional interaction (Nie *et al*., 2024).

Between physical and virtual space, it is necessary to provide synchronised mapping of equipment, process, and production status based on high-precision models, and dynamic optimisation of quality control in physical space through the results of simulation, and to combine VR/AR/MR technology to build an immersive expression of physical and virtual space. The integration of AR/MR technology facilitates the construction of an immersive virtual-reality interaction scene (Guo 2019), intuitively presenting the behaviour and feedback of the DT model.

Concurrently, the integration of the Internet of Things, cloud computing, and artificial intelligence enables data-driven, collaborative decision-making between the real and virtual worlds (Cai *et al*., 2021), thereby establishing a closed loop of “sensing-simulation-optimisation” and enabling the dynamic integration of all elements of intelligent quality control.

5 DISCUSSION
5. RASPRAVA

The present study systematically constructs a DT workshop quality control model and an integrated framework spanning the entire lifecycle from design to after-sales service. The study directly addresses the fragmented research gap in quality control for custom furniture, resolving the inefficiencies of traceability and reactive quality management. Whilst extant research has proposed FDTS architectures and production line optimisation schemes (OuYang *et al*., 2022; Wu and Zhu, 2023), demonstrating the value of DT technology in enhancing localised efficiency during production phases, these approaches struggle to resolve systemic information silos between design, warehousing, production, and after-sales operations. Consequently, this study extends beyond local optimisation to achieve full lifecycle integration. The construction of a bespoke furniture-quality control framework, integrating multi-source data across the entire lifecycle, enables the integration of quality twin data from all stages. This establishes the fundamental prerequisites for predictive quality control and root-cause traceability.

Furthermore, the three key technologies proposed in this study do not merely offer generic solutions. The conceptual framework of custom furniture quality control is transformed into an actionable implementation roadmap, offering the industry a practical, technology-driven approach. However, the proposed solutions still have limitations, primarily because this integrated framework has not yet been fully deployed and validated in real-world corporate environments. Future case studies are urgently needed to demonstrate its practical benefits and expand the application scope of DT technology in the furniture industry.

6 CONCLUSIONS
6. ZAKLJUČAK

DT technology is a key enabler for the furniture industry to achieve intelligent manufacturing and industrial digital transformation. It will strongly support furniture enterprises in product quality control, flexible production, personalised customisation, and supply chain collaboration. This study moves beyond the prevalent workshop-centric application of DT technology in furniture research by proposing a holistic, lifecycle-encompassing quality control framework for customised furniture. The primary theoretical contribution lies in systematically bridging the identified research gap-fragmented quality management-through an integrated model that connects design, warehousing, production, and after-sales via a unified digital thread. In practical terms, this research provides a clear implementation roadmap for industry, shifting the paradigm from experience-driven, reactive quality checks to a data-driven, predictive, and closed-loop control system. Identifying three key enabling technologies offers actionable focal points for enterprises embarking on their digital transformation journey in quality management. In the future, with further research and development of DT technology, the shortcomings in real-time data collection, high-precision model construction, and virtual reality integration will be improved, and the deep integration with emerging technologies such as artificial intelligence and the Internet of Things will bring higher levels of intelligence to quality control, promoting the furniture industry to move towards intelligent manufacturing.

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7 REFERENCES
7. LITERATURA

1. Bai, X. X., 2023: Research and application of digital twin technology for metal furniture production line. MSc Thesis, Nanchang University.
2. Cai, B.; Zhu, W. H.; Shi, Q. Y.; Liu, S., 2021: Research on the experimental platform of industrial robots combining virtual and reality. Machine Tool & Hydraulics, 49 (23): 54-60. https://doi.org/10.3969/j.issn.1001-3881.2021.23.011
3. Cao, J. Y.; Lv, W. Z.; Tang, D.; Zheng, Y. J., 2021: Process planning and simulation validation of welding production line for automotive front floor based on Tecnomatix. Machinery Design & Manufacture, 10: 174-178. https://doi.org/10.19356/j.cnki.1001-3997.2021.10.038
4. Cheng, Z. W.; Tong, S. G.; Tong, Z. M.; Zhang, Q. G., 2021: Review of digital design and digital twin of industrial boiler. Journal of Zhejiang University (Engineering Science), 55 (8): 1518-1528. https://doi.org/10.3785/j.issn.1008-973X.2021.08.013
5. Cui, J.; Lin, X. X.; Wei, W. C.; Huang, H. X.; Yu, Y. S., 2020: Exploration of quality control management under lean production in furniture enterprise. Furniture & Interior Design, 3: 54-55. https://doi.org/10.16771/j.cn43-1247/ts.2020.03.016
6. Fang, Z., 2020: Research on quality management information system of panel custom furniture based on MES. Zhejiang Agriculture and Forestry University. https://doi.org/10.27756/d.cnki.gzjlx.2020.000204
7. Fang, Z.; Yu, X. H.; Shen, L. M., 2020: Construction of quality management information system of incoming material in customized panel furniture enterprise. Furniture, 41 (3): 70-74. https://doi.org/10.16610/j.cnki.jiaju.2020.03.016
8. Gou, N.; Cheng, K.; Huo, D., 2021: Multiscale modelling and analysis for design and development of a high-precision aerostatic bearing slideway and its digital twin. Machines, 9 (5): 85. https://doi.org/10.3390/machines9050085
9. Grieves, M.; Vickers, J., 2016: Origins of the digital twin concept. Florida Institute of Technology, 8: 3-20. https://doi.org/10.13140/RG.2.2.26367.61609
10. Guo, J. Y., 2019: 3R virtual scenarios in reading promotion. Computer Knowledge and Technology, 15 (29): 217-218. https://doi.org/10.14004/j.cnki.ckt.2019.3492
11. Guo, Y. H.; Yao, Y.; Li, Y. H., 2025: Research on flaw detection and automatic digging-filling of wood-board for wood machine tools. Manufacturing Technology & Machine Tool, 1: 75-85. https://doi.org/10.19287/j.mtmt.1005-2402.2025.01.011
12. Hu, C. W.; Liu, Z. H., 2023: Research progress of quality control technology based on digital twin. Ordnance Industry Automation, 42 (1): 26-32. https://doi.org/10.7690/bgzdh.2023.01.005
13. Kuo, Y.; Yang, T.; Huang, T. L., 2022: Optimizing U-shaped production line balancing problem with exchangeable task locations and walking times. Applied Sciences, 12 (7): 3375. https://doi.org/10.3390/app12073375
14. Lee, J.; Kao, H. A.; Yang, S., 2014: Service innovation and smart analytics for industry 4.0 and big data environment. Procedia CIRP, 16: 3-8. https://doi.org/10.1016/j.procir.2014.02.001
15. Leng, B. H.; Xia, T. B.; Sun, H.; Wang, H.; Xi, L. F., 2022: Digital twin mapping modeling and method of monitoring and simulation for reconfigurable manufacturing system. Journal of Zhejiang University (Engineering Science), 56 (5): 843-855. https://doi.org/10.3785/j.issn.1008-973X.2022.05.001
16. Li, Z. D.; Wu, X. F., 2023: Digital twin study of the furniture manufacturing industry. JUShe, (35):15-18.
17. Nie, W. X.; Chen, C.; Yang, Z. H.; Zhang, Q. S.; Yang, H. L.; Chen, H. Z., 2024: Research review of virtual-real fusion based on digital twin workshop. Machine Tool & Hydraulics, 52 (2): 187-198. https://doi.org/10.3969/j.issn.1001-3881.2024.02.029
18. Ouyang, Z. Z.; Wu, Y. Q.; Tao, T.; Dai, X. D.; Huang, Y. L.; Chen, X. Y.; Wang, X.; Hao, S. P.; Zhan, X. L., 2022: Construction of furniture digital twin shop-foor (FDTS) and prospect of key technologies for „Made in China 2025". Furniture & Interior Design, 29 (8): 1-7. https://doi.org/10.16771/j.cn43-1247/ts.2022.08.001
19. Shafto, M.; Conroy, M.; Doyle, R.; Glaessgen, E.; Kemp, C.; LeMoigne, J.; Wang, L., 2010: Draft modeling, simulation, information technology & processing roadmap. Technology Area, 11: 1-32.
20. Singh, M.; Fuenmayor, E.; Hinchy, E. P.; Qiao, Y.; Murray, N.; Devine, D., 2021: Digital twin: Origin to future. Applied System Innovation, 4 (2): 36. https://doi.org/10.3390/asi4020036
21. Tao, F.; Liu, W. R.; Zhang, M.; Hu, T. L.; Qi, Q. L., 2019: Five-dimension digital twin model and its ten applications. Computer Integrated Manufacturing Systems, 25 (1): 1-18. https://doi.org/10.13196/j.cims.2019.01.001
22. Wang, X. M., 2025: Research on the manufacturing transformation path driven by digital twin. PKU Business Review, (11): 25-27.
23. Wu, J.; Yang, Y.; Cheng, X. U. N.; Zuo, H.; Cheng, Z., 2020: The development of digital twin technology review. Chinese Automation Congress (CAC), pp. 4901-4906. https://doi.org/10.1109/CAC51589.2020.9327756
24. Wu, X. H.; Zhu, J. G., 2023: Discussion on the digital twin model of intelligent workshop of custom panel furniture. Chinese Journal of Wood Science and Technology, 37 (1): 25-32. https://doi.org/10.12326/j.2096-9694.2022043
25. Wu, Y.; Yao, L. Y.; Xiong, H.; Zhuang, B. C.; Zhao, H. R.; Liu, J. H., 2019: Quality control method of complex product assembly process based on digital twin technology. Computer Integrated Manufacturing Systems, 25 (6): 1568-1575. https://doi.org/10.13196/j.cims.2019.06.024
26. Xie, Q. Y., 2024: Digital twin model of CNC cutting machine for panel furniture Research on construction and

virtual debugging technology. Central South University of Forestry and Technology. https://doi.org/10.27662/d.cnki.gznlc.2024.000121
27. Xiong, X. Q.; Fu, S. J.; Yue, X. Y.; Zhang, M.; Wang, G. K., 2024: Construction and technology of digital twin model in customized-furniture intelligent manufacturing workshop. Chinese Journal of Wood Science and Technology, 38 (6): 69-78. https://doi.org/10.12326/j.2096-9694.2024066
28. Xiong, X. Q.; Guo, W. J.; Huang, Q. T.; Fang, L.; Pang, X. R.; Wu, Z. H., 2017: Study of the quality control technology in furniture digital manufacturing. Journal of Forestry Engineering, 2 (4): 152-157. https://doi.org/10.13360/j.issn.2096-1359.2017.04.024
29. Xiong, X. Q.; Yue, X. Y., 2022: Research and application progress of home intelligent manufacturing technologies in China. Journal of Forestry Engineering, 7 (2): 26-34. https://doi.org/10.13360/j.issn.2096-1359.202107006
30. Xiong, X. Q.; Yuan, Y. Y.; Fang, L.; Liu, H.; Wu, Z. H., 2018: Status and development trends of intelligent manufacturing in China's furnishings industry. Forest Products Journal, 68 (3): 328-336. https://doi.org/10.13073/FPJ-D-18-00002
31. Yan, D.; Liu, Q.; Leng, J.; Zhang, D.; Zhao, R.; Zhang, H.; Wei, L., 2021: Digital twin-driven rapid customized design of board-type furniture production line. Journal of Computing and Information Science in Engineering, 21 (3): 031011. https://doi.org/10.1115/1.4050617
32. Ye, Q. H.; Qin, Y. H.; Chen, F., 2019: Analysis of the quality status quo of customized furniture and exploration of quality testing. Quality and Standardization, 8: 45-48. https://doi.org/10.3969/j.issn.2095-0918.2019.08.016
33. Zhuang, C.; Liu, J.; Xiong, H.; Ding, X.; Liu, S.; Weng, G., 2017: Connotation, architecture and trends of product digital twin. Computer Integrated Manufacturing Systems, CIMS, 23 (4): 753-768. https://doi.org/10.13196/j.cims.2017.04.010

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Bending Performance of *Populus Deltoides* Wood: Influence of Ammonia, Sodium Hydroxide, Temperature and Additives

Svojstva savijanja drva *Populus deltoides*: utjecaj amonijaka, natrijeva hidroksida, temperature i aditiva

ORIGINAL SCIENTIFIC PAPER

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ABSTRACT • *Wood bending has a wide range of possible uses, such as in making bent furniture, musical instruments, and sporting goods. The study is centred on using a full factorial design of experiments to understand the main and interaction effects of factors like ammonia (20 % and 25 %), NaOH (2.5 % and 0 %), temperature (90 °C and room temperature), and additives (10 % polyethylene glycol (PEG) and 10 % fabric conditioner (FC) on the bending properties of Populus deltoides wood specimens of size 20.3 cm × 1 cm × 1 cm. Two levels of each factor were used to find the response to wood bending properties. Deflection to the load ratio (D/L) was evaluated for the treated specimens using a universal testing machine. The ease of bending, bending defects, and spring-back properties of bent wood were also evaluated. Results indicate that NaOH and temperature have significant influences on the D/L ratio and ease of bending. The bending defect was influenced not only by factors like use of NaOH and temperature but also by the interaction effect between ammonia-NaOH and NaOH-temperature. Although the effect of ammonia on wood bending was significant, no difference was found between the two ammonia concentrations (20 % and 25 %) on the bending properties of the wood. Factors such as FC and PEG did not exhibit any significant influences on wood bending properties. These findings suggest that focusing on factors like NaOH, temperature, and ammonia would be more effective in achieving the desired wood bending outcomes.*

KEYWORDS: *Populus deltoides; wood bending; NaOH; temperature; ammonia*

SAŽETAK • *Savijanje drva čest je postupak u proizvodnji namještaja, primjerice u izradi savijenog namještaja, glazbenih instrumenata i sportske opreme. Istraživanje je usmjereno na primjenu potpunog faktorskog dizajna eksperimenata kako bi se razumjeli glavni i interakcijski utjecaji čimbenika poput amonijaka (20 i 25 %), NaOH (2,5 i 0 %), temperature (90 °C i sobne temperature) te aditiva (10 % polietilen glikola – PEG i 10 % omekšivača za tkanine – FC) na svojstva savijanja uzoraka drva Populus deltoides dimenzija 20,3 cm × 1 cm × 1 cm. Za pronalaženje odgovora o utjecaju navedenih čimbenika na svojstva savijanja drva odabrane su dvije razine svakoga*

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od njih. Omjer progiba i opterećenja (D/L) za tretirane uzorke procijenjen je uz pomoć univerzalnog uređaja za ispitivanje. Također su procijenjene lakoća savijanja, greške savijanja i elastični povrat savijenog drva. Rezultati pokazuju da NaOH i temperatura znatno utječu na omjer D/L i lakoću savijanja. Na greške savijanja utjecali su upotreba NaOH i temperatura, ali i interakcija između amonijaka i NaOH te između NaOH i temperature. Iako je utjecaj amonijaka na savijanje drva bio znatan, nije utvrđeno da je na svojstva savijanja utjecala razlika između dviju koncentracija amonijaka (20 i 25 %). Čimbenici poput FC-a i PEG-a nisu pokazali bitan utjecaj na svojstva savijanja drva. Navedeni rezultati upućuju na to da bi za postizanje željenih rezultata savijanja drva bilo učinkovitije fokusiranje na čimbenike poput NaOH, temperature i amonijaka.

KLJUČNE RIJEČI: *Populus deltoides; savijanje drva; NaOH; temperatura; amonijak*

1 INTRODUCTION
1. UVOD

Wood is a versatile and sustainable natural resource that has been used for various applications for thousands of years. Wood stiffness is a desirable property for engineering applications. However, stiffness prevents the bending of wood for various applications like furniture, arches, etc. The potential applications of wood bending are vast and include the manufacturing of curved furniture, architectural features, musical instruments, and sports equipment. The use of wood plasticization can allow for creation of unique and intricate designs that would be difficult or impossible to achieve using traditional woodworking techniques. Additionally, the use of wood as a renewable and sustainable material can contribute to the development of environmentally friendly products.

The degree of plasticity in wood is primarily influenced by the softening of the middle lamella, which contains lignin as its primary component. Lignin plays a crucial role in determining the plastic properties of wood, although it is not the sole factor. The glass transition temperature (T_g) of lignin in its dry state is approximately 205 °C, but various studies have reported different glass transition temperature for lignin that is dependent on various temperature conditions, e.g., 60 °C (Kelley *et al*., 1987), 50 to 100 °C (Furuta *et al*., 1997) and 170 °C (Ibach, 2010). Increased moisture content or using a plasticizer can lower the T_g for all wood components (Ibach, 2010), lignin exhibiting a T_g of about 100 °C, when wood is saturated with water. Additionally, the T_g of cellulose, hemicellulose and lignin in wet conditions can range from 222 to 250 °C, 54 to 142 °C, and 77 to 128 °C, respectively (Goring, 1963).

There are three major theories of wood bending: Lubricity theory suggests that polymer deformation arises from intermolecular friction; Gel theory proposes that the rigidity of a polymer stems from its internal three-dimensional structure formed through loose attachment along polymer chain; and Free Volume Theory indicates that increased polymer mobility is facilitated by the expansion of the free volume induced by plasticizer (Sunny, 2021).

Steaming of wood allows for bending by softening its fibers through heat and moisture. However, pressurized steam is not effective as it can lead to compression, wrinkling and increased resistance to curvature (Kollmann and Cote, 1968). Spring-back commonly occurs in steam bending (Kang, 2010). Wood impregnated with anhydrous, liquid ammonia or aqueous solution of ammonia allows it to be bent and retain the desired shape after the ammonia evaporates. NH_3 penetrates the amorphous region of cell walls, cellulose crystal structure, and phenolic lignin bonds, disrupting H-bonds responsible for wood rigidity (Huttumen, 1975). Softening the cellular structure enables fibers to slide past each other under external forces and upon ammonia evaporation, H-bond reforms, restoring the original rigidity of wood (Hon and Shiraishi, 2000). Apart from NH_3, NaOH can also be utilized for wood bending. NaOH treatment has significant effects on wood such as delignification, swelling, and surface modification and it also has the potential for damage of the wood structure when used excessively or for prolonged periods (Nakano and Nakano, 1995).

Temperature and moisture content have a significant effect on the physical and mechanical properties of wood; with a decrease in strength, the plastic deformability increases (Miksik *et al.,* 2023). Higher temperatures facilitate better solution penetration into the wood fibers, resulting in improved flexibility and pliability for bending purposes (Gaff *et al*., 2017). Fabric conditioner (FC), which is a mixture of quaternary ammonium compounds and fatty acids, can also penetrate the cell walls of wood and soften cellulose. Polyethylene Glycol (PEG), on the other hand, is a water-soluble polymer that can penetrate the cell walls of wood and fill the pores, resulting in increased dimensional stability and water resistance.

The present study employs a design of experiment approach to investigate the influence of NaOH, NH_3, temperature, and additives (PEG and FC) on wood bending properties. This research aims to uncover sustainable and efficient methods for enhancing wood bending and its interaction. By utilizing a factorial design experiment, it was aimed to identify the most effective parameters and their impact on wood bending, with implications for the construction and furniture industries. This systematic approach ensures a reliable and practical exploration of wood bending solution.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Preparation of wooden specimens
2.1. Priprema uzoraka drva

Poplar logs (*Populus deltoides*), from tree aged 5-6 years, were flat sawn into wood specimens of dimensions of 20.3 cm × 1 cm × 1 cm. Mean density of the wood was 0.45 g/cm^3. The specimens with any type of defects, fungal infection, knots, etc. were discarded in the beginning. The specimens were air dried to moisture content range of 15-18 %.

2.2 Preparation of treatment solution: preliminary experimentation
2.2. Priprema otopine za tretiranje uzoraka drva: preliminarno istraživanje

To determine an acceptable ammonia concentration that balances effectiveness with tolerable pungency, a brief sensory survey was conducted using aqueous ammonia solutions of 20 %, 25 %, 30 %, and 35 %. The survey indicated that concentrations below 30 % (i.e., 25 % and 20 %) were within a bearable range for working conditions. Therefore, these two concentrations (20 % and 25 %) were selected for subsequent experiments.

The treatment solutions were formulated to promote wood plasticization primarily through physicochemical interactions rather than through chemical reactions among the components. Aqueous ammonia penetrates the amorphous regions of the cell wall, disrupts hydrogen bonding in lignin and hemicelluloses, and induces reversible swelling, whereas sodium hydroxide contributes to partial delignification, particularly in the middle lamella, leading to loosening of the cell wall structure. At the concentrations and treatment durations used, no significant chemical reaction between ammonia and NaOH was expected; instead, their effects are considered additive or synergistic, with ammonia enhancing matrix accessibility and facilitating NaOH penetration. The additives (PEG and fabric conditioner) are not expected to react chemically with the alkali treatments and likely act as secondary softening agents by reducing intermolecular friction within the cell wall, thereby enhancing temporary plasticization and bendability. In the initial phase, ten test specimens were immersed in each of five treatment solutions: (i) 20 % aqueous ammonia, (ii) 25 % aqueous ammonia, (iii) 20 % aqueous ammonia containing 10 % FC, (iv) 20 % aqueous ammonia containing 10 % PEG (PEG-1000), and (v) water (control). The specimens were submerged for four hours, after which their deflection-to-load (D/L) ratio till breaking point was measured using a universal testing machine.

2.3 Testing specimen deflection to load ratio (D/L ratio)
2.3. Ispitivanje omjera progiba i opterećenja uzoraka (omjer D/L)

Using a universal testing machine, a three-point static bending test (as shown in Figure 1) was carried out, and the load (kg) and deformation (mm) of each specimen was recorded to calculate D/ L ratio. The applied load was recorded in kilogram-force (kgf) as displayed by the universal testing machine; for reference, 1 kgf (kg) corresponds to 9.81 N. The D/L ratio data was used for ANOVA and post-hoc analyses (Tukey's HSD test) using SPSS statistical software package. Based on the results, further experimentation was carried out using full factorial design of experiment technique.

All test specimens were prepared from flat-sawn boards with a consistent annual ring orientation, and the ring position was kept uniform across all treatments to minimize its influence on bending results.

2.4 Full factorial experimental design
2.4. Potpuni faktorski dizajn eksperimenata

For the full factorial experimental design, four factors, each with two levels, were taken for the study: aqueous ammonia solution, NaOH, temperature and additives (FC and PEG). Table 1 presents the factors and their levels.

Ten wood specimens for each treatment combination were submerged in the respective solution for four hours. After treatment, the specimens were remo-

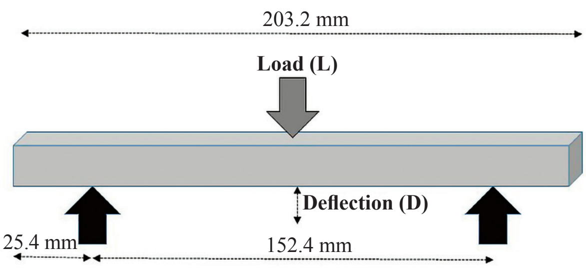

Figure 1 Scheme of static bending tests
Slika 1. Shema statičkih ispitivanja savijanja

Table 1 Treatment combinations
Tablica 1. Kombinacije tretmana

Sl. No. / *Red. br.*	Factors / *Čimbenici*	Level 1 / *Razina 1.*	Level 2 / *Razina 2.*
1.	Aqueous ammonia solution / *vodena otopina amonijaka*	20 %	25 %
2.	NaOH solution / *otopina NaOH*	2.5 %	0 %
3.	Solution temperature / *temperatura otopine*	90 °C	Room temperature
4.	Additives (10 %) / *aditivi (10 %)*	Fabric softener	PEG

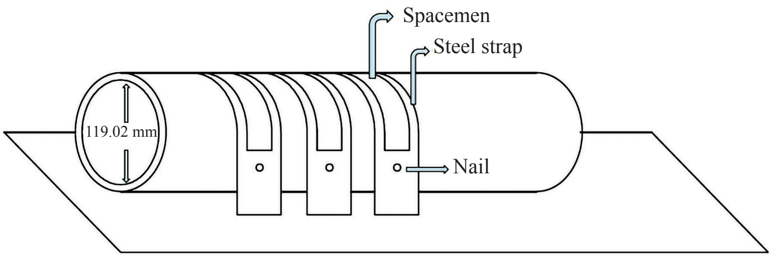

Figure 2 Diagram of curved frame setup
Slika 2. Dijagram postavljanja zakrivljenog okvira

ved, the excess solution was wiped off, and they were subjected to bending tests.

Unscrambler 10.2 software (CAMO Software AS, Oslo, Norway) was used for the full factorial experimental design. A factorial design (2^4) was created with 2 replications of each experiment. Thus, 16 experiments were replicated 2 times to make a total of 32 experiments with the measurement of 4 response variables. The power of experiment was 0.9 after the randomization. The software generated randomized order of the experiments was used to carry out the experiments. The response variables were analyzed using the Unscrambler software.

A general form of the model (two-way interaction) can be represented as follows:

$$y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ik} x_i x_k + \sum \beta_{ii} x_i^2 \tag{1}$$

Where: y is the dependent variable (response); β_i is the coefficients of factor/variable; β_{ik} is the coefficient of interactions and x_i is factor/variable. This model represents the effects of process variables (Aqueous ammonia solution, NaOH, temperature and additives) and their interactions on the response variables (D/L ratio, ease of bending, spring-back and bending defects). On the basis of the analysis of variance (ANOVA), validity of the models was established.

2.5 Response variables
2.5. Istraživane varijable

Four response variables viz. D/L ratio, ease of bending, spring-back and bending defects were recorded for each experiment. The process of recording the response variable values is explained in the next section.

2.6 Wood bending and evaluation of ease of bending
2.6. Savijanje drva i procjena lakoće savijanja

For the bending test, a cylinder with a diameter of 119.02 mm was used. The samples were securely held onto the cylinder using steel straps and nails, and the specimens were bent and kept in bend condition for a duration of 24 hours (Figure 2). All bending tests and ease-of-bending assessments were performed by the same trained operator in a randomized sequence, with regular rest intervals and limited session duration to minimize fatigue and maintain consistent physical and mental conditions. The operator was asked to grade the ease with which bending was done from scale 0 (difficult to bend) to 10 (easy to bend) after bending each specimen.

2.7 D/L ratio
2.7. Omjer D/L

After the treatment, D/L ratio was recorded immediately by adopting the methodology as explained in the previous section.

2.8 Spring-back in bent specimens
2.8. Elastični povrat savijenih uzoraka

After keeping the bent wooden specimens clamped in the curved frame for 24 hours, they were unclamped, and the distance between the two ends of each specimen was measured (D1). The specimens were then fully dried in an electric kiln at 45 °C and 70 % RH till the final moisture content came in the range of 8-12 %, after which the distance between the two ends was measured again (D2). The difference between these two measurements represented the spring-back of the specimen: a negative value indicated shrinkage (inward movement), while a positive value indicated a tendency of the specimen to return toward its original straight form (Figure 3).

2.9 Evaluation of bending defects
2.9. Evaluacija grešaka savijanja

After the samples were fully dried to the final moisture content of 10-12 %, a defect rating scale ranging from 0 (no defects) to 10 (severe defects) was used to assess the quality and presence of any defects in the samples (Table 2). Any major crack and wood failure during bending was given defect score 10, whereas less severe crack was given defect score 9. A seve-

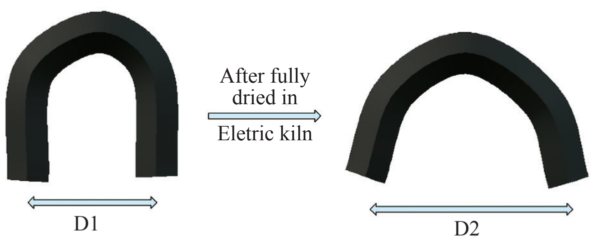

Figure 3 Movement in test specimens
Slika 3. Pomak ispitivanih uzoraka

Table 2 Defect rating scale (0–10) used for visual evaluation of bending defects in wooden specimens, where 0 indicates no defects and 10 indicates complete failure
Tablica 2. Ljestvica ocjenjivanja grešaka (0 – 10) za njihovu vizualnu procjenu pri savijanju uzoraka drva, na kojoj 0 znači da nema grešaka, a 10 označava potpuni lom drva

Bent wooden specimens / *Savijeni uzorci drva*	**Defect value** / *Ocjena greške*
	0
	1
	2
	3
	4
	5
	6
	7
	8
	9
	10

re failure at central line (slip) was given score 8, whereas medium and minor failure were given the defect scores 7 and 6, respectively. Defect scores 5 and below were given to the minor defects based on severity. The wooden specimens with no defects were allotted defect score 0.

3 RESEARCH METHODS
3. METODE ISTRAŽIVANJA

3.1 Effect of ammonia and additives (PEG and FC) on bendability of wood: results of preliminary experiments
3.1. Utjecaj amonijaka i aditiva (PEG i FC) na savitljivost drva: rezultati preliminarnih istraživanja

Table 3 presents test results of D/L ratio at various combinations using 20 % ammonia, PEG and FC. The mean D/L ratio varied considerably among the different treatments. Samples treated with 20 % ammonia alone exhibited the highest mean D/L ratio (0.14 mm/ kg load ± 0.06), followed by 20 % ammonia combined with 10 % PEG (0.12 mm/ kg load ± 0.05) and 20 % ammonia with 10 % FC (0.10 mm/ kg load ± 0.04). In contrast, treatments with 10 % PEG (0.08 mm/ kg load ± 0.03) or 10 % FC alone (0.07 mm/ kg load ± 0.03) showed only slight increases over the control (0.07 mm/ kg load ± 0.01). The 95 % confidence intervals indicated that ammonia-based treatments resulted in higher D/L ratios than the control, whereas the effect of additives alone was marginal. These observations suggest that ammonia is the primary factor responsible for improving the D/L ratio, while the addition of PEG or FC alone has little effect. When combined with ammonia, these additives slightly moderated the effect but did not surpass the impact of ammonia alone.

An ANOVA analysis of D/L ratio showed a significant difference among the treatments ($p = 0.005$). The post hoc analysis using Duncan's test categorized all variables into four subsets i.e. set 1 (control and FC 10 %), set 2 (PEG 10 % and Ammonia + FC 10 %), set 3 (Ammonia 10 % + PEG 10 %), set 4 (20 % Ammonia). It can be interpreted that ammonia has the highest significance among all six variables.

The post hoc analysis provides valuable insights into the significance of different variables in wood bending. It highlights the strong impact of ammonia and indicates that the presence of other variables in combination with ammonia may alter its effects. Ammonia solution infiltrates plant cell lignin, swelling cellulose and altering its crystal lattice, disrupting hydrogen bonds in wood polysaccharides. Liquid ammonia softens fibers, promoting macromolecule flow, inducing tension or compression in wood (Schuerch *et al.*, 1966). Conversely, FC and PEG do not show a significant influence on wood bending according to this analysis.

3.2 Results of full factorial experiments
3.2. Rezultati potpunih faktorskih eksperimenata

3.2.1 Cube plots
3.2.1. Kockasti dijagrami

The cube plot of factor interactions (Figure 4a) shows the combined influence of ammonia concentration (A), NaOH concentration (B) and temperature (C) on the deflection/load (D/L) ratio. The values at the vertices indicate that the highest D/L ratio (0.5425 mm/kg) was obtained when all three factors were at their high levels, whereas the lowest values (0.1925 – 0.2205 mm/kg) occurred when all factors were at low levels. Among the three factors, ammonia concentration exerted the strongest positive effect on the D/L ratio, with a marked increase whenever it was at its higher level. NaOH concentration and temperature also contributed positively, but their effects were more evident when combined with high ammonia. The interaction patterns

Table 3 Deflection to load ratio due to effect of ammonia in isolation and in combination
Tablica 3. Omjer progiba i opterećenja zbog utjecaja amonijaka kao jedinog aditiva i u kombinaciji s drugim aditivima

Treatments *Tretmani*	*N*	**D/ L ratio, mm/kg load** *Omjer D/L, mm/kg opterećenja*	**Std. Deviation** *SD*	**Std. Error** *SE*	**95 % Confidence interval for mean** *95 %-tni interval pouzdanosti za srednju vrijednost*		**Minimum, mm/kg load** *Minimum, mm/kg opterećenja*	**Maximum, mm/kg load** *Minimum, mm/kg opterećenja*
					Lower bound *Donja granica*	Upper bound *Gornja granica*		
20 % ammonia	10	0.14	0.06	0.02	0.10	0.18	0.08	0.22
20 % ammonia+10 % FC	10	0.10	0.04	0.01	0.07	0.13	0.06	0.18
20 % ammonia+10 % PEG	10	0.12	0.05	0.02	0.08	0.15	0.06	0.22
10 % PEG	10	0.08	0.03	0.01	0.06	0.11	0.06	0.12
10 % FC	10	0.07	0.03	0.01	0.06	0.11	0.05	0.13
Control	10	0.07	0.01	0.00	0.06	0.08	0.05	0.09

highlight that ammonia is the dominant factor influencing the D/L ratio, with synergistic effects arising from its combination with NaOH and elevated temperature.

The cube plot depicting the combined effects of ammonia concentration (A), NaOH concentration (B) and temperature (C) on the ease of bending (Figure 4b) reveals that the ease of bending improved substantially when all three factors were maintained at their high levels, resulting in the highest score (5.4550). Conversely, the lowest values (approximately 2.8330 – 3.0980) were recorded when the factors were at their low levels. Among the three factors, ammonia concentration again showed the most pronounced influence, with a marked increase in bending ease observed at its higher level. The effects of NaOH concentration and elevated temperature were comparatively smaller when applied individually, but their interaction with high ammonia produced synergistic improvements. These results indicate that chemical softening combined with heat treatment has a cumulative effect on improving the bending performance of wood.

The combined effects of ammonia concentration (A), NaOH concentration (B) and temperature (C) on spring-back are shown in Figure 4c. Negative values indicate a reduction in spring-back, which is desirable for improved shape stability after bending. The plot reveals that the largest negative value (-22.15) was obtained when all three factors were at their high levels, signifying the greatest reduction in spring-back. Conversely, minimal changes (-0.65 to -1.50) were obser-

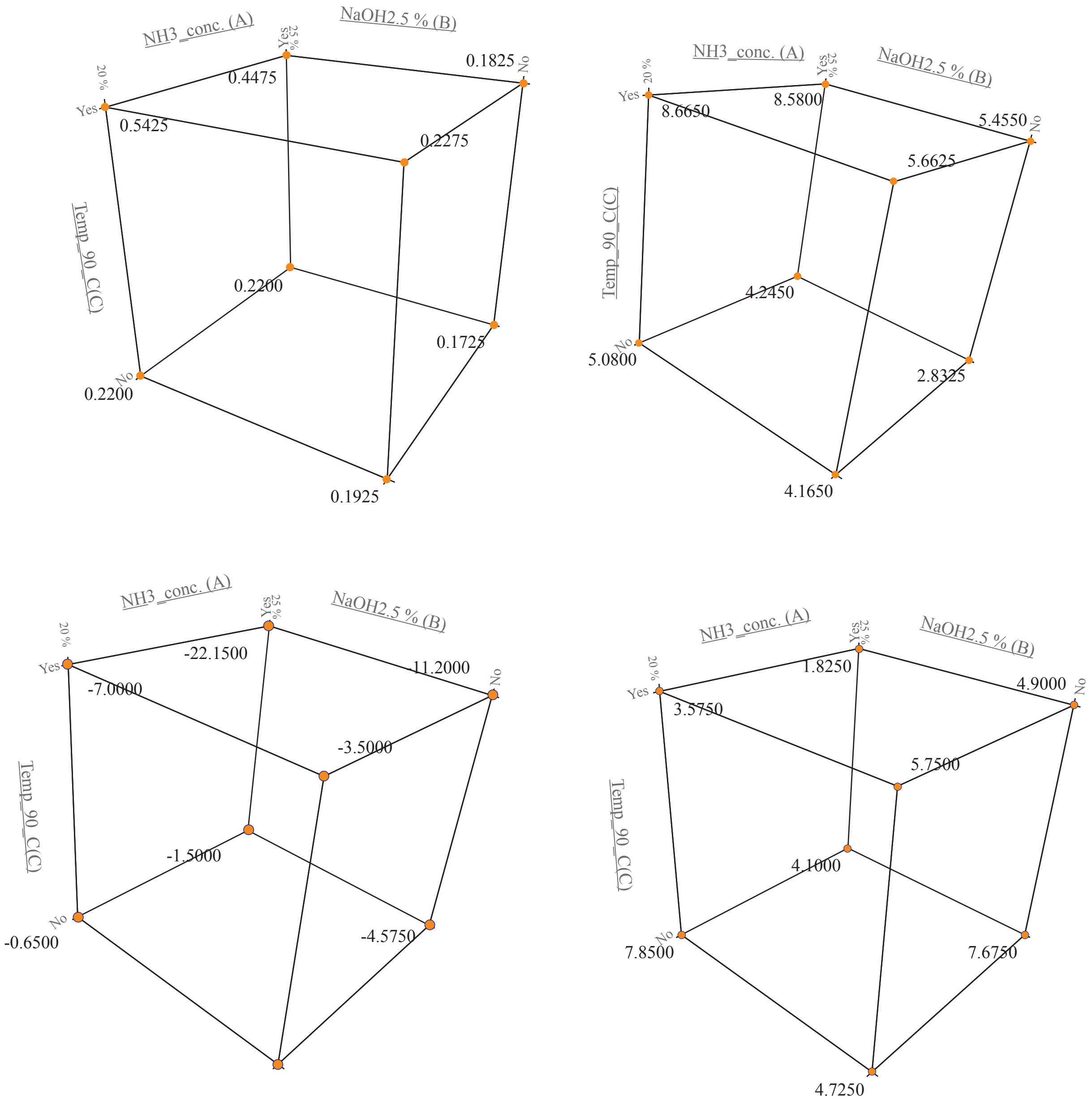

Figure 4 Cube plots influence of Ammonia, NaOH and temperature on deflection/ load ratio (a), ease in bending (b), spring-back (c) and defects due to bending (d)
Slika 4. Kockasti dijagrami utjecaja amonijaka, NaOH i temperature na omjer progib/opterećenje (a), lakoću savijanja (b), elastični povrat (c) i greške savijanja (d)

ved when the factors were at their low levels. Ammonia concentration exerted the strongest influence, and the effect was amplified when combined with higher NaOH concentration and elevated temperature. This interaction suggests that chemical softening, particularly using ammonia, in combination with heat treatment, is effective in reducing spring-back and enhancing the dimensional stability of bent wood.

The influence of ammonia concentration (A), NaOH concentration (B) and temperature (C) on the occurrence of bending defects is illustrated in Figure 4d. Lower values correspond to fewer visible defects. The cube plot shows that the minimum defect score (1.8250) occurred when all three factors were maintained at high levels, whereas the maximum defect scores (7.6750 – 7.8500) were recorded when the factors were at their low levels. Ammonia concentration again appeared to be the most dominant factor, substantially reducing the number of defects when applied at its higher level. The combined use of high NaOH concentration and elevated temperature further minimized the occurrence of defects. These results demonstrate that chemical softening using ammonia, supplemented with NaOH and heat treatment, significantly improves the bending quality by reducing surface and internal defects.

3.2.2 ANOVA table and effect summary
3.2.2. ANOVA tablica i sažetak utjecaja

Table 4 presents ANOVA table and effect summary of the models, ammonia concentration, NaOH, temperature, additives and their combined interaction effects on deflection/ load ratio, ease in bending, spring-back and defects values. The fitted model for D/L was statistically significant ($p = 0.0026$), explaining approximately 67 % of the total variability ($R^2 = 0.6688$). Among the individual factors, NaOH concentration ($F = 16.59$; $p = 0.0006$) and temperature ($F = 13.66$; $p = 0.0013$) had highly significant effects on the response, whereas ammonia concentration (20 % and 25 %) alone was not significant ($p = 0.3315$). A significant interaction was observed between NaOH concentration and temperature ($F = 9.84$; $p = 0.0050$), indicating a synergistic effect when these two factors were combined. Neither the FC nor its interactions contributed significantly to the response ($p > 0.05$). The lack-of-fit test was not significant, confirming that the model adequately described the data. Overall, the results highlight that NaOH concentration and temperature are the dominant factors affecting the response variable D/L ratio, with their combined influence being particularly important.

The results of the analysis of variance (ANOVA) for ease in bending revealed that the fitted model was statistically significant ($p = 0.0031$), explaining 66.18 % of the total variation in the response with an adjusted R^2 of 0.5008. Among the individual factors, NaOH concentration ($p = 0.0027$) and temperature ($p = 0.0001$) exerted a significant influence on the response, whereas NH_3 concentration (20 % and 25 %) ($p = 0.3347$) and the FC ($p = 0.4041$) were not significant. This can be explained by the partial delignification that leads to a partial loosening of the cell wall. None of the two-way interaction terms showed a significant effect ($p > 0.05$), indicating that the factors acted largely independently. The model check confirmed that a linear model adequately described the data ($p = 0.0002$) without a significant contribution from higher-order interactions. Although the model exhibited a reasonable fit, the relatively low predicted R^2 (0.2147) and a coefficient of variation of 31.54 % suggest moderate variability and scope for improving predictive performance in ease of bending.

ANOVA (Table 3) showed that the model for spring-back was significant ($p = 0.0161$) with an R^2 of 0.59, although the adjusted (0.39) and predicted (0.05) R^2 values indicate limited predictive strength. Among the factors, NaOH concentration ($p = 0.0036$) and the soft additive ($p = 0.0133$) had significant effects, as well as the interaction between temperature and the soft additive ($p = 0.0305$). Other main effects and interactions were not significant. The linear model was adequate ($p = 0.0061$), but the high variability (CV = 63.7 %) suggests scope for improvement.

The model for bending defects was significant ($p = 0.0248$) with an R^2 of 0.5661, though the adjusted R^2 was 0.3595 and the predicted R^2 was very low (-0.0075), suggesting weak predictive ability. Among the factors, temperature ($p = 0.0068$) had the strongest effect, followed by the interaction between NH_3 concentration and NaOH ($p = 0.0121$); NaOH concentration was marginally significant ($p = 0.0520$). Other main effects and interactions were not significant. The linear model was adequate ($p = 0.0187$), but the high variability (CV = 38.7 %) indicates scope for model refinement. Temperature increased the solubility of treatment chemicals, enabling more thorough and efficient penetration into the structure of the wood. Better interaction between the treatment compounds and the wood components was made possible by this greater penetration, which may have improved the wood bending capabilities (Suleman, 2015). The effect of temperature on wood bending is two-pronged as many studies demonstrate that the higher temperature reduces the wood strength significantly. Bending strength and modulus of elasticity decrease as temperature is increased (Sonderegger and Niemz, 2006, Zhong *et al.*, 2015).

Moreover, the effect of NaOH on wood delignification rate is doubled on a temperature increase of 10 °C (Lusby and Maass,1937). NaOH causes partial

Table 4 ANOVA table and effect summary
Tablica 4. ANOVA tablica i sažetak utjecaja

Factors and interactions *Čimbenici i njihova međusobna djelovanja*	**D / L**		**Ease in bending** *Lakoća savijanja*		**Spring-back** *Elastični povrat*		**Defects** *Greške*	
	p-value	Effect value	p-value	Effect value	p-value	Effect value	p-value	Effect value
Model (p-value) *model (p-vrijednosti)*	*0.0026*		*0.0031*		*0.3346*		*0.0248*	
Ammonia conc. (A) *koncentracija amonijaka (A)*	0.3315	-0.04	0.3347	-0.615	0.1627	-5.6688	0.2328	-0.85
Sodium hydroxide (B) *natrijev hidroksid (B)*	0.0006	0.1638	0.0027	2.1138	0.6875	-1.6063	0.052	-1.425
Temperature (C) *temperatura (C)*	0.0013	0.1488	0.0001	3.01	0.0611	-7.8813	0.0068	-2.075
Additives (D) *aditivi (D)*	1	0	0.4044	-0.53	0.4739	-2.8688	0.6182	-0.35
A × B	0.8539	-0.0075	0.8059	0.155	0.5645	-2.3313	0.0121	-1.9
A × C	0.4642	0.03	0.46	0.4687	0.9211	-5.7563	0.5225	-0.45
B × C	0.005	0.1263	0.1421	0.95	0.3241	-5.6188	0.0975	-1.2
A × D	0.83	-0.0087	0.3674	-0.5738	0.3033	0.7313	0.4564	0.525
B × D	0.8062	-0.01	0.4402	0.49	0.1042	4.1688	0.4999	-0.475
C × D	0.4283	0.0325	0.7558	-0.1963	0.9099	-0.4563	0.5456	-0.425

loosening of the cell wall through partial delignification. Increasing the temperature enhances the solubility of treatment agents, allowing for better penetration into the wood structure and potentially improving bending properties. On the other hand, the main effects of NH_3 concentration and the presence of FC are non-significant, suggesting no significant impact on defects.

An interesting interaction effect trend is observed between NH_3 and NaOH on bending defects. Bending defects reduced significantly when NH_3 was used in presence of NaOH. The ligno-cellulose surface area is increased by the ammonia treatment (Mankar *et al.*, 2021), allowing NaOH to more easily de-lignify the cell wall. Hence, mixing NH_3 and NaOH at greater concentrations lowers bending defects, and applying 2.5 % NaOH at 90 °C further reduces defects, probably as a result of delignification, partial cell-wall loosening, and enhanced plasticization. In comparison to other combinations, the synergistic effect of temperature and NaOH concentration results in better bending performance and bending defects.

Two concentrations of ammonia (20 % and 25 %) have been compared and presented in Table 3. It may be seen that the difference due to concentrations of NH_3 on all the four responses (deflection/ load ratio, ease in bending, spring-back and defects) is non-significant ($p > 0.05$) at alpha 0.05, i.e. the performance of ammonia at 20 % was found to be equal to that of 25 %.

Across all four ANOVA models, the regression analyses confirm that the process is predominantly influenced by temperature and NaOH concentration, while NH_3 concentration and the additives generally have weaker or inconsistent effects. In most models, interaction effects were largely insignificant, with only a few cases (e.g., temperature × additive and NH_3 × NaOH) showing statistical significance. The models are statistically valid overall ($p < 0.05$), but their predictive capability is limited, as reflected by moderate R^2 values (0.56–0.66), low adjusted and predicted R^2, and high coefficients of variation. These results suggest that temperature and alkali concentration are the primary drivers of the response, and future model refinement (e.g., additional factors, non-linear terms) may be needed to improve prediction accuracy.

4 CONCLUSIONS
4. ZAKLJUČAK

The factorial design of the experiment resulted in significant models using the effects of factors like ammonia, NaOH, temperature, and additives on the responses deflection/load (D/L) ratio, ease of bending, and bending defects. However, the model was not significant for spring-back response. The comprehensive analysis of the experimental results highlights the varying effects of different variables on wood bending properties. NaOH and temperature demonstrated significant influences on the D/L ratio and ease of bending. The most important factor in reducing spring-back was temperature. Bending defects are influenced not only by factors like NaOH and temperature but also by the interaction effect between ammonia-NaOH and NaOH-temperature. The effect of ammonia on wood bending was significant, but no difference was found between the effects due to the two ammonia concentrations (20 % and 25 %). Factors such as FC and PEG did not exhibit any significant influences on wood bending properties. These findings imply that the reaction is primarily driven by temperature and alkali concentration in combination with ammonia, and that more model modification (e.g. additional components, non-linear terms) may be required to increase forecast accuracy.

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5 REFERENCES
5. LITERATURA

1. Furuta, Y.; Aizawa, H.; Yano, H.; Norimoto, M., 1997: Thermal-softening properties of water-swollen wood: IV. Effects of chemical constituents of the cell wall on the thermal-softening properties of wood. Mokuzai Gakkaishi, 43 (9): 725-730.
2. Gaff, M.; Gašparík, M.; Babiak, M.; Vokatý, V., 2017: Bendability characteristics of wood lamellae in plastic region. Composite Structures, 163: 410-422. https://doi.org/10.1016/j.compstruct.2016.12.052
3. Goring, D. A., 1963: Thermal softening of lignin, hemicellulose and cellulose. Pulp and Paper in Canada, 64 (12): 517-527.
4. Hon, D. N.; Shiraishi, N., 2000: Wood and cellulosic chemistry, revised and expanded. CRC press. https://doi.org/10.1201/9781482269741
5. Huttunen, J., 1975: *Method for plasticizing wood*. U.S. Patent No. 3,894,569. Filed July 26, 1973; issued July 15, 1975.
6. Ibach, R. E., 2010: Specialty treatments. In: Wood Handbook: Wood as an Engineering Material, General technical report FPL; GTR-190. U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, pp. 19.1-19.16.
7. Kang, H.-G., 2010: *A study on the technique and process of bending wood*. Journal of the Korean Furniture Society, 21 (6): 459-468.
8. Kelley, S. S.; Timothy, G. R.; Glasser, W. G., 1987: Relaxation behaviour of the amorphous components of wood. Journal of Material Science, 22 (2): 617-624.
9. Kollmann, F. F. P.; Cote Jr., W. A., 1968: Principles of wood science and technology solid wood, vol. 1. Springer-Verlag, New York, USA, pp 592.
10. Lusby, G. R.; Maass, O., 1937: The delignification of wood by strong alkaline solutions. Canadian Journal of Research, 15 (12): 536-544.
11. Mankar, A. R.; Pandey, A.; Modak, A.; Pant, K. K., 2021: Pretreatment of lignocellulosic biomass: A review on recent advances. Bioresource Technology, 334: 125235. https://doi.org/10.1016/j.biortech.2021.125235
12. Mikšik, M.; Pervan, S.; Klarić, M.; Čavlović, A. O.; Španić, N.; Prekrat, S., 2023: Factors influencing behaviour of solid wood bending process. Drvna industrija, 74 (1): 105-114. https://doi.org/10.5552/drvind.2023.0020
13. Nakano, S.; Nakano, T., 2015: Morphological changes induced in wood samples by aqueous NaOH treatment and their effects on the conversion of cellulose I to cellulose II. Holzforschung, 69 (4): 483-491. https://doi.org/10.1515/hf-2014-0074
14. Schuerch, C.; Burdick, M. P.; Mahdalik, M., 1966: Liquid ammonia-solvent combinations in wood plasticization. Chemical treatments. Industrial & Engineering Chemistry Product Research and Development, 5 (2): 101-105.
15. Sonderegger, W.; Niemz, P., 2006: Der Einfluss der Temperatur auf die Biegefestigkeit und den Elastizitätsmodul bei verschiedenen Holzwerkstoffen. Holz Roh Werkst, 64: 385-391. https://doi.org/10.1007/s00107-006-0096-x
16. Suleman, Y. H., 2015: Softening and bending of black poplar (*Populus nigra* L.) wood with chemicals. Tikrit Journal for Agricultural Sciences, 15 (4): 15-20.
17. Sunny, P., 2021: Wood Plasticization. https://www.slideshare.net/pavinsunny/wood-plasticization (Accessed: Feb. 14, 2023).
18. Zhong, Y.; Zhou, H.; Wen, L., 2015: The effect of elevated temperature on bending properties of normal wood inside Chinese larch wood during fire events. BioResources, 10 (2): 2926-2935.

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Technical, Energy, and Environmental Performance Evaluation of an Industrial-Scale Solar–Steam Hybrid Wood Drying System in Tropical Climate of Vietnam

Evaluacija tehničkih, energetskih i ekoloških performansi hibridnoga solarno-parnog industrijskog sustava za sušenje drva u tropskoj klimi Vijetnama

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ABSTRACT • *This study presents an industrial-scale evaluation of a 100 m³ per batch solar–steam hybrid wood drying system operating under tropical climate conditions in Vietnam. A full drying cycle of approximately 480 hours was performed on 13-mm Acacia mangium lumber using a multi-point monitoring system that recorded dry- and wet-bulb temperatures, relative humidity, air velocity, solar irradiance, and the thermal and electrical energy inputs at 10-minute intervals. The integrated roof collector achieved an average thermal efficiency of ~46 % (peaking at ~52 %), delivering 15,687 kWh of useful heat and supplying 40 – 52 % of the daytime thermal demand. Compared with a conventional steam kiln, the hybrid system reduced biomass consumption by 50 %, electricity use by 34.3 %, and total energy input by 45.2 %. The Specific Energy Consumption (SEC) decreased from 1.99 to 1.09 kWh/kg of water removed (- 45.2 %), confirming hypothesis H1. The solar fraction reached 44.3 % (thermal basis) and 33.8 % (total basis), supporting hypothesis H3. Wood quality assessments following TCVN 8929/8930 showed that the hybrid kiln maintained comparable levels of product quality, with surface and internal check rates of 2.8 % and 1.0 %, respectively. The average warping was 2.2 mm, exhibiting an improving trend compared with the control kiln (p = 0.054), thereby further supporting hypothesis H2. Environmental analysis following IPCC 2006/2019 guidelines indicated that the hybrid system reduced non-biogenic CO_2 emissions by 34.3 %, consistent with hypothesis H4. Overall energy costs decreased by 38.7 % per batch, resulting in a payback period of approximately 3.04 years, which remained below 4 years under CAPEX variations of ± 20 %. Collectively, the findings demonstrate that the solar–steam hybrid system is an efficient, stable, and economically viable solution for industrial wood drying under tropical conditions, contributing to reduced fossil-based CO_2 emissions and supporting sustainable production pathways.*

KEYWORDS: *solar-steam hybrid wood drying; solar-assisted drying; specific energy consumption (SEC); solar fraction; industrial-scale experiment; acacia mangium; energy efficiency; CO_2 emissions; hygrothermal performance*

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SAŽETAK • *Studija donosi evaluaciju hibridnoga solarno-parnoga industrijskog sustava za sušenje drva kapaciteta 100 m³ po seriji, kakav radi u tropskim klimatskim uvjetima u Vijetnamu. Za potrebe istraživanja proveden je puni ciklus sušenja drva Acacia mangium debljine 13 mm u trajanju od približno 480 sati. Primjenom sustava mjerenja u više je točaka bilježena temperatura suhoga i vlažnog termometra, relativna vlažnost, brzina zraka, Sunčevo zračenje te potrošnja toplinske i električne energije u intervalima od deset minuta. Integrirani krovni kolektor postigao je prosječnu toplinsku učinkovitost od 46 % (s vrhuncem od 52 %), isporučujući 15 687 kWh korisne topline i osiguravajući 40 – 52 % dnevno potrebne topline. U usporedbi s konvencionalnom parnom sušarom, hibridni sustav smanjio je potrošnju biomase za 50 %, potrošnju električne energije za 34,3 %, a ukupnu potrošnju energije za 45,2 %. Specifična potrošnja energije (SEC) smanjila se s 1,99 na 1,09 kWh/kg uklonjene vode (–45,2%), potvrđujući hipotezu H1. Solarni udio dosegnuo je 44,3 % (toplinska osnova) i 33,8 % (ukupna osnova), što potvrđuje hipotezu H3. Procjene kvalitete drva prema TCVN 8929/8930 pokazale su da hibridna sušara osigurava usporedive razine kvalitete proizvoda, uz ocjenu pojave površinskih i unutarnjih pukotina od 2,8 % odnosno 1,0 %. Prosječna deformacija bila je 2,2 mm, što pokazuje trend poboljšanja u usporedbi s kontrolnom sušarom (p = 0,054), čime se dodatno potkrepljuje hipoteza H2. Analiza okoliša prema smjernicama IPCC-a 2006/2019 pokazala je da je hibridni sustav smanjio nebiogene emisije CO_2 za 34,3 %, što je u skladu s hipotezom H4. Ukupni troškovi energije smanjili su se za 38,7 % po seriji, što je rezultiralo razdobljem povrata od približno 3,04 godine, dakle manje od 4 godine, uz varijacije CAPEX-a od ± 20 %. Zaključno, rezultati pokazuju da je hibridni solarno-parni sustav učinkovito, stabilno i ekonomski isplativo rješenje za industrijsko sušenje drva u tropskim uvjetima i da pridonosi smanjenju emisija CO_2 iz fosilnih goriva te podupire održive proizvodne procese.*

KLJUČNE RIJEČI: *hibridno sušenje drva solarno-parnim sustavom; sušenje uz pomoć solarne energije; specifična potrošnja energije (SEC); solarni udio; pogonsko ispitivanje; Acacia mangium; energetska učinkovitost; emisije CO_2; higrotermalna svojstva*

1 INTRODUCTION
1. UVOD

1.1 Background
1.1. Dosadašnje spoznaje

Wood drying is one of the most energy-intensive stages in the timber processing chain, typically accounting for 50 – 70 % of the total energy consumption in sawmills and furniture manufacturing facilities (Ya Meng *et al.,* 2019). In Vietnam and most Southeast Asian countries, conventional steam kilns fueled by biomass – such as sawdust, bark, and wood chips – remain the dominant technology. While compatible with local production practices, these systems exhibit substantial limitations, including low thermal efficiency, significant heat losses due to non-uniform stacking, high fuel costs, and considerable emissions of biogenic CO_2 and particulate matter resulting from biomass combustion.

Vietnam's tropical monsoon climate, characterized by high solar irradiance, long sunshine duration, and pronounced hygrothermal fluctuations, offers strong potential for integrating solar energy into industrial thermal processes such as wood drying (Rahman *et al.,* 2025). Solar-assisted and hybrid drying technologies have been shown to reduce energy consumption and CO_2 emissions while providing milder drying conditions that help mitigate internal stresses within the wood. However, most existing studies on solar-assisted or hybrid wood drying have been limited to laboratory-scale or small pilot-scale experiments. Industrial-scale evaluations (≥ 80 – 100 m³ per batch), which involve more complex influences from weather variability, operational practices, and raw material heterogeneity, remain scarce – particularly under the tropical climate conditions of Southeast Asia.

Therefore, implementing and evaluating a 100 m³ per batch industrial-scale solar–steam hybrid wood drying system at an operational manufacturing facility serving export markets (EU, US) is essential to validate its technical feasibility, energy-saving potential, and impact on product quality under real production conditions.

1.2 Research gaps
1.2. Istraživačke praznine

Although previous studies have contributed meaningfully to the understanding of solar-assisted and hybrid wood drying, several critical scientific gaps remain:

(i) Limited industrial-scale research in tropical climates: Most prior studies have been conducted at laboratory or pilot scales, or in temperate regions with relatively stable solar radiation and humidity patterns, limiting their relevance to the highly dynamic climatic conditions of tropical Southeast Asia (Elustondo *et al.,* 2023).

(ii) Insufficient technical transparency: Many studies lack essential details regarding collector geometry, airflow configuration, insulation design, sensor placement, and control logic-parameters crucial for experimental reproducibility and accurate numerical modeling (Martynenko and Vieira, 2023).

(iii) Lack of multi-dimensional performance assessment: Most research focuses on thermal efficiency or energy savings, while critical dimensions such as CO_2 emissions, energy costs, economic performance, and post-drying wood quality are seldom evaluated concurrently (Khouya, 2022).

(iv) Absence of standardized international metrics: Indicators such as Specific Energy Consumption (*SEC*), Solar Fraction (*SF*), collector efficiency, and system-boundary-based energy balances are often reported inconsistently or incompletely. Notably, no existing study has evaluated CO_2 emissions following IPCC (2006; 2019) guidelines.

(v) Lack of critical hygrothermal measurements: Key determinants of wood drying performance – including relative humidity (RH), wet-bulb temperature (T_{wb}), and the spatial distribution of airflow velocity within the kiln – are frequently overlooked or measured insufficiently.

(vi) Inadequate statistical analysis and uncertainty quantification: Most prior work does not assess measurement uncertainty, fails to report 95 % confidence intervals, and lacks rigorous statistical hypothesis testing, limiting the reliability of conclusions and complicating cross-study comparisons.

These gaps underscore the need for an industrial-scale experimental study employing a multi-dimensional analytical framework supported by a comprehensive, high-resolution dataset collected under Vietnamese tropical climate conditions.

1.3 Research hypotheses
1.3. Istraživačke hipoteze

Building upon the contextual analysis and identified research gaps, this study is structured around four testable hypotheses:

H1: The solar–steam hybrid wood drying system reduces Specific Energy Consumption (SEC) by ≥ 30 % compared with a conventional steam kiln;

H2: The post-drying wood quality produced by the hybrid system exhibits no statistically significant difference compared with the steam kiln at a significance level of $p > 0.05$;

H3: Under the tropical climate of Vietnam's Central Highlands, the hybrid system achieves a Solar Fraction > 0.30;

H4: Non-biogenic CO_2 emissions decrease proportionally with the energy savings achieved, whereas biogenic CO_2 is accounted for separately following IPCC guidelines to ensure international comparability.

1.4 Research objectives
1.4. Ciljevi istraživanja

This study aims to comprehensively evaluate the performance of the industrial-scale hybrid wood drying system in Vietnam, covering technical, hygrothermal, energy, wood quality, economic, and environmental dimensions. The specific objectives are to:

1. Evaluate the operational characteristics, hygrothermal variability, and heat–mass transfer behavior of the 100 m³ per batch hybrid drying system;

2. Establish an energy balance based on clearly defined system boundaries to quantify core performance indicators including Specific Energy Consumption (*SEC*), total Solar Fraction (SF_{total}), and collector efficiency;

3. Compare total energy consumption, electricity consumption, fuel use, drying duration, and the influence of control logic between the hybrid and conventional steam systems;

4. Assess post-drying wood quality in accordance with TCVN 8929/8930, combined with appropriate statistical testing;

5. Analyze economic performance (energy costs, payback period) and conduct sensitivity analysis under ± 20 % variations in major economic parameters;

6. Evaluate CO_2 emissions following IPCC 2006/2019 guidelines, distinguishing clearly between biogenic and non-biogenic CO_2;

7. Identify technical limitations and propose directions for future research.

1.5 Novelty
1.5. Znanstveni doprinos

To the best of the authors' knowledge, this study presents the following novel contributions:

1. First industrial-scale evaluation of a 100 m³ per batch solar–steam hybrid wood drying system in Southeast Asia under tropical climate conditions.

2. A multi-dimensional analytical framework (Technical – Energy – Economic – Environmental – Wood Quality), extending beyond earlier studies that primarily focused on thermal efficiency.

3. Comprehensive technical transparency, detailing collector geometry, airflow pathways, insulation structure, and control logic components often only briefly mentioned in prior research.

4. Application of statistical analysis and measurement uncertainty assessment, improving the reliability and comparability of *SEC*, *SF*, and CO_2 indicators.

5. Proposal of the SF_{total} metric and the separation of biogenic CO_2 following IPCC guidelines, contributing to the standardization of performance assessment for hybrid drying systems.

Compared with previous hybrid-drying studies (Tarigan and Tekasakul, 2005; Lamrani *et al.,* 2021; Ferrari *et al.,* 2024), this study demonstrates three distinctive and verifiable innovations:

- Integrated roof collector (Large-area, Dual-layer Design): Unlike externally mounted collectors in earlier studies, the kiln roof itself functions as a 243.7 m² solar absorber, reducing thermal losses and eliminating ducting inefficiencies;
- 100 m³ Industrial scale (50 × larger than prior laboratory systems): Most previous works were 2 – 10 m³; this study evaluates a fully operational 100 m³

kiln, representing the largest documented hybrid system in tropical Asia;.

- Full hygrothermal instrumentation and uncertainty analysis: This work includes T_{db}, T_{wb}, RH, EMC, airflow 3D mapping, DNI, POA irradiance, and CI95 % – providing a dataset uncommon in prior research.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Study site and experimental design
2.1. Mjesto istraživanja i postavke eksperimenta

2.1.1 Study site and climatic conditions
2.1.1. Mjesto istraživanja i klimatski uvjeti

The study was conducted at a large-scale industrial wood processing facility in Gia Lai Province, Vietnam (13°59′N; 108°00′E), situated within the tropical savanna climate zone (Aw) of the Central Highlands. This region features two distinct seasons: a rainy season (May–November) and a dry season (December–April). During the dry season, high solar irradiance, long sunshine duration, and low relative humidity provide favorable conditions for applying solar thermal technologies to industrial wood drying.

Recent meteorological studies have reported Direct Normal Irradiance (DNI) levels of 1,000 – 1,200 W/m² on clear dry-season days in the Central Highlands (Nguyen *et al*., 2024; Rahman *et al.,* 2025), indicating substantial solar energy potential. To accurately characterize environmental influences on collector performance, an automated meteorological station was installed directly at the collector site. Three key parameters were continuously recorded at 10-minute intervals throughout the 480-hour drying cycle: (i) ambient temperature (°C), (ii) relative humidity (%RH), and (iii) solar irradiance (W/m²).

Solar irradiance was measured using a PCE-SPM1 pyranometer oriented perpendicular to the sun's rays, enabling direct measurement of DNI and providing an accurate representation of usable solar energy reaching the collector. The maximum recorded irradiance reached 1,245 W/m², consistent with typical peak DNI values in the region during intense dry-season conditions. The time-series data collected were subsequently used to determine collector efficiency, calculate the Solar Fraction (SF), and evaluate measurement uncertainty associated with energy indicators.

2.1.2 Experimental design
2.1.2. Postavke eksperimenta

The experiments were carried out at the manufacturing facility of Thanh Tam Wood Processing JSC in Gia Lai Province, Vietnam. Two industrial-scale drying systems, each with a nominal capacity of approximately 100 m³ per batch, were operated simultaneously in parallel: (i) Hybrid Kiln – a solar–steam hybrid drying system, and (ii) Control Kiln – a conventional steam-heated drying system. The experimental objective was to compare the two systems in terms of energy performance, wood quality, environmental emissions, and economic efficiency under actual industrial operating conditions. Detailed technical descriptions of both systems are provided in Section 2.4.

Timing and Experimental Conditions: The experimental campaign was implemented during the dry season (March–April 2025). Two drying batches were operated in parallel under strictly synchronized schedules to ensure comparability across kilns. Each kiln was charged with approximately 90 m³ of sawn timber, corresponding to 80 – 90 % of the system nominal design capacity. This loading rate reflects standard industrial practice at the factory and is known to promote stable airflow distribution and thermal uniformity inside the drying chamber. The characteristics of processed timber are detailed in Section 2.2. The lumber loaded into both kilns had identical cross-sectional dimensions, similar biological and anatomical properties, and was stacked using the same standardized procedures adopted by the factory to minimize variability between batches.

2.2 Timber material
2.2. Drvni materijal

The timber used in this study was *Acacia mangium*, a major plantation species in Vietnam widely utilized for export-oriented furniture manufacturing. *Acacia mangium* is known for its high permeability and substantial variation in initial moisture content, making it particularly prone to drying defects such as checking and warping when exposed to unstable drying conditions. These characteristics make it an appropriate material for evaluating the performance and robustness of the hybrid drying system (Martynenko and Vieira, 2023).

To ensure experimental uniformity, the raw timber was sourced from a single logging batch with consistent stand age, site conditions, and storage history. The sawn boards had standardized dimensions of 13 mm (thickness) × 200 mm (width) × 3,000 mm (length). Lumber stacks were prepared using industrial stacking procedures with 20-mm stickers to facilitate optimal airflow channels, minimize stagnant air pockets, and ensure uniform air velocity distribution within the kiln.

Determination of Initial moisture content (MC_i): The initial moisture content was measured using 30 randomly selected boards (n = 30) assessed with a CEM DT-129 resistance-type moisture meter. These readings were calibrated against 10 samples determined by the gravimetric (oven-dry) method following

Table 1 Complete drying schedule for 13-mm *Acacia mangium*
Tablica 1. Potpuni režim sušenja za drvo *Acacia mangium* debljine 13 mm

Phase *Faza*	**Target *MC*, %** *Ciljani sadržaj vode,* %	T_{db}, °C	T_{wb}, °C	**RH, %**	**EMC, %**	**Air velocity, m/s** *Strujanje zraka,* m/s	**Notes** *Napomene*
Heating *zagrijavanje*	>45	50	48	70 – 75	19.0	1.5 – 2.0	Gradual warm-up *postupno zagrijavanje*
Pre-drying *predsušenje*	45 – 40	50	46	65 – 70	15.5	1.8 – 2.2	RH controlled via venting *regulacija relativne vlažnosti zraka putem ventilacije*
Main drying *glavno sušenje*	35 – 25	55	49	55 – 60	12.0	2.0 – 2.4	Maximum solar utilization *maksimalno iskorištenje solarne energije*
Final drying *završno sušenje*	25 – 15	60	50	50 – 55	9.5	2.0 – 2.3	Reduced vent aperture *uz pritvoren ventilacijski otvor*
Equalizing *izjednačivanje*	15	60	52	60 – 65	10.5	1.5 – 2.0	Stress relief and conditioning *oslobađanje naprezanja i kondicioniranje*

ISO 13061-1: 2014. The results showed an average MC_i of 50.2 % with a standard deviation of 3.1 %, indicating low variability and confirming the homogeneity of the input material – an essential condition for comparing the two drying systems.

The target final moisture content was set at (12 ± 3) %, meeting quality requirements for furniture products destined for EU and US export markets (Elustondo *et al.,* 2023).

2.3 Drying schedule and control strategy
2.3. Režim sušenja drva i način kontrole

The drying schedule plays a critical role in balancing drying efficiency and final product quality. In this study, the schedule for 13-mm *Acacia mangium* lumber was designed by integrating empirical operational experience with heat and mass transfer principles. The goal was to simultaneously regulate the dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and airflow velocity to maintain an appropriate moisture gradient between the core and the surface, thereby preventing moisture shock and mitigating internal stresses.

Five-Phase Drying Schedule: The drying schedule consists of five distinct phases, each reflecting the evolving moisture behavior of the wood throughout the process.

System Control Logic: A central controller monitored real-time data from a sensor network distributed inside the kiln and continuously adjusted the setpoints. The system controlled: Venting aperture, regulating humidity discharge; Heat source selection, switching between the solar collector and the steam boiler; Circulation fan speed, adjusted via Variable frequency drives (VFDs).

Venting strategy: The controller applied an RH-deviation algorithm whereby: When measured RH exceeded the setpoint → vents opened proportionally. When RH fell → vents gradually closed to conserve thermal energy. This approach minimized abrupt RH fluctuations, a common cause of surface checking.

Airflow distribution: Airflow uniformity was evaluated using 12 anemometers arranged in a three-dimensional grid (three vertical levels × three horizontal positions within the lumber stack). The measured values yielded a mean air velocity of 2.1 m/s with a standard deviation of ± 0.4 m/s, corresponding to a coefficient of variation of approximately 19 %. This level of variability is considered acceptable for industrial kilns, indicating that no major stagnant zones were present.

Energy Integration strategy: The hybrid system followed a “Solar-Priority” operational principle, defined as follows: Daytime with high solar irradiance: The system operated in Solar-only mode, using thermal energy exclusively from the roof collector. Hybrid mode: When solar energy was insufficient to maintain T_{db} setpoints, the system automatically switched to Hybrid mode, supplementing solar heat with steam from the boiler. This adaptive logic optimized energy consumption while maintaining drying stability.

2.4 System description
2.4. Opis sustava

This section provides a complete and detailed description of the drying system to clarify the interactions between the kiln structure, the integrated solar collector, the air circulation subsystems, and the control logic-factors that directly influence energy efficiency, thermal distribution within the lumber load, and final product quality. The system examined in this study is a hybrid configuration in which the arched kiln roof simultaneously acts as an integrated solar air collector, while saturated steam supplied by a biomass-fired boiler serves as the auxiliary heat source when solar energy is insufficient.

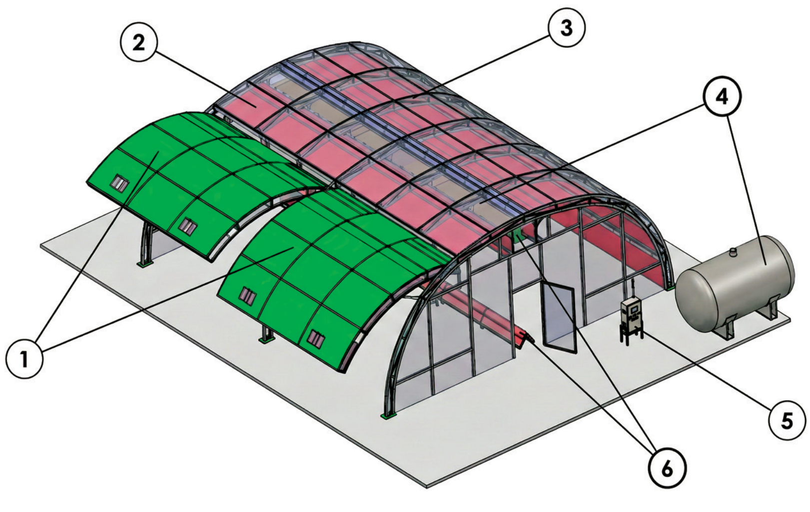
The drying kiln has overall dimensions of 12.6 m (length) × 12 m (width) × 5.1 m (height). It is constructed using a load-bearing steel frame combined

Figure 1 Schematic diagram of the experimental solar–steam hybrid wood drying system: a) Exterior view of the kiln; b) Interior view of the kiln during drying
Slika 1. Prikaz eksperimentalnoga hibridnog solarno-parnog sustava za sušenje drva: a) vanjski pogled na sušaru; b) pogled u unutrašnjost sušare tijekom sušenja

with 50-mm polyurethane (PU) sandwich insulation panels to reduce lateral heat transfer, thereby stabilizing internal kiln temperature against external environmental fluctuations. The interior walls are lined with galvanized steel sheets to improve corrosion resistance, ensuring long-term durability under continuous industrial operation. The combination of a large chamber volume (design capacity 100 m³, operational capacity 90 m³) and high-performance insulation is essential for maintaining the required thermal gradient and minimizing heat loss through the walls and floor.

A key design feature that distinguishes this hybrid system is the geometry of the integrated collector. Instead of employing stand-alone flat-plate collectors, the system utilizes the entire dual-layer polycarbonate roof structure as the glazing layer. The roof consists of 10-mm twin-wall polycarbonate panels (solar transmissivity $\tau \geq 0.85$), beneath which a black-chrome coated aluminum absorber plate (solar absorptivity $\alpha \geq 0.95$) is installed. The cavity between the glazing and the absorber, approximately 360 mm wide, serves as the hot-air channel for solar heat collection and transport. With this configuration, the kiln roof becomes a large-area solar collector with a useful absorption area of $A_c \approx 243.7$ m².

This integrated collector design shortens the heat transfer path and reduces thermal losses compared with externally mounted collector configurations. During operation, air is drawn from the chamber and circu-



1 – New-generation power-assisted lifting door / *vrata nove generacije s električnim podizanjem*
2 – Absorber unit and insulated kiln shell / *kolektor i izolirani plašt sušare*
3 – Main kiln frame and saturated steam heat supply / *glavni okvir sušare i opskrba zasićenom toplom parom*
4 – Auxiliary steam heating system / *pomoćni sustav grijanja parom*
5 – Dual-source drying control system / *sustav upravljanja sušenjem s dva izvora*
6 – Airflow deflectors / *deflektori protoka zraka*

Figure 2 Overall configuration of the experimental solar–steam hybrid wood drying system, including the integrated roof solar collector, circulation fans, moisture exhaust fans, saturated steam supply, and data acquisition network
Slika 2. Potpuna konfiguracija eksperimentalnoga hibridnog solarno-parnog sustava sušenja drva, uključujući integrirani krovni solarni kolektor, cirkulacijske ventilatore, ventilatore za odvod vlage, dovod zasićene pare i mrežu za prikupljanje podataka

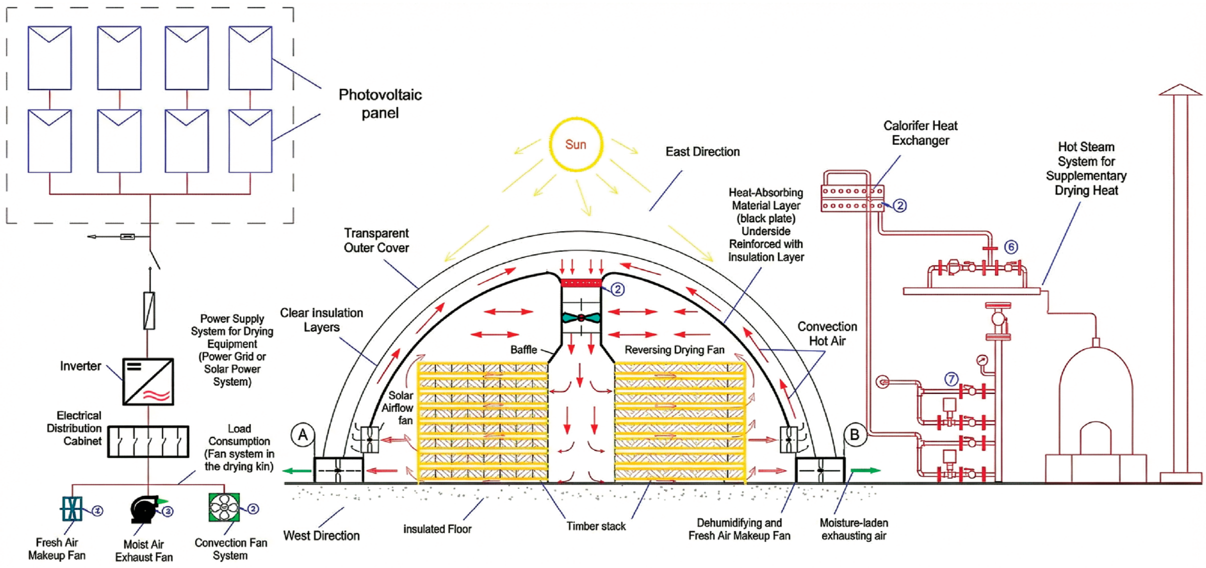


Figure 3 Schematic diagram of the hybrid drying system
Slika 3. Shematski dijagram hibridnog sustava sušenja

lated through the collector channel by the circulation fans, where it absorbs heat from the absorber plate before being blown back into the drying chamber to heat the lumber load. The airflow rate through the collector is regulated according to the thermal requirements of each drying phase: airflow is increased during the constant-rate drying period to maximize heat transfer and reduced during later phases to retain heat or to prevent excessive surface drying. The control system continuously monitors the relationship between collector airflow rate, solar heat gain, and the surface moisture transfer coefficient to optimize collector utilization.

The fan system is functionally stratified: Ten circulation fans (rated at 2.2 kW per fan) generate forced convection within the chamber, ensuring uniform temperature and humidity distribution across the lumber stacks. Seven moisture exhaust fans, installed along the side walls (with balanced intake and exhaust flow), have a combined electrical capacity of approximately 1.2 kW and operate intermittently when humidity removal is required.

During daytime operation, when solar irradiance is high, the circulation fans can operate at high capacity to maximize heat collection. At night, they reduce speed to an "idle mode" (~30 % of rated capacity) via VFDs, conserving electricity while maintaining minimum thermal uniformity. This flexible load modulation strategy is one of the main factors contributing to the reduced total electricity consumption of the hybrid system, even though the drying duration is slightly longer due to the factory's policy of not supplying steam at night.

The heat source control logic follows a Solar-Priority principle. When the irradiance on the Plane of Array (POA) exceeds the safety threshold of 150 W/m², the system switches to Solar-Only Mode. When POA decreases or the chamber temperature remains ≥ 5 °C below the setpoint for 20 consecutive minutes, the system automatically activates the steam valve to transition into Hybrid Mode. The use of a time-dependent temperature deviation algorithm—rather than instantaneous on/off switching – prevents large thermal oscillations and reduces unnecessary boiler activation, thereby conserving energy.

Operational log data from the entire drying batch shows that the temporal ratio between Solar-Only Mode and Hybrid Mode is relatively balanced (≈ 48 – 52 %), indicating that solar energy makes a substantial contribution to the overall thermal demand of the drying process.

For comparison, the Control Kiln is constructed with equivalent dimensions, loading volume, and fan layout. However, as all heat is supplied by saturated steam, the circulation fans must operate continuously at high load to maintain uniform heat distribution. As a result, the Control Kiln consistently exhibits higher electricity consumption compared with the hybrid system, which can dynamically modulate fan load in response to changing solar availability.

2.5 System boundary definition for energy and mass balance
2.5. Definicija granica sustava za bilancu energije i mase

To ensure clarity, consistency, and reproducibility in evaluating system performance, a formal system boundary was established following ASHRAE, 2010 and IPCC (2006; 2019) guidelines. The defined boundaries apply to all energy indicators – Specific Energy Consumption (*SEC*), Solar Fraction (SF_{total}), and useful thermal energy (Q_{solar} and Q_{steam}).

Thermal energy boundary – This boundary includes all useful heat delivered to the drying chamber:

Solar thermal energy (Q_{solar}) collected through the integrated roof absorber; Auxiliary steam heat (Q_{steam}) supplied by the biomass boiler. Excluded from the boundary: Conduction losses through walls, floor, and roof; Fan-induced heat; Heat stored in wood mass.

Electrical Energy Boundary (E_{elec}) – Includes electrical consumption from: Circulation fans (10 × 2.2 kW); Exhaust fans (7 × 0.17 kW); PLC, control system, and data acquisition.

Boundary for Specific Energy Consumption (SEC): $SEC = \frac{E_{biomass} + E_{elec}}{m_{evap}}$

Where: $E_{biomass} = m_{biomass} \cdot 3.89\ \text{kWh/kg}$ (IPCC 2006), E_{elec} = measured electricity, m_{evap} = evaporated water (kg).

Boundary for Solar Fraction (SF_{total}): $SF_{total} = \frac{Q_{solar}}{Q_{solar} + Q_{steam}}$

All energy values were computed using 10-minute interval data across 480 hours, capturing full daytime–nighttime variability.

CO_2 Accounting Boundary (IPCC-compliant): Non-biogenic CO_2: derived from grid electricity. Biogenic CO_2: reported separately, not included in net emissions, following IPCC rules

This distinction ensures comparability with international GHG inventories.

2.6 Data acquisition and processing system
2.6. Sustav za prikupljanje i obradu podataka

2.6.1 Data collection
2.6.1. Prikupljanje podataka

To ensure the reliability of the measurements and to support comprehensive energy analysis, the drying system was equipped with a multi-point sensor network integrated with an automated Data Acquisition System (DAS). The system operated continuously throughout the entire drying cycle, recording data at 10-minute intervals. This sampling frequency provides sufficiently high temporal resolution to capture variations in energy, moisture, and temperature, while optimizing the data volume for subsequent statistical analysis and modeling.

Measurement of Dry- and Wet-Bulb Temperatures (T_{db}, T_{wb}): Temperature measurements were obtained using Type-K thermocouples with an accuracy of ± 0.5 °C after calibration. The T_{wb} sensors were equipped with standard cotton wicks and distilled water to maintain strictly saturated wet-bulb conditions. Sensors were positioned at six representative locations inside the chamber: near the air inlet, at the chamber center, at the end of the airflow path, and in the middle layer of the timber stack. Sensors were positioned at six locations representing the inlet, center, outlet, and mid-stack layers, providing spatial coverage of the kiln thermal field.

Measurement of Air Relative Humidity (RH): RH inside the kiln was measured using a Honeywell HIH-4000 capacitive sensor with an accuracy of ± 2.0 % RH. Combined with T_{db} and T_{wb}, RH data were used to determine the Equilibrium Moisture Content (EMC) under corresponding psychrometric conditions.

EMC calculation: The Equilibrium Moisture Content (EMC) for *Acacia mangium* was computed using the widely accepted Hailwood–Horrobin model:

$$EMC = \frac{1800}{W}\left(K_1 \cdot \frac{h}{1-h} + K_2 \cdot \frac{h}{(1-h)^2}\right) \quad (1)$$

Where: h – relative humidity (decimal), $W = 330 + 0.452T + 0.00415T^2$, $K_1 = 0.791 + 4.63 \cdot 10^{-4}T - 8.44 \cdot$

Table 2 List of measurement instruments used
Tablica 2. Popis upotrijebljenih mjernih uređaja

Measured parameter *Mjerni parametar*	**Instrument** *Uređaj*	**Measurement range** *Raspon mjerenja*	**Accuracy / uncertainty** *Točnost / mjerna nesigurnost*	**Location / quantity** *Položaj / količina*
Solar irradiance *Sunčevo zračenje*	PCE-SPM1 pyranometer	0 – 2,000 W/m²	±10 W/m²	Oriented for DNI / 1 *orijentirano za DNI / 1*
Temperature (T_{db}, T_{wb}) *temperatura* (T_{db}, T_{wb})	Type K Thermocouple	–50 to 200 °C	±0.75 °C	6 positions inside the kiln *6 pozicija unutar sušare*
Ambient RH *relativna vlažnost zraka*	HT-3009 hygrometer	10 – 95 %RH	±3 %RH	Outdoor / 1 *vani / 1*
Wood MC *sadržaj vode u drvu*	Resistance probe	6 – 90 %	±2 %	8 positions within the stack *8 pozicija unutar složaja drva*
Wood MC check *provjera sadržaja vode u drvu*	CEM DT-129	6 – 90 %	±2 %	Manual checks *ručne provjere*
Air velocity *brzina strujanja zraka*	Vane anemometer	0.3 – 30 m/s	±3 %	12 points on the stack *12 mjernih mjesta na složaju*
Electricity *električna energija*	Power meter	–	±1 %	Main electrical cabinet *glavni električni ormar*
Steam flow *protok pare*	Steam flow meter	–	±2.5 %	Steam supply line *dovod pare*

$10^{-7}T^2$, $K^2 = 6.34+7.75 \cdot 10^{-4}T - 9.35 \cdot 10^{-5}T^2$, T – dry-bulb temperature (°C).

This formulation ensures high accuracy for tropical kiln-drying conditions within 40 – 70 °C, consistent with ASHRAE and widely cited wood-drying studies.

Measurement of air velocity: Air velocity was measured using a vane-type anemometer (TSI-9545) with an accuracy of ± 0.03 m/s. A total of 12 measurement points, arranged in a three-dimensional grid, were deployed to evaluate airflow distribution, identify potential dead-air zones, and verify the effectiveness of the circulation-fan system.

Measurement of Solar Irradiance: Solar irradiance was measured using the PCE-SPM1 pyranometer. The sensor head was oriented perpendicular to the sun's rays, allowing the measurement of Direct Normal Irradiance (DNI). DNI was subsequently converted to Plane-of-Array (POA) irradiance based on the 15° roof tilt angle for collector-efficiency calculations.

Measurement of Wood Moisture Content (MC): The moisture content of the timber was monitored using a two-step approach:

- Rapid resistance-type measurements at 30 fixed sampling points;
- Verification by the gravimetric oven-dry method following ISO 13061-1: 2014.

This dual-method approach improves calibration accuracy and enhances data reliability.

Data Logging and Synchronization: All data were recorded via the DAS (Advantech ADAM-6000) synchronized with the central PID. Data were stored in *.CSV* format and visualized in real time, supporting energy-performance analysis and monitoring of deviations from the drying schedule.

2.6.2 Calibration
2.6.2. Kalibracija

All measurement devices – including the pyranometer, hygrometer, thermocouples, moisture meters, steam flow meter, and power meter – were inspected and calibrated prior to the experiment following manufacturer recommendations. Calibration information (reference values, calibration date, and deviation) was documented in the factory's instrument-log records.

2.6.3 Data processing
2.6.3. Obrada podataka

Data preprocessing included removing abnormal points caused by sensor malfunction, cross-checking measurements among identical sensors, and applying a three-point moving average to smooth variables with rapid short-term fluctuations when necessary.

For statistical analysis: Quantitative variables (e.g., warping) were compared using the two-sample independent t-test. Proportional variables (e.g., surface checks, internal checks) were evaluated using the two-sample z-test. The statistical significance threshold was set at $\alpha = 0.05$.

2.6.4 Analysis of measurement uncertainty and data representativeness
2.6.4. Analiza mjerne nesigurnosti i reprezentativnosti podataka

Industrial-scale drying cycles (90 – 100 m³; ~480 h) inherently limit the feasibility of repeated batch experiments. Therefore, the study adopted two methodological approaches to ensure data representativeness: (i) standardized industrial procedures, and (ii) statistical characterization of spatial sensor data. Nevertheless, the reliability and representativeness of the collected data were ensured through the following two methodological approaches:

(1) Industrial Standardization: The experiment was conducted at a large-scale wood-processing factory with extensive experience in supplying export markets such as the United States and the European Union. Therefore, all stages of sample preparation – from raw-material selection (*Acacia mangium*), sawing, to stacking techniques – strictly followed the factory's Standard Operating Procedures (SOPs) and Quality Control (QC) systems. The factory's standardized procedures for sawing, stacking, and QC ensure consistent input conditions across batches, reducing variability associated with material preparation.

(2) Statistical Analysis Using Spatial Sensor Data: Spatial data from the multi-point sensor network were utilized to quantify within-batch variability, serving as an alternative to experimental replicates. Continuous data were collected from 10 wood-MC measurement points and 12 air-velocity points distributed throughout the kiln.

A Bootstrap method with 1,000 resamples (B = 1,000 bootstrap resamples, not physical sample count) was applied to estimate the Standard Deviation (SD) and 95 % Confidence Interval (95 % CI) for key performance indicators such as final MC, Specific Energy Consumption (*SEC*), and Solar Fraction (*SF*). Bootstrap resampling (B = 1,000) was applied to quantify measurement uncertainty for *MC*, *SEC*, and *SF*, following established practices in industrial-scale process monitoring.

2.6.5 Assessment of dried wood quality
2.6.5. Procjena kvalitete osušenog drva

A total of $n = 120$ boards were sampled from each batch to assess dried-wood quality, including surface checking, internal checking, and warping. Evaluations were performed using a blind-assessment method by two independent technicians to minimize subjective bias. The 95 % Confidence Intervals (95 % CI) for the defect indicators were computed from the observational data and are reported directly in the results table.

2.7 Energy analysis
2.7. Energetska analiza

In this study, energy analysis was conducted through three core components: moisture balance, energy balance, and system performance evaluation based on the indicators *SEC*, *SF*, and collector efficiency. The objective of the analysis is to quantify all energy flows entering and leaving the system throughout the drying cycle, determine the portion of solar-derived energy, and assess the effectiveness of the hybrid configuration compared to the conventional control steam kiln.

2.7.1 Moisture balance
2.7.1. Ravnotežni sadržaj vode

The amount of water removed from the timber, denoted as m_{water}, is calculated using the initial moisture content MC_i, the final moisture content MC_f, and the dry mass m_{dry}:

$$m_{water} = m_{dry} \cdot \frac{MC_i - MC_f}{100} \tag{2}$$

In this study, with $MC_i = 50.2$ % và $MC_f = 12$ %, the amount of evaporated water per cubic meter of green timber is approximately ≈ 314 kg water/m^3. This value was established based on gravimetric mass measurements following ISO 13061-1:2014, ensuring accuracy and providing the foundation for *SEC* calculations and the energy balance.

2.7.2 System energy balance
2.7.2. Energetska bilanca sustava

To eliminate inconsistencies in reporting energy values, the study defined system energy boundaries according to international standards. Three energy components were quantified:

- Useful energy gain from the solar collector: Q_{solar}
- Supplementary steam energy: Q_{steam}
- Electrical energy consumption: E_{elec}

The total energy input to the system is expressed as: $Q_{in} = Q_{solar} + Q_{steam} + E_{elec}$

The useful energy required for water evaporation is: $Q_{evap} = m_{water} \cdot h_{fg}$

Where: $h_{fg} \approx 2{,}350$ kJ/kg is the latent heat of vaporization at the average drying temperature of 55 ^{0}C. The difference between Q_{in} and Q_{evap} reflects thermal losses through the kiln shell, venting airflow, and surface convection from the wood, and these losses are considered in the overall energy model.

2.7.3 Specific energy consumption (*SEC*)
2.7.3. Specifična potrošnja energije (*SEC*)

Specific Energy Consumption (*SEC*), the key indicator for evaluating the energy efficiency of the drying process, is defined as:

$$SEC = \frac{Q_{steam} + E_{elec}}{m_{water}} \tag{3}$$

SEC was calculated for both the hybrid system and the control steam kiln. The value is presented together with the standard deviation (SD) and the 95 % confidence interval (CI95 %):

$$\mathrm{CI}_{95\%} = SEC \pm 1.96 \cdot \frac{SD}{\sqrt{n}} \tag{4}$$

This presentation ensures transparency and enables direct comparison of energy savings between the two systems.

2.7.4 Collector efficiency
2.7.4. Učinkovitost kolektora

Collector thermal efficiency η_c was determined based on the ASHRAE 93-2010 model:

$$\eta_c = \frac{Q_{solar}}{A_c \cdot G_{POA}} \tag{5}$$

Where: $A_c \approx 243.7$ m^2 effective absorber area, G_{POA}: plane-of-array irradiance, converted from DNI, Q_{solar}: useful thermal energy gained from the collector.

Efficiency was analyzed on an hourly basis and across irradiance bands to reflect the operational characteristics of the collector under the real climatic conditions of the Central Highlands of Vietnam.

2.7.5 Solar fraction (*SF*)
2.7.5. Solarni udio (*SF*)

Two indicators were used to quantify the contribution of solar energy:

1. Thermal Solar Fraction (SF_t):

$$SF_t = \frac{Q_{solar}}{Q_{solar} + Q_{steam}} \tag{6}$$

2. Total Solar Fraction (SF_{total}):

$$SF_{total} = \frac{Q_{solar}}{Q_{solar} + Q_{steam} + E_{elec}} \tag{7}$$

where Q_{solar}, Q_{stream}, and E_{elec} were integrated over the full 480-hour drying cycle using 10-minute intervals. All energy components were converted to the same energy unit (kWh) to ensure internal consistency.

2.8 Economic analysis
2.8. Ekonomska analiza

The economic assessment of the solar–steam hybrid wood drying system was developed based on the Life Cycle Costing (LCC) analytical framework. The objective of this method is to comprehensively evaluate the long-term economic performance of the hybrid system in comparison with a conventional steam kiln through the components of investment cost (CAPEX), operational and maintenance costs (OPEX), energy savings, and payback period. All costs are standardized over the same analysis period in accordance with ISO 15686 guidelines and established LCC practices within the industry.

1. Capital expenditures (CAPEX): The CAPEX analysis focuses on incremental components introduced by the hybrid system, including: the dual-layer polycarbonate glazing of the roof-integrated collector; the black-chrome thermal absorber; the collector air channels and associated auxiliary supporting structures; the integration of the new control system and its interface with the existing PID. The investment cost of the hybrid system is compared with that of a conventional steam kiln of equivalent capacity and fan configuration. The incremental increase in investment cost is expressed as a percentage to facilitate comparison relative to operational gains. This analysis excludes asset depreciation to ensure independence from the financial strategies of individual enterprises.

2. Operating expenditures (OPEX): Operating costs are divided into three main groups:

a) Biomass Fuel Cost: The amount of heat supplied by the solar collector during periods of high irradiance is used to determine the reduction in supplementary steam required from the boiler. This approach enables the calculation of the corresponding decrease in biomass fuel consumption based on the fuel's Lower Heating Value (LHV) and boiler efficiency.

b) Electricity Cost: Electric OPEX is calculated based on the rated capacity of the circulation and exhaust fans, the time-dependent operating modes (high-load mode during daytime – idle mode at night), and the operating hours in each mode. Electricity consumption is standardized using industrial electricity tariffs to determine the electrical OPEX.

c) Maintenance Cost: Collector maintenance costs include routine cleaning of the glazing surface (1 – 2 times per month) and inspection of the absorber and auxiliary structural components. The LCC method does not include maintenance costs of conventional steam kilns, due to large variation among different factories, but instead calculates only the incremental maintenance costs induced by the collector.

3. Simple Payback Period (*PBP*)

The Simple Payback Period is determined by:

$$PBP = \frac{CAPEX_{\text{add}}}{Annual\ OPEX\ Savings} \tag{8}$$

where the annual OPEX savings are calculated based on the reduction in biomass fuel costs, electricity costs, and differential maintenance costs relative to the conventional steam kiln. The PBP method is selected because it aligns with the practical investment tendencies and short investment cycles (3 – 5 years) preferred by domestic wood-processing enterprises.

4. Sensitivity Analysis: To evaluate the stability of economic performance, sensitivity analysis is conducted using three key variables:

- CAPEX variation of ± 20 % (reflecting fluctuations in material prices such as steel and polycarbonate),
- Biomass fuel price variation of ±25 % (reflecting seasonal market variability),
- Operating frequency of 10 – 14 batches per year (reflecting the actual utilization rate of the factory).

Given that Vietnamese wood-processing enterprises commonly adopt simple Payback indicators and have short investment horizons (3 – 5 years), the LCC analysis in this study uses PBP instead of NPV/IRR.

2.9 Environmental Assessment
2.9. Procjena utjecaja na okoliš

The environmental assessment was conducted to quantify greenhouse gas (GHG) emissions associated with the wood drying process and to elucidate the role of solar energy in reducing emissions compared with a conventional steam kiln. The emission accounting method follows the IPCC Guidelines (2006; updated 2019), in which CO_2 is classified into two independent categories: biogenic CO_2 from biomass combustion, and fossil CO_2 from electricity consumption and auxiliary fossil-based energy sources. This separation ensures transparency and enables international comparability across different energy systems.

• Biogenic CO_2: In the context of Vietnam's wood-processing sector, biomass (sawdust, bark, wood residues) is the primary fuel source for steam boilers. The biogenic CO_2 emitted from biomass combustion is calculated using the standard emission factor for dry biomass: Biogenic CO_2 emission factor = 1.83 kg CO_2 per kg of dry biomass. According to IPCC regulations, biogenic CO_2 is not counted toward net energy-related emissions because the carbon cycle associated with biomass is considered closed. However, biogenic CO_2 must still be reported to ensure full transparency and completeness. In this study, biogenic CO_2 emissions are presented separately and are not combined with fossil CO_2 emissions. Biogenic CO_2 emissions were reported separately from fossil CO_2 emissions following IPCC (2006; 2019) guidelines, which classify biogenic carbon within the short-term biogenic carbon cycle

• Fossil CO_2 (Electricity-Related Emissions): Fossil CO_2 emissions mainly arise from electricity consumption by the circulation fans, exhaust fans, control equipment, and other electrical loads. As the solar-steam hybrid system can operate the fans in low-load mode at night or during low-irradiance periods, electricity consumption is significantly reduced compared with the conventional steam kiln. Consequently, fossil CO_2 emissions decrease correspondingly.

Electricity-related CO_2 emissions are calculated using the official Vietnam grid emission factor (Ministry of Natural Resources and Environment, 2022):

Electricity emission factor = 0.6811 kg CO_2 per kWh.

This emission factor is consistently applied throughout all calculations in the study.

• Material- and Equipment-Related Emissions Over the System Life Cycle

The use of a roof-integrated collector – instead of standalone flat-plate collectors or evacuated-tube collectors – reduces the need for additional materials such as tempered glass, steel framing, and heat-transfer fluids. This design choice decreases the material footprint and the associated indirect life-cycle emissions.

Furthermore, the integrated collector design requires minimal maintenance (primarily periodic cleaning of the polycarbonate glazing and inspection of the absorber surface), thereby reducing indirect emissions associated with maintenance activities.

Summary and Significance: Reporting CO_2 emissions in both biogenic and fossil forms, while applying the Vietnam national electricity emission factor, ensures that the study meets international standards of transparency, consistency, and comparability. This methodological approach provides a robust foundation for fully evaluating the environmental benefits of the solar-steam hybrid wood drying system under industrial application conditions in Vietnam.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Solar radiation and thermal characteristics of the collector
3.1. Sunčevo zračenje i toplinska obilježja kolektora

The radiation intensity in this study was continuously measured using a spectroradiometer with the sensor head oriented perpendicular to the incident beam; therefore, the recorded values represent the Direct Normal Irradiance (DNI), which is the most important radiation component for high-efficiency selective collectors, as their absorbed energy is directly proportional to the direct radiation component.

The continuous data series at a 10-minute interval recorded throughout the entire drying cycle shows that the dry-season climatic conditions in Gia Lai, Vietnam, are particularly favorable for harnessing solar energy. The peak DNI reached 1,245 W/m², reflecting the high atmospheric transparency of the Central Highlands during clear, intense sunshine. During the prime hours from 08:00 to 15:30, DNI remained stable within the range of 850 – 1,050 W/m², providing abundant thermal energy that enabled the system to operate entirely in Solar-Only mode without any supplemental steam from the boiler. The daily DNI profile can be segmented into three distinct phases:

1. Acceleration phase (Early morning): As the solar altitude rises rapidly, the energy absorption rate of the collector also increases sharply, causing the absorber layer temperature to rise quickly within the first 30 – 45 minutes.

2. Stabilization phase (Midday): DNI is maintained at its highest level, allowing prolonged Solar-Only operation. This is the period when the collector achieves maximum efficiency.

3. Decline phase (Late afternoon): Solar radiation decreases rapidly, marking the transition point at which the system gradually shifts to Hybrid Mode to compensate for heat and maintain the drying schedule.

The variation in radiation is clearly reflected in the temperature of the drying air after passing through the collector. When DNI exceeds 900 W/m², the temperature difference between the air exiting the collector and the air inside the drying chamber (ΔT) reaches 12 – 18 °C. This level of heating is sufficient to maintain the required drying temperature without consuming steam.

The instantaneous thermal efficiency of the collector (η_c), defined as the ratio of useful thermal power gained to incident solar radiation, ranges from 28 % to 52 % depending on the time of day. The average value over the entire cycle is approximately 46 % with a 95 % confidence interval of ± 3 %. The major thermal losses are attributed to convection through the polycarbonate glazing layer and fluctuations in airflow velocity within the collector channel.

The total useful solar energy collected throughout one drying batch reached 15,687 kWh, equivalent to contributing 40 – 52 % of the total heat demand depending on the drying stage. This is a significant result, confirming the system's capability to replace nearly half of the heat load from biomass fuel, forming the basis for reducing operating costs and greenhouse gas emissions.

The solar radiation chart presented in the article represents a "typical clear-sky day" selected from the 480-hour dataset based on the criterion: DNI ≥ 900 W/m² for at least 5 consecutive hours. This criterion accurately reflects stable and high-intensity radiation conditions, enabling the clearest demonstration of the thermal performance of the integrated roof collector under cloud-free conditions. Meanwhile, all energy analyses (Q_{solar}, SF, SEC, and energy balance) were calculated using the full 480-hour dataset, including periods of low radiation and meteorological fluctuations. This two-layer approach ensures both representativeness in graphical visualization and comprehensiveness in quantitative analysis.

3.2 Drying process evolution
3.2. Razvoj procesa sušenja

The drying process is a complex combination of moisture migration kinetics within the wood, the thermal–humidity conditions inside the chamber, and the

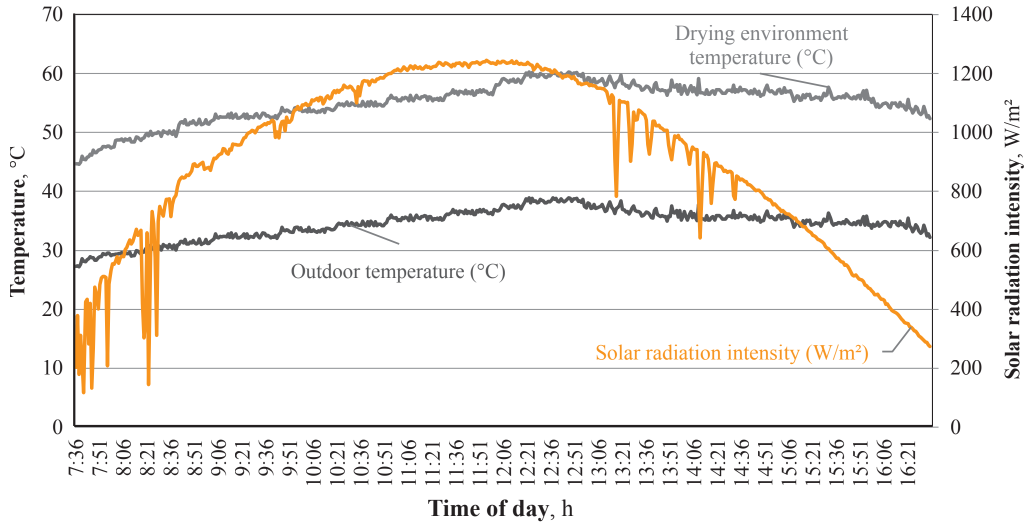


Figure 4 Relationship between solar irradiance (W/m²), ambient temperature (°C), and outlet air temperature (°C) over a typical sunny day
Slika 4. Odnos između Sunčeva zračenja (W/m²), temperature okoline (°C) i temperature izlaznog zraka (°C) tijekom tipičnoga sunčanog dana

response of the control system. The core parameters, including wood moisture content (*MC*), dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and relative humidity (RH), were analyzed to clarify the differences in operating mechanisms between the hybrid system and the reference system.

3.2.1 Moisture kinetics and drying curve
3.2.1. Kinetika sadržaja vode i krivulja sušenja

Both systems exhibit the characteristic falling-rate drying curve of 13-mm-thick *Acacia mangium* wood.

Reference boiler system: Reached the target *MC* of 12.0 ± 3.0 % after 448 hours.

Hybrid system: Reached the same moisture level after 480 hours.

The longer duration is inherent to the intermittent nighttime regime of the hybrid system, in which forced-steam heating is avoided. This operating mode reduces electricity use and stabilizes surface moisture conditions. When solar radiation decreases at night, the system operates only in maintenance mode with fans running at low load, instead of forced heating as in the boiler system. This results in significant reductions in nighttime electricity and fuel consumption, avoidance of sudden moisture-removal rates, and the creation of relaxation periods, allowing moisture from the wood core to migrate uniformly toward the surface without inducing surface tensile stress.

As a result, the system maintains drying quality while optimizing energy use. Statistical analysis from 10 measurement points shows that the final *MC* standard deviation of the hybrid system reached ± 2.8 %, nearly equivalent to that of the reference system (± 2.5 %), confirming uniformity despite variations in the heat source due to weather fluctuations.

3.2.2 Temperature and relative humidity evolution
3.2.2. Razvoj temperature i relativne vlažnosti

Dry-bulb temperature (T_{db}): The hybrid system maintained T_{db} within the range of 50 – 60 °C during the daytime thanks to the collector. At night, the temperature decreased slightly but remained within safe limits due to the PU insulation layer and the closed-circulation mode.

Wet-bulb temperature (T_{wb}) and RH: T_{wb} was maintained between 46 – 52 °C; RH fluctuated within the range of 50 – 70 % without any abnormal peak occurrence. This indicates that the controller responded stably to all external variations.

3.2.3 Ventilation behavior and exhaust-air damper control
3.2.3. Ponašanje ventilacije i upravljanje zaklopcima zraka

The exhaust fan in the hybrid drying system operated at a significantly lower frequency compared with the boiler system. Evaporation in the hybrid system occurs in a “naturally driven” manner, increasing gradually with solar radiation, unlike the “forced evaporation” that occurs with continuous steam supply.

Daytime: venting occurs steadily at low intensity → preventing moisture shock.

Nighttime: venting is almost closed → creating a high-humidity environment → mild reconditioning, helping reduce surface tensile stress.

This is one of the fundamental reasons for the lower defect rate in the hybrid system.

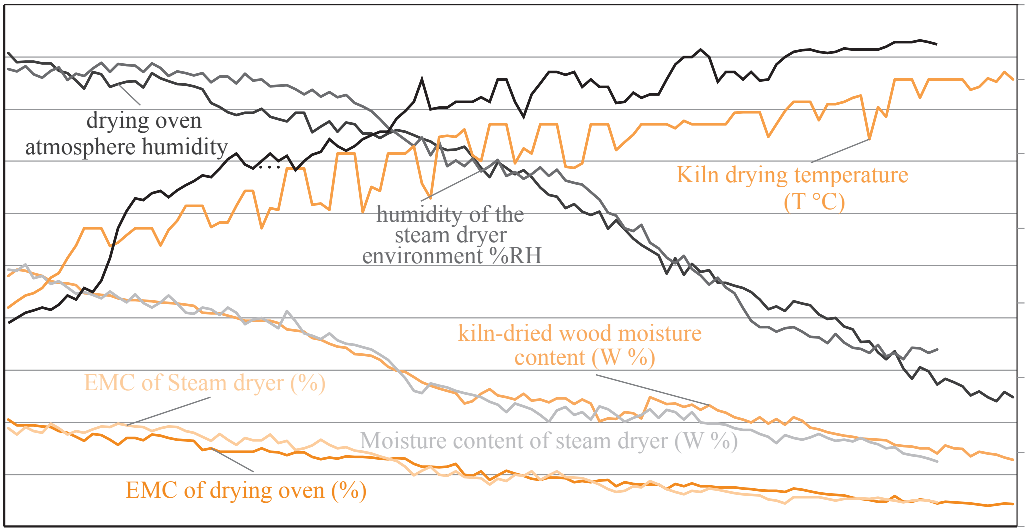


Figure 5 Temperature and drying curves of the control and hybrid drying systems over time
Slika 5. Krivulje temperature i sušenja kontrolnoga i hibridnog sustava sušenja tijekom vremena

3.2.4 Overall comparison of operating characteristics
3.2.4. Zbirna usporedba radnih svojstava

Although the drying time is longer, the hybrid system demonstrates several important operational advantages:

No occurrence of thermal shock due to the avoidance of sudden steam on/off cycles;

The $T_{db} - T_{wb}$ difference is well controlled, preventing overly rapid surface drying;

The moisture-removal process proceeds more smoothly, consistent with the sensitive drying behavior of *Acacia* wood;

Optimization of electricity and fuel consumption, particularly during nighttime.

3.3 Wood quality after drying
3.3. Kvaliteta drva nakon sušenja

Wood quality after drying is the most important metric for evaluating the feasibility of applying the hybrid wood-drying technology in real industrial production environments. The quality assessment was conducted in strict accordance with two national standards: TCVN 8929: 2013 for surface defects and internal checking, and TCVN 8930: 2013 for post-drying deformation and warping.

A total of 120 boards for each system (n = 120) were randomly sampled from 10 different positions within the lumber stack to ensure spatial representativeness. The evaluation procedure was conducted by two independent experts using a blind assessment method to eliminate subjective bias. The agreement level between the two experts exceeded 95 %, reflecting high consistency and reliability of the assessment.

3.3.1 Statistical analysis
3.3.1. Statistička analiza

To evaluate whether the differences in wood quality between the two drying systems reached statistical significance, independent hypothesis tests were applied

Table 3 Comparison of dried-wood quality between the two systems
Tablica 3. Usporedba kvalitete osušenog drva u dva procesa sušenja

Variable *Varijabla*	**Control (n=120)** *Kontrolna skupina (n = 120)*	**Hybrid (n=120)** *Hibridna skupina (n = 120)*	**Difference[a] (Mean ± SD)** *Razlika[a] (srednja vrijednost ± SD)*	**95 % CI of Diff.** *95 % CI razlike*	***p*-value** *p-vrijednost*	**Effect size** *Veličina utjecaja*
Surface checking, % *površinske pukotine, %*	3.1 % (CI_{95} %: 2.1 – 4.2)	2.8 % (CI_{95} %: 1.9 – 3.7)	0.3 pp	[−2.9; 3.5]	0.891	h = 0.018
Internal checking, % *unutarnje pukotine, %*	1.2 %	1.0 %	0.2 pp	[−1.8; 2.2]	0.882	h = 0.019
Warping, mm *deformacija,* mm	2.50 ± 1.21	2.20 ± 1.19	0.30 ± 0.15	[−0.005; 0.605]	0.054	*d* = 0.25

Note: n = 120 boards per batch; two independent blind inspectors. 95 % CI shown directly in the table; [a]Difference = Hybrid – Control; SD – Standard Deviation; pp – percentage points.
Napomena: n = 120 ploča po seriji; dva neovisna ocjenitelja. 95 % CI prikazano izravno u tablici; [a]razlika = hibridna skupina – kontrola skupina; SD – standardna devijacija; pp – postotni bodovi.

depending on the characteristics of each variable. For the two proportion-based indicators (surface checking and internal checking), the two-sample Z test for proportions showed no significant differences between the systems: surface checking ($z = 0.13$, $p = 0.89$) and internal checking ($z = 0.15$, $p = 0.88$). This confirms that the hybrid solar–steam drying system does not increase the likelihood of defect formation and maintains wood quality equivalent to that of traditional boiler kilns.

For the continuous indicator of warping, the hybrid system yielded a lower mean value (2.20 ± 1.19 mm) compared with the control system (2.50 ± 1.21 mm). The two-sample t-test indicated that this difference was at the borderline of significance ($p = 0.054$, Cohen's $d = 0.25$), with the 95 % confidence interval of the difference including zero (-0.005; 0.605). Although the conventional statistical significance threshold at $\alpha = 0.05$ was not strictly met, the low p-value and small effect size suggest a clear trend: the hybrid system tends to improve the dimensional stability of wood. This trend is likely related to the "soft" thermal regime during periods without sunlight, which promotes internal moisture redistribution and reduces internal stress development, thereby limiting deformation.

3.3.2 Observations and mechanistic interpretation
3.3.2. Opažanja i mehanicistička interpretacija

Although the statistical results show differences that are not statistically significant, the mean values of the hybrid system are consistently lower than those of the steam-heated system. This outcome results from three important physical mechanisms:

(1) Nighttime "rest" period: During nighttime, when solar radiation is absent and the system shifts into a heat-maintenance mode, the moisture-removal rate decreases substantially. This phase allows intrinsic moisture from the core to migrate to the surface through slow diffusion, reducing the moisture gradient and lowering surface tensile stress → thereby limiting surface checking and internal checking.

(2) Maintaining stable temperature difference ($T_{db} - T_{wb}$): Throughout the drying process, the hybrid system maintains the temperature difference within the range of 6 – 10 °C, which is much lower than in steam systems that experience large fluctuations due to steam-valve on/off cycles. This prevents "thermal shocks", limits sudden evaporation at the surface, and reduces thermal stress within the wood cell structure.

(3) Uniform airflow distribution: Wind-speed data measured at 12 positions show that the integrated collector roof structure and optimized fan arrangement promote uniform airflow distribution, minimizing dead-air zones, localized hot/cold spots, and sudden thermal–humidity fluctuations within the wood layers. This airflow stability directly contributes to reducing warping and defects.

3.3.3 Comparison with international studies
3.3.3. Usporedba s međunarodnim istraživanjima

Many studies on solar drying, such as Khouya *et al.* (2022), report high surface-checking rates (5 – 10 %) due to highly variable heat sources affected by weather and the absence of timely heat-compensation mechanisms.

In contrast, the hybrid system in this study maintained a surface-checking rate of only 2.8 %, significantly lower. This success arises from the hybrid control mechanism, which uses steam for heat compensation when solar radiation declines, completely avoiding moisture shock and maintaining a gentle drying state.

This demonstrates that the hybrid system meets the stringent quality requirements of EU–US export production and reinforces the industrial feasibility of the technology.

Table 4 Energy balance of the two systems
Tablica 4. Energetska bilanca dvaju sustava sušenja

Indicator *Indikator*	**Unit** *Jedinica*	**Steam system** *Parni sustav*	**Hybrid solar – Steam system** *Hibridni solarno-parni sustav*	**Reduction / Increase** *Smanjenje / povećanje*
Biomass consumption *potrošnja biomase*	kg	9,689	4,845	–50.0 %
Q_{steam}	kWh	39,413	19,707	–50.0 %
Electrical energy, E_{elec} *električna energija, E_{elec}*	kWh	16,800	11,040	–34.3 %
Useful solar energy, Q_{solar} *korisna solarna energija, Q_{solar}*	kWh	–	15,687	–
Total energy input *ukupni unos energije*	kWh	56,213	30,747	–45.2 %
SEC	kWh/kg water	1.99	1.09	–45.2 %

Note: Lower heating value of biomass *LHV* ≈ 4.07 kWh/kg; boiler efficiency ~ 80 %.
Napomena: Donja ogrjevna vrijednost biomase LHV ≈ 4,07 kWh/kg; učinkovitost kotla ~ 80 %.

3.4 Energy performance
3.4. Energetska učinkovitost

Energy performance is the central focus of this study, evaluating the system's capability to save fuel, reduce operating costs, and enhance energy conversion efficiency through the integration of the solar collector.

3.4.1 Total energy consumption
3.4.1. Ukupna potrošnja energije

The energy balance results of the two drying batches are presented in Table 4.

The hybrid system reduced biomass demand by approximately 50 %, reduced electricity consumption by 34.3 %, and reduced total purchased energy by 45.2 %.

3.4.2 Solar energy contribution ratio
3.4.2. Omjer doprinosa solarne energije

(a) Thermal Solar Fraction – SF_{th}:

$$SF_{th} = \frac{15,687}{15,687 + 19,707} \approx 44.3\ \%$$

→ 44.3 % of the thermal demand was supplied by solar energy.

(b) Total Solar Fraction – SF_{total}:

$$SF_{total} = \frac{15,687}{15,687 + 19,707 + 11,040} \approx 33.8\ \%$$

→ Solar energy contributed ~33.8 % of the total operating energy.

3.4.3 Specific energy consumption (*SEC*)
3.4.3. Specifična potrošnja energije (*SEC*)

- Steam wood-drying system: 1.99 kWh/kg water
- Hybrid drying system: 1.09 kWh/kg water
- Reduction: 45.2 %

The value of 1.09 kWh/kg is close to the latent heat of vaporization of water, demonstrating the extremely high energy efficiency of the hybrid system under tropical climatic conditions.

3.4.4 Mechanisms improving energy performance
3.4.4. Mehanizmi za poboljšanje energetske učinkovitosti

Three main mechanisms enable the hybrid system to achieve high efficiency:

(1) Free daytime solar heat: During 09:00 – 15:00, the roof collector supplies most of the thermal demand, significantly reducing the required steam input.

(2) Fan dynamic control (VFD): Reducing fan speed during the maintenance phase lowers electricity consumption according to the cubic wind-speed law: $P \propto v^3$→ resulting in substantial electricity savings.

(3) Reduced heat losses: Avoiding high-temperature operation at night reduces heat loss through the kiln walls and decreases the need for steam-based heat compensation.

These results confirm hypotheses H1 and H3, demonstrating the overall effectiveness of the hybrid system.

3.5 Economic performance
3.5. Ekonomski učinak

The economic performance of the drying system is a key factor determining the feasibility of applying the technology in real industrial production. The economic analysis in this study was conducted based on the direct operating costs, including biomass fuel cost and electricity cost for one 90 m³ drying batch. Two drying batches were analyzed corresponding to the two systems: the traditional steam system and the hybrid solar-steam system. The results are summarized in Table 5.

3.5.1 Energy operating costs
3.5.1. Troškovi energije

The results show that the hybrid system reduced total energy cost from 51.49 to 31.56 million VND, equivalent to a reduction of 38.7 %. Two key factors contributed to this saving: biomass cost was reduced by half due to solar energy replacing daytime thermal load, and electricity cost was reduced by 34.3 % thanks to the ability to operate fans in low-power mode during nighttime.

Although the drying time increased from 448 to 480 hours, the total operating cost still decreased significantly due to the large contribution from solar energy.

3.5.2 Simple payback period (PBP)
3.5.2. Jednostavno razdoblje povrata (PBP)

The payback period was calculated based on the additional investment cost for the hybrid system, including the polycarbonate-absorber roof collector, accessories, ducts, and control system.

Table 5 Energy costs for one drying batch of the two systems
Tablica 5. Troškovi energije za jednu seriju sušenja i dva sustava sušenja

Indicator *Indikator*	Unit *Jedinica*	Steam system *Parni sustav*	Hybrid solar – Steam system *Hibridni solarno-parni sustav*
Drying time / *vrijeme sušenja*	hours	448	480
Biomass cost / *trošak biomase*	VND	14,533,500	7,267,500
Electricity cost / *trošak električne energije*	VND	36,960,000	24,288,000
Total energy cost / *ukupni trošak energije*	VND	51,493,500	31,555,500

The total investment cost was estimated at 850 million VND.

With an average energy saving of 19.94 million VND per batch and an operating frequency of 14 batches per year, the annual economic benefit is:

Annual saving = 19.94 × 14 = 279.2 million VND/year.

The simple payback period is: $PBP = \frac{850}{279.2} \approx 3.04$ year.

A *PBP* value of approximately 3.0 years is considered highly attractive for large-scale industrial drying systems, especially in the context of fluctuating energy costs and increasing pressure to reduce emissions.

3.5.3 Sensitivity analysis
3.5.3. Analiza osjetljivosti

To evaluate the stability of economic performance, a sensitivity analysis was conducted with ± 20 % variation in investment cost: CAPEX + 20 % (1,020 million VND): PBP ≈ 3.65 years; CAPEX – 20 % (680 million VND): *PBP* ≈ 2.43 years.

The results show that under all scenarios, the payback period remains within 2.4 – 3.7 years, confirming the robustness of economic performance even when investment costs or technical configurations vary.

3.5.4 *Overall assessment*
3.5.4. Ukupna procjena

The economic analysis shows that the hybrid solar-steam drying system reduces energy cost by approximately 40 %, provides a short payback period (≈ 3 years), and exhibits high stability under variations in CAPEX or OPEX. This demonstrates that integrating solar energy into the steam-drying process is not only feasible but also offers clear economic benefits for the wood-processing industry in Vietnam.

3.6 Environmental performance
3.6. Ekološki učinak

The evaluation of environmental performance was carried out based on the amount of CO_2 emissions associated with energy consumption throughout the operation process. According to the IPCC 2006/2019 guidelines, CO_2 from biomass is considered carbon-neutral (biogenic CO_2) and is not included in net emissions. Therefore, this study focuses on CO_2 generated from grid electricity consumption (Scope 2).

The Vietnamese grid emission factor for 2022 is: EF_{grid} = 0.6811 kg CO_2/kWh

The hybrid system reduced CO_2 emissions from 11.44 to 7.52 tons CO_2 per batch, equivalent to –34.3 %, directly reflecting the reduction in electricity consumption.

3.6.1 Contribution of solar energy to emission reduction
3.6.1. Doprinos solarne energije smanjenju emisija

Solar energy provides environmental benefits through two main mechanisms:

(1) Reduced electricity consumption → Reduced CO_2 Scope 2

Electricity reduction: ΔE = 5,760 kWh/batch

Corresponding CO_2 reduction: ΔCO_2 = 5,760 · 0.6811 = 3,925 kg CO_2 ≈ 3.93 tons CO_2

(2) Reduced steam demand from biomass: Although biogenic CO_2 is not counted in net emissions, reducing biomass consumption brings indirect environmental benefits: lower harvesting and transportation needs, reduced particulate matter, NO_x, and SO_2 emissions at the boiler, and reduced seasonal pressure on wood residue supply. This contributes to the overall sustainability of the system.

3.6.2 Overall evaluation
3.6.2. Ukupna evaluacija

With a 34.3 % reduction in CO_2 Scope 2 emissions, the hybrid solar–steam drying system demonstrates significant environmental benefits without compromising drying quality or productivity. When considering the indirect benefits from reduced biomass use, the system aligns with sustainable development goals, emission-reduction pathways, and the requirements of major export markets such as the EU and the United States.

3.7 Comparison with international studies
3.7. Usporedba s međunarodnim istraživanjima

To place the research findings in a global context, Table 7 summarizes international studies with verified DOIs on solar-assisted or hybrid wood-drying technologies. The selected studies meet three criteria: Availability of complete experimental data; Reporting

Table 6 CO_2 emissions (Scope 2) from electricity consumption
Tablica 6. Emisije CO_2 (opseg 2.) iz potrošnje električne energije

Indicator *Indikator*	**Unit** *Jedinica*	**Steam system** *Parni sustav*	**Hybrid solar – Steam system** *Hibridni solarno-parni sustav*
Electricity consumption / *potrošnja struje*	kWh/batch	16,800	11,040
Emission factor / *faktor emisije*	kg CO_2/kWh	0.6811	0.6811
CO_2 emissions (Scope 2) / *emisije CO_2 (opseg 2.)*	tons CO_2/batch	11.44	7.52

Table 7 Comparison of the hybrid solar-steam system with international studies
Tablica 7. Usporedba hibridnoga solarno-parnog sustava s međunarodnim istraživanjima

Author *Autor*	**Technology** *Tehnologija*	**Scale** *Veličina*	**SEC, kWh/kg H_2O**	**Solar fraction** *Solarni udio*	**Remarks** *Napomena*
Ferrari *et al.*, 2024	Solar-biomass hybrid *hibrid solar-biomasa*	5 m³	~1.80	~35 %	Small scale; high nighttime losses *mali sustav; veliki noćni gubitci*
Lamrani *et al.*, 2021	Solar-heat pump *solar-toplinska pumpa*	2 m³	0.95	~60 %	High SF but lab-scale only *visoka vrijednost SF-a, ali samo u laboratorijskim uvjetima*
Tarigan and Tekasakul, 2005	Solar-biomass *solar-biomasa*	10 m³	~1.50	~55 %	Box-type collector, high losses *kolektor kutijastog tipa, veliki gubitci*
This study	Hybrid solar-steam *hibrid solar-para*	100 m³	1.09	40 – 52 %	Industrial scale; integrated roof collector *industrijski sustav; integrirani krovni kolektor*

of key energy indicators such as *SEC* and *SF*; Comparable collector configuration or hybrid principle.

(1) *SEC*: The hybrid solar–steam system achieved: *SEC* = 1.09 kWh/kg H_2O

→ the lowest among the technologies with complete experimental data: 39 % lower than Ferrari *et al.,* 27 % lower than Tarigan & Tekasakul and comparable to Lamrani *et al.,* despite being 50× larger in scale.

(2) Solar Fraction: *SF* = 40 – 52 %. Higher than most conventional solar–biomass hybrid models.

(3) Industrial scale: This study's 100 m³ system is the largest in the comparison group. Achieving high SF and low *SEC* at such scale demonstrates stronger applicability than pilot-scale systems.

(4) Data completeness: This study ensures high reliability with: 10-minute interval data over 480 hours; full sensor suite (temperature, humidity, radiation, airflow, steam, electricity); complete CI_{95} %, error, bootstrap analyses; wood-quality assessment per TCVN 8929/8930.

The 100 m³/batch hybrid solar–steam drying system in Vietnam exhibits the lowest SEC, a high and stable SF, the largest industrial scale in the comparison group, high data reliability, and strong performance under tropical climatic conditions. This confirms the technical, economic, and environmental superiority and practical applicability of the hybrid solar–steam model.

3.8 Synthesis and evaluation of results
3.8. Sinteza i evaluacija rezultata

The industrial-scale experimental results of this study provide a comprehensive picture of the technical, energy, environmental, and product-quality performance of the hybrid solar–steam wood-drying system. All obtained results are consistent and directly support the four initial hypotheses H1 – H4.

(1) Energy-collection performance and thermodynamic characteristics: The solar radiation conditions in Gia Lai during the dry season play a decisive role in the performance of the integrated roof collector. The average DNI during peak hours reached 570 – 820 W/m², with maximum values up to 1,245 W/m² on clear-sky days, creating highly favorable conditions for thermal collection. The integrated roof collector achieved: an average efficiency of ~46 %, a peak efficiency of ~52 %, a total useful solar energy of ~15,687 kWh per cycle, and a contribution of 40 – 52 % of the daytime heat demand. This solar contribution directly reduces the required steam input during peak hours.

(2) Drying-process kinetics and operational stability: The *MC*–time drying curve of the hybrid system follows the three characteristic phases of wood drying and closely tracks the established drying schedule. Although the total drying time is 480 hours, longer than the traditional steam system (448 hours), analysis of T_{db} – T_{wb} – RH indicates that nighttime heat load decreases substantially because the collector is inactive, the fans operate in energy-saving mode due to VFD control, and the slower nighttime moisture-removal rate allows internal moisture equilibration, reducing stress. Therefore, although the process is longer, the overall performance remains high due to soft and stable operation.

(3) Post-drying wood quality and defects: Indicators according to TCVN 8929: 2013 and TCVN 8930: 2013 show that the hybrid system maintains wood quality equivalent to, and with a tendency to be better than, the steam system: surface checking 2.8 % (hybrid) vs 3.1 % (steam), internal checking 1.0 % (hybrid) vs 1.2 % (steam), and mean warping 2.2 mm (hybrid) vs 2.5 mm (steam). Statistical tests show no difference in checking rates ($p > 0.88$). However, warping shows a borderline significant reduction ($p = 0.054$). This confirms that integrating solar energy not only maintains quality but also improves dimensional stability due to reduced internal stress during rest phases.

(4) Energy performance and *SEC*-reduction mechanisms: Energy indicators clearly reflect the superiority of the hybrid system: ~50 % reduction in biomass consumption, 34.3 % reduction in electricity consumption, 45.2 % reduction in total purchased energy, and *SEC* reduction from 1.99 kWh/kg to 1.09 kWh/kg (–45.2 %).

Two Solar Fractions were achieved: $SF_{thermal}$ = 44.3 %, $SF_{total} \approx 33.8$ %

The mechanisms reducing *SEC* come from four factors:

(1) The integrated roof collector with large area and stable efficiency;

(2) Hybrid control logic based on ΔT – 20 minutes, limiting continuous steam activation;

(3) VFD reducing fan speed at night, lowering electricity consumption according to the cubic "fan law";

(4) Reduced heat loss due to optimized airflow distribution and kiln-chamber structure. The coordinated interaction of the three energy components (steam – electricity – solar) confirms the validity of hypothesis H1.

(5) Economic performance and payback period: With savings of 19.94 million VND per batch, an average of 14 batches per year, and an additional investment cost of 850 million VND, the payback period is calculated as: *PBP* = 3.04 years.

Sensitivity analysis with CAPEX ± 20 % yields: CAPEX +20 % → PBP = 3.65 years; CAPEX –20 % → PBP = 2.43 years. The hybrid drying system shows a PBP in the range of 2.4 – 3.7 years, which is within the preferred threshold of enterprises (< 5 years). This confirms the strong economic performance of the model.

(6) Environmental impacts and CO_2 emission reduction: With the Vietnamese grid emission factor: EF_{grid} = 0.6811 kg CO_2/kWh.

Scope 2 CO_2 emissions decreased from 11.4 tons to 7.5 tons CO_2 per batch, equivalent to a 34.3 % reduction. Biogenic CO_2 from biomass is treated according to IPCC 2006/2019 (carbon-neutral), ensuring international comparability. Overall, the hybrid system significantly contributes to CO_2 reduction targets in the wood-exporting sector.

(7) Position of the study in the international context: Compared with international studies with verified DOIs: *SEC* of 1.09 kWh/kg is the lowest in the group; *SF* = 40 – 52 %, equal to or higher than many pilot-scale studies; and the 100 m³ scale is the largest among all compared works. This confirms the pioneering nature, industrial feasibility, and reference value of the study within Southeast Asia and internationally.

The technical–energy–environmental–economic results consistently confirm that the hybrid solar–steam drying system operates stably, significantly reduces energy consumption, maintains wood quality, reduces CO_2 emissions, delivers strong economic benefits, and is fully suitable for large-scale industrial application.

The analysis incorporates measurement uncertainty for all key variables, including ± 0.75 °C (thermocouples), ± 3 %RH (hygrometers), ± 0.03 m/s (anemometers), and ± 1 % (electricity). Propagated uncertainty for *SEC* and *SF* was quantified using 10,000-sample bootstrap resampling, producing 95 % confidence intervals of: *SEC* = 1.09 ± 0.04 kWh/kg, SF_{total} = 0.46 ± 0.03. These narrow intervals demonstrate that the findings are statistically robust and reproducible under similar tropical conditions.

3.9 Implications for industrial deployment
3.9. Implikacije za industrijsku primjenu

The research results show that the hybrid solar–steam drying system has high application potential in industrial production, especially for factories operating kilns with capacities of 80 – 120 m³ per batch, which are commonly used in Vietnam and the Southeast Asian region. The 45.2 % reduction in specific energy consumption (*SEC*), the 34.3 % reduction in electricity usage, and the ~50 % reduction in biomass demand demonstrate that the hybrid wood-drying system not only provides significant operating-cost benefits but also reduces the instantaneous thermal load on the boiler. This has important practical implications: the boiler operates under more stable load conditions, reducing the frequency of rapid load increases or decreases, thereby extending equipment lifespan, lowering maintenance frequency, and improving the overall operational efficiency of the production line.

From an environmental perspective, the 34.3 % reduction in non-biogenic CO_2 (Scope 2) based on the Vietnamese grid emission factor (0.6811 kg CO_2/kWh) is fully consistent with the IPCC 2006/2019 accounting methodology. The reduction of non-biogenic CO_2 emissions is aligned with the accounting structure of IPCC 2006/2019 and is relevant for compliance with emerging carbon-regulation frameworks (e.g., CBAM). Maintaining wood quality equivalent to the traditional steam kiln, and even slightly reducing defect rates, eliminates concerns about product risks when using a heat source with natural variability such as solar energy. On the contrary, the hybrid system creates a milder and more stable drying environment due to the hybrid control strategy and nighttime "rest" phase.

From an economic perspective, the payback period of approximately 3.0 years (ranging from 2.43 – 3.65 years depending on ± 20 % CAPEX variation) is highly attractive for wood-processing enterprises, which typically operate with short investment cycles and moderate profit margins. In the context of rising operating costs for biomass boilers due to fluctuations in fuel prices, biomass transportation costs, ash-handling requirements, and increasingly stringent emission regulations, significantly reducing reliance on steam provides long-term economic benefits. With a design lifespan of over 15 years, the hybrid system delivers sustainable and stable economic returns.

An important point is that the hybrid solar–steam drying system also increases the operational flexibility of the boiler. During periods of high DNI, especially from 09:00 to 15:00 in the dry season, the solar collector can replace steam completely for many consecutive hours, allowing the boiler to shift to low-load or standby mode, operating more stably and efficiently. This is particularly beneficial for small-capacity boilers, which often struggle with rapidly fluctuating loads. These results open promising prospects for large-scale deployment of the hybrid model in Vietnam in the coming years, especially for enterprises undergoing transitions toward digitalization, automation, energy conservation, and emission reduction in compliance with international standards.

3.10 Limitations and future research directions
3.10. Ograničenja i budući smjerovi istraživanja

Although the study provides a highly valuable industrial-scale experimental dataset, several limitations should be carefully considered to expand applicability and enhance the reliability of the model:

(1) Limited number of drying batches: The study conducted one batch for each system (hybrid and control). Although the two batches were operated in parallel under the same weather conditions and loading plan, the limited number of batches restricts the statistical reliability of low-frequency indicators (internal checking, warping). Future studies should conduct ≥ 3 repeated batches for each system to increase statistical robustness and reduce random error.

(2) Limitations regarding wood species and thickness: The current results apply to 13-mm-thick *Acacia mangium* – a species that is relatively easy to dry. More challenging species (Eucalyptus, Rubberwood) or larger dimensions (25 – 40 mm) may exhibit more complex thermo–hygrometric kinetics, especially during the falling-rate and equilibrium phases. Future work should expand the research to other species to assess the generalizability of the hybrid drying system.

(3) Seasonal and weather limitations: The experiment was conducted in the dry season, characterized by high DNI and low RH. To evaluate year-round operation under tropical monsoon climates, additional drying batches during the rainy season are needed to analyze: the probability of steam activation, the reduction in Solar Fraction (SF), and the impacts on productivity and product quality.

(4) Limitations of the control algorithm: The ΔT 5 °C/20-minute control logic and DNI threshold of 150 W/m^2 operate stably but are not optimized for individual drying stages. The current algorithm does not incorporate hourly DNI forecasting or multivariable optimal adjustment. Future research could integrate: DNI forecasting using meteorological models, predictive control, and AI/ML techniques to optimize energy use and product quality in real time.

(5) Limitations in airflow modeling and measurement: Although airflow velocity was measured at 12 positions, the system has not yet been simulated using CFD (Computational Fluid Dynamics) to evaluate the spatial distribution of thermal–humidity fields within the lumber stack. Incorporating CFD simulation would help optimize fan design, airflow configuration, and vent locations to reduce losses and improve drying quality.

(6) Limitations in long-term assessment: The study has not evaluated performance degradation over time, including dust accumulation on polycarbonate sheets, absorber aging, reduced efficiency of fans/VFD, maintenance costs, and decreased transmittance after years of operation. Long-term monitoring of ≥ 12 months would help develop a more accurate model of actual operating costs and system lifetime.

4 CONCLUSIONS
4. ZAKLJUČAK

This study conducted a comprehensive evaluation of the technical, energy, and environmental performance of an industrial-scale hybrid solar–steam wood-drying system under the tropical climatic conditions of Vietnam. Using a 480-hour experimental dataset obtained directly from an export-oriented wood-processing factory, the analysis results show that the hybrid drying system outperforms the traditional steam kiln and essentially satisfies the four hypotheses H1 – H4 initially proposed:

First**,** the hybrid system achieved a specific energy consumption of SEC = 1.09 kWh/kg of evaporated water, corresponding to a 45.2 % reduction compared with the reference system, significantly exceeding the target set in hypothesis H1 ($\geq$ 30 %). At the same time, the solar fraction exceeded 30 %, meeting hypothesis H3 regarding the role of solar energy in replacing the boiler thermal load, and is comparable to international studies on hybrid wood-drying technologies. This confirms the very high energy-conversion efficiency of the integrated roof collector under Vietnamese climatic conditions.

Second**,** the post-drying wood quality of the hybrid system remains equivalent to the control system and even shows a tendency toward improvement. Evaluations based on TCVN 8929/8930 show no occurrence of serious defects such as end checking, abnormal warping, or moisture deviations beyond the standard. The surface- and internal-checking rates of the two systems are statistically equivalent, while the average warping of the hybrid system decreased with borderline significance (p = 0.054), indicating a trend toward improved dimensional stability due to the intermittent drying regime that reduces internal stress. These results show that integrating solar energy does not impair process stability when the system is controlled using an appropriate hybrid control strategy. This confirms hypothesis H2 and provides valuable industrial-scale experimental evidence for renewable-energy-based wood drying.

Third, in terms of environmental performance, the hybrid drying system reduced non-biogenic CO_2 emissions (Scope 2) by 34.3 % compared with the traditional steam kiln, based on the Vietnamese grid emission factor of 0.6811 kg CO_2/kWh and the IPCC 2006/2019 accounting methodology. This result confirms hypothesis H4 regarding the linear relationship between energy savings and greenhouse-gas emission reduction. At the same time, the system contributes to reducing biomass usage, fuel transportation, and boiler-related emissions.

Fourth, the economic analysis shows that the hybrid drying system reduces energy costs per batch by 38.7 %, corresponding to a saving of 19.94 million VND per batch. With an additional investment cost of approximately 850 million VND, the payback period ranges from 3 to 4 years even if CAPEX increases by 20 %. This level of performance is favorable for Vietnamese wood-processing enterprises, especially in the context of volatile energy prices and increasing emission-reduction requirements in international supply chains.

Despite these positive outcomes, the study still has several limitations, including the limited number of experimental batches, the narrow scope of application (only *Acacia mangium*, 13 mm), and the absence of a thermal energy storage (TES) system. Future studies should increase the number of repeated batches, diversify wood species and thicknesses, incorporate seasonal variations (dry vs. rainy season), and develop smart control algorithms with radiation forecasting and airflow optimization via CFD, as well as integrate TES to enhance thermal stability.

Overall, the results confirm that the hybrid solar–steam wood-drying system is an effective, sustainable, and highly feasible solution for the wood-drying industry in Vietnam. The 480-hour industrial experimental dataset provides significant reference value, contributing to the transition toward clean energy in industrial thermal processes and opening pathways for the development of high-efficiency drying technologies aligned with emission-reduction and energy-sustainability strategies.

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5 REFERENCES
5. LITERATURA

1. Elustondo, D.; Matan, N.; Langrish, T.; Pang, S., 2023: *Advances in wood drying research and development.* Drying Technology, 41 (6): 890-914. https://doi.org/10.1080/07373937.2023.2205530
2. Ferrari, S.; Cuccui, I.; Cerutti, P.; Allegretti, O., 2024: *A hybrid solar/biomass active indirect kiln dryer for timber in DR Congo*. International Journal of Ambient Energy, 45 (1). https://doi.org/10.1080/01430750.2024.2367109
3. Khouya, A., 2022: Energy analysis of a combined solar wood drying system. Solar Energy, 231: 270-282. https://doi.org/10.1016/j.solener.2021.11.068
4. Lamrani, B.; Draoui, A.; Kuznik, F., 2021: Thermal performance and environmental assessment of a hybrid solar-electrical wood dryer integrated with photovoltaic/thermal air collector and heat recovery. Solar Energy, 221: 60-74. https://doi.org/10.1016/j.solener.2021.04.035
5. Martynenko, A.; Vieira, M., 2023: Sustainability of drying technologies: system analysis. Sustainable Food Technology, 1: 629-640. https://doi.org/10.1039/D3FB00080J
6. Yang Meng, Y.; Chen, G.; Hong, G.; Wang, M.; Gao, J.; Chen, Y., 2019: Energy efficiency performance enhancement of industrial conventional wood drying kiln by adding forced ventilation and waste heat recovery system: A comparative study. Maderas. Ciencia y Tecnología, 21 (4): 545-558. http://dx.doi.org/10.4067/S0718-221X2019005000410
7. Nguyen, P.; Tran, H.; Hoang, N., 2024: High-resolution DNI characteristics in the Central Highlands of Vietnam. Energy Conversion and Management, 302: 117902 (in Vietnamese).
8. Rahman, M.; Hasnain, M.; Paramasivam, P.; Zairov, R.; Ayanie, A., 2025: Solar Drying for Domestic and Industrial Applications: A Comprehensive Review of Innovations and Efficiency Enhancements, 9 (2): 2400301. https://doi.org/10.1002/gch2.202400301
9. Tarigan, E.; Tekasakul, P., 2005: A combined solar-biogas dryer and its energy performance. Energy and Buildings, 37(8): 813-821.
10. ***ASHRAE, 2010: *Standard 93-2010: Methods of Testing to Determine the Thermal Performance of Solar Collectors.* American Society of Heating, Refrigerating and Air-Conditioning Engineers.
11. ***IPCC, 2006: Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES), Japan.
12. ***IPCC, 2019: Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Switzerland.
13. ***ISO 13061-1, 2014: Physical and mechanical properties of wood – Test methods for small clear wood

specimens. Part 1: Determination of moisture content for physical and mechanical tests. International Organization for Standardization. Geneva, Switzerland.

14. ***ISO 15686-5, 2017: Buildings and constructed assets – Service life planning. Part 5: Life-cycle costing. International Organization for Standardization. Geneva, Switzerland.
15. ***Ministry of Natural Resources and Environment, 2022: Technical report for the national greenhouse gas inventory. Hanoi, Vietnam (in Vietnamese).
16. ***TCVN 8929, 2013: Round timber – Defects – Terms and definitions. Ministry of Science and Technology. Hanoi, Vietnam (in Vietnamese).
17. ***TCVN 8930, 2013: Round timber – Defects – Classification. Ministry of Science and Technology. Hanoi, Vietnam (in Vietnamese).
18. ***Vietnam MONRE, 2022: Vietnam National Grid Emission Factor 2022. Ministry of Natural Resources and Environment. Hanoi (in Vietnamese).

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The Structure of Price Dynamics for Timber Products on World and Russian Markets

Struktura dinamike cijena drvnih proizvoda na svjetskome i ruskom tržištu

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ABSTRACT • *This research endeavor seeks to address the scientific challenge of discerning recurring patterns of price fluctuation in both international and national markets for timber and other forest-derived goods. Databases on prices for forest products have been created, which required careful processing and structuring of the data obtained: the information is structured into tables; search systems and visualization of dashboards in excel have been implemented; regular updates are carried out. Based on the created databases on prices for forest products, time series of prices with different interval time lags (monthly average, quarterly average and annual average) have been developed, considering market segments. The primary statistical analysis of price time series with the definition of statistical indicators was carried out. A comprehensive analysis of the data obtained from various sources allowed us to compile a detailed picture of the price dynamics of forest products, namely to: Determine the structure of the dynamics of prices for forest products; Identify promising areas of activity, taking into account the growing demand for certain types of forest products and the reduction in consumption of other types of products; Predict price dynamics: knowing the trends in prices for forest products allows enterprises to more accurately forecast their profits and plan investments; Assess the competitiveness of Russian timber products in the domestic and global markets.*

KEYWORDS: *price policy; prices; forestry; forecasting and simulation: models and applications; methodology for collecting, estimating, and organizing macroeconomic data*

SAŽETAK • *Predmet ovog istraživanja bio je znanstveni izazov prepoznavanja ponavljajućih modela fluktuacije cijena na međunarodnome i nacionalnom tržištu drva i ostalih drvnih proizvoda. Izrađene su baze podataka o cijenama drvnih proizvoda, što je zahtijevalo pomnu obradu i strukturiranje dobivenih podataka. Informacije su svrstane u tablice, implementirani su sustavi pretraživanja i vizualizacije tablica u Excelu te su provođena redovita ažuriranja. Na temelju izrađenih baza podataka o cijenama drvnih proizvoda razvijeni su vremenski nizovi cijena uzimanjem u obzir tržišnih segmenata različitih vremenskih intervala (mjesečnog prosjeka, tromjesečnog prosjeka i godišnjeg prosjeka). Provedena je primarna statistička analiza vremenskih nizova cijena s definicijom statističkih pokazatelja. Sveobuhvatna analiza podataka dobivenih iz različitih izvora omogućila nam je sastavljanje detaljne*

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slike dinamike cijena drvnih proizvoda, kao i utvrđivanje strukture dinamike cijena drvnih proizvoda; identificiranje obećavajućih područja djelovanja uključivanjem i rastuće potražnje određenih vrsta drvnih proizvoda i smanjenja potrošnje drugih vrsta proizvoda; predviđanje dinamike cijena (poznavanje trendova cijena drvnih proizvoda omogućuje poduzećima da točnije predvide svoju dobit i planiraju ulaganja) te procjenu konkurentnosti ruskih drvnih proizvoda na domaćem i svjetskom tržištu.

KLJUČNE RIJEČI: *politika cijena; cijene; šumarstvo; predviđanje i simulacija: modeli i primjene; metodologija prikupljanja, procjene i organiziranja makroekonomskih podataka*

1 INTRODUCTION
1. UVOD

Fluctuations in prices for forestry products (logging, woodworking, pulp and paper industry, plate production) are a complex and multifaceted problem affecting both producers and consumers and the economies of exporting countries.

The main problems caused by these fluctuations are:

1. For enterprises of the forestry complex:

- The impossibility of long-term planning: Sharp price spikes make it difficult to invest in modernization, expansion of production, and development of new products.
- Reduced profitability and loss risks: Falling prices for finished products with fixed or rising costs for raw materials, energy and logistics lead to financial losses. • Problems with contract fulfillment: Long-term supply contracts become risky, as the price at the time of execution may differ significantly from the price at the time of conclusion.
- Shortage of working capital: During periods of low prices, revenue decreases, which leads to a shortage of money for salaries, taxes and purchases of raw materials.

2. For end users and related industries (construction, furniture industry, retail):

- Unpredictability of project costs: Spikes in prices for lumber, plywood, and slabs make it impossible to accurately estimate construction costs.
- Decrease in demand: A sharp rise in prices (as it was in 2021-2022) can “freeze” demand for housing and repairs, which affects the entire chain.
- Search for substitutes: Consumers are starting to look for alternative materials (plastic, metal, composites), which can lead to an unrecoverable wood market loss.

3. For the economies of exporting countries (for example, Russia, Finland, Canada):

- Instability of foreign exchange earnings: Timber exports are an important source of income. Price fluctuations create instability in the trade balance and budget.
- Regional destabilization: Many forest regions of Russia are monospecialized, therefore, falling prices lead to unemployment and social problems.

The main reasons for fluctuations in prices for timber products:

A) Cyclical and market factors:

1. Macroeconomic situation: Global and national crises, economic growth/recession rates (especially in key consumer countries: USA, China, EU). Construction boom or bust.

2. Seasonality: The demand for building materials increases in spring and summer, which affects prices.

3. Changes in exchange rates: For export-oriented industries (like Russia), the strengthening of the national currency reduces profitability in local terms.

4. Energy prices and logistics: The timber industry is energy- and transport-intensive. Rising fuel and freight prices directly affect the cost.

B) Industry and structural factors:

5. Supply and demand imbalance: Fires, bark beetle outbreaks, and epidemics of forest diseases (as in Europe) reduce the supply of raw materials and inflate prices. On the other hand, overproduction (for example, after restrictions are lifted) leads to a collapse in prices.

6. Policy decisions and trade barriers:

- Export duties and quotas (as in Russia) artificially limit supply on the world market, affecting prices.
- Trade wars and sanctions (sanctions against Russian timber in the EU) dramatically reshape logistics chains, creating shortages in some regions and oversupply in others.
- Environmental regulations (FSC requirements, logging bans) increase costs and limit the raw material base.

C) Speculative factors:

7. Stock trading: Prices for some timber (for example, lumber) are formed on commodity exchanges (for example, CME), where not only real supply/demand, but also the actions of financial investors and hedge funds play an important role.

The topic of price fluctuations in the timber market has become particularly relevant in recent years. These are no longer just cyclical changes, but the result of a complex interweaving of global and local factors, which is confirmed by reports from industry analytical agencies and consulting companies (practical data and forecasts). The FAO (Food and Agriculture Organization of the United Nations) (FAO, 2024) and the United Nations Economic Commission for Europe (UNECE,

2024) publish forest market surveys (FAO Forestry) and statistics. ITTO (International Tropical Timber Organization, 2026) provides monthly market reports, especially on tropical timber. Leading global analytical agencies in the field of forestry such as Forest Economic Advisors (FEA, 2026), RISI (Fastmarkets, 2025), and Wood Resources International (WRI, 2026) publish reports, reviews, and press releases on trends in the forest products market.

Deloitte's "2024 forestry industry outlook" indicates that volatility has become the "new normal" (Deloitte, 2024). Companies are encouraged to invest in digitalization and data analysis for better forecasting. PwC in the Global Forest report, Paper & The Packaging Industry Survey notes that the main risks for the industry remain macroeconomic instability, energy costs and supply chains, which directly supports the thesis of ongoing price fluctuations (PwC, 2026).

Analytical agencies (Fastmarkets, RISI) in their weekly and monthly market reports constantly contain statements like "the market is looking for balance," "uncertainty persists," "prices are showing mixed dynamics," which is direct evidence of instability. The current analytical picture fully confirms our thesis – not "just fluctuations", but "structural volatility" – this is the term that experts are increasingly using. The timber products market has become a complex system where traditional factors (supply and demand) are reinforced by extreme external shocks (geopolitics, climate disasters, global inflation).

An accurate forecast of price dynamics in the Russian forest industry requires an understanding of the broader global context in which the domestic market operates. Developments in the world market for forest products shape external economic conditions, trade restrictions and demand trends that indirectly affect pricing mechanisms within Russia. Therefore, an analysis of the global market environment is an important analytical prerequisite for subsequent forecasting of prices in the Russian forest sector.

The purpose of scientific research is to develop adaptive models for forecasting prices for forest products. Achieving this goal involves solving a number of interrelated tasks, including analyzing retrospective data on prices for major types of forest products, identifying key factors influencing their dynamics, and developing mathematical models that can take into account the complex relationships between these factors. Special attention was paid to the study of the impact of macroeconomic indicators, such as inflation rates, currency exchange rates and the geopolitical situation, on pricing in the forestry complex. An important aspect of the research is to take into account the specifics of individual segments of the timber products market, such as lumber, pulp, paper and wood boards, since each of them has its own unique characteristics and is influenced by various factors. The results of the study will form the basis for the development of practical recommendations for forestry enterprises on managing risks associated with price volatility and optimizing planning and production strategies. The created forecasting models will make it possible to make more informed decisions in the field of pricing, procurement of raw materials and investments in new technologies. The research objectives included: to analyze modern theoretical approaches to forecasting prices for forest products; to collect, process and analyze statistical data on prices for key types of forest products; to analyze modern approaches to forecasting prices for forest products; to collect, process, and analyze statistical data on prices; to identify trends, cyclical and seasonal components of price dynamics using econometric and spectral methods; and to assess price volatility and structural features of time series. Adaptive forecasting models (such as ARIMA models) are considered a promising direction for further research to develop practical recommendations on the application of adaptive models for timber companies and industry management bodies.

Thus, the implementation of scientific research will make a significant contribution to the development of the theory and practice of forecasting prices for forestry products and will help to increase the competitiveness of the industry in the global market.

2 RELEVANCE OF THE RESEARCH
2. RELEVANTNOST ISTRAŽIVANJA

Various econometric methods are used in the study and forecasting of indicators. However, now, the use of adaptive methods for predicting one-dimensional time series is becoming the most popular (McConnell *et al.*, 2021; Shiller, 2020; International Monetary Fund, 2020). Understanding the dominant current trend, rather than the overall average trend across a given timeframe, is crucial because it holds the most significant influence on the process in question. This allows you to more accurately predict the future values of the time series and take into account changes in its dynamics. For this reason, the information of the deadline period becomes the most relevant. Adaptive time series forecasting methods are relevant and widely used in various fields because they allow you to take into account changes in time series and predict their future values. They make it possible to obtain more accurate forecasts compared to other methods, such as static models, which do not take into account changes in the dynamics of the series (Dzerjinsky *et al.*, 2020: McConnell *et al.*, 2021; Medvedev *et al.*, 2022). Furthermore, adaptive methodologies prove valuable in process quality analysis and control, price forecasting for products and services, and financial market analysis. The essence of adaptive forecasting methods is that they take into account the different informational significance of the time series levels through a system of weights determined depending on the novelty of data. Adaptive models are based on moving average and autoregression schemes. The estimation of the coefficients of the adaptive model is based on a recurrent method, which avoids the re-calculation of all calculations when new data becomes available. In this case, the model is adapted iteratively. The forecasting model incorporates a mechanism for adjusting predictions based on real-world data. When actual data points become available, the discrepancy between these and the previously predicted values is calculated as the forecast error. This error term is then integrated back into the model, influencing its transition to subsequent states and thereby refining future predictions. The next step is to change the parameters to ensure a greater degree of consistency between the behavior of the model and the dynamics of the series. The final stage is to determine the forecast value for the future period. The described process is iterative, which helps the adaptive model to regularly receive up-to-date data, adapt to them and reflect the current direction of development. Adaptive methods are well suited for short-term forecasting one or more steps ahead. Adaptive forecasting of economic processes plays a key role in modern economic analysis, increasing the accuracy of forecasts in conditions of instability and uncertainty. Over the past twenty years, similar methods have been actively developed in Russian practice, due to the need for flexible planning in conditions of frequent economic crises. The use of adaptive models allows taking into account the dynamics of changing factors and timely response to them.

Choosing the optimal forecasting method is a critically important aspect of predictive analytics and presents a significant challenge in academia. Modeling and forecasting of socio-economic trends have a rich history (Landsberg *et al*., 1965; Meadows *et al*., 1991; Pestel, 1994; Starikov *et al*., 2022). In the XX and XXI centuries, there has been increased interest in this field, which has led to increased requirements for the rigor of methodology and scientific validity of approaches. Economists from both the United States and Europe are actively involved in large-scale forecasting projects. An example is the study by G. Landsberg, L. Fishman and J. Fischer's "Resources in America's Future: Needs and Opportunities to Meet Them, 1960-2000." (Burdakova *et al*., 2023; Dewhurst *et al*., 1961; Kondratiev *et al*., 2003).

New publications on forecasting methods include a significant number of works on forecasting prices of non-oil and gas, financial instruments, and currencies. Special attention is paid to the development and application of new mathematical models and algorithms for forecasting. Neural networks, machine learning methods, and hybrid approaches combining traditional statistical methods with modern IT technologies are showing promising results. Big Data analysis is also an important area, which makes it possible to identify hidden patterns and correlations that can be used to improve the accuracy of forecasts. K. A. Saprykin considered various methods for predicting the price of URALS gray oil, including statistical methods such as autoregressive integrated moving average models, exponential smoothing. The author also introduced new machine learning methods (linear regression, support vector machines, artificial neural networks, long-term short-term memory) (Saprykin, 2023). A group of scientists D. Orazmukhamedov, K. Tyachmuradov, M. Nurmukhammedov, M. Rakhmanov evaluated various approaches to forecasting in conditions of uncertainty and market volatility, including econometric models, time series methods and machine learning (Orazmuhammedov *et al*., 2024). The authors have substantiated the advantages and disadvantages of different forecasting methods, as well as their practical application. The author focused on the accuracy of forecasts of various models and their adaptability to changing market conditions (Azarnova *et al*., 2025). T. V. Azarnova, N. G. Asnina, A. I. Kolosov, A.V. Lependin used machine learning methods to predict the consumer price index: PyAF, StatsForecastAutoARIMA, Prophet, recurrent neural networks LSTM (Azarnova *et al*., 2025). S. V. Veretekhina used different theories (dynamic systems, price behavior of Dow, fractals, sets) to predict the average price of exported goods and mathematical analysis. To assess the persistence of the series, the Hurst coefficient was calculated (Veretekhina, 2025). V. D. Yezhkin and M. V. Radionova applied machine learning and neural network methods to build models and select the best model to obtain predicted Bitcoin price values (Yezhkin and Radionova, 2024). The topic of forecasting oil prices is also presented in the work of A. P. Samatova and I. V. Filimonova. The paper provides an overview of methods for forecasting oil prices. It is shown that the existing methods of forecasting oil prices can be divided into quantitative and qualitative methods. The main limitations of the existing approaches are revealed, the advantages and disadvantages of the most popular methods are shown. The classification of machine learning methods is presented (Samatova and Filimonova, 2025).

In the present study, adaptive forecasting methods are discussed as an important methodological background. However, the empirical analysis focuses on identifying the structural components of price dynamics (trend, cycles, seasonality and volatility) rather than on producing adaptive short-term forecasts.

3 THEORETICAL REVIEW OF STUDIES
3. TEORIJSKI PREGLED ISTRAŽIVANJA

In the 1970s, outstanding researchers, J. P. Morgan and D. Meadows, made a significant contribution to the development of global forecasting (Shvets *et al.*, 2020). Their fundamental work "Limits of Growth" introduced the concept of "models of system dynamics" to the scientific community. Mesarovich and Pestel were the first to apply an innovative methodological approach that made it possible to analyze the interrelationship of the main regions of the world (Deng *et al*., 2022). By the mid-1980s, more than fifteen international scientific forecasts, called "models of the world," had been distributed. At the end of the 20th century, there was a revival of interest in forecasting long-term socio-technological trends for periods from 50 to 1000 years. In this area of research, the work of authors such as Nesbitt and Eburdin has spread ("What awaits us in the 90s: megatrends. 2000) and Peterson ("The Path to 2015"). The contributions of the scientists such as J.F. Coates, J.B. Mahaffy, and E. Hines, among others, deserve recognition and further study (Kim *et al*., 2024). In the final period of the twentieth century, there was a significant increase in the use of mathematical modeling, which was due to rapid progress in the field of information technology and the creation of advanced software products. Modern information technologies and computational methods provide researchers with the opportunity to conduct in-depth analysis of complex phenomena and processes. The increasing negative trends emphasize the importance of developing accurate and reliable forecasts based on mathematical modeling.

The intricate nature of current forecasting tools and methodologies presents significant challenges. Selecting the most appropriate method and assessing the trustworthiness of the resulting predictions pose persistent dilemmas. Scientists express concern that a major drawback across various forecasting systems lies in the lack of transparency regarding their methodologies. In most instances, detailed descriptions of the forecasting methods employed are absent. Due to the complexity of forecasting models, it is extremely difficult to ascertain the precise cause of any discrepancies between predicted and actual outcomes. We cannot definitively determine whether such deviations result from limitations within the model's structure or methodology, or from unforeseen external factors (Federal State Statistics Service, 2024; UNECE/FAO, 2021; U.S. Department of Labor, Bureau of Labor Statistics, 2020). The inherent intricacy of most economic processes often defies accurate representation through simple mathematical functions, necessitating the development of more sophisticated models capable of addressing this complexity.

The field of modeling and forecasting employs a variety of methodologies. Given its practical importance, it is crucial to share ongoing scientific research and knowledge. Both governmental and private entities dedicate substantial resources and expertise to advance this domain, driving both theoretical and applied progress.

Forecasting methods are divided into quantitative and qualitative ones. The forecasting methodology is selected based on the nature of the task, the volume and quality of the available information, as well as the objectives of the forecast (FAOSTAT, 2024.; UNECE/FAO, 2021). Quantitative forecasting methods rely on mathematical and statistical analysis of historical data to identify patterns and trends that can be used to estimate future values. Quantitative methods rely on numerical data and mathematical models. Examples include time series analysis for identifying patterns in historical data, extrapolation for projecting trends, regression analysis for establishing relationships between variables, and Monte Carlo simulation for modeling probabilities and uncertainties. Qualitative methods, conversely, leverage expert knowledge and insights. These approaches are particularly valuable when data is scarce or subject to significant uncertainty. Notable qualitative techniques encompass the Delphi method, which employs structured questionnaires to gather consensus from a panel of experts; brainstorming, which encourages creative idea generation within a group setting; and focus groups, where moderated discussions facilitate the exploration of opinions and perspectives among a targeted audience.

However, the subjective nature of qualitative methods and their limited capacity to capture dynamic changes in economic systems constrain their applicability in the analysis of time-dependent processes. As economic environments become increasingly volatile and data availability improves, the need arises for forecasting approaches that can incorporate new information and adjust to evolving conditions in a systematic and formalized manner. In this context, adaptive forecasting methods are employed.

Adaptive forecasting methods are defined as approaches that allow the construction of self-correcting (self-adjusting) economic and mathematical models capable of rapidly responding to changing conditions by taking into account the results of previous forecasts and considering the differing informational value of time-series observations. In the scientific literature, adaptive forecasting encompasses a broad range of approaches based on exponential smoothing, autoregressive relationships, and various modifications of moving averages, as well as other methods aimed at

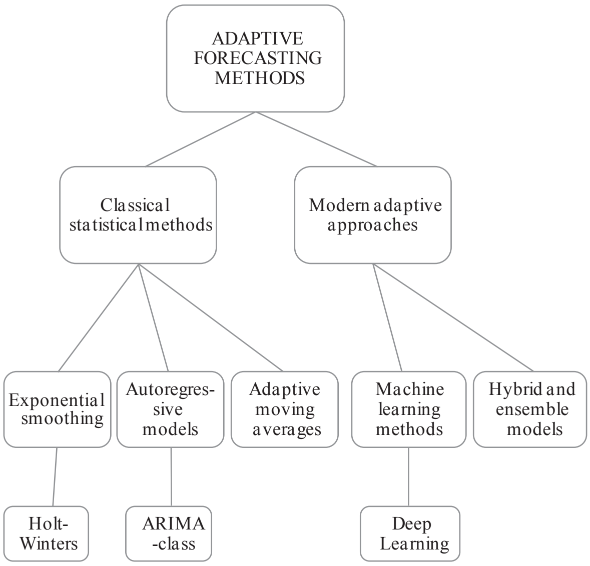

Figure 1 Classification of adaptive forecasting methods: compiled according to Pyzhyev (2024) and Shiller (2020)
Slika 1. Klasifikacija adaptivnih metoda predviđanja: sastavljeno prema Pyzhyev (2024.) i Shiller (2020.)

capturing trend-related and dynamic components of economic time series.

The main groups of adaptive forecasting methods discussed in the literature are summarized in Figure 1.

The peculiarity of adaptive methods is that they are able to take into account changes in the studied processes and adapt to them. With exponential smoothing, the time series is determined by a weighted moving average. This method has several modifications: simple exponential smoothing, the Holt method (double exponential smoothing) for series with a trend, and the Holt-Winters method (triple exponential smoothing) for series with a trend and seasonality. Autoregression is based on the fact that future values of a time series are calculated based on previous observations of the same series. The current value of a variable is explained by its previous values and a random deviation. Polynomial models are used if it is assumed that the trend of a process can be described by a polynomial of degree n, then the coefficients of the predicting polynomial are calculated using exponential averages of the corresponding orders. Another important group of adaptive methods includes autoregressive and autoregressive moving average models, particularly ARIMA-class models. These models combine autoregressive components, differencing procedures to achieve stationarity, and moving-average terms to account for random shocks. ARIMA models are capable of capturing both inertia and stochastic fluctuations in time series and are widely applied in price forecasting and macroeconomic analysis. However, their effectiveness depends on strict assumptions regarding stationarity and error structure. With a moving average, the actual levels of the time series are replaced by calculated levels that are less susceptible to fluctuations. The main types of moving averages that are used in adaptive forecasting are simple moving average, adaptive moving average. Among the current trends in statistical forecasting, we can single out the following methods: hybrid models and ensembles – combining various approaches (statistical methods, machine learning, expert assessments) into a single predictive system; deep learning for time series – using specialized neural network architectures (LSTM, GRU, transformers) to model complex nonlinear dependencies in data with long-term patterns; causal modeling is the transition from correlation models to causal ones, which make it possible not only to predict, but also to model the effects of interventions in the system.

Despite their advantages, adaptive forecasting methods vary significantly in terms of transparency, data requirements, and interpretability. Therefore, the choice of a specific adaptive method should be determined by the research objectives, data availability, and the balance between model complexity and analytical clarity. In the present study, adaptive forecasting methods are considered as an important theoretical foundation and a promising direction for further research, while the empirical analysis focuses on identifying the structural components of price dynamics using trend, cyclical, and volatility analysis.

4 RESEARCH OBJECTIVES AND METHODS
4. CILJEVI I METODE ISTRAŽIVANJA

Monitoring prices for forest products is especially relevant in conditions of global economic instability, when factors such as changes in raw material prices or environmental influences can significantly affect the cost of products. The analysis and calculation indicators required statistical materials from the Russian state services (Azarnova *et al*., 2025). This analysis utilizes a comprehensive range of data sources to ensure its accuracy and reliability. Information regarding forest resources and management practices was drawn from the Federal Forestry Agency, as well as statistical databases and reports published by international organizations such as the European Commission, the World Bank, the International Institute for Sustainable Development, FAOSTAT, UNEP, and UNCTAD (Samatova and Filimonova, 2025; Shvets *et al*., 2020; Veretekhina, 2025; Yezhkin and Radionova, 2024). Regional integration associations have also provided data for this analysis. Furthermore, insights from specialized industry organizations and associations provided valuable context and perspective. Thus, the analysis of data obtained from various sources allows us to obtain a complete picture of the price dynamics for the products of the forest complex. Calculations and price estimates were made in the national currency of Russia (ruble). A similar study was also conducted by the authors regarding world prices for forest products; however, it was not possible to compare the results in this article due to the limited scope of the research.

At the initial stage of the study, preliminary processing of the raw data was carried out, including checks of the time series for completeness, homogeneity, and the presence of anomalous values. Missing observations were adjusted using interpolation methods while preserving the original logic of price dynamics. To eliminate the effects of heterogeneous time intervals, the raw data were aggregated into monthly, quarterly, and annual series depending on the objectives of the analysis and the specific characteristics of each product category. All time series were converted into a comparable format, which made it possible to correctly analyze price dynamics across different segments of the forest products market.

After the initial data processing, a preliminary statistical examination was carried out in order to reveal the main features of price behavior. At this stage, basic descriptive indicators were computed, such as average values, measures of variability, standard deviation, and the coefficient of variation, which made it possible to evaluate both the magnitude and intensity of price instability for individual product categories. On the basis of these results, products were provisionally grouped according to their volatility levels, allowing the most risk-sensitive segments of the market to be identified. The subsequent phase of the research focused on the structural analysis of price time series. To achieve this, decomposition techniques were employed to separate long-term trends, seasonal effects, cyclical movements, and random disturbances. Trend dynamics were assessed using regression methods, while the reliability of the estimated parameters was verified through standard statistical tests, including the t-statistic and the coefficient of determination.

The seasonal component was analyzed by comparing intra-annual price fluctuations, while cyclical movements were identified based on an analysis of medium-term deviations from the long-term trend.

To conduct a more in-depth examination of the periodicity of price fluctuations, spectral analysis was employed, making it possible to identify hidden frequency characteristics of the time series. The use of this method allowed dominant cycles to be determined and their stability over time to be assessed. Spectral estimates made it possible to compare the frequency structure of prices for different product types and to identify similarities or differences in the mechanisms underlying price dynamics in domestic and global markets.

Within the framework of the empirical analysis, trend–cyclical decomposition, linear regression modeling, and spectral analysis were applied to study price dynamics. These methods were used to identify long-term trends, cyclical patterns, and volatility characteristics of forest product prices. Prior to model estimation, the stationarity of the series was tested, and differencing procedures were applied when necessary. Model parameters were selected based on information criteria and the quality of approximation, while model adequacy was assessed through residual analysis and retrospective forecast validation. The use of adaptive approaches made it possible to account for changes in the market environment and for the weakening stability of traditional relationships under external shocks.

As one of the widely used adaptive forecasting approaches discussed in the literature, ARIMA models can be described as follows (Eq. 1):

$$yt = \alpha+\varphi 1yt-1+\ldots+\varphi pyt-p+\varepsilon t+\theta 1\varepsilon t-1+\ldots +\theta q\varepsilon t-q \quad (1)$$

ARIMA models use three different parameters: p, d, and q.

These parameters define the structure of the model and allow it to take into account seasonal fluctuations, trends, and noise components of the data. The model is written as ARIMA (p, d, q).

The parameter p is the autoregressive order. It determines how much the current values of the time series are related to its past values. Thanks to this, you can adjust the model based on the use of previous data. For example, if the last three days were hot, then tomorrow will most likely also be warm.

The parameter d denotes the degree of integration, which helps to eliminate the trend and make the time series stationary. The smaller the difference between the current and previous values, the easier it will be to predict the future – for example, temperature, if the difference over the last three days is minimal.

The q parameter is associated with the moving average and describes the impact of past prediction errors on the current result. It allows the model to take into account noise deviations and adjust predictions based on past errors.

The final stage of the methodological procedure involved synthesizing the results of the quantitative analysis and interpreting them in the context of the functioning of the forest sector. The estimates obtained were used to compare price dynamics across different product groups, identify general patterns, and determine specific features of individual market segments. The integrated application of statistical, econometric, and spectral methods ensured a comprehensive approach to analyzing prices for forest products and provided a methodological basis for further forecasting and the development of practical recommendations.

In this study, ARIMA models are not directly estimated; the description is provided to illustrate potential directions for further model development.

The study of data obtained from various sources allowed us to create a detailed picture of the price dynamics for the products of the forest complex:

- Identify promising areas of activity: taking into account the growing demand for certain types of forest products allows you to focus on the development of production of these types of products.
- Understanding pricing trends within the forestry industry empowers businesses to make more precise profit projections and formulate well-informed investment strategies.
- Knowledge of pricing fluctuations in the forestry sector enables companies to develop more accurate profitability forecasts and make sound investment decisions.

5 RESULTS OF ANALYSIS
5. REZULTATI ANALIZE

The results presented below correspond to the applied trend-cyclical and regression-based analytical framework and do not represent adaptive forecast outputs. During the analyzed period, there has been a significant fluctuation in prices for round softwood lumber for sawing and planing on the Russian market, which can be attributed to several key factors (Ryabova *et al.*, 2020). Fluctuations in the demand for construction materials, driven by economic factors and evolving regulations concerning forestry practices, have significantly influenced market dynamics. Furthermore, geopolitical tensions and trade restrictions have introduced volatility into supply chains, subsequently impacting pricing strategies. For example, in 2018, there was an increase in prices for timber against the background of an increase in construction volumes. Since mid-2019, economic sanctions and revisions to export policies have led to a significant decline in exports of round softwood timber suitable for sawing and planing. Statistical data indicate that prices for this timber within the Russian market remained around 2500 per cubic meter throughout 2020. Since the beginning of 2021, prices for round softwood lumber for sawing and planing in the Russian market have begun to grow actively, and by the end of the 1st quarter of 2022 they increased by 50-55 % (Figure 2). Market conditions in the period of 2024-2025 are anticipated to be shaped by global events (Pyzhyev, 2024). Nevertheless, domestic developments such as enhanced logistics and sustainable production practices are expected to contribute to price stabilization within the softwood lumber market. In 2024, prices for softwood rose by 29 % on the domestic market. The analysis showed that the time series of monthly and quarterly lumber prices from 2003 to 2023 contain an increasing trend, cyclical and seasonal components. The trend parameters are estimated, and the statistical significance is verified using the coefficient of determination and the Fisher criterion. The statistical significance of the trend parameters is confirmed by hypothesis testing: the null hypothesis of a zero slope is rejected at the 5 % significance level, while the coefficient of determination indicates a satisfactory model fit. The equation of the increasing trend for the dynamics of world prices is: $y = 546.74 \cdot x + 11900$. The validity of the estimated trend is supported by a sufficiently high coefficient of determination (R^2), indicating that a substantial share of price variation is explained by the model. The slope coefficient is statistically significant according to standard hypothesis testing ($p < 0.05$). The equation of the increasing trend for the dynamics of monthly domestic prices for softwood lumber is: $y = 106.32 \cdot x + 3737.9$. In contrast to the dynamics of monthly domestic prices for lumber, the trend of annual price dynamics has a negative constant indicator. The cyclical component of the time series of lumber prices for the global market is determined by the period of 12-17 quarters. For the time series of prices for lumber for the domestic market in the period 1998-2023, it also amounts to 11-16 quarters. The main feature of the dynamics of time series of lumber prices is an increase in the amplitude of cycles after 2015. Seasonal fluctuations in prices on the global and domestic lumber markets are expressed slightly and are associated to a greater extent with the period of activity in the construction market.

Compared to July 1, 2024, in August 2024, prices for round softwood lumber for sawing and planing increased by 1279.61 rubles. The maximum increase was observed on August 1, 2024 (1279.61 rubles). The minimum increase was recorded on May 1, 2024 (-895.03 rubles). The rising cost of round softwood lumber intended for sawing and planing is decelerating, suggesting a reduction in demand for this material.

The analysis of the dynamics of lumber prices on the world market was carried out from 2003 to 2024. The specified timeframe was characterized by substantial volatility driven by multiple influences. These included shifts in supply and demand dynamics, economic downturns, and modifications to both legal frameworks and environmental regulations. At the beginning of the period under review, from 2003 to 2007, there was a steady increase in prices, provoked by high demand for building materials in developing countries. However, with the onset of the global financial crisis in 2008, lumber prices plummeted, which caused serious consequences for many producers. Since 2010, the market began to recover, and by 2018 prices had reached new records, helped by the recovery of the

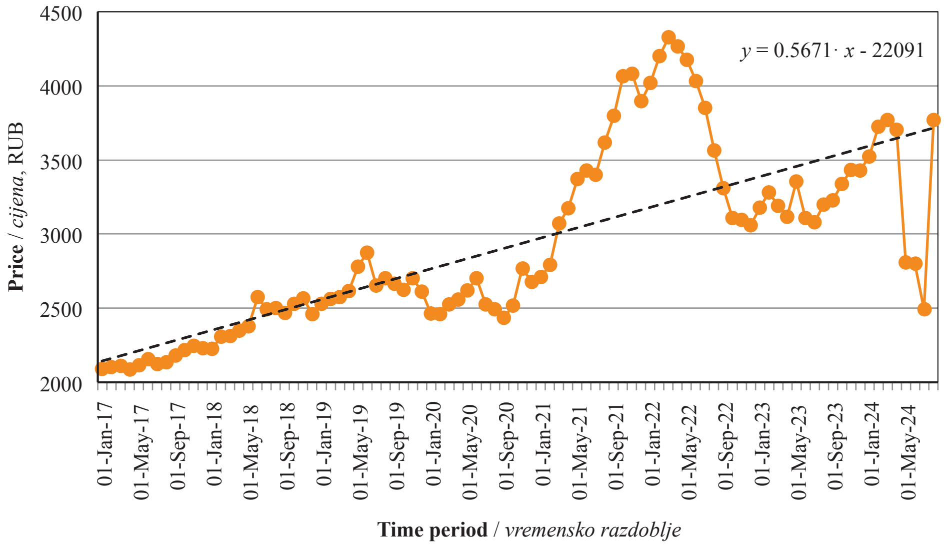

Figure 2 Prices for round softwood timber for sawing and planing on the Russian market (according to Federal State Statistics Service, 2024; FAOSTAT, 2024.; UNECE/FAO, 2021)
Slika 2. Cijene oblog drva četinjača za piljenje i blanjanje na ruskom tržištu (prema Federalnoj državnoj statističkoj službi, 2024.; FAOSTAT, 2024.; UNECE/FAO, 2021.)

construction sector and lack of resources. However, in 2020, the COVID-19 pandemic once again caused instability, which affected supply chains and demand. In 2023-2024, the market is showing signs of adaptation, but it is impossible to predict exactly how lumber prices will develop in an ever-changing global context. Lumber prices exhibited significant volatility between 2003 and 2024. The most substantial price increase was recorded in the fourth quarter of 2021, reaching 20,358 rubles. Conversely, the first quarter of 2022 witnessed a decline of 35,721 rubles, indicating a period of price reduction. The overall trend suggests an upward trajectory in lumber prices. By the second quarter of 2024, compared to the first quarter of 2003, prices had surged by 46,631 rubles, representing a 277 % increase. This data highlights a notable acceleration in the price dynamics of lumber during this period (Figure 3). In 2024, hardwood pilomaterialy prices rose by 77 % domestically.

A recent, extensive analysis examined global plywood pricing trends over a 21-year span, encompassing the years 2003 through 2024. During this period, there were significant price fluctuations caused by a variety of economic, political and environmental factors. From 2003 to 2007, there was a consistent increase in the cost of building materials. This price escalation was primarily attributed to a significant rise in demand, which was stimulated by the rapid growth of

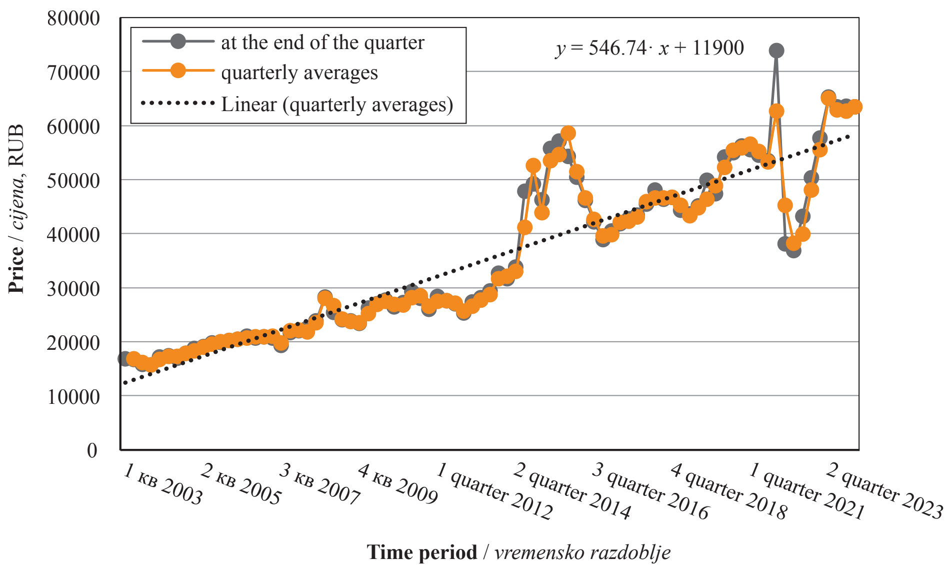

Figure 3 Prices for hardwood on the Russian market (according to Federal State Statistics Service, 2024; FAOSTAT, 2024; UNECE/FAO, 2021)
Slika 3. Cijene listača na ruskom tržištu (prema Federalnoj državnoj statističkoj službi, 2024.; FAOSTAT, 2024.; UNECE/FAO, 2021.)

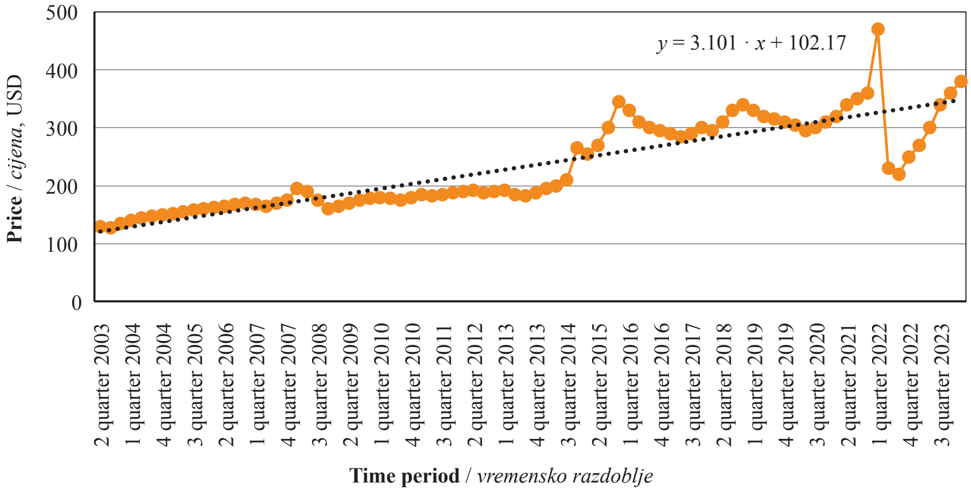

Figure 4 Prices of plywood on the world market (according to Federal State Statistics Service, 2024; FAOSTAT, 2024; UNECE/FAO, 2021)
Slika 4. Cijene furnirske ploče na svjetskom tržištu (prema Federalnoj državnoj statističkoj službi, 2024.; FAOSTAT, 2024.; UNECE/FAO, 2021.)

the construction industry in emerging economies. However, with the onset of the global financial crisis in 2008, there was a sharp drop in plywood prices, which caused an oversupply and the closure of many small and medium-sized enterprises. In the 2010s, the market gradually recovered, but the recorded growth was uneven. During the initial six months of 2019, inflationary pressures re-emerged. This resurgence was attributed to a confluence of factors, including elevated import tariffs and a scarcity of timber resources stemming from legislative modifications implemented by several nations. The prospects for 2023-2024 suggest further adaptation of the market to environmental standards and a growing interest in sustainable materials, which will have an impact on the pricing policy and the structure of offers in this niche. Plywood prices experienced their most significant surge in the second quarter of 2022, with an increase of 120.19 rubles. Conversely, the third quarter of 2022 witnessed the smallest price increase, a decrease of 242.04 rubles. The data indicates a sustained rise in plywood prices, suggesting that the rate of price increase is accelerating (Figure 4). In 2024, plywood prices increased by 21 % on the Russian market.

This study examined cellulose prices for NBSK (Europe, China, USA) and BHKP (in Europe and China). Data was sourced from the PIX index database, which provides weekly price measurements for various cellulose types. The time series data for both NBSK and BHKP demonstrate territorial comparability, encompassing a similar range of objects, consistent units of measurement, synchronized recording periods, and reliable reporting. Therefore, these samples are considered representative, allowing for conclusions drawn from the analysis to accurately reflect broader market trends within the cellulose industry. The maximum price increase is observed in Q1 2021 (200 USD), and the minimum increase is recorded in Q1 2019 (-121 USD). The rate of price increase in the analyzed dynamics shows that there are opposite trends in the dynamics of a number, which must be taken into account when developing a trend-cyclical price model. The study highlighted key trends reflecting changes in market value and production costs. In 2017, there was a steady increase in prices due to an increase in prices for raw materials and an increase in demand from the printing industry. From 2019 to 2021, there was a significant price fluctuation caused by global economic factors such as trade wars and instability in international markets. Manufacturers have adapted to the new conditions, eliminating excess costs and optimizing production processes. Since 2022, as the economy has emerged from the pandemic crisis, active price growth has resumed, due to increased consumption and the restoration of supplies (Figure 5). In 2024, wood cellulose prices decreased by 0.2 % on the domestic market.

The analysis of the dynamics of prices for offset paper of Russian manufacturers was carried out from 2017 to 2024. Forecasts for 2024 show positive changes, but risks remain associated with inflationary pressures and instability in the supply of key components. In August 2024, compared to July 2024, the price of offset paper decreased by 924.89 rubles. or by 1.3 %. The maximum increase is observed in May 2021 (2375.74 rubles). The minimum increase was recorded in 2020 (-2971.72 rubles). The rate of increase shows that the trend of the series is decreasing, which indicates a slowdown in the dynamics of prices for offset paper (Figure 6). The analysis showed that the time series of monthly and quarterly paper prices from 1998 to 2023 contain an increasing trend, cyclical and seasonal components. The main feature of the dynamics of time series of paper prices is an increase in the amplitude of

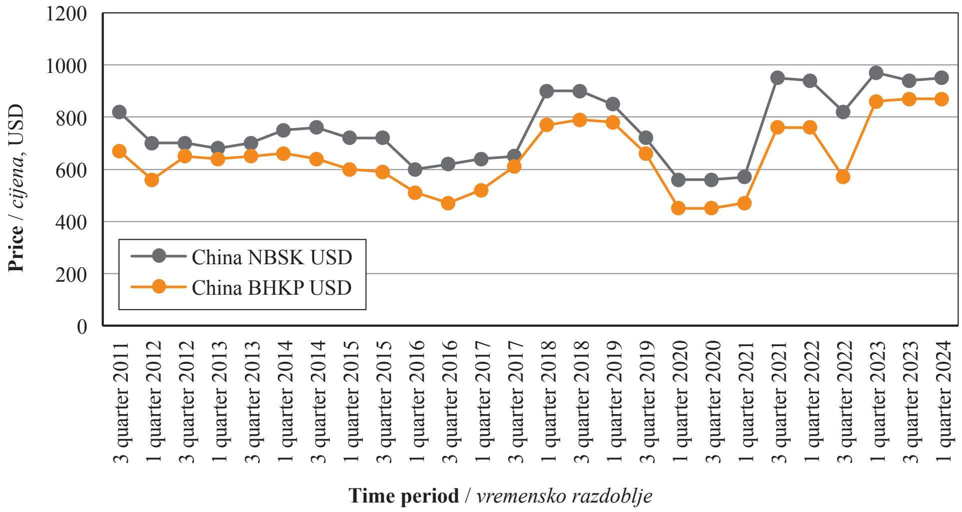

Figure 5 Prices of pulp on the world market (according to Federal State Statistics Service, 2024; FAOSTAT, 2024; UNECE/FAO, 2021)
Slika 5. Cijene celuloze na svjetskom tržištu (prema Federalnoj državnoj statističkoj službi, 2024.; FAOSTAT, 2024.; UNECE/FAO, 2021.)

cycles after 2015. Seasonal fluctuations in prices on the domestic paper market are not pronounced and are mostly associated with a period of activity in a number of consuming industries.

The analysis of the dynamics of prices for cardboard from Russian manufacturers was carried out from 2017 to 2024. During this period, there is a noticeable fluctuation in prices due to a variety of factors. In 2017-2019, cardboard prices had high volatility against the background of constant demand from the packaging industry and steady production rates. However, starting in mid-2020, against the background of global economic changes and volatility in commodity markets, there has been a sharp increase in prices. The COVID-19 pandemic, beginning in 2021, has substantially impacted the situation by causing disruptions to both manufacturing processes and supply chain operations. This increased competition for raw materials, which also affected the price dynamics. At the beginning of 2022, there is a repeated price spike associated with the restoration of demand for cardboard in the context of the global economic recovery. However, in 2023-2024, prices began to adjust again, as the market adapted to new conditions and consumer preferences changed. On August 1, 2024, compared to July 1, 2024, the price of cardboard from Russian manufacturers increased by 1555.3 rubles or by 2 %. The maximum increase is observed in January 2022 (18320.5 rubles). The minimum increase was recorded On January 1, 2020 (-14885.8 rubles). The rate of increase shows that the trend is increasing, which indicates an acceleration in prices for cardboard from Russian manufacturers (Figure 7). In 2024, kraft-liner cardboard prices rose by 7 %, while corrugated cardboard increased by 6 %.

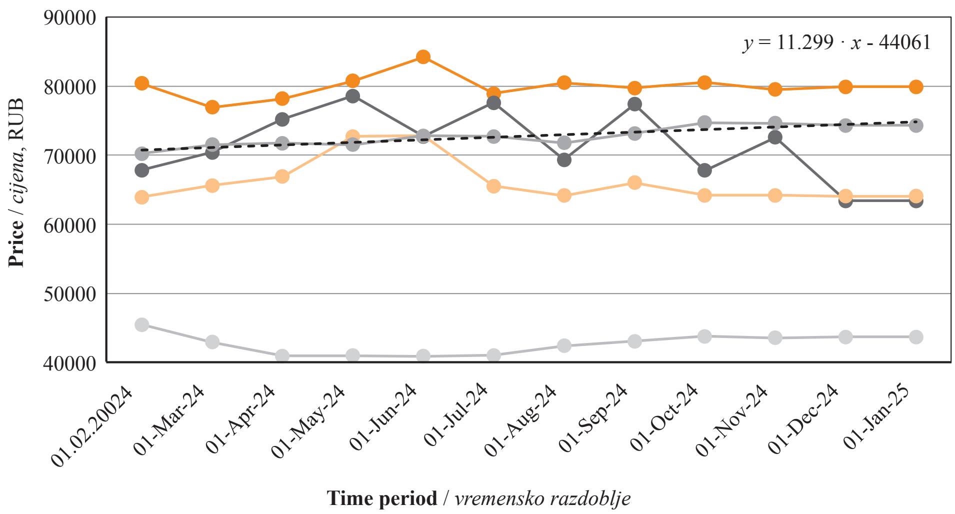

Figure 6 Prices for offset paper from Russian manufacturers, RUB/ton. (according to Federal State Statistics Service, 2024; FAOSTAT, 2024; UNECE/FAO, 2021)
Slika 6. Cijene ofsetnog papira ruskih proizvođača, RUB/t (prema Federalnoj državnoj statističkoj službi, 2024.; FAOSTAT, 2024.; UNECE/FAO, 2021.)

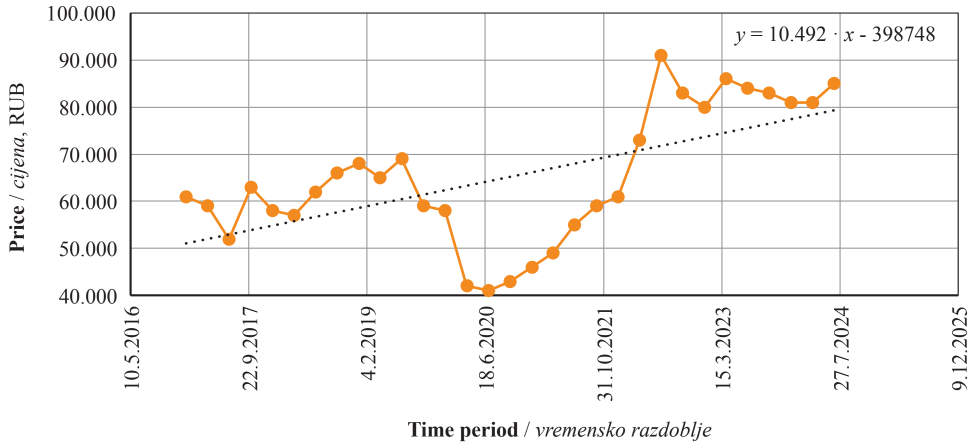

Figure 7 Prices of cardboard on the world market, RUB/ton (according to Federal State Statistics Service, 2024; FAOSTAT, 2024; UNECE/FAO, 2021)
Slika 7. Cijene kartona na svjetskom tržištu, RUB/t (prema Federalnoj državnoj statističkoj službi, 2024.; FAOSTAT, 2024.; UNECE/FAO, 2021.)

The study also examined price fluctuations in various product categories. This analysis reinforced the findings regarding the alignment and interconnectedness of domestic, export, and global prices. Specifically, it demonstrated that the pricing trends for forestry products exhibit a consistent and synchronized pattern, albeit occasionally with minor temporal discrepancies.

Based on the conducted analysis, key patterns in the price dynamics of major forest products were identified in both the Russian and global markets. Instead of repeating similar descriptions for each product, the main results are summarized in consolidated tables, which allows for a clear comparison of trend characteristics, cyclicality, and volatility. Analysis of monthly and quarterly time series from 2003 to 2023 (for some products from 1998 to 2023) revealed the presence of an increasing trend, cyclical, and seasonal components for most products. The main feature of price dynamics after 2015 is the increase in the amplitude of cycles. Seasonal fluctuations are weak and mainly associated with periods of activity in the construction sector and related industries. A compact visual summary of the quantitative analysis of price time series for five key categories of forest products is presented in Table 1. All trend coefficients are statistically significant at a level not lower than 5 %.

It is important to remember that price dynamics is a complex process that cannot always be predicted. One of the important aspects of the process of forecasting the dynamics of prices for forest products is the definition of its structure and the allocation of elements. The structure of price dynamics for timber products includes several elements, each of which has its own significance for understanding price changes in the market. The nature of the price dynamics structure is influenced by many factors, and understanding all the key elements of price dynamics will allow you to navigate the market more effectively and make more informed decisions (Table 2).

Forest product prices exhibit three recurring patterns over time: trend, seasonality, and cyclical fluctuations. These patterns can be mathematically represented as a function of these components, along with a random error term. This function can be expressed as $Yt = f(T, S, C, E)$, where Yt represents the observed price level at a given time point (t). The trend component (T) captures the long-term upward or downward movement in prices. The seasonal component (S) accounts for regular, predictable fluctuations that occur

Table 1 Summary of trend and cycle analysis results for key forest products
Tablica 1. Sažetak rezultata analize trendova i ciklusa za ključne drvne proizvode

Product *Proizvod*	**Trend equation ($y = bx + a$)** *Jednadžba linearnog trenda ($y = bx + a$)*	**Coefficient of determination (R^2)** *Koeficijent determinacije (R^2)*	**Statistical significance of trend (p-value)** *Statistička značajnost trenda (p-vrijednost)*
World lumber prices / *svjetske cijene drva*	$y = 546.74 \cdot x + 11900$	0.78	$p < 0.001$
Domestic softwood lumber prices *domaće cijene četinjača*	$y = 106.32 \cdot x + 3737{,}9$	0.65	$p < 0.01$
Domestic paper prices / *domaće cijene papira*	$y = 85.41 \cdot x + 12050$	0.71	$p < 0.001$
Pulp (global market) prices *cijena celuloze (globalno tržište)*	$y = 45.23 \cdot x + 8500$	0.60	$p < 0.05$
Plywood (global market) prices *cijena furnirskih ploča (globalno tržište)*	$y = 320.15 \cdot x + 10500$	0.69	$p < 0.01$

Table 2 Formatting sections, subsections and subsubsections
Tablica 2. Formatiranje odjeljaka, pododjeljaka i potpododjeljaka

Component *Komponenta*	**Classification** *Klasifikacija*	**Definition** *Definicija*	**Causes and duration of exposure** *Uzroci i trajanje izloženosti*
Trend – T	Systematic *sustavna*	A stable long-term trend *stabilan dugoročni trend*	The general economic situation with a duration of up to 20 years *opće gospodarsko stanje s trajanjem do 20 godina*
Cyclic – C *ciklička – C*	Systematic *sustavna*	Recurring ups and downs, going through 4 phases: depression, rise, peak, recession *ponavljajuća kretanja gore-dolje kroz 4 faze: depresiju, rast, vrhunac, recesiju*	The interaction of supply and demand factors with a duration of 8-14 sq. m. with varying intensity *međusobno djelovanje ponude i potražnje s trajanjem od 8 do 14 godina, uz različiti intenzitet*
Seasonal – S *sezonska – S*	Systematic *sustavna*	Regular periodic fluctuations occurring in the short term during the year *redovite periodične fluktuacije koje se pojavljuju kratkoročno tijekom godine*	Weather conditions, social habits, religious traditions throughout the year *vremenski uvjeti, društvene navike, religijske tradicije tijekom godine*
Irregular – E *neredovita – E*	Random *slučajna*	Residual fluctuation remaining after removal of systematic components *preostala fluktuacija nakon uklanjanja sustavnih komponenata*	Random unforeseen events. Short duration or delayed exposure *slučajni nepredviđeni događaji, kratko trajanje ili odgođeni učinak*

within a year. The cyclical component (*C*) represents longer-term cycles that extend beyond a single year. Finally, the random component (*E*) incorporates unpredictable, short-term variations in prices.

The following are the results of a spectral analysis of the prices of some types of forest products, conducted to identify hidden patterns and the frequency of data (Figure 8-12).

Based on the spectrum graphs, the frequency characteristics of time series of prices can be analyzed for each product. The peaks on the graph correspond to the frequencies that are most pronounced in the data. Higher amplitudes at low frequencies may indicate long-term trends, while higher amplitudes at higher frequencies may indicate short-term fluctuations or seasonality. Higher amplitudes at higher frequencies indicate short-term fluctuations or seasonality, e.g., 12-month cycles linked to seasonal harvesting constraints (winter logging reductions in northern regions) or annual construction peaks. The identified 11-16 quarter cycles (3-4 years) align with economic drivers like construction boom-bust cycles, influenced by real estate markets or recessions (post-2008 recovery patterns), and supply disruptions from environmental regulations or trade policies in the forest sector. These cycles may continue into 2024-2025, with production forecasts indicating modest growth in softwood biomaterial (+2 %) but decline in hardwood (-10 %).

Trend, seasonality, cycles and noise in the dynamics of prices for forest products are interrelated and can enhance or weaken each other's effect. The connectedness and mutual influence of the elements of price dynamics for forest products in retrospect and perspective is also changing. Some elements manifest themselves more strongly in historical periods and may weaken in the future. The impact and interaction of elements on the structure of price dynamics for forest products in retrospect and in the future can be represented as follows.

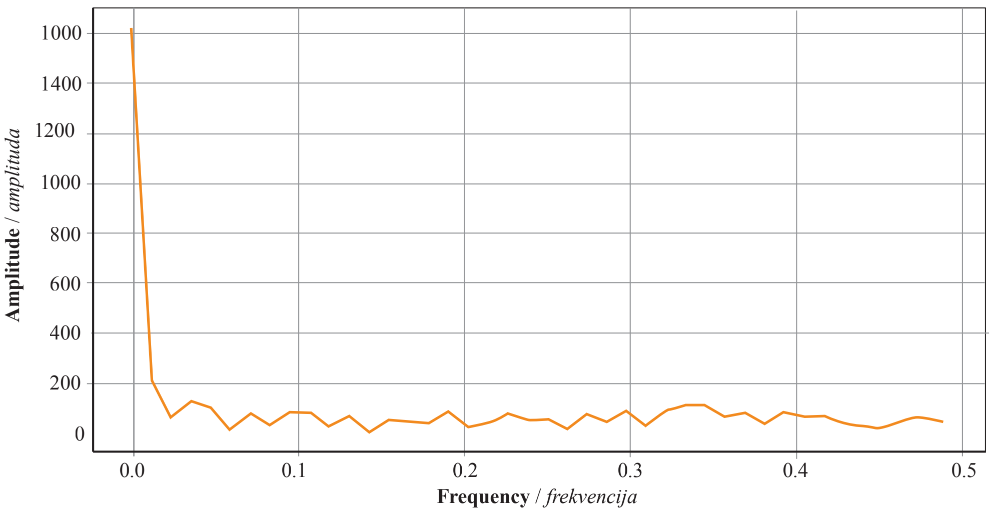

Figure 8 Range of product prices: Corrugated cardboard in rolls or sheets (compiled by the authors based on calculations performed)
Slika 8. Raspon cijena za valoviti karton u rolama ili listovima (sastavili autori na temelju provedenih izračuna)

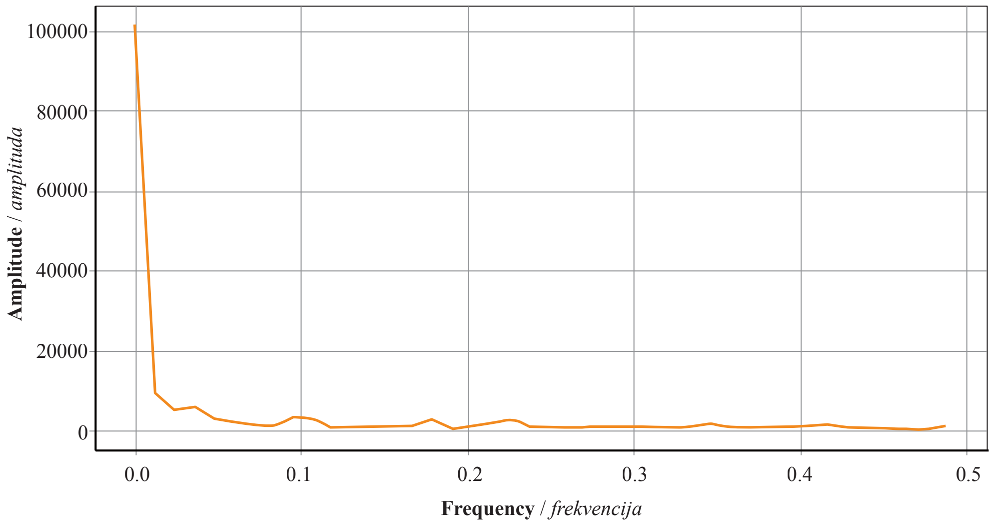

Figure 9 Range of product prices: Round hardwood timber for the production of pulp and wood pulp (compiled by the authors based on calculations performed)
Slika 9. Raspon cijena za oblo drvo listača za proizvodnju celuloze i drvne pulpe (sastavili autori na temelju provedenih izračuna)

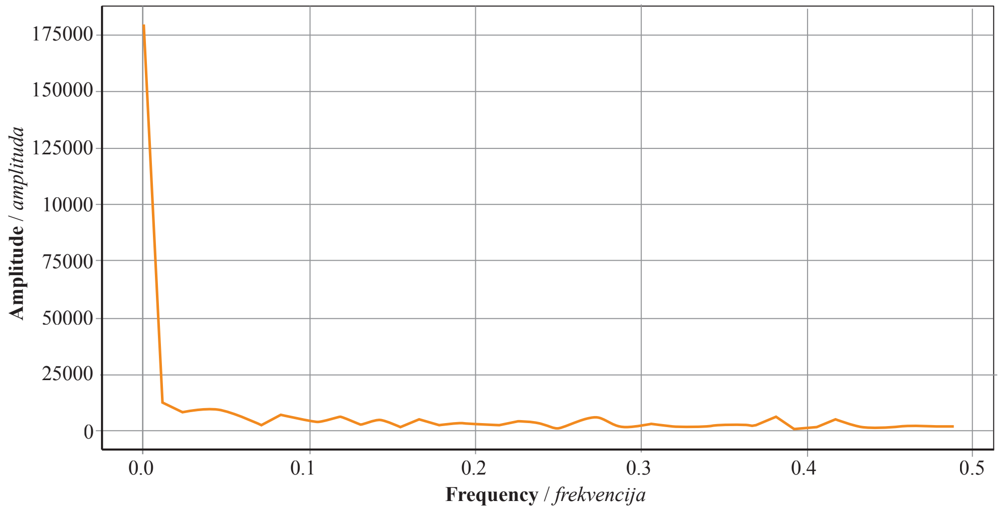

Figure 10 Range of product prices: Round hardwood lumber for sawing and planing (compiled by the authors based on calculations performed)
Slika 10. Raspon cijena za drvo listača za piljenje i blanjanje (sastavili autori na temelju provedenih izračuna)

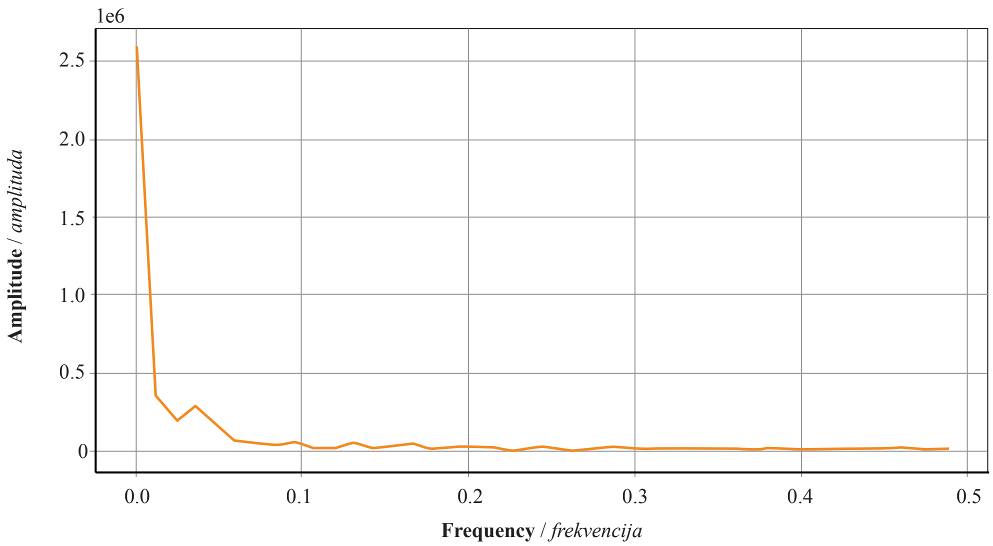

Figure 11 Range of product prices: Plywood (compiled by the authors based on calculations performed)
Slika 11. Raspon cijena za furnirsku ploču (sastavili autori na temelju provedenih izračuna)

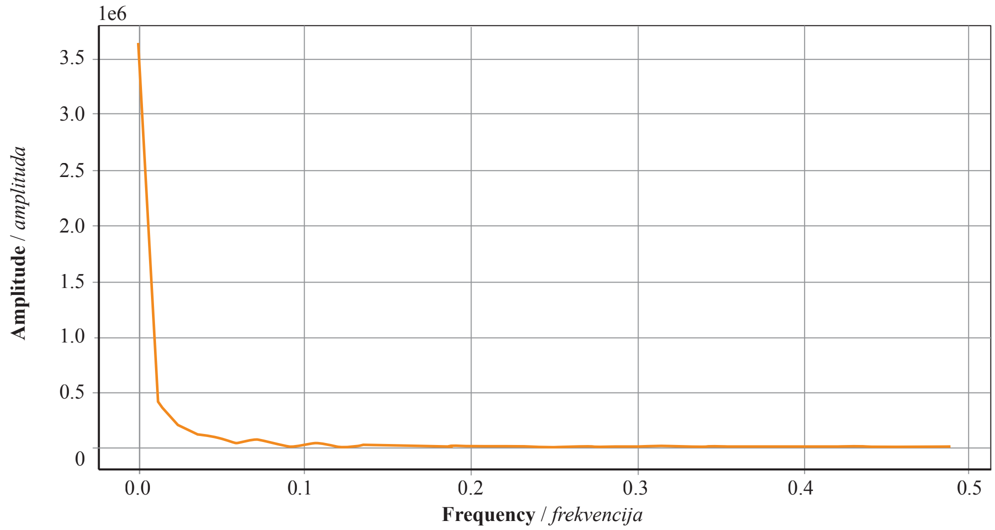

Figure 12 Range of product prices: Wood pulp and cellulose of other fibrous materials (compiled by the authors based on calculations performed)
Slika 12. Raspon cijena za drvnu pulpu i celulozu od ostalih vlaknastih materijala (sastavili autori na temelju provedenih izračuna)

Over the past century, price fluctuations in the forest products market were primarily driven by overarching trends. Seasonal variations exerted a notable influence, while cyclical patterns were less evident and random fluctuations were minimal. The observed patterns of change over time exhibit an increasing prevalence of both ascending, stable, and descending trends. Concurrently, cyclical fluctuations have become more pronounced and impactful. Furthermore, there has been a notable rise in random variation, particularly in recent decades. Future market trends for forestry products will be shaped by the interplay of global supply and demand, technological advancements, and the evolution of environmental regulations. While seasonal price fluctuations may lessen due to international trade expansion and new technologies, cyclical patterns will remain a significant driver of price dynamics. Furthermore, market volatility is expected to rise as a result of increasing complexity and unpredictability in the global economic and political landscape.

Price volatility is analyzed to find out how much the prices of forest products fluctuated from 2017 to 2024 (Table 3).

Based on Table 3, the highest price volatility is observed for corrugated cardboard (standard deviation = 9186.25), while the lowest volatility characterizes pulp and cellulose products (standard deviation = 7.82). The coefficient of variation provides a relative measure, showing that plywood has the highest relative risk (125.2 %) despite lower absolute SD, due to its lower mean price. The line graph illustrated the dynamics of prices for goods with high and low volatility, showing significant fluctuations for «Corrugated cardboard in rolls or sheets» and a much more stable trend for «Wood pulp and cellulose of other fibrous materials» (Figure 13).

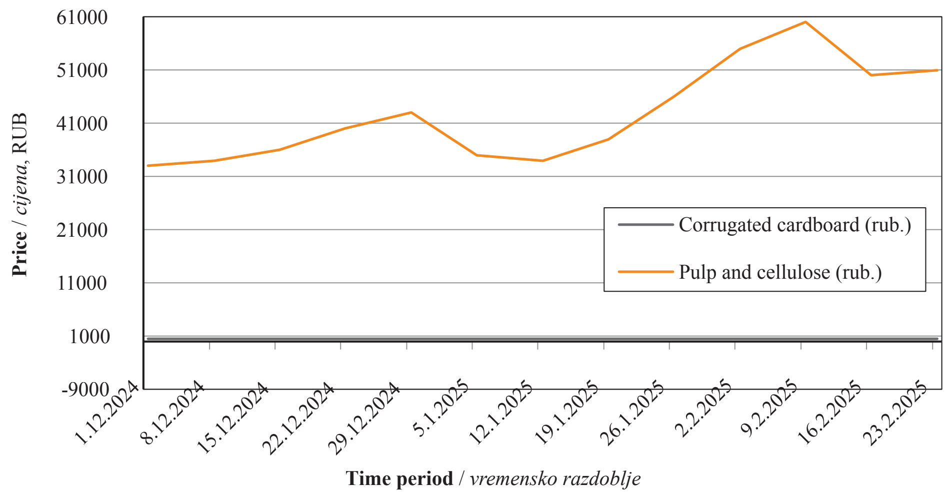

Figure 13 Price dynamics of products with high and low volatility, RUB/ton (corrugated cardboard and pulp and cellulose)
Slika 13. Dinamika cijena proizvoda s visokom i niskom volatilnošću (valovitog kartona i celuloze), RUB/t

When projecting future price trends for forest products, particularly over extended periods, it is essential to consider all relevant factors. This emphasizes the complexity of long-term price forecasting in the forestry sector and highlights the need for a comprehensive approach that accounts for various influential elements.

6 CONCLUSIONS
6. ZAKLJUČAK

Thus, empirical analysis confirmed the high volatility of prices for timber products at the second stage. The volatility observed in current price determination stems from a multifaceted dynamic structure. This structure incorporates not only long-term trends but also recurring seasonal and cyclical patterns, further complicated by unpredictable, random variations. The timber market inherent price fluctuations pose a significant threat to the financial well-being of timber producers. This instability is further compounded by the interconnectedness and predictability of timber prices within Russia, as well as on the global market. Essentially, the text highlights the vulnerability of timber producers to both domestic and international price swings, emphasizing the need for risk management strategies in this volatile industry. The coherence and consistency of the price dynamics of internal and external prices for forest products is confirmed by a high degree of correlation. The future pricing of forest products is projected to remain volatile in both domestic and international markets due to a confluence of intricate factors. The instability inherent in the global and Russian forest products market creates serious economic problems for countries that are heavily dependent on the forest sector. In addition, there are discrepancies between domestic prices for Russian timber products and world prices, primarily due to differences in trade policies of different countries. In this policy, national interests are often put at the forefront by imposing trade barriers such as tariffs, duties and subsidies. Reducing these trade barriers would lead to greater alignment of domestic and international prices. The pricing of timber products in the global market is greatly influenced by the leading exporting and importing countries, which have significant power due to competitive strategies. Large exporters with production advantages can exert downward pressure on prices during periods of weak demand, forcing other participants to adjust their actions accordingly. Ultimately, the balance between supply and demand remains the most important factor determining timber pricing. Therefore, a comprehensive analysis of price levels, trends and relationships between domestic, export and international prices for forest products is crucial for both short-term forecasting and long-term planning in the forest sector.

The practical use of the results of this study opens up prospects for the economy of the forest sector. First of all, the applied analytical framework makes it possible to improve the understanding of price dynamics and enhance the quality of planning and decision-making in the forestry sector, which leads to optimization of production and logistics processes, reduction of risks associated with price fluctuations, and increased profitability of forestry enterprises. Improved forecasting of market conditions allows enterprises to adapt more effectively to changes in demand, reduce costs and increase competitiveness in domestic and foreign markets. In addition, the developed models can be used for the purposes of state regulation of the forestry complex, in particular, to develop measures to support enterprises, stimulate investment and ensure a balanced pricing policy, which will create favorable conditions for the development of the complex.

Based on the results of the project, the scientific team plans to conduct further testing in the activities of business entities of the forest complex, which will allow for the refinement and improvement of the new result. Accurate and timely price forecasting allows companies to make informed decisions in the areas of production planning, raw material procurement, pricing and inventory management. The integration of the developed model into the existing information systems of the enterprise makes it possible to automate the forecasting process and promptly obtain analytical data for making managerial decisions, which reduces dependence on expert assessments, increases the accuracy of forecasts and reduces the risks associated with an incorrect assessment of the market situation. In addition to operational management, the results of the project can be used for long-term strategic planning. Forecasting prices for forest products for several years ahead allows enterprises to assess the profitability of investment projects, develop production development plans and optimize the structure.

Acknowledgements – Zahvala

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5 REFERENCES
5. LITERATURA

1. Azarnova, T. V.; Asnina, N. G.; Kolosov, A. I.; Lependin, A. V., 2025: Modifying methodological machine learning approaches for predicting the consumer price index. Urgant, 13 (2): 15-23.
2. Burdakova, G. I.; Byankin, A. S.; Meshkov, A. S., 2023: Research of regional demand for timber industry products under conditions of external sanctions pressures.

π-Economy, 16 (1): 98-113. https://doi.org/10.18721/JE.16107
3. ***Consumer Price Index Manual, 2020: Concepts and Methods. Washington, DC, International Monetary Fund, p. 506., ISBN 978-1-4843-5484-1.
4. Dewhurst, J. F.; Coppock, J. O.; Yates, P. L., 1961: Europe's needs and resources. New York, The Twentieth Century Fund.
5. Dzerjinsky, R. I.; Pronina, E. N.; Dzerzhinskaya, M. R., 2020: Structural analysis of world gold price dynamics. Advances in Intelligent Systems and Computing: 352-365. https://doi.org/10.1007/978-3-030-51971-1_29
6. Jankowska, A.; Zbieć, M.; Kozakiewicz, P.; Koczan, G.; Oleńska, S.; Beer, P., 2018: The wettability and surface free energy of sawn, sliced and sanded European oak wood. Maderas: Ciencia y Tecnología, 20 (3): 443-454. https://doi.org/10.1007/s13213-011-0384-5
7. Kärki, T., 2001: Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz als Roh- und Werkstoff, 59: 79-84. https://doi.org/10.1007/s001070050479
8. Landsberg, G. G.; Fishman, L. L.; Fisher, J. L., 1965: U.S. resources in the future, vol. 1-2. Washington, DC.
9. McConnell, T. E.; Da Silva, B. K.; Sun, C.; Tanger, S. M., 2021: Forest to mill timber price trends and volatility for Mississippi timber products. Forest Products Journal, 71 (2): 177-187. https://doi.org/10.13073/fpj-d-21-00010
10. Meadows, D. H.; Meadows, D. L.; Randers, J.; Behrens, S., 1991: The limits to growth: The 20-year update. White River Junction, Chelsea Green Publishing.
11. Medvedev, S.; Mokhirev, A.; Rjabova, T., 2022: The added value of products as a key factor in the development of the forest industry. IOP Conference Series: Earth and Environmental Science, 988 (3): 032048. https://doi.org/10.1088/1755-1315/988/3/032048
12. Pyzhyev, A. I., 2024: Elasticity of demand for forest products in the macroregions of Russia: Modeling for forecasting industry development. Terra Economicus, 22 (1): 104-116. https://doi.org/10.18522/2073-6606-2024-22-1-104-116
13. Rjabova, T. G.; Mokhirev, A. P.; Medvedev, S. O.; Lyshko, A. S., 2020: Dynamics and factors of timber value in the forest industry of Russia. Fundamental Research, 4: 94-98. https://doi.org/10.17513/fr.42730
14. Saprykin, K. A., 2023: Price forecasting of oil brands: Comparison of machine learning and statistical approaches. Innovations and Investments, 11: 322-325.
15. Samatova, A. P.; Filimonova, I. V., 2025: Methodological basis for oil price forecasting. Interexpo Geo-Siberia, 2 (2): 54-59. https://doi.org/10.33764/2618-981X-2025-2-2-54-59
16. Shiller, R. J., 2020: Popular economic narratives advancing the longest U.S. expansion 2009 – 2019. Journal of Policy Modeling, 42 (4): 791-798.
17. Starikov, E. N.; Evseeva, M. V.; Naumov, I. V., 2022: Industrial growth and specialisation: The impact of government support tools. Journal of New Economy, 23 (3): 86-108. https://doi.org/10.29141/2658-5081-2022-23-3-5
18. Veretekhina, S. V., 2025: Forecasting average export prices using mathematical analysis. Marketing in Russia and Abroad, 1: 39-43.
19. Yezhkin, V. D.; Radionova, M. V., 2024: Machine learning methods for Bitcoin price forecasting. Actual Issues of Economics, 7: 217-226.
20. ***Consumer Price Index Manual, 2020: Concepts and Methods. Washington, DC, International Monetary Fund, p. 506. ISBN 978-1-4843-5484-1.
21. ***Federal State Statistics Service, 2024: Price statistics [online]. Available at: https://rosstat.gov.ru/statistics/price (Accessed: Nov. 2024).
22. ***Finnish birch plywood, 2018: Metsä Wood [online]. Available at: https://www.metsawood.com (Accessed: Jan. 25, 2026).
23. ***Forest Products Annual Market Review 2023 – 2024: [online]. FAO. Available at: https://openknowledge.fao.org/items/0966581f-f8ad-42bd-a69c-8ffcd9ee325d (Accessed: Jan. 25, 2026).
24. ***Forest Products Annual Market Review 2023 – 2024: [online]. UNECE. Available at: https://unece.org/forests/publications/forest-products-annual-market-review-2023-2024 (Accessed: Jan. 25, 2026).
25. ***Global Forest Products Prices & Market Analysis [online]. Fastmarkets. Available at: https://www.fastmarkets.com/forest-products/ (Accessed: Jan. 25, 2026).
26. ***The global tropical timber market is experiencing a new dawn: the stabilization of supplies in Africa signals the recovery of trade [online]. SHD Wood. Available at: https://www.shdtimber.com/ru/global-tropical-timber-market-sees-new-dawn-african-supply-stabilizes-signaling-trade-recovery.html (Accessed: Jan. 25, 2026).

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National Wood Product Material Flow Analysis: PRODCOM Data on Wood Products Supporting Improved Macro-Level Sectoral Assessments in Slovenia

Nacionalna analiza toka materijala za drvne proizvode: podatci PRODCOM-a o drvnim proizvodima koji podržavaju poboljšane sektorske procjene na makrorazini u Sloveniji

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ABSTRACT • *The study investigates the production of harvested wood products in Slovenia by applying the volumetric material flow analysis (MFA) from processed roundwood to secondary product. The study provides the methodological approach for data collection and consistency assessment to support nation-wide wood MFA by complementing FAOSTAT data with selected data categories of PRODCOM data. Consistency between the two datasets was found to be satisfactory, suggesting that the two datasets can together support wood product MFA. However, for PRODCOM to be applied without extensive prior analysis, further methodological improvements of the databases would be required. MFA for Slovenia for the period 1994 – 2021 was carried out to understand pathways and magnitudes of wood flows in Slovenia. The MFA demonstrated that for many secondary products produced in Slovenia, there is clearly a lack of domestic resources (veneer, particle boards, and sulphite chemical and mechanical wood pulp). On the contrary, despite the abundance of the primary resource, few secondary products are made using non-coniferous wood. This research highlights the importance of detailed and accurate wood product data to support the MFA in identifying missed opportunities to create value and/or reduce environmental footprint of the national wood products industry.*

KEYWORDS: *harvested wood products; material flow analysis; PRODCOM database; FAOSTAT Forestry Production and Trade; secondary wood products*

SAŽETAK • *U radu se istražuje proizvodnja artikala od drva posječenoga u Sloveniji, i to volumetrijskom analizom toka materijala (MFA) od prerađene oblovine do sekundarnog proizvoda. Studija donosi metodološki pristup*

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prikupljanju podataka i procjeni konzistentnosti kako bi se podržala nacionalna analiza toka materijala drva dopunjavanjem podataka FAOSTAT-a odabranim kategorijama podataka PRODCOM-a. Utvrđeno je da je konzistentnost između dva skupa podataka zadovoljavajuća, što sugerira da dva skupa podataka zajedno mogu podržati MFA drvnih proizvoda. Međutim, da bi se PRODCOM primijenio bez opsežne prethodne analize, potrebna su daljnja metodološka poboljšanja baza podataka. Volumetrijska analiza toka materijala za Sloveniju za razdoblje 1994. – 2021. provedena je kako bi se razumjeli putovi i veličine tokova drva u Sloveniji. Analiza je pokazala da za mnoge sekundarne proizvode proizvedene u Sloveniji očito nedostaje domaćih resursa (furnira, iverice te sulfitne kemijske i mehaničke drvne pulpe). Usto, unatoč obilju primarnih resursa, malo se sekundarnih proizvoda proizvodi od listača. U istraživanju se naglašava važnost detaljnih i točnih podataka o drvnim proizvodima kako bi se podržala MFA u prepoznavanju propuštenih prilika za stvaranje vrijednosti i/ili smanjenje utjecaja nacionalne industrije drvnih proizvoda na okoliš.

KLJUČNE RIJEČI: *proizvodi od posječenog drva; analiza toka materijala; baza podataka PRODCOM-a; šumarska proizvodnja i trgovina FAOSTAT-a; sekundarni drvni proizvodi*

1 INTRODUCTION
1. UVOD

Environmental aspects of wood use are becoming increasingly important due to the global societal climate and biodiversity crises (Ripple *et al*., 2020). In Slovenia, forests are sustainably managed using close-to-nature management techniques which avoids clear cuts. On average, around 50 % of the yearly stock increase is harvested (Pisek *et al*., 2023). Slovenia managed to strengthen the role of forestry, wood processing and the paper industry in the circular bioeconomy in recent years (Ščap and Triplat, 2023). However, there are still unexploited opportunities to substitute carbon intensive materials with wood as well as improve the environmental footprint of industry and construction in line with the Strategy of Development of Slovenia (Šooš *et al*., 2017), which aims to increase the GDP per CO_2 emission eq. by at least 10 % by 2030. Wood-based carbon storage can offset a significant share of CO_2 emissions in the mid-term (Steel, 2021) if the industry favours the production of long-lasting products, such as construction wood as opposed to using wood for short-lived products like wood fuel or paper products.

Besides the favourable environmental profile of wood use, wood products manufacturing is also an important sector of economic activity. The added value of forestry, primary wood processing, the furniture industry and the paper sector, has accounted for an average of 2 % of gross domestic product in the period 2021–2023 (SORS, 2024). The bottleneck of Slovenian wood-based value chain is the poorly integrated and technologically outdated wood-processing industry (Arnič *et al*., 2024). Forest-based industry experienced a significant down-sizing in the last 30 years after Slovenia's independence, Slovenia's entrance to the European Union, and change of the currency from tolar to euro. According to the Slovenian Forestry Institute, the share of exported forest wood assortments for industrial processing has been gradually decreasing since 2016. However, it was still estimated to account for 39 % of forest wood assortment production in 2023 (Ščap, 2024). According to available sources, Slovenia exports more wood-based products with a low added value (e.g. roundwood) and less products with high added-value (e.g. furniture) (Sodja, 2018).

Due to the great potential of wood manufacturing in the societal transition towards a low carbon, green, circular society, an understanding of the material flows of wood from harvest to final product is important.

Nation-wide assessments of the environmental potential of wood use in Slovenia have been undertaken a few times in the recent past. Piškur and Krajnc (2009) outlined the roundwood flow from harvest to primary wood product, including waste streams. Schau *et al*. (2023), Kutnar *et al*. (2020), and Tavzes *et al*. (2024) concluded that the lack of data currently represents a limitation for the optimisation of the Slovenian wood-processing chains in environmental, economic, and social terms. While there are several studies available on primary wood products (Ščap, 2020; Ščap, 2024), few analyses of national production of secondary wood products have been carried out.

Internationally, there are studies of life cycle analyses that compare single wood products to non-wooden alternatives abound (D'Amato *et al*., 2020), but for upscaling the results of micro level studies to macro scale circularity studies of the sector, more comprehensive data on manufactured products and wood flows is needed. According to existing studies, the coupling of the established methodologies of life cycle and material flow analysis (Barkhausen *et al*., 2023; Merli *et al*., 2017) holds promise for more accurate macro-level assessments. For Slovenia, currently available data in the FAO Forestry Production and Trade database (FAO, 2024) includes sawmill products, cellulose/boards and secondary paper products. This dataset does not include secondary wood products, specifically wooden consumer goods and secondary products used in construction. However, these products represent the largest potential of wood as a resource to improve societal environmental performance, as they are characterised not only by a lower environmental footprint than the alternatives used today but also by high substitution potential (Hurmekoski *et al*., 2021). Comprehensive material flow analysis of the wood value chain would enable the advancement of the methodology of macro level (regional or national scale) environmental performance of wooden products (Wang and Haller, 2024), which is currently still challenging to quantify due to the lack of comprehensive data on final products (Elia *et al*., 2017; Hurmekoski *et al*., 2021).

The present study aims to merge the FAOSTAT (FAO, 2024) and PRODCOM (SORS, 2009) wood product data for the period of 1994 – 2021, evaluate their usability and analyse their data. The first objective was to examine the methodological approach to data collection for nation-wide wood MFA, including an evaluation of accuracy of the identified data sources. The second objective was to undertake an analysis of historical wood MFA for Slovenia to understand pathways and magnitudes of wood flows. The research question of the study was whether PRODCOM data can complement FAOSTAT data for secondary wood product categories and whether the resulting joined dataset can support a national MFA.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The paper followed the established methodological guidelines on wood material flow analysis (Marques *et al*., 2020) as well as the community guidelines for the presentation of results (Pauliuk, 2021). After undertaking the steps for obtaining wood flows and analysing their accuracy, a network of input and output flows of the system defined is presented in Figure 1.

2.1 System boundaries
2.1. Granice sustava

Due to the fact that most products in FAOSTAT and PRODCOM datasets are reported in volumetric units, this was the selected approach for the material flow analysis. Figure 1 shows volumetric flows from harvested wood until the secondary wood products, limiting the system boundaries to the domestically harvested wood. However, it is important to note that intermediate producers could have imported the resource to produce their products and that the wood harvested in Slovenia could have been directly exported, both of which was not observed in this study. However, the producers have to report all manufactured quantities to PRODCOM, even if the products are later exported. The MFA therefore corresponds to quantities produced in Slovenian factories and not to quantities that enter the market or are consumed domestically.

In relation to residues and wastes, only a small part is reported in the framework of PRODCOM/FAOSTAT data, as most residues are used already internally by the manufacturers, either as a filler or as a source of heat/electricity. The known amounts of residues (agglomerates – pellets and briquettes, sawdust, chips and particles) were categorised as 'wood fuel products', which includes all wood products intended for the production of heat and/or electricity. It is still important to note that some of these quantities could have also re-entered the material flow elsewhere (for example board manufacturing), but in the present study we did not have the information to what extent and where this occurs.

There are other important factors to consider when observing volumetric flows. Moisture content is generally reduced from harvest to secondary product, going from 20 % of the total mass to as low as 6 % of the total mass in boards or secondary products (FAO, ITTO and United Nations, 2020). The volume of harvested wood in Slovenia is recalculated to 20 % moisture even if it contains more in reality, to ensure comparability of data regardless of the time and weather conditions around the harvest (Geršak, 2021). Below 20 % moisture content, 1 % moisture causes a decrease of 0.25 in volume, meaning that going from a mass content moisture of 20 % to 6 % in the investigated MFA in certain products introduces an error of 3.5 % in the entire MFA. Considering the poor availability of moisture content data and relatively low effect on the volumetric flow, the moisture content was not observed in this study.

Another factor affecting volumetric flows are additives, which are mostly added in the production of paper products and boards. For cellulose products, a recalculation into solid wood required per metric ton of product was made, using conversion factors as provided by Slovenian Pulp and Paper Institute (Table 1). For boards, additives account for about 10 % of total mass. However, as they mostly fill empty spaces in the product (fibreboard, plywood), their effect was neglected in this study.

2.2 Materials
2.2. Materijali

FAOSTAT Forestry data is annually prepared by the Statistical Office of the Republic of Slovenia (SORS) in cooperation with the Slovenian Forestry Institute – SFI (Ščap *et al*., 2019; Ščap *et al*., 2020; Ščap *et al*., 2021) via an analysis of roundwood production structure obtained at the source, which is further broken down to end-uses. The SFI obtains this data annually, directly from stakeholders of the forest-wood chain (Ščap, 2022). PRODCOM, on the other hand, is managed by the SORS and includes the quantities of industrial products (in case of wood products volume,

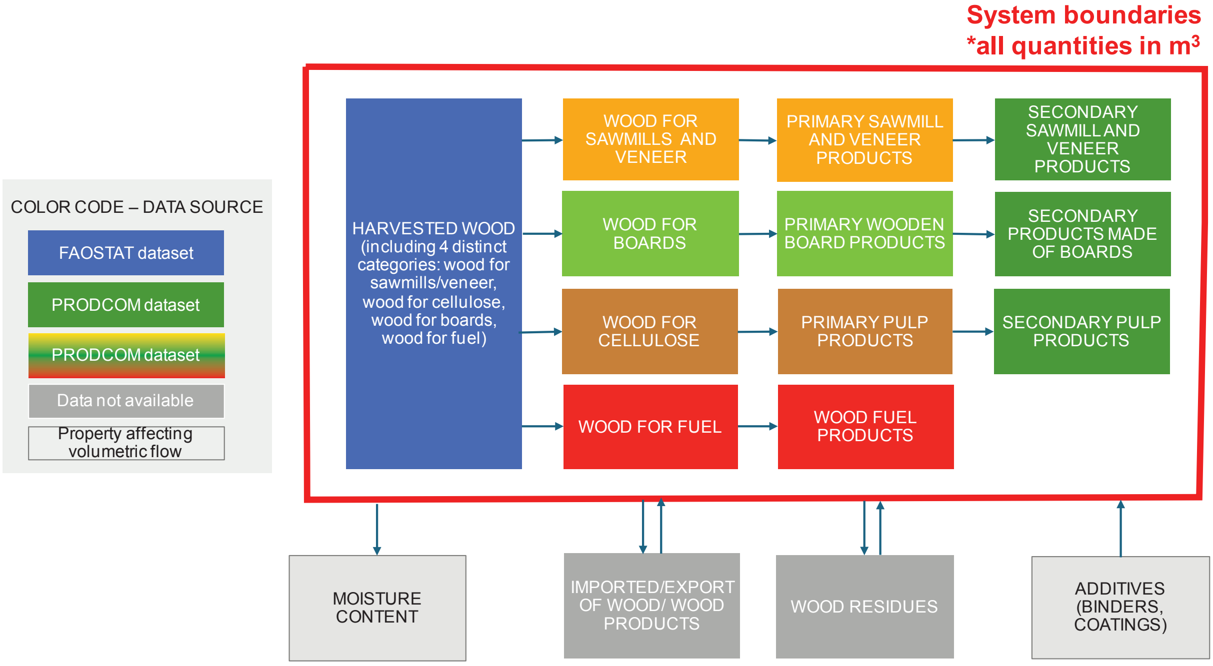

Figure 1 System boundaries of the study (red dotted line) and the dataset used (blue boxes: FAOSTAT, yellow/green/brown/red boxes: PRODCOM)
Slika 1. Granice sustava studije (crvena isprekidana linija) i uključeni skup podataka (plavi okviri: FAOSTAT, žuti/zeleni/smeđi/crveni okviri: PRODCOM)

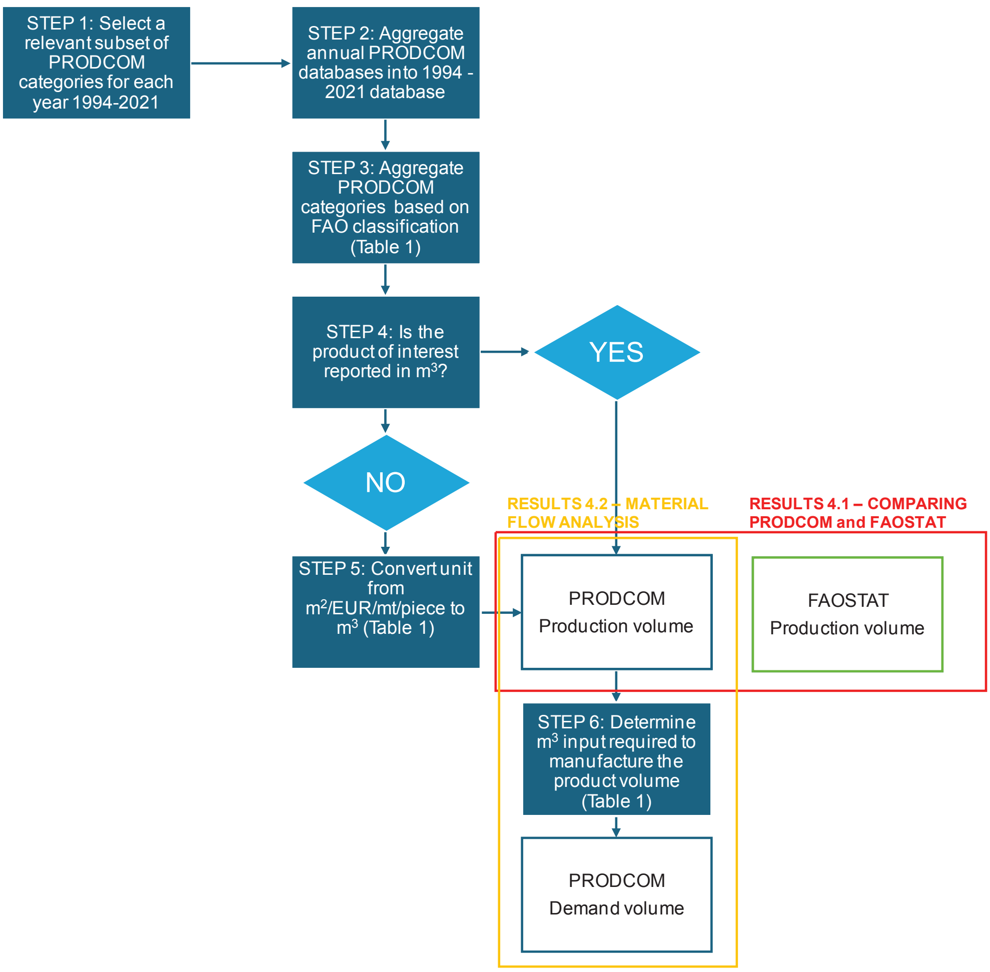

Figure 2 Flowchart illustrating the steps for restructuring PRODCOM databases into the studied FAO wood product categories
Slika 2. Dijagram toka koji ilustrira korake za restrukturiranje PRODCOM-ovih baza podataka u proučavane FAO kategorije drvnih proizvoda

mass, number of items, or the value of items), which have undergone a process of industrial transformation, annually reported by the companies according to EU Regulation (Regulation (EU) 2019/2152 of the European business statistics, 2019).

Data selection, cleaning, aggregation and unit conversion had to be carried out to ensure that the data was robust and comparable with FAOSTAT data. PRODCOM Classification underwent changes during the observed period 1994 – 2021, which means that the categories of registered products were not identical in every year and reconciliation between years was needed.

During data processing, PRODCOM categories were selected (Step 1, Figure 2) and aggregated (Step 2, Figure 2) applying SPSS to categories of wood products, which existed throughout the observed period and also appeared in the FAO database (Step 3, Figure 2). Then, all categories of interest were converted into the unit of volume of wood (Step 4 and 5, Figure 2), since in PRODCOM one finds not just volumetric units, but also mass (categories of wood chips, particles, flour, consumer products), number of items (consumer products) and value (wooden houses). All products, reported in a unit other than volumetric, were recalculated to m3 product according to forest product conversion factors (FAO, ITTO and United Nations, 2020) and are summarised in Table 1. From the resulting production volume of a specific product, the wood demand for the manufacturing was calculated (Step 6, Figure 2) based on the input – output ratios found in literature (Table 1).

Table 1 List of categorised wood products included in the study (obtained from both FAOSTAT and PRODCOM databases) with corresponding conversion units
Tablica 1. Popis kategoriziranih drvnih proizvoda uključenih u studiju (dobivenih iz baza podataka FAOSTAT-a i PRODCOM-a) s odgovarajućim konverzijskim jedinicama

Category *Kategorija*	**Wood product** *Drvni proizvod*	**PRODCOM Reporting unit** *PRODCOM-ova izvještajna jedinica*	**Unit conversion** / *Pretvorba jedinica*	
			Factor for converting PRODCOM unit into m^3 *Faktor za pretvorbu PRODCOM-ove jedinice u* m^3	**Input required for 1 m^3 product (roundwood in case of primary products and sawnwood/particle boards in case of secondary products)** *Ulaz potreban za 1* m^3 *proizvoda (oblovine za primarne proizvode i piljene građe/iverice za sekundarne proizvode)*
Primary sawmill and veneer products *primarni pilanski i furnirski proizvodi*	Coniferous sawnwood *piljena građa četinjača*	m^3	Already in m^3 *već izraženo u* m^3	1.8 m^3 roundwood / *oblovine*
	Non-coniferous sawnwood *piljena građa listača*	m^3	Already in m^3 *već izraženo u* m^3	1.7 m^3 roundwood / *oblovine*
	Boards with rounded edges or ends *piljenice zaobljenih rubova ili krajeva*	m^3	Already in m^3 *već izraženo u* m^3	1.8 m^3 roundwood / *oblovine*
	Veneer *furnir*	m^3	Already in m^3 *već izraženo u* m^3	1.8 m^3 roundwood / *oblovine*
Primary pulp products *primarni proizvodi od pulpe*	Plywood *uslojene furnirske ploče*	m^3	Already in m^3 *već izraženo u* m^3	2.3 m^3 roundwood / *oblovine*
	Particle boards *ploče iverice*	m^3	Already in m^3 *već izraženo u* m^3	1.3 m^3 roundwood / *oblovine*
	Fibreboard *ploče vlaknatice*	m^3	already in m^3 *već izraženo u* m^3	1.7 m^3 roundwood / *oblovine*
	Mechanical wood pulp *mehanička drvna pulpa*	t	2.6 m^3 wood per ton *2,6* m^3 *drva po toni*	1.04 m^3 roundwood / *oblovine*
	Sulphite chemical wood pulp / *sulfitna kemijska drvna pulpa*	t	4 m^3 wood per ton *4* m^3 *drva po toni*	1.04 m^3 roundwood / *oblovine*
Wood fuel products *proizvodi za ogrjev*	Chips and particles *iverje i čestice*	kg	150 kg/m^3	1 m^3 roundwood (waste product) *1* m^3 *oblovine (drvnih ostataka)*
	Pellets and agglomerates *peleti i aglomerati*	kg	652 kg/m^3	1 m^3 roundwood (waste product) *1* m^3 *oblovine (drvnih ostataka)*
	Wood waste agglomerates *aglomerati drvnog otpada*	kg	652 kg/m^3	1 m^3 roundwood (waste product) *1* m^3 *oblovine (drvnih ostataka)*

Table 1 Nastavak
Tablica 1. Continued

Category *Kategorija*	**Wood product** *Drvni proizvod*	**PRODCOM Reporting unit** *PRODCOM-ova izvještajna jedinica*	**Unit conversion** / *Pretvorba jedinica*	
			Factor for converting PRODCOM unit into m³ *Faktor za pretvorbu PRODCOM-ove jedinice u* m³	**Input required for 1 m³ product (roundwood in case of primary products and sawnwood/particle boards in case of secondary products)** *Ulaz potreban za 1* m³ *proizvoda (oblovine za primarne proizvode i piljene građe/iverice za sekundarne proizvode)*
Secondary sawmill and veneer products *sekundarni pilanski i furnirski proizvodi*	Packing boxes *kutije za pakiranje*	kg	470 kg/m³	1.1 m³ sawnwood / *piljenog drva*
	Pellets / *peleti*	no. of items *broj komada*	0.04012 m³/per pellet	1.1 m³ sawnwood / *piljenog drva*
	Windows / *prozori*	no. of items *broj komada*	18.27 kg/window, density 470 kg/m³ *18,27* kg*/prozor, gustoća 470* kg/m³	2.04 m³ sawnwood for glulam (calculated from yield 48.8 %), 2.08 m³ glulam for window glulam (calculated from yield 48 %) *2,04* m³ *piljenog drva za lijepljeno lamelirano drvo (izračunano prema iskorištenju 48,8 %), 2,08* m³ *lijepljenoga lameliranog drva za prozore (izračunano prema iskorištenju 48 %)*
	Doors / *vrata*	no. of items *broj komada*	29.7 kg/door, density 728.9 kg/m³ *29,7* kg*/vrata, gustoća 728,9* kg/m³	1.2 m³ sawnwood / *piljenog drva*
	Concrete shuttering *betonske oplate*	kg	450 kg/m³	1.1 m³ sawnwood / *piljenog drva*
	Flooring panels *podne ploče*	cm	1.5 cm/m²	1.1 m³ sawnwood / *piljenog drva*
	Office furniture *uredski namještaj*	no. of items *broj komada*	item weight 39 kg, material density 728.9 kg/m³ / *masa jedinice 39* kg*, gustoća materijala 728,9* kg/m³	1.2 m³ particle board / *ploča iverica*
	Salesroom furniture *namještaj za prodajni prostor*	no. of items *broj komada*	item weight 21.2 kg, material density 728.9 kg/m³ / *masa jedinice 21,2* kg*, gustoća materijala 728,9* kg/m³	1.2 m³ particle board / *ploča iverica*
	Kitchen furniture *kuhinjski namještaj*	no. of items *broj komada*	item weight 33.2 kg, material density 728.9 kg/m³ / *masa jedinice 33,2* kg*, gustoća materijala 72,9* kg/m³	1.2 m³ particle board / *ploča iverica*
	Bed slats *letvice za krevet*	no. of items *broj komada*	item weight 9.6 kg, material density 470 kg/m³ / *masa jedinice 9,6* kg*, gustoća materijala 470* kg/m³	1.2 m³ sawnwood / *piljenog drva*
	Bedroom furniture *namještaj za spavaću sobu*	no. of items *broj komada*	item weight 40.1 kg, material density 470 kg/m³ / *masa jedinice 40,1* kg*, gustoća materijala 470* kg/m³	1.2 m³ sawnwood / *piljenog drva*
	Dining and living room furniture *namještaj za blagovaonicu i dnevni boravak*	no. of items *broj komada*	item weight 38.4 kg, material density 470 kg/m³ / *masa jedinice 38,4* kg*, gustoća materijala 470* kg/m³	1.2 m³ sawnwood / *piljenog drva*
	Other wooden furniture *ostali drveni namještaj*	no. of items *broj komada*	item weight 30 kg, material density 728.9 kg/m³ / *masa jedinice 30* kg*, gustoća materijala 728,9* kg/m³	1.2 m³ particle board / *ploča iverica*

Table 1 Nastavak
Tablica 1. Continued

Category *Kategorija*	**Wood product** *Drvni proizvod*	**PRODCOM Reporting unit** *PRODCOM-ova izvještajna jedinica*	**Unit conversion** / *Pretvorba jedinica*	
			Factor for converting PRODCOM unit into m³ *Faktor za pretvorbu PRODCOM-ove jedinice u m³*	**Input required for 1 m³ product (roundwood in case of primary products and sawnwood/particle boards in case of secondary products)** *Ulaz potreban za 1 m³ proizvoda (oblovine za primarne proizvode i piljene građe/iverice za sekundarne proizvode)*
Secondary paper and pulp products *sekundarni proizvodi od papira i pulpe*	Graphic papers *grafički papiri*	t	3.7 m³ of roundwood per ton product *3,7 m³ oblovine za tonu proizvoda*	1.01 m³ chemical/mechanical pulp *1,01 m³ kemijske/mehaničke pulpe*
	Sanitary and household papers *sanitarni papir i papir za kućanstvo*	t	4.9 m³ of roundwood per ton product *4,9 m³ oblovine za tonu proizvoda*	1.01 m³ chemical/mechanical pulp *1,01 m³ kemijske/mehaničke pulpe*
	Packaging materials *materijali za pakiranje*	t	4 m³ of roundwood per ton product *4 m³ oblovine za tonu proizvoda*	0.01 m³ chemical/mechanical pulp *1,01 m³ kemijske/mehaničke pulpe*

*Conversion factors come from FAO, ITTO and UN (2020) report "Forest product conversion factors" and are provided by experts from InnoRenew CoE, Slovenian forestry Institute and Pulp and Paper Institute of Slovenia.
**Faktori konverzije potječu iz izvješća FAO-a, ITTO-a i UN-a (2020.) „Faktori konverzije šumskih proizvoda", kao i od stručnjaka iz InnoRenew CoE-a, Slovenskoga šumarskog instituta i Slovenskog instituta za celulozu i papir.*

2.3 Methods
2.3. Metode

2.3.1 Accuracy of PRODCOM wood product data in relation to FAOSTAT data
2.3.1. Točnost PRODCOM-ovih podataka o drvnim proizvodima s obzirom na podatke FAOSTAT-a

PRODCOM data of wood products were analysed observing the accuracy of the data in relation to FAOSTAT. While undertaking the analysis, historical trends were examined to provide additional insights into the discrepancies where they appear.

The accuracy of PRODCOM data in relation to FAOSTAT data is evaluated by calculating relative percentage difference between wood products volumes of both datasets. The relative percentage difference (RPD) between two product values is calculated by determining the relative difference between both quantities across different measurements or samples and dividing it with a mean value of the quantities (Tornqvist *et al.*, 1985) as described in Eq. 1, while Eq. 2 specifies average relative percentage difference, RPD_A. Based on the visual characteristics of the data, the following cut-off values were used to visualise the result more easily: 20 % RPD as satisfactory, up to 30 % as acceptable, and over 30 % indicates an issue in PRODCOM data accuracy. Low data accuracy means that more research is needed to explain the high RPD, and a further data validation study should be done prior to using PRODCOM data for the MFA.

$$RPD = \frac{|FAOSTAT - PRODCOM|}{\left(\frac{FAOSTAT + PRODCOM}{2}\right)} \cdot 100 \quad (1)$$

For an overall RPD, an average of annual RPD values was calculated for each category of wood products (Eq. 2).

$$RPD_A = \frac{|RPD_{1994}| + |RPD_{1995}| + \ldots + |RPD_{2021}|}{No.RPD} \quad (2)$$

2.3.2 Material flow model based on PRODCOM and FAOSTAT data
2.3.2. Model toka materijala utemeljen na podatcima PRODCOM-a i FAOSTAT-a

Material flows of the volumes (m³) of wood from roundwood produced to secondary products in Slovenia for the years 1994 and 2021 are demonstrated and analysed with the help of Sankey diagrams. The arrows in diagrams demonstrate the transformations of wood volume from one state to another, whereby the width is proportional to the flow rate.

Sankey diagrams also contain volumes of losses at the production stage, which are calculated based on the difference between the roundwood going into sawmills/pulpmills/fuelwood production and the quantity of products coming out of this process. This difference was considered as production waste.

In cases where primary wood products do not satisfy the demand to produce a given secondary product, the Sankey diagram includes a depiction of 'imported resource'. This is not a representation of the total imported resource in a given year, but rather the minimum import required to produce the secondary products as specified in the PRODCOM database.

Categories of products, which were produced in quantities of less than 10.000 m³, were excluded from the chart. Additional limitation of the study is that it does not include real data on trade of wood products (import and export). The limitation was mitigated by defining the system boundaries to be domestically manufactured products. The method assumed that the available quantity of (domestically sourced) input material is converted in the manufacturing process, although we are aware that in reality some of the resource is exported and some is imported, depending on the market dynamics.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Trends in quantities of wood products for different product groups 1994 – 2021
3.1. Kretanje količina drvnih proizvoda za različite skupine proizvoda od 1994. do 2021.

Historical trends in wood product manufacturing are a result of numerous factors, such as natural processes in the forests (e.g. bark beetle infestations, severe weather events, fires) and business environment (government measures, trade dynamics, closures/openings of production lines and other changes in the value chain). Small deviations between PRODCOM and FAOSTAT data are expected, as the sources are different, but large discrepancies might indicate reduced accuracy of PRODCOM data. Therefore, it is important to know in which categories of products PRODCOM data shows good accuracy, as it means that it can effectively complement other datasets in wood MFA.

3.1.1 Manufactured primary sawmill and veneer products
3.1.1. Proizvedeni primarni pilanski i furnirski proizvodi

The data on manufactured sawmill and veneer products in Slovenia in the period 1994 – 2021 is presented in Figure 3. PRODCOM data shows a marked increase of sawmill products from the 90s (approximately 600,000 m^3) to the present day (1,200,000 m^3). Coniferous and non-coniferous sawn wood production was constant until 2007, after which a reduction was observed until 2013, followed by a 3-to-4-fold growth in the last 10 years (Figure 3). The amount of coniferous sawnwood produced in 2021 was much higher compared to 1994 (ca. 1,002,000 m^3 vs 258,000 m^3). The amount of non-coniferous sawnwood steadily dropped from 160,000 m^3 to 53,000 m^3 in 2010 and then gradually increased again to 179,000 m^3 in 2021. Production of non-coniferous products stagnated after 2013. Boards with rounded edges were no longer existent in the PRODCOM classification after 2016. This might explain a part of the increase in the coniferous sawn wood. Production of veneer was already low in 1994 (23,000 m^3), but ceased by 2021, due to the closure of the production lines.

Most product quantities are within 20 % relative difference between both sources (Figure 3), some within 30 %, and the only years that surpass this are 2010 – 2013 (Table 2), with an average of absolute RPD_A of 21 %, so excluding RPD > 30 %, the RPD_A is 13 %.

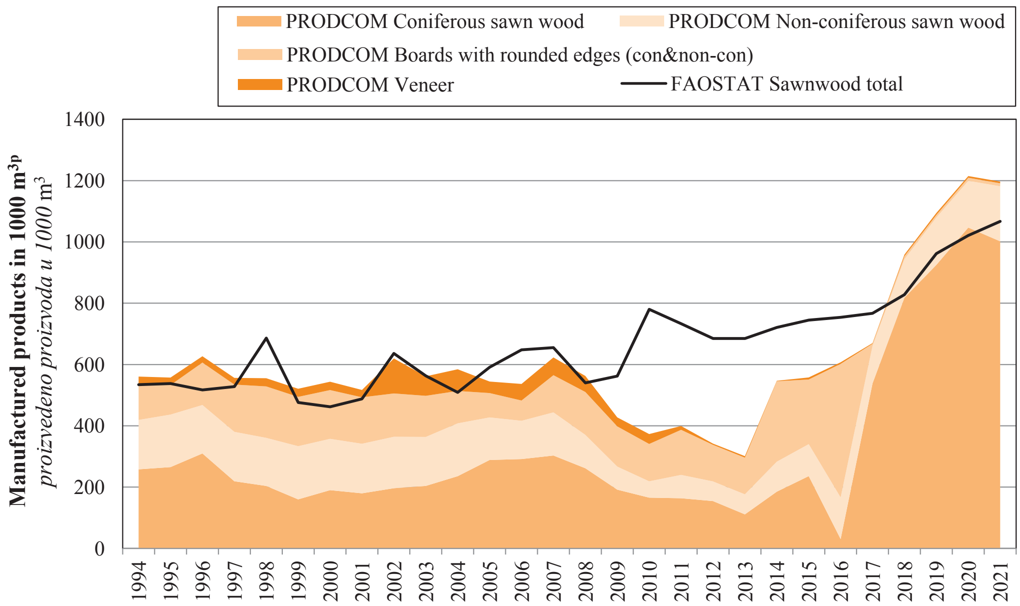

Figure 3 Manufactured primary sawmills and veneer products in 1000 m^3 according to FAOSTAT and PRODCOM
Slika 3. Količina proizvedenih primarnih pilanskih i furnirskih proizvoda u 1000 m^3 prema podatcima FAOSTAT-a i PRODCOM-a

Table 2 Relative percentage differences in specific years and product categories (gray marks RPD below 20 %, light orange marks RPD between 20 and 30 % and orange marks RPD above 30 %)
Tablica 2. Relativne postotne razlike u određenim godinama i kategorijama proizvoda (siva označava RPD niži od 20 %, svjetlo narančasta predočuje RPD između 20 i 30 %, a narančasta označava RPD viši od 30 %)

Year *Godina*	**RPD Manufactured primary sawmill and veneer products** *RPD proizvedenih primarnih pilanskih i furnirskih proizvoda*	**RPD Manufactured primary pulp products** *RPD proizvedenih primarnih proizvoda od pulpe*	**RPD Manufactured primary wooden board products** *RPD proizvedenih primarnih proizvoda od drvnih ploča*	**RPD Manufactured wood fuel products** *RPD proizvedenih proizvoda za ogrjev*
1994	5 %	18 %	5 %	71 %
1995	4 %	24 %	6 %	72 %
1996	19 %	23 %	36 %	39 %
1997	5 %	22 %	3 %	6 %
1998	21 %	22 %	16 %	9 %
1999	9 %	18 %	9 %	12 %
2000	16 %	18 %	7 %	24 %
2001	6 %	14 %	3 %	75 %
2002	-3 %	15 %	12 %	68 %
2003	0 %	7 %	14 %	39 %
2004	14 %	18 %	7 %	27 %
2005	-8 %	4 %	15 %	37 %
2006	-19 %	61 %	23 %	1 %
2007	-5 %	93 %	15 %	170 %
2008	4 %	163 %	20 %	150 %
2009	27 %	123 %	14 %	157 %
2010	71 %	4 %	27 %	172 %
2011	59 %	0 %	23 %	172 %
2012	67 %	2 %	23 %	166 %
2013	78 %	7 %	16 %	148 %
2014	27 %	1 %	12 %	152 %
2015	29 %	5 %	14 %	113 %
2016	22 %	2 %	16 %	112 %
2017	14 %	2 %	22 %	81 %
2018	15 %	0 %	27 %	12 %
2019	13 %	0 %	21 %	6 %
2020	17 %	0 %	28 %	15 %
2021	11 %	0 %	29 %	7 %
Average of absolute RPD$_A$ *Prosjek apsolutnog RPD$_A$*	**18 %**	**24 %**	**13 %**	**75 %**

3.1.2 Manufactured primary pulp products
3.1.2. Proizvedeni primarni proizvodi od pulpe

Total volume of wood pulp products according to PRODCOM data (sum of sulphite chemical wood pulp and mechanical wood pulp) grew from 1994 – 2000 and then dropped from around 180,000 tonnes (90 % dry matter) to less than 20,000 tonnes (90 % dry matter) and reached around 80,000 tonnes (90 % dry matter) in 2021 (Figure 4). After 2007, there has been no sulphite chemical wood pulp production in Slovenia due to bankruptcy of the producers, while mechanical wood pulp remained relatively stable at around 20,000 – 40,000 tonne per year until 2007, after which it steadily grew to over 80,000 tonnes (90 % dry matter). This could be due to the conversion of some of the sulphite chemical wood pulp production lines.

Important to note here is that the data presented in Figure 4 is in metric tonnes (90 % dry matter), while in the following sections the quantities are converted to m3 roundwood equivalent using the factors from Table 1.

The RPD values (Table 2) show that PRODCOM wood pulp production values are well comparable with FAOSTAT, except for the years 2006 – 2009, in which the RPD surpasses 30 %. The abrupt gap between data sources in the years 2006 – 2009 indicates poor accuracy of PRODCOM data in relation to FAOSTAT. This could be due to the time lag of information on quantities. Excluding these few years where the gap is large, there is good coherence in the

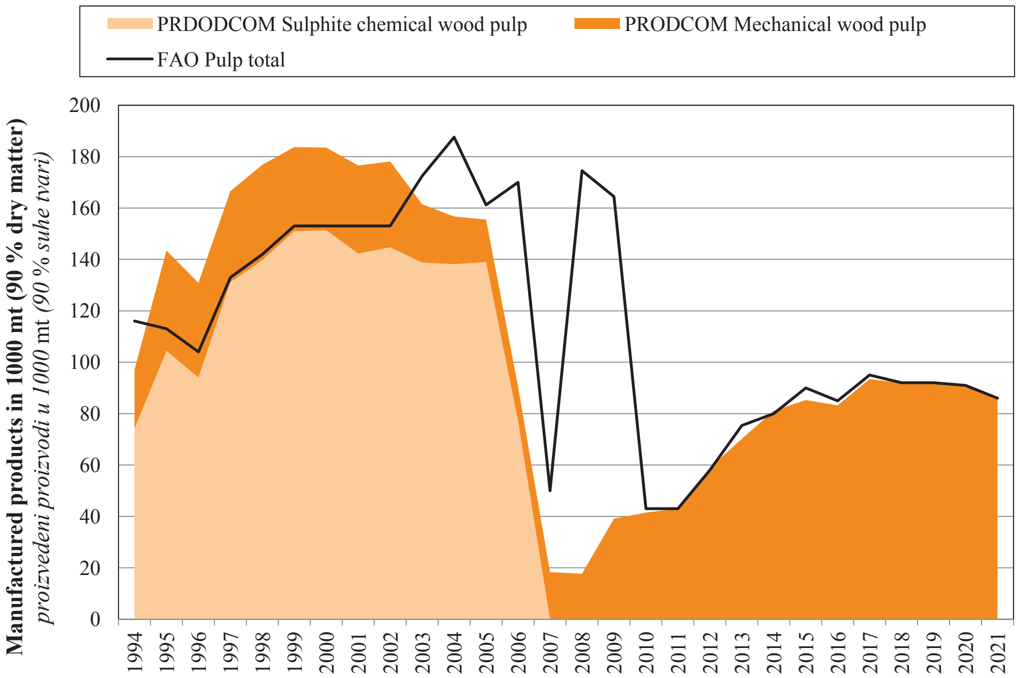

Figure 4 Manufactured primary pulp products in 1000 tonnes (90 % dry matter) according to FAOSTAT and PRODCOM data
Slika 4. Količina proizvedenih primarnih proizvoda od pulpe u 1000 tona (90 % suhe tvari) prema podatcima FAOSTAT-a i PRODCOM-a

manufacturing trend of wood pulp products between the two datasets, (RPD_A of 9 %).

3.1.3 Manufactured primary wooden board products
3.1.3. Proizvedeni primarni proizvodi od drvnih ploča

PRODCOM data indicates an increase in production of wooden boards from 1994 until 2002 (from 400,000 m^3 to 500,000 m^3), occurring due to an increase in particle board production (Figure 5). This is followed by a drop in veneer and particle board manufacturing until 2005, an increase up to 2008, followed by a sustained decline in manufacturing of veneer and particle boards until 2011 and 2014, respectively, when the production was stopped completely. Plywood production, on the other hand, first peaked in 2009, then decreased and grew again until 2021, similar to fibreboard. Observing the sum of the total volume of boards produced, a decline can be seen from 2007 to 2016 and stagnant levels of production until 2021, when it summed to around 300,000 m^3.

Most product quantities are within RPD of 20 % (Figure 5), some within 30 % and the only year when

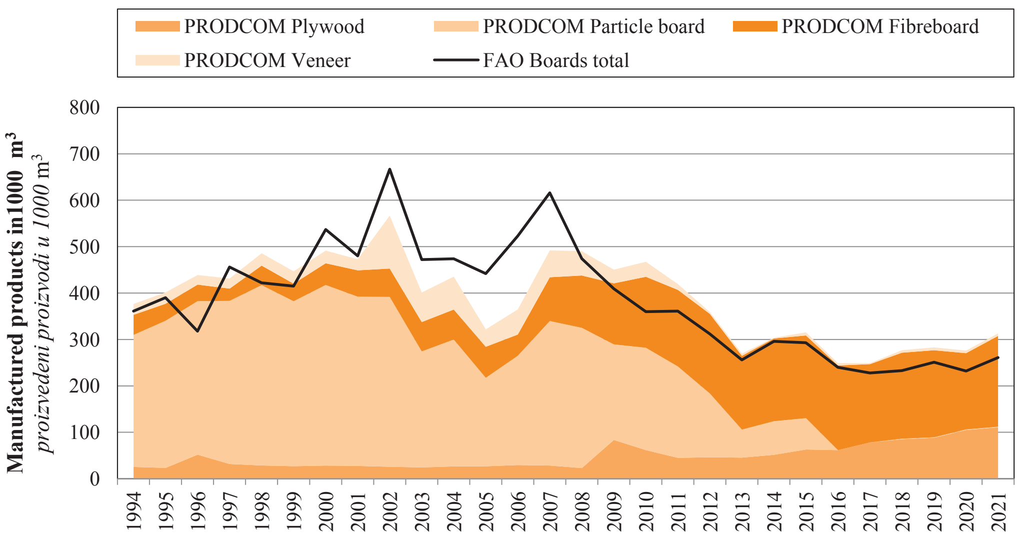

Figure 5 Manufactured primary wooden board products in 1000 m^3 according to FAOSTAT and PRODCOM data (stacked chart in orange represents PRODCOM data and black line chart FAOSTAT data)
Slika 5. Količina proizvedenih primarnih proizvoda od drvnih ploča u 1000 m^3 prema podatcima FAOSTAT-a i PRODCOM-a (složeni grafikon u narančastoj boji predočuje podatke PRODCOM-a, a crni linijski grafikon podatke FAOSTAT-a)

this was surpassed is 1996 (Table 2). The RPDA is 13 %. This indicates good accuracy of PRODCOM data when compared to FAOSTAT for this category of wood products.

3.1.4 Manufactured wood fuel products
3.1.4. Proizvedeni ogrjevni proizvodi

The data on manufactured wood fuel products together with wood residues in the period 1994 – 2021 is presented in Figure 6. The RPDs are the highest in this category (Table 2). The RPDA, which was below 35 % for sawnwood, wood pulp and wooden boards categories, was 75 % for wood fuel products. A particularly large gap between the data sources is noticeable between 2007 and 2017.

It is important to note that FAOSTAT data include an estimation of roundwood used for firewood in households, where people burn wood (often from their private forest) in furnaces to heat their homes. This is not included in the PRODCOM data, as no industrial transformation takes place. Furthermore, PRODCOM classification did not contain an adequate category for reporting of wood pellets until 2016, as the only three available categories were chips and particles, sawdust and wood waste agglomerates. After the introduction of wood pellets in 2015, PRODCOM data becomes more in line with the FAOSTAT data source. On the other hand, categories of sawdust and wood waste agglomerates only appear in PRODCOM until 2006. Therefore, it is assumed that the gap in manufactured wood fuel products between both data sources is due to classification categories for reporting in the PRODCOM database.

Better coherence between the two data sources is seen in the most recent years. After 2014, RPD becomes acceptable. After 2016, the trends demonstrate an increase in chips and particles production in both data sources – from 100,000 m^3 to almost 10-fold in 2021. An increase in production of pellets and agglomerates is recorded from 2017 – 2021 from 50,000 m^3 to almost 100,000 m^3. In total, since 2019, production of wood fuel has been decreasing slightly due to a small decrease in chips and particles production.

Due to high RPD values, PRODCOM data is less adequate to be used for material flow analysis of wood fuel products until the year 2018 because the classification did not include appropriate categories to account for wood pellets and to distinguish what amount of sawdust, chips and particles and wood waste agglomerates was destined to be used as wood fuel. PRODCOM records the type of industrial transformation but does not distinguish products obtained based on their end use as is needed when considering wood fuel products.

3.2 Material flow analysis of wood products
3.2. Analiza toka materijala drvnih proizvoda

As demonstrated in Section 3.1, FAOSTAT and PRODCOM datasets show good data coherence in the following categories: Sawnwood products 1994 – 2009 and 2016 – 2021, wood pulp products 1994 – 2006 and 2010 – 2021 as well as production of boards for the entire period and wood fuel products 2018 – 2021. For

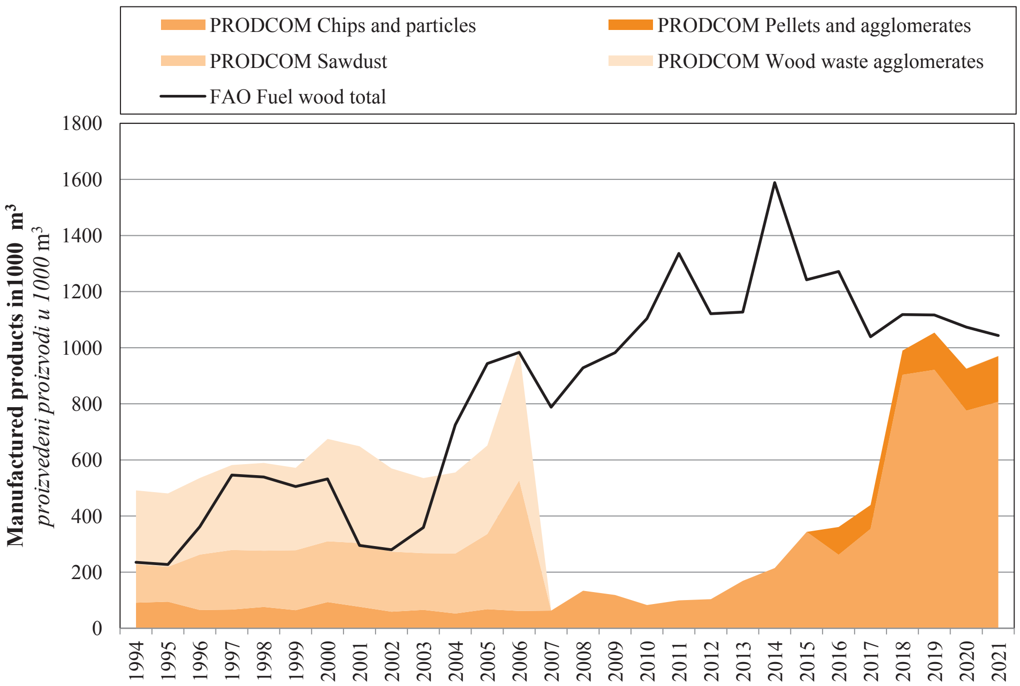

Figure 6 Manufactured wood fuel products in 1000 m^3 according to FAOSTAT and PRODCOM data (stacked chart in orange represents PRODCOM data and black line chart FAOSTAT data)
Slika 6. Količina proizvedenih ogrjevnih proizvoda u 1000 m^3 prema podatcima FAOSTAT-a i PRODCOM-a (složeni grafikon u narančastoj boji predočuje podatke PRODCOM-a, a crni linijski grafikon podatke FAOSTAT-a)

the years 1994 and 2021 the accuracy of quantities as recorded by PRODCOM was satisfactory when compared to the FAOSTAT data, except for the category of wood fuel in 1994.

The first blue arrows in Figure 7 and 8 represents FAOSTAT data on roundwood produced. After that, PRODCOM data is used to further detail the wood material flow with arrows in yellow, green and red, representing the input volumes of the categories of wood for sawmills, pulpmills and wood fuel products. Further right are the manufactured volumes of intermediate (primary) wood products, which are further processed into secondary wood products (dark green arrows). Grey arrows are not a part of the analysed system boundaries (Table 1), but as they highlight important trends, they are used where the data regarding input and output product do not match. A grey outwards pointing arrow indicates a loss of resource, either due to the efficiency property of the manufacturing process or because export of the preceding resource occurred. A grey inward pointing arrow is used when nationally available resource does not satisfy the production demand; a box depiction of 'import needed to satisfy demand' was therefore included in the flow model.

Figures 7 and 8 show a balanced material flow of wood volume, even though two different data sources have been used. Generally, this indicates that PRODCOM data can complement FAOSTAT data for the selected years and products.

Comparing wood volume flows as demonstrated in Figure 7 and 8, a significant increase in roundwood produced can be noted. This increase is translated mostly into production of coniferous sawn wood and wood fuels. In 1994, coniferous sawn wood and wood fuel products represent a total of 28 % of the total roundwood produced, and in 2021, the same two categories have a share of 51 % of the total roundwood produced. The share of production of cellulose and boards decreased from 44 % in 1994 to 24 % in 2021. Similar trend can be observed in the manufacturing of non-coniferous sawnwood, which represented a share of 8 % of the total roundwood produced in 1994 and 5 % of roundwood produced in 2021. The complete cessation of the production of particle boards and sulphite chemical pulp is also evident. Particle boards decreased from 15 % of total roundwood produced in 1994 to zero in 2021, and sulphite chemical pulp decreased from 12 % of total roundwood produced to zero in 2021. On the other hand, more fibreboard, plywood and mechanical wood pulp were produced. All these products were not produced at all in 1994, but in 2021, and the share of volume quantities of these products in relation to total roundwood produced was 5 %, 3 % and 6 %, respectively.

Although the study did not include import and export of products, certain observations can be made based on wood flows and differences in quantities when industrial transformations occur. In 1994, FAOSTAT data on produced roundwood plus is lower than the demand based on the primary products recorded by PRODCOM. This means that a part of the resource must have either been imported from abroad, or production waste was used as input. For both parameters, data was not easily attainable to be included in this study. However, as the amount of waste seen in the flow diagram can potentially cover this demand, the reuse of waste streams was considered to be a more likely scenario. In 2021, roundwood produced as per FAOSTAT and PRODCOM database data on production of goods match well, meaning that the domestic roundwood satisfies domestic demand for production of primary products.

Based on the differences in quantities between the secondary products produced and the available primary product used as a resource, we could determine where importing resource was needed to fulfil the resource demand for secondary product production. In 1994, this was the case with pulp, where 187,000 m^3 had to be imported (10 % of the total roundwood produced), which increased to 666,000 m^3 in 2021 (17 % of the total roundwood produced). Furthermore, in 2021, import of particle boards of 102,000 m^3 was required to satisfy the demand of the furniture industry, as there was no domestic production of particle boards. Based on the PRODCOM database, currently there is no secondary wood product manufactured in Slovenia that would utilise non-coniferous sawn wood (category of flooring exists but was not shown in the material flow model as the quantities were not significant).

The wood volume flow analysed showed that despite an increase in roundwood produced, the demand for resources has been met less by domestic resources in 2021 than in 1994 as the need for import of particle boards and wood pulp increased.

Beyond the wood flow analyses available before this study, MFA also includes secondary wood products. In 1994, there has been 774,000 m^3 of secondary wood products, 587,000 m^3 of which have been produced with domestic resources (75 %). In 2021, there have been 1,245,000 m^3 of secondary wood products (579,000 m^3 of those from domestic roundwood, 47 %). When calculating the amount of secondary products as a percentage of roundwood produced, it is seen that it was 43 % in 1994 and only 15 % in 2021. It is evident that despite the increase in quantity of secondary wood products, they are produced by using less m3 of domestic roundwood than in 1994.

MFA shows that in 2021 Slovenia produced 12,000 m^3 of wood that was used in construction, which is only about 0.3 % of the roundwood produced annually in 2021 (in previous years the quantities were

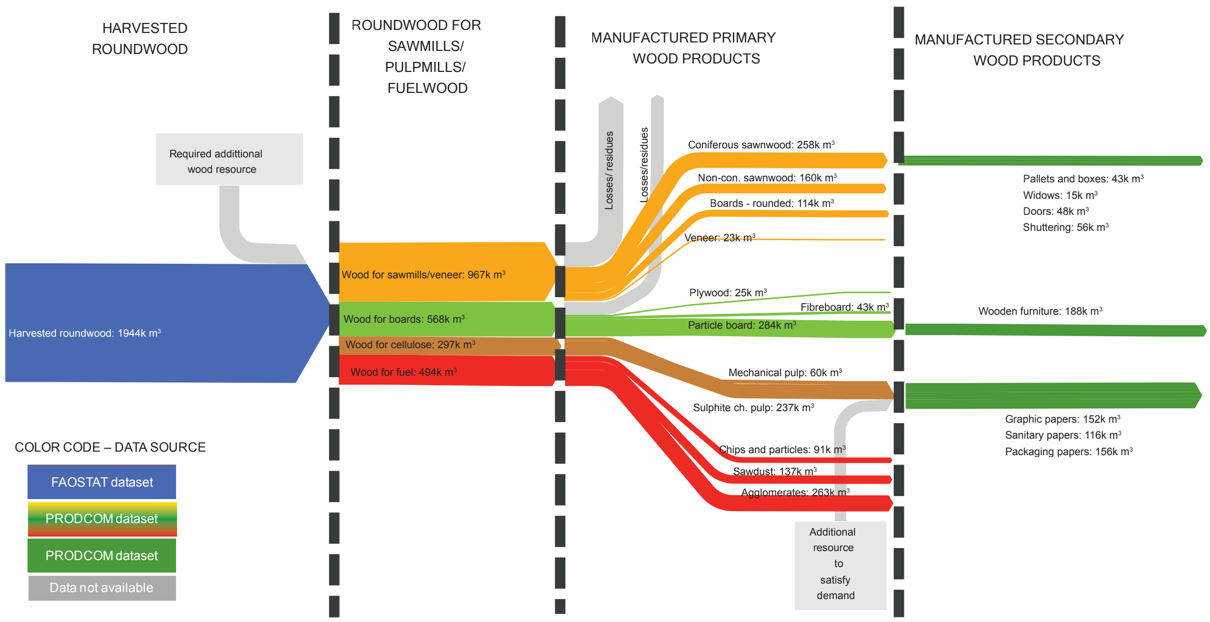

Figure 7 Wood product flow from processed roundwood in blue (FAOSTAT data) to primary products in light green, yellow, red and secondary wood products in dark green (PRODCOM data) for 1994 in 1000m^3. The numbers reported refer to the volume of roundwood/manufactured products with the moisture content as is.
Slika 7. Tok materijala drvnih proizvoda od prerađene oblovine označen je plavom bojom (podatci FAOSTAT-a) do primarnih proizvoda označenih svjetlozelenom, žutom i crvenom bojom te sekundarnih drvnih proizvoda označenih tamnozelenom bojom (podatci PRODCOM-a) za 1994. godinu u 1000 m^3. Prikazani brojevi odnose se na volumen oblovine/proizvoda s jednakim sadržajem vode.

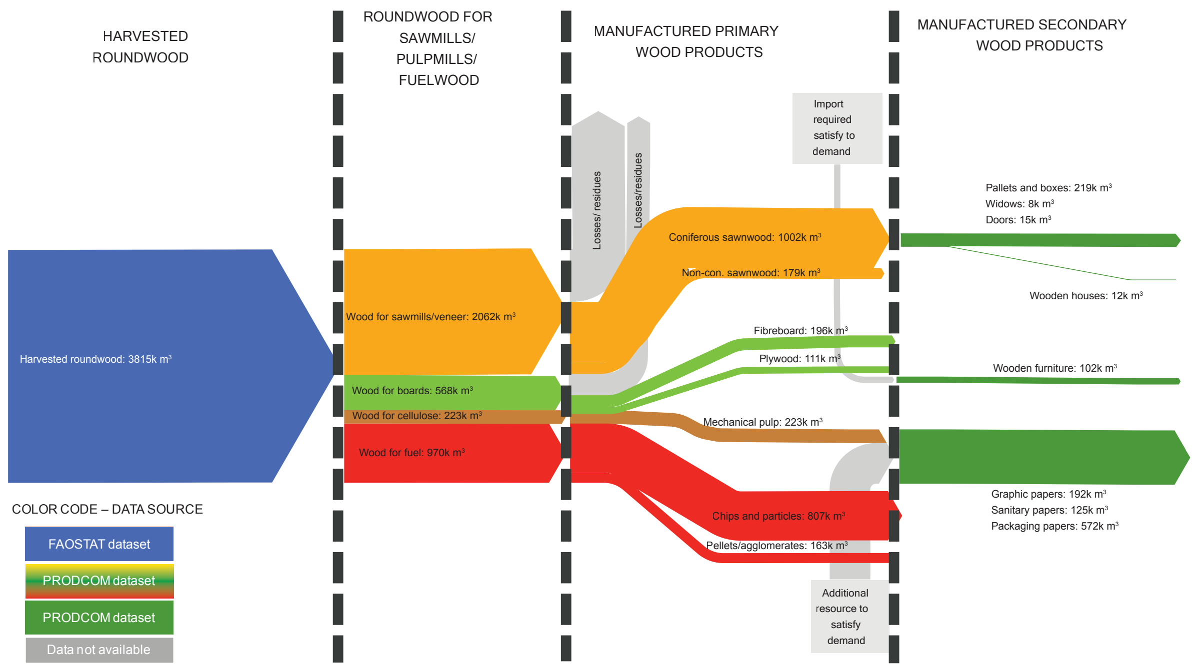

Figure 8 Wood product flow from processed roundwood in blue (FAOSTAT data) to primary products in light green, yellow, red and secondary wood products in dark green (PRODCOM data) for 2021 in 1000 m^3. The numbers reported refer to the volume of roundwood/manufactured products with the moisture content as is.
Slika 8. Tok materijala drvnih proizvoda od prerađene oblovine označen je plavom bojom (podatci FAOSTAT-a) do primarnih proizvoda označenih svjetlozelenom, žutom i crvenom bojom te sekundarnih drvnih proizvoda označenih tamnozelenom bojom (podatci PRODCOM-a) za 2021. godinu u 1000 m^3. Prikazani brojevi odnose se na volumen oblovine/proizvoda s jednakim sadržajem vode.

insignificant). Contrary to the idea of using wood products as an opportunity to store carbon, Slovenia used a quarter of domestic roundwood production for fuel. As the roundwood produced for fuel from private forests was not reported, this number is likely even higher. Considering that wood produced in Slovenia is sustainable and locally produced, failing to (a) scale up wood construction and (b) failing to use domestic resource for long lasting products is environmentally unacceptable. Government should take into account the fact that the share of wood used for fuel in Slovenia is increasing and consider measures to encourage cleaner alternatives for fuel and utilise wood for long-lasting products instead.

4 CONCLUSIONS
4. ZAKLJUČAK

The applied methodology to arrive to a complete dataset of wood products, primary as well as secondary, by complementing FAOSTAT data with selected data categories of PRODCOM data was found to be appropriate to perform the MFA of wood products. The answer to the research question is that PRODCOM data was found out to be of satisfactory quality in most categories of products to complement FAOSTAT data on wood flows with some specificities. Poorer accuracy of PRODCOM has been discovered in the category of sawn wood in the period 2009 – 2016, wood pulp from 2006 – 2009 and selected wood fuel products wood data in general.

One scientific limitation was the lack of data about wood loss and residue streams stemming from the manufacturing of the product. The most accurate way of collecting this additional data would be to make this issue an integral part of PRODCOM questionnaire or by linking it with other existing reports/datasets.

Another shortcoming of PRODCOM is that there are no meta information or disclaimers included with the reported data (such as density, thickness, or sometimes even volume). Without knowing the dimensions of items, errors are possible when converting the number of items into volume of wood.

Another difficulty encountered while analysing PRODCOM data were changes in classification from one year to another. Such changes in the data classification should be avoided in the future as they negatively affect data integrity and hinder longitudinal comparisons. Between the year 1994 and 2021, such changes in PRODCOM occurred at least 5 times, adding complexity to analysis. Effort should be made to internationally harmonise databases such as FAOSTAT and PRODCOM and make available the conversion keys to ease the work of analysts who wish to extract meaningful results from data. In the category of wood fuel products, more clarity regarding the aggregated category of 'Manufactured wood fuel products' would be welcome. Here, limitations of PRODCOM remain, such as clarity of final use of the categorised products and inclusion of the data of the non-industrially produced wood fuel products (such as firewood and in a smaller degree, coal). Furthermore, it is hard to determine for some products where they re-enter the material flow, whether it is production of boards or wood fuel products.

Despite these noted differences and shortcomings between PRODCOM and FAOSTAT quantities, PRODCOM has been found to be usable for filling the gaps in current knowledge of wood flows in Slovenia. The study demonstrated the type of insights one can acquire using wood product data from PRODCOM and FAOSTAT data jointly to support MFA. It is widely known that the positive environmental impact of wood products can be maximised by using wood for long-lasting applications. However, the MFA of wood products in Slovenia have indicated trends contrary to this logic. The MFA showed that Slovenian forest-based sectors are increasingly less oriented towards the production of secondary, long lasting, high value wood products and positioned more towards the export of unprocessed wood as well as to consumption of wood as an energy source (Arnič *et al.*, 2024; Ščap *et al.*, 2023). Despite a growing production of roundwood, the MFA suggests that for many secondary products produced, there is no resource available domestically, meaning that it is likely imported. Based on the MFA, the opportunities for domestic production in Slovenia could be the lack of industrial capacities and subsequent low volume of production of veneer, particle boards, and sulphite chemical and mechanical wood pulp (Straže *et al.*, 2023; Kropivšek, 2017). Similar is true for the production of non-coniferous sawnwood (Arnič, 2023). According to Slovenian forestry Institute (SFI) data, the share of non-coniferous tree species in the growing stock is 56 % (Pintar *et al.*, 2024), but in Slovenia few high added-value products are made from this wood. Furthermore, a stagnation of non-coniferous wood is evident, despite the fact that non-coniferous wood-based materials can also be used for construction (Ozarska, 1999) and are gaining traction (Straže *et al.*, 2023). The described trends lead to an unexploited opportunity to avoid carbon emissions by replacing other intensive materials with lasting wood products.

The MFA analyses as presented in the study play a key role in the design of effective and sustainable policies in the forest-wood sector, as they provide a comprehensive overview of biomass flows – from harvest to final product (Khan *et al.*, 2024). The present MFA results can support strategic decisions and sustainable environmental policies such assessing how the forest-wood chain can contribute to climate change mitigation. Based on the results, government can design measures to increase the use of wood, which enables carbon storage over longer periods. The results of the study will also contribute to the implementation of EU policies, e.g. the New EU Forest Strategy for 2030 (COM (2021) 572 final), which support a sustainable forest-based bioeconomy by promoting the processing of wood into durable wood products as well as the updated EU Bioeconomy Strategy (COM (2018) 673 final), whose main objective is to develop a sustainable and circular bioeconomy that serves Europe's society, environment, and economy. Policy makers should consider the trends observed and introduce measures to stimulate:

- carbon mitigation in wood products through a discouragement of wood fuel products and encouragement of long-lasting products;
- value creation in industry by implementing measures to encourage domestic processing of harvested wood instead of importing secondary wood products, with an initial focus on products that are currently imported to fill gaps in domestic production (particle boards, pulp);
- value creation by implementing measures for processing of non-coniferous wood into high value-added items.

In conclusion, while caution is required when utilising data from PRODCOM together with more established datasets like FAOSTAT, the insights gained are significant. This study highlights the potential of using PRODCOM for MFA, despite the current methodological shortcomings and data limitations. It represents an important step toward a more comprehensive understanding of Slovenian wood flows, providing a foundation for future research and policy development aimed at enhancing the sustainability of the forest-wood sector.

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5 REFERENCES
5. LITERATURA

1. Arnič, D., 2023: Impact of climate change on wood increment in European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) Karst.) and potential consequences for the bioeconomy in Slovenia. PhD Thesis, Repository of the University of Ljubljana. (in Slovenian).
2. Arnič, D.; Loizou, E.; Ščap, Š.; Prislan, P.; Juvančič, L., 2024: Evaluating alternative transformation pathways of wood-based bioeconomy: application of an input – output model. Forests, 15 (12): 2084. https://doi.org/10.3390/f15122084
3. Barkhausen, R.; Rostek, L.; Miao, Z. C.; Zeller, V., 2023: Combinations of material flow analysis and life cycle assessment and their applicability to assess circular economy requirements in EU product regulations. A systematic literature review. Journal of Cleaner Production, 407: 137017. https://doi.org/10.1016/j.jclepro.2023.137017
4. Buendia, E.; Tanabe, K.; Kranjc, A.; Jamsranjav, B.; Fukuda, M.; Ngarize, S.; Osako, A.; Pyrozhenko, Y.; Shermanau, P.; Federici, S., 2019: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC Task Force on National Greenhouse Gas Inventories.
5. D'Amato, D.; Gaio, M.; Semenzin, E., 2020: A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. Science of the Total Environment, 706: 135859. https://doi.org/10.1016/j.scitotenv.2019.135859
6. Elia, V.; Gnoni, M. G.; Tornese, F., 2017: Measuring circular economy strategies through index methods: A critical analysis. Journal of Cleaner Production, 142 (4): 2741-2751. https://doi.org/10.1016/j.jclepro.2016.10.196
7. 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. https://doi.org/10.1088/1748-9326/ac386f
8. Khan, M. T.; Pettenella, D.; Masiero, M., 2024: Material flow analysis of the wood-based value chains in a rapidly changing bioeconomy: A literature review. Forests, 15: 2112. https://doi.org/10.3390/ f1512211
9. Krajnc, N.; Piškur, M., 2006: Roundwood and wood waste flow analysis for Slovenia. Zbornik gozdarstva in lesarstva, Gozdarski inštitut Slovenije, Biotehniška fakulteta, 80: 31-54 (in Slovenian).
10. Kropivšek, J.; Gornik Bučar, D., 2017: Added value of products in the forest wood supply chain – Case: primary beechwood processing. Les/Wood, 66 (1): 61-72. https://doi.org/10.26614/les-wood.2017.v66n01a06 (in Slovenian).
11. Kutnar, A.; Tavzes, Č.; Schau, E.; DeVallance, D.; Kržič, A.; Rwankuba, E.; Skender, G.; Pezdir, M., 2021: Študija podnebnega svežnja „Fit for 55", Ministrstvo RS za gospodarski razvoj in tehnologijo, Ljubljana, Slovenia.
12. Marques, A.; Cunha, J.; de Meyer, A.; Navare, K., 2020: Contribution towards a comprehensive methodology for wood-based biomass material flow analysis in a circular economy setting. Forests: 11 (1): 106. https://doi.org/10.3390/f11010106
13. Merli, R.; Preziosi, M.; Acampora, A., 2018: How do scholars approach the circular economy? A systematic literature review. Journal of Cleaner Production, 178: 703-722. https://doi.org/10.1016/j.jclepro.2017.12.112
14. Ozarska, B., 1999: A review of the utilisation of hardwoods for LVL. Wood Science and Technology, 33: 341-351. https://doi.org/10.1007/s002260050120
15. Pauliuk, S., 2021: Guidelines for Data Modeling and Data Integration for Material Flow Analysis and Socio-Metabolic Research, Version 1.0 of June 2021. International Society for Industrial Ecology (ISIE) – Topical Section for Research on Socio-Economic Metabolism (SEM), ISIE-SEM Section Board.
16. Pintar, A. M.; Ferreira, A.; Krajnc, L.; Kušar, G.; Skudnik, M., 2024: Diversity and occurrence of native and non-native tree and shrub species in national forest in-

ventory plots in Slovenia. Acta Silvae et Ligni, 134: 11-26. https://doi.org/10.20315/ASetL.134.2 (in Slovenian).
17. Pisek, R.; Nève Repe, A.; Guček, M., 2023: Slovenian Environment Agency Indicator GZ03 (Wood stock increase and harvest), Zavod za gozdove Slovenije. https://kazalci.arso.gov.si/sl/content/lesna-zaloga-s-prirastkom-posekom-5 (Accessed: Aug. 29, 2024).
18. Ripple, W. J.; Wolf, C.; Newsome, T. M.; Barnard, P.; Moomaw, W. R., 2020:World scientists' warning of a climate emergency. Bioscience, 70 (1): 8-12. https://doi.org/10.1093/biosci/biz088
19. Schau, E. M.; Gavrić, I.; Šušteršič, I.; Prelovšek Niemelä, E.; Dávid, B.; Pečnik, J. G.; DeVallance, D. B.; Tavzes, Č., 2023: Modelling the Slovenian Wood Industry's Response to the Slovenia's National Inventory Report 2023: GHG emissions inventories 1986 – 2021, Submitted under the United Nations Framework Convention on Climate Change.
20. Sodja, A., 2018: Prihodnost je v izdelkih z višjo dodano vrednostjo. Glas gospodarstva, februar 2018. https://www.gzs.si/Portals/SN-informacije-Pomoc/Vsebine/GG/2018-februar/23-25-lesna%20industrija.pdf (Accessed: Aug. 31, 2024).
21. Steel, E. A., 2021: Carbon storage and climate change mitigation potential of harvested wood products. Background Paper prepared for the 61st Session of the FAO Advisory Committee on Sustainable Forest-based Industries.
22. Straže, A.; Gornik Bučar, D.; Kropivšek, J.; 2023: Identification of value chains in the Slovenian forest and wood bioeconomy. Les/Wood, 72 (1): 33-46. https://doi.org/10.26614/les-wood.2023.v72n01a03
23. Ščap, Š., 2020: Analysis of the data on production of sawn wood in Slovenia for the period 2014 – 2018, gathered and managed by statistical office of RS. Gozdarski vestnik, 78, 4: 178-184 (in Slovenian).
24. Ščap, Š., 2022: Tokovi okroglega lesa. V: Triplat, Matevž (ur.). Kazalniki gospodarjenja z gozdovi v Sloveniji. Gozdarski inštitut Slovenije, Založba Silva Slovenica, pp. 48-59. https://doi.org/10.20315/SFS.183
25. Ščap, Š., 2024. Roundwood flows in Slovenia in 2023. InfoGozd: taking care of the forest, 5 (11): 6-10. https://doi.org/10.20315/10.20315/IG.2024.0052 (in Slovenian).
26. Ščap, Š.; Kocjan, D.; Arnič, D.; Krajnc, N.; Remic, T., 2019: Wood products market statement with forecasts. Slovenian Forestry Institute and Ministry of Agriculture, Forestry and Food.
27. Ščap, Š.; Stare, D.; Krajnc, N.; Remic, T., 2020: Wood products market statement with forecasts. Slovenian Forestry Institute and Ministry of Agriculture, Forestry and Food.
28. Ščap, Š.; Stare, D.; Krajnc, N.; Remic, T., 2021: Wood products market statement with forecasts. Slovenian Forestry Institute and Ministry of Agriculture, Forestry and Food.
29. Ščap, Š.; Triplat, M., 2023: Utilisation, market volumes and projections of the potential of hardwood roundwood in Slovenia. Les/Wood, 72 (1): 5-20. https://doi.org/10.26614/les-wood.2023.v72n01a02
30. Šooš, T.; Lautar, K.; Urbančič, H.; Kobe Logonder, N.; Kmet Zupančič, R.; Fajič, L., 2017: Strategija razvoja Slovenije 2030. Služba Vlade Republike Slovenije za razvoj in evropsko kohezijsko politiko, Ljubljana, Slovenia.
31. Tavzes, Č., 2024. Analiza scenarijev uporabe lesa za zmanjševanje emisij TGP, Project Report. Innorenew CoE, Izola, Slovenia.
32. Törnqvist, L.; Vartia, P.; Vartia, Y. O., 1985: How Should Relative Changes Be Measured? The American Statistician, 39 (1): 43-46. https://doi.org/10.2307/2683905
33. Wang, R.; Haller, P., 2024: Enhancing wood efficiency through comprehensive wood flow analysis: Methodology and strategic insights. Forest Ecosystems, 11: 100179. https://doi.org/10.1016/j.fecs.2024.100179
34. ***FAO, 2022: Classification of forest products.
35. ***FAO, 2024: Forestry Production and Trade database, last updated in June 2024.
36. ***FAO, ITTO and United Nations, 2020: Forest product conversion factors.
37. ***FAOSTAT, 2022: The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome, FAO.
38. ***Greenhouse Gas Paris Agreement and the EU "Fit for 55" Green Transition Plan. Sustainability, 15 (10): 8376, 5.
39. ***Regulation 2019/2152: 2019: Regulation (EU) No 2019/2152 of the European Parliament and of the Council on European business statistics, repealing 10 legal acts in the field of business statistics, 2019. Official Journal L 327, December 2019, p. 1-35.
40. ***SORS, 2009: Nomenklatura industrijskih proizvodov 2008, klasifikacije. Ljubljana, Statistics Office of Slovenia (SORS).
41. ***SORS, 2024: Production structure of GDP (production, intermediate consumption and value added by activity, SKD 2008), Slovenia, annually. Accessed on 16th of February 2025 at https://pxweb.stat.si/SiStatData/pxweb/sl/Data/-/0301915S.px (Accessed: Feb. 16, 2024).
42. ***SORS, 2024: Sales of industrial products and services by area and 2-digit CPA activity code in 2022. https://pxweb.stat.si/SiStatData/pxweb/sl/Data/-/H252S.px (Accessed: Jun. 20, 2024).

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Performance Evaluation of Coco Wood Chairs Constructed with Traditional Joints

Evaluacija svojstava stolica od drva kokosove palme izrađenih tradicionalnim spojevima

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ABSTRACT • *Furniture is an engineered structure that is subjected to various loads throughout its service life. As a result, to guarantee that furniture satisfies the standards of the target market for strength and durability, it must be designed and constructed with the appropriate strength features. This study, therefore, assesses the structural and aesthetic performance of three chairs made from West African Tall Coco Wood (Cocos nucifera) using three traditional joints: mortise and tenon, halving, and dowel joints. With rising demand for sustainable alternatives to tropical hardwoods, coco wood represents an underutilised yet promising material in Ghana's furniture sector. The coco wood was obtained from the Abura Asebu Kwamankese District in the Central Region of Ghana. The chairs were produced at the Asuansi Technical Institute and were tested at the laboratory of the Wood Mechanic and Furniture Testing Centre (FORIG), Kumasi, according to European Standards (EN 1022 and EN 1728). The results indicate that mortise and tenon joints performed best, followed by halving joints and dowel joints. On the aesthetic side, coco wood was found to be visually attractive and comparable to many commonly used hardwoods, thus making it suitable for furniture that does not undergo heavy use. Overall, the study suggests that coco wood can be a sustainable and eco-friendly material choice for light to medium furniture. Mortise and tenon joints are recommended for furniture that requires load-bearing. Dowel and halving joints are suitable for secondary and decorative purposes. The study demonstrates the potential for wider adoption of coco wood in Ghana's furniture sector and provides guidance for improved joint selection and furniture design.*

KEYWORDS: *coco wood; mortise and tenon joint; halving joint; dowel joint; eco-friendly furniture*

SAŽETAK • *Namještaj je proizvod koji je tijekom svog vijeka trajanja izložen različitim opterećenjima. Zbog toga mora biti dizajniran i izrađen tako da posjeduje odgovarajuću čvrstoću kako bi zadovoljio standarde ciljanog tržišta u smislu čvrstoće i trajnosti. U ovom se istraživanju procjenjuju strukturna i estetska svojstva triju stolica od drva zapadnoafričke visoke kokosove palme (Cocos nucifera) izrađenih primjenom triju tradicionalnih spojeva: čepa i rupe, spoja na preklop i spoja s moždanicima. U uvjetima sve veće potražnje održivih alternativa tropskim listačama, drvo kokosove palme nedovoljno je iskorišten, ali obećavajući materijal u industriji namještaja u Gani.*

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Za potrebe ovog istraživanja drvo kokosove palme nabavljeno je iz okruga Abura Asebu Kwamankese u središnjoj regiji Gane. Stolice su proizvedene u Tehničkom institutu Asuansi i ispitane u laboratoriju Centra za mehaniku drva i ispitivanje namještaja (FORIG) u Kumasiju, i to prema europskim normama (EN 1022 i EN 1728). Istraživanjem je utvrđeno da spoj s čepom i rupom daje najbolje rezultate, a slijedi spoj na preklop i spoj s moždanicima. S obzirom na estetska obilježja, drvo kokosove palme pokazalo se vizualno privlačnim i usporedivim s mnogim uobičajeno upotrebljavanim vrstama drva listača, što ga čini pogodnim za namještaj koji nije u intenzivnoj uporabi. Zaključno, rezultati studije sugeriraju da drvo kokosove palme može biti održiv i ekološki prihvatljiv materijal za lagani do srednje teški namještaj. Spoj s čepom i rupom preporučuje se za namještaj od kojega se očekuje veća nosivost. Spojevi s moždanicima i na preklop prikladni su za namještaj koji ima sekundarnu i dekorativnu namjenu. Studija je potvrdila potencijal drva kokosove palme za širu primjenu u proizvodnji namještaja u Gani i ponudila je smjernice za odgovarajući odabir spojeva i bolji dizajn namještaja.

KLJUČNE RIJEČI: *drvo kokosove palme; spoj s čepom i rupom; spoj na preklop; spoj s moždanicima; ekološki namještaj*

1 INTRODUCTION
1. UVOD

Traditional woodworking joints play a critical role in determining the structural integrity and overall quality of furniture manufactured from coco wood, a material valued for its natural appearance, strength, and durability (Vlaović, 2024). For Ghana's furniture industry to remain competitive in the global market, particularly within the emerging coco wood sector, there is a growing need to adopt designs that balance mechanical performance with aesthetic appeal. In recent years, the furniture design industry has transitioned from predominantly traditional practices toward more innovative and performance-oriented approaches (Han *et al*., 2021; Rame *et al*., 2023).

Furniture design integrates functionality, stability, continuity, and aesthetics. Coco wood furniture exemplifies this balance due to the material's strength, sustainability, and visual appeal (Fathi *et al*., 2023; Hummel, 2023).

Previous studies indicate that the selection of appropriate joints is fundamental to woodworking and directly influences the mechanical performance and durability of furniture (Carpenter, 2021; Zhu *et al*., 2022). In addition, joints contribute significantly to the visual quality and perceived craftsmanship of furniture products (Furniture Crafters, 2022; Hughes, 2023).

Aesthetic quality, defined by balance, order, and visual harmony, is another important factor affecting consumer preference (Goldman, 2001; Handy *et al*., 2008). Aesthetic judgment can be formed independently of material properties, highlighting the role of design perception in market competitiveness (Schepman *et al*., 2018; Sibley, 2001).

The decline in traditional hardwood resources has increased interest in alternative materials such as coco wood. Ghana's deforestation rate is estimated at approximately 2 % annually (IUCN, 2022), thereby encouraging the exploration of sustainable materials derived from senile and non-productive coconut palms (Fathi *et al*., 2023; Hummel, 2023; Okai *et al*., 2004).

However, the anatomical variability of coco wood affects its physical and mechanical properties (Fathi, 2014). Studies indicate that density ranges from 0.41–1.11 g/cm³ and moisture content from 50 % to 400 %. Despite such variability, coco wood exhibits relatively low shrinkage and swelling, making it less prone to warping (Fathi *et al*., 2023). Density strongly influences its performance, while moisture content has little effect (Gonzalez *et al*., 2014).

Despite the availability of coco wood and its growing use in construction and furniture, limited information exists on the influence of joint type on the structural performance and aesthetic quality of the coco wood chair. This lack of data constrains evidence-based design decisions among Ghanaian furniture manufacturers.

Therefore, this study evaluates the structural performance of mortise and tenon, halving, and dowel joints in a coco wood chair construction to support durable, aesthetically pleasing, and sustainable furniture design.

1.1 Objectives of the study
1.1. Ciljevi istraživanja

The objectives of this study are:

1. To evaluate the structural performance of coco wood chairs constructed with mortise and tenon, halving, and dowel joints in accordance with the EN 1022 and EN 1728 standards;
2. To assess the durability and load-bearing capacity of the joints under stability and fatigue loading conditions;
3. To examine the aesthetic qualities of coco wood chairs in comparison with those of traditional hardwood furniture;
4. To identify the most suitable joinery methods for both functional and decorative applications in sustainable furniture design.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Study area and sample selection
2.1. Područje istraživanja i odabir uzoraka

Coco wood samples were collected from Abakrampa in the Abura Asebu Kwamankese (AAK) District of Ghana's Central Region (5°05′N–5°25′N; 1°05′W–1°20′W). The district covers approximately 380 km² and spans ecological zones ranging from coastal savanna to tropical rainforest (GDS, 2024).

Two senile *Cocos nucifera* palms of the West African Tall variety, infected with Cape St. Paul wilt disease, were purposively selected to ensure uniformity in age, disease condition, and stem diameter.

The selected palms were approximately 20 years old, with an average height of about 30 m and a stem diameter of 45 cm. Mean ambient temperatures at the collection site ranged between 26 and 28 °C.

2.2 Sample collection and preparation
2.2. Prikupljanje i priprema uzoraka

Felling and Cutting: The selected palms were felled in accordance with environmental and safety guidelines. Logs were converted into planks measuring 50 mm × 150 mm × 2400 mm using a chainsaw. The planks were sawn radially from the outer stem zone toward the inner stem zones.

Air-Drying: The planks were air-dried for three days before machining to reduce surface moisture and minimise machining defects.

Chair Production: Three coco wood chairs were constructed, each representing a different traditional joint type: mortise and tenon, halving, and dowel joints. Each chair incorporated twelve joints. For each joint type, four replicate joints were tested, resulting in a total of 12 joints per joint category. The sample size was determined based on material availability and is consistent with similar exploratory studies on timber joints.

Chair fabrication was carried out in the Furniture Design Technology Department Workshop of Asuansi Technical Institute.

2.3 Material properties of coco wood
2.3. Svojstva drva kokosove palme

The physical and mechanical properties of the coco wood used in this study were determined in accordance with BS 373:1957 and ASTM D143 standards. Measured properties included density, moisture content, modulus of elasticity (*MOE*), modulus of rupture (*MOR*), hardness, and shrinkage. The results are summarised in Table 1.

2.4 Equipment
2.4. Oprema

Workshop Equipment: Personal protective equipment (PPE), thickness planer, circular saw, cross-cut saw, surface planer, dimension saw, band saw, hollow-chisel mortiser, sanding machine, drilling machine, air compressor, spray gun, and chainsaw.

Consumables: Polyvinyl acetate (PVA) wood adhesive and clear lacquer finish.

2.5 Chair design and construction
2.5. Dizajn i konstrukcija stolice

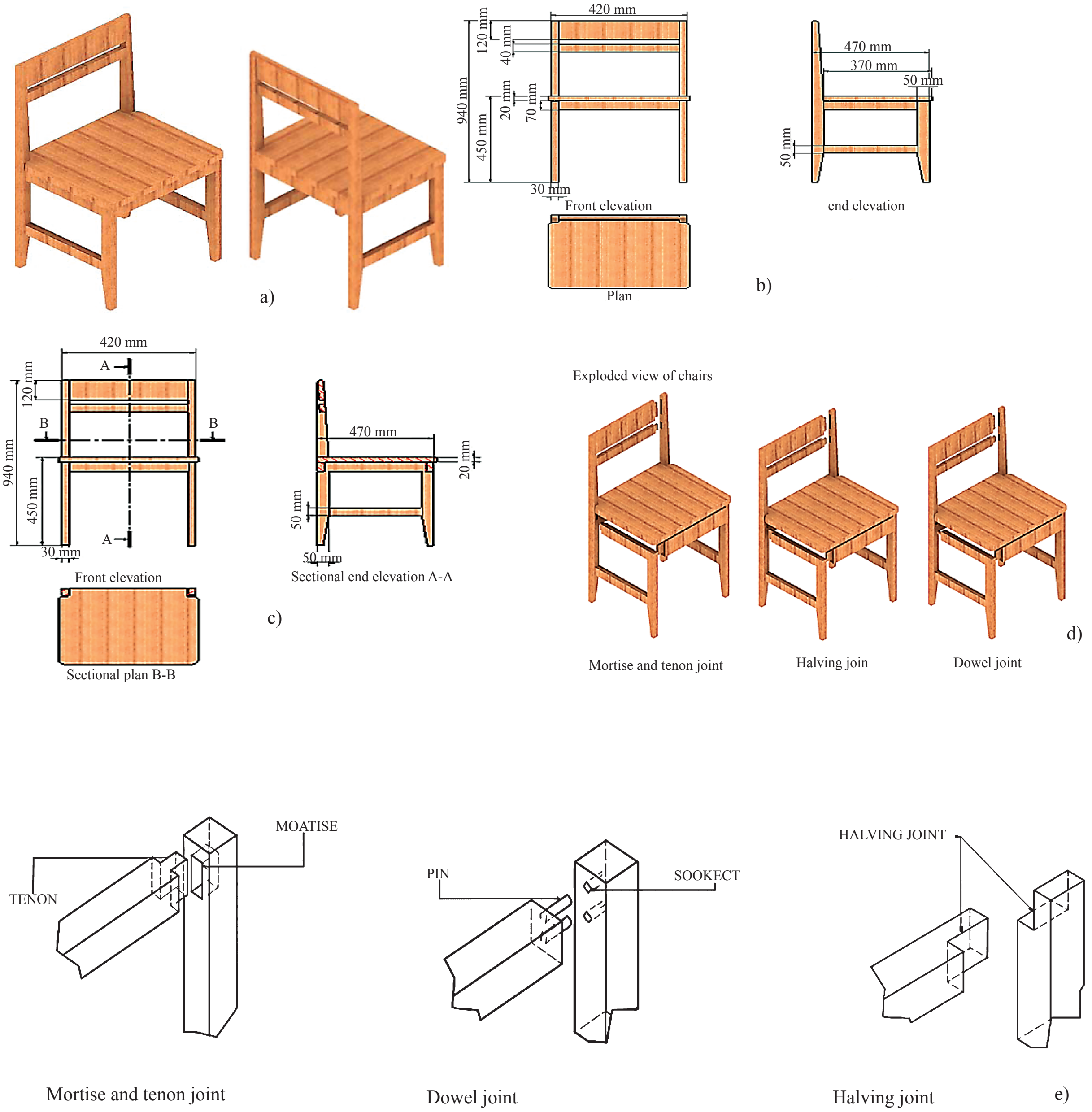
Working drawings, including isometric, orthographic, sectional, and exploded views, were developed using Autodesk Inventor software (version 2008). These drawings were used to prepare a cutting list (Table 2), which guided accurate preparation of materials and ensured dimensional consistency.

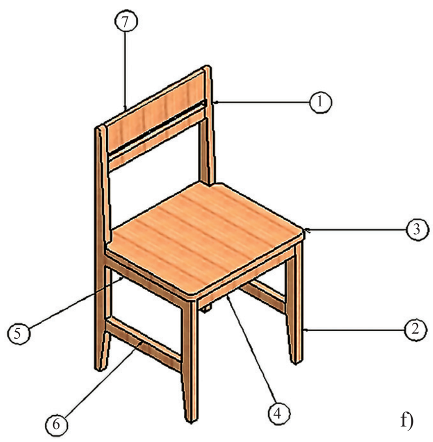
To ensure comparability among specimens, the geometric dimensions of all joint types were kept constant. Mortise and tenon joints were fabricated with a tenon length of 30 mm, a width of 40 mm, and a thickness of 10 mm, fitted into corresponding mortises of identical dimensions. Halving joints were produced with a half-depth overlap of 15 mm over a joint width of 40 mm. Dowel joints consisted of two cylindrical dowels, each 10 mm in diameter and 40 mm in length, inserted into pre-drilled holes with a centre-to-centre spacing of 50 mm.

All joints were bonded using polyvinyl acetate (PVA) wood adhesive and assembled under uniform clamping pressure to ensure adequate glue-line contact.

Table 1 Physical and mechanical properties of west African tall coco wood
Tablica 1. Fizička i mehanička svojstva drva zapadnoafričke visoke kokosove palme

Property *Svojstvo*	Value *Vrijednost*	Unit *Jedinica*
Density (oven-dry) / *gustoća u apsolutno suhom stanju*	0.62 ± 0.05	g/cm³
Moisture content (air-dried) / *sadržaj vode (u zrakosuhom drvu)*	12 ± 1.5	%
Modulus of elasticity (*MOE*) / *modul elastičnosti (MOE)*	10,500 ± 300	MPa
Modulus of rupture (*MOR*) / *modul loma (MOR)*	75 ± 5	MPa
Janka hardness / *tvrdoća prema Janki*	3,200 ± 100	N
Radial shrinkage / *radijalno utezanje*	3.5 ± 0.2	%
Tangential shrinkage / *tangentno utezanje*	5.8 ± 0.3	%





Parts list / *Popis dijelova*	
Part No. *Broj dijela*	Description *Opis*
1	Back leg / *stražnja noga*
2	Front leg / *prednja noga*
3	Seat / *sjedalo*
4	Front rail / *prednja okvirnica*
5	Side rail / *bočna okvirnica*
6	Bottom rail / *poveznik nogu*
7	Back rest / *naslon*

Figure 1 Working drawings of the coco wood chair components: a) isometric view, b) orthographic view, c) sectional view, d) exploded view, e) details of joint construction, f) parts list
Slika 1. Radni crteži dijelova stolice od drva kokosove palme: a) izometrijska projekcija, b) ortogonalna projekcija, c) presjek, d) rastavljeni prikaz, e) detalji konstrukcije spoja, f) popis dijelova

Table 2 Cutting list for coco wood chair components
Tablica 2. Krojna lista dijelova stolice od drva kokosove palme

Item *Stavka*	Description *Opis*	Qty *Količina*	Dimension, mm *Dimenzija*, mm	Material *Materijal*	Finish *Premaz*
1	Front leg / *prednja noga*	2	430 × 50 × 30	Coco wood / *drvo kokosove palme*	Lacquer / *lak*
2	Back leg / *stražnja noga*	2	940 × 50 × 30	Coco wood / *drvo kokosove palme*	Lacquer / *lak*
3	Seat / *sjedalo*	1	470 × 460 × 20	Coco wood / *drvo kokosove palme*	Lacquer / *lak*
4	Side rail / *bočna okvirnica*	2	410 × 70 × 30	Coco wood / *drvo kokosove palme*	Lacquer / *lak*
5	Front rail / *prednja okvirnica*	1	400 × 70 × 30	Coco wood / *drvo kokosove palme*	Lacquer / *lak*
6	Back rest / *naslon*	1	400 × 70 × 30	Coco wood / *drvo kokosove palme*	Lacquer / *lak*
7	Bottom rail / *poveznik nogu*	2	410 × 50 × 30	Coco wood / *drvo kokosove palme*	Lacquer / *lak*

2.6 Construction process
2.6. Proces izrade

The chair construction process included planing, ripping, shooting, cross-cutting, marking out, joint fabrication, trial assembly, final assembly, seat lamination, sanding, and application of the final surface finish.

2.7 Experimental setup
2.7. Postavke eksperimenta

All tests were conducted at the Wood and Furniture Testing Centre of the Forest Research Institute of Ghana (FORIG), Kumasi, in accordance with European standards (EN 1022 and EN 1728; CEN, 2018). Elaeis

Figure 2 Construction stages of the three coco wood chairs: a) planing, b) ripping, c) shooting, d) cross-cutting, e) marking out and joint construction, f) trial and final assembly of joints, g) sanding of the chair structure, h) lamination of the chair seat, i) application of the final coating material, j) final products
Slika 2. Faze izrade triju stolica od drva kokosove palme: a) ravnanje, b) uzdužno raspiljivanje, c) blanjanje, d) poprečno piljenje, e) označivanje i izrada spojeva, f) probno i konačno sastavljanje spojeva, g) brušenje stolice, h) laminiranje sjedala stolice, i) nanošenje završnog premaza, j) gotovi proizvodi

guineensis, is by far the most important global oil crop, supplying about 40 % of all traded vegetable oil. Palm oils are key dietary components consumed daily by over three billion people, mostly in Asia, and also have a wide range of important non-food uses including in cleansing and sanitizing products. Main body: Oil palm is a perennial crop with a > 25-year life cycle and an exceptionally low land footprint compared to annual oilseed crops. Oil palm crops globally produce an annual 81 million tonnes (Mt Prior to testing, all chairs were conditioned in a climate-controlled environment at 20–25 °C and 60–65 % relative humidity for 24 hours.

During the testing procedure, the chairs were placed on a rigid, level surface, and loads were applied vertically or horizontally at specified locations on the seat, backrest, and legs using a calibrated loading system. The loading direction, support conditions, and points of load application were kept constant across all specimens to ensure repeatability. The ultimate load sustained prior to failure was recorded. In cases where no failure occurred, testing was terminated once the performance requirements specified in the relevant standards had been satisfied.

Figure 3 Experimental testing of coco wood chairs in accordance with EN standards: a) chairs in a climate-controlled room, b) chair at the marking-out centre, c) forward stability test, d) sideways stability test, e) rearward stability test, f) seat and back static load test, g) leg forward and sideways static load test, h) combined seat and back durability test, i) seat impact test
Slika 3. Ispitivanje stolica od drva kokosove palme u skladu s EN normama: a) klimatiziranje, b) označivanje, c) ispitivanje stabilnosti prema naprijed, d) ispitivanje bočne stabilnosti, e) ispitivanje stabilnosti prema natrag, f) ispitivanje statičkog opterećenja sjedala i naslona za leđa, g) ispitivanje statičkog opterećenja nogu prema naprijed i bočno, h) kombinirano ispitivanje trajnosti sjedala i naslona za leđa, i) ispitivanje sjedala udarom

Table 3 Summary of the performance of coco wood chairs constructed with mortise and tenon, halving, and dowel joints according to European test standards
Tablica 3. Sažetak performansi stolica od drva kokosove palme izrađenih spojem s rupom i *čepom*, spojem na preklop i spojem s moždanicima, ispitanih prema europskim standardima

Joint type *Vrsta spoja*	**Test (EN standard)** *Ispitivanje* (EN standard)	**Specified force** *Odabrana sila*	**Ultimate load, N** *Krajnje opterećenje,* N	**Result** *Rezultat*
Mortise and tenon *rupa i čep*	Forward stability / *stabilnost prema naprijed* (EN 1022, 6.2)	600 N	625 ± 15	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Rearward stability / *stabilnost prema natrag* (EN 1022, 6.6)	600 N	640 ± 20	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Sideways stability / *bočna stabilnost* (EN 1022, 6.4)	600 N	580 ± 10	Failed / *nije zadovoljavajući*
Mortise and tenon *rupa i čep*	Seat & back static load / *statičko opterećenje sjedala i naslona za leđa* (EN 1728, 6.4)	1600 N, 410 N	1620 ± 25	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Seat front edge static load / *statičko opterećenje prednjeg ruba sjedala* (EN 1728, 6.5)	1300 N	1325 ± 20	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Combined seat & back durability / *kombinirana trajnost sjedala i naslona za leđa* (EN 1728, 6.17)	1000 N, 330 N, 25,000 cycles	1010 ± 30	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Leg forward static load / *statičko opterećenje nogu prema naprijed* (EN 1728, 6.15)	1000 N	1020 ± 18	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Leg sideways static load / *statičko opterećenje nogu bočno* (EN 1728, 6.16)	1000 N	1015 ± 20	Passed / *zadovoljavajući*
Mortise and tenon *rupa i čep*	Seat impact / *udar na sjedalo* (EN 1728, 6.24)	600 N	610 ± 12	Passed / *zadovoljavajući*
Halving *preklop*	Forward stability / *stabilnost prema naprijed* (EN 1022, 6.2)	600 N	610 ± 12	Passed / *zadovoljavajući*
Halving *preklop*	Rearward stability / *stabilnost prema natrag* (EN 1022, 6.6)	600 N	625 ± 15	Passed / *prošao*
Halving *preklop*	Sideways stability / *bočna stabilnost* (EN 1022, 6.4)	600 N	555 ± 10	Failed / *nije zadovoljavajući*
Halving *preklop*	Seat & back static load / *statičko opterećenje sjedala i naslona za leđa* (EN 1728, 6.4)	1600 N, 410 N	1605 ± 28	Passed / *zadovoljavajući*
Halving *preklop*	Seat front edge static load / *statičko opterećenje prednjeg ruba sjedala* (EN 1728, 6.5)	1300 N	1310 ± 18	Passed / *zadovoljavajući*
Halving *preklop*	Combined seat & back durability / *kombinirana trajnost sjedala i naslona za leđa* (EN 1728, 6.17)	1000 N, 330 N, 25,000 cycles	1005 ± 25	Passed / *zadovoljavajući*
Halving *preklop*	Leg forward static load / *statičko opterećenje nogu prema naprijed* (EN 1728, 6.15)	1000 N	1008 ± 20	Passed / *zadovoljavajući*
Halving *preklop*	Leg sideways static load / *statičko opterećenje nogu bočno* (EN 1728, 6.16)	1000 N	1002 ± 22	Passed / *zadovoljavajući*
Halving *preklop*	Seat impact / *udar na sjedalo* (EN 1728, 6.24)	600 N	605 ± 15	Passed / *zadovoljavajući*
Dowel *moždanici*	Forward stability / *stabilnost prema naprijed* (EN 1022, 6.2)	600 N	600 ± 10	Passed / *zadovoljavajući*
Dowel *moždanici*	Rearward stability / *stabilnost prema natrag* (EN 1022, 6.6)	600 N	615 ± 15	Passed / *zadovoljavajući*
Dowel *moždanici*	Sideways stability / *bočna stabilnost* (EN 1022, 6.4)	600 N	540 ± 12	Failed / *nije zadovoljavajući*
Dowel *moždanici*	Seat & back static load / *statičko opterećenje sjedala i naslona za leđa* (EN 1728, 6.4)	1600 N, 410 N	1595 ± 30	Passed / *zadovoljavajući*
Dowel *moždanici*	Seat front edge static load / *statičko opterećenje prednjeg ruba sjedala* (EN 1728, 6.5)	1300 N	1305 ± 18	Passed / *zadovoljavajući*
Dowel *moždanici*	Combined seat & back durability / *kombinirana trajnost sjedala i naslona za leđa* (EN 1728, 6.17)	1000 N, 330 N, 25,000 cycles	1000 ± 20	Passed / *zadovoljavajući*
Dowel *moždanici*	Leg forward static load / *statičko opterećenje nogu prema naprijed* (EN 1728, 6.15)	1000 N	1005 ± 18	Passed / *zadovoljavajući*
Dowel *moždanici*	Leg sideways static load / *statičko opterećenje nogu bočno* (EN 1728, 6.16)	1000 N	998 ± 20	Passed / *zadovoljavajući*
Dowel *moždanici*	Seat impact / *udar na sjedalo* (EN 1728, 6.24)	600 N	600 ± 12	Passed / *zadovoljavajući*

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Furniture test results: mortise and tenon joint, halving join, and dowel joint
3.1. Rezultati ispitivanja namještaja: spoj rupe i čepa, spoj na preklop i spoj s moždanikom

Ultimate loads were recorded for all chair joint configurations. Mortise and tenon joints consistently exhibited the highest mean ultimate loads across all tests, followed by halving and dowel joints. In cases where failure did not occur, tests were terminated once the performance criteria specified in EN 1022 and EN 1728 criteria were satisfied. One-way analysis of variance (ANOVA) indicated significant differences between the joint types ($p < 0.05$), confirming that mortise and tenon joints exhibit significantly greater load-bearing capacity compared to halving and dowel joints. These findings highlight the mechanical superiority of mortise and tenon joints for structural applications in coco wood chair construction.

3.2 Stability tests and failure mechanisms
3.2. Ispitivanje stabilnosti i mehanizmi loma

3.2.1 Forward stability (EN 1022, 6.2)
3.2.1. Stabilnost prema naprijed (EN 1022, 6.2)

All three chair types demonstrated adequate resistance to forward tipping and maintained structural integrity under repeated loading conditions. No glue-line separation or wood failure was observed, confirming the effectiveness of the coco wood joints in ensuring functional stability (Ceylan *et al.,* 2021).

3.2.2 Rearward stability (EN 1022, 6.6)
3.2.2. Stabilnost prema natrag (EN 1022, 6.6)

The chairs successfully resisted rearward forces of 600 N without any indication of structural weakness. Neither glue-line separation nor wood failure was observed. These results support Dunbar's (2023) findings that rearward stability is a critical determinant of user safety and further validate the structural capacity of coco wood chairs under such loading conditions.

3.2.3 Sideways stability (EN 1022, 6.4)
3.2.3. Bočna stabilnost (EN 1022, 6.4)

All chair configurations failed under lateral loading, indicating a limitation in sideways stability. Mortise and tenon and halving joints mainly failed due to wood splitting near the joint, while dowel joints showed occasional glue-line failure. This suggests that dowel joints are more susceptible to adhesive-related stresses under lateral loading conditions. The findings are consistent with Vlaović (2024), who recommends that future designs incorporate cross-bracing elements or increased joint dimensions to enhance lateral performance.

Figure 4 Typical failure modes observed during testing
Slika 4. Tipični načini loma uočeni tijekom ispitivanja

3.2.4 Seat and back static load (EN 1728, 6.4)
3.2.4. Statičko opterećenje sjedala i naslona za leđa (EN 1728, 6.4)

All chairs withstood static loads of 1600 N on the seat and 410 N applied to the back without any visible damage. No glue-line separation or wood failure was observed, indicating high resistance to static loading. These results are consistent with Kasal *et al.* (2016), who emphasised the importance of joint selection in the effective distribution of static loads.

3.2.5 Seat front edge static load (EN 1728, 6.5)
3.2.5. Statičko opterećenje prednjeg ruba sjedala (EN 1728, 6.5)

Under a 1300 N static load applied at the front edge of the seat, all chairs successfully passed the test. Minor wood compression was observed near the joints in halving and dowel joint chairs, whereas mortise and tenon joints remained fully intact, confirming their superior load-bearing performance. These findings further support Kasal *et al*., (2016) assertion that front-edge structural integrity is essential for long-term furniture functionality.

3.2.6 Combined seat and back durability (EN 1728, 6.17)
3.2.6. Ispitivanje trajnosti sjedala i naslona za leđa (EN 1728, 6.17)

All chair configurations remained structurally sound after 25,000 loading cycles of 1000 N on the seat and 330 N on the backrest. No glue-line failure was recorded, demonstrating high durability under cyclic loading conditions. These results align with Smardzewski (2015), who identified endurance under repeated use as a key criterion of furniture quality.

3.2.7 Leg static load (EN 1728, 6.15 & 6.16)
3.2.7. Statičko opterećenje nogu prema naprijed i bočno (EN 1728, 6.15 i 6.16)

Both forward and sideways leg loading tests confirmed that the coco wood joints effectively distributed applied forces. These results corroborate the findings of Uysal *et al*. (2015), who reported that joints such as mortise and tenon and dowel joints provide excellent resistance to cyclic stresses.

3.2.8 Seat impact (EN 1728, 6.24)
3.2.8. Udarno ispitivanje sjedala (EN 1728, 6.24)

All chairs withstood repeated impact loading without structural failure. Minor surface cracking was observed only in dowel joints, indicating slightly reduced resistance to sudden loading compared with mortise and tenon and halving joints. These findings support Antal *et al*. (2015) the functions has always significant priority. The ever changing design philosophies require accommodations to the new viewpoints. These adaptations, along with technical and technological advances, eventually will lead to the decrease of products or production expenses. The objective may be realised by the application of cost – analysis of design and development methodology, prior to production. Thus, the unnecessary expenses could be eliminated. The essence of usage of functional analysis method in design is an abstract approach where the functions of the products are used to model the realisation of demands. The relationships between functions and function-expenses are defined and designed at every step of the development (design, who emphasised that furniture design must balance aesthetic quality and functional strength.

3.2.9 Novelty of the study
3.2.9. Izvornost istraživanja

The novelty of this study lies in its integrated evaluation of coco wood (*Cocos nucifera*) as a sustainable alternative to conventional hardwoods for furniture production in Ghana. Unlike previous studies that primarily focused on material properties, this research combines structural performance testing of traditional joints with an assessment of aesthetic suitability, using European testing standards.

The findings provide new insights into joint behaviour, durability, and design limitations – particularly lateral stability – thereby supporting evidence-based furniture design using locally available materials.

4 CONCLUSIONS
4. ZAKLJUČAK

The results indicate that coco wood chairs constructed with mortise and tenon, halving, and dowel joints exhibit satisfactory structural performance and acceptable aesthetic quality for light to medium-duty furniture applications. With the exception of sideways stability, all joint types met the relevant European performance standards. Mortise and tenon joints consistently demonstrated the highest strength and reliability, making them most suitable for load-bearing furniture applications.

Although halving and dowel joints performed adequately under most loading conditions, their reduced resistance to lateral forces highlights the need for design modifications, such as the incorporation of cross-bracing or increased joint dimensions.

Overall, coco wood has been shown to be a practical and sustainable material for furniture production with high potential for diversifying Ghana's timber resources. Future research should focus on enhancing lateral stability, increasing the sample size, and evaluating the economic feasibility of large-scale coco wood furniture manufacturing.

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5 REFERENCES
5. LITERATURA

1. Antal, M. R.; Horváth, P. G.; Domljan, D., 2015: Furniture design using function analysis. In: Proceedings of International Conference on Wood Science and Technology (ICWST 2015), March, 1-7.
2. Carpenter, D., 2021: Wood joinery: A comprehensive guide. Family Handyman.
3. Ceylan, E.; Güray, E.; Kasal, A., 2021: Structural analyses of wooden chairs by finite element method (FEM) and assessment of the cyclic loading performance in comparison with allowable design loads. Maderas: Ciencia y Tecnología, 23(1): 1-16. https://doi.org/10.4067/s0718-221x2021000100419
4. Dunbar, M., 2023: Furniture design: The four objectives – designing furniture. Snow Valley Furniture.
5. Fathi, L., 2014: Structure and Mechanical Properties of the Wood from Coconut Palms, Oil Palms and Date Palms. PhD Thesis, University of Hamburg, Germany.
6. Fathi, L.; Hasanagić, R.; Bjelić, A.; Bahmani, M., 2023: Performance of coconut wood in timber structures: A review of its properties and applications. IOP Conference Series: Materials Science and Engineering, 1298 (1): 012014. https://doi.org/10.1088/1757-899x/1298/1/012014
7. Goldman, A., 2001: The aesthetic. In: The Routledge Companion to Aesthetics. Routledge, London.

8. Gonzalez, O. M.; Gilbert, B. P.; Bailleres, H.; Guan, H., 2014: Senile coconut palm hierarchical structure as foundation for biomimetic applications. Applied Mechanics and Materials – Advances in Computational Methods, 553: 344-349. https://doi.org/10.4028/www.scientific.net/AMM.553.344
9. Han, J.; Forbes, H.; Schaefer, D., 2021: An exploration of how creativity, functionality and aesthetics are related in design. Research in Engineering Design, 32 (3): 289-307. https://doi.org/10.1007/s00163-021-00366-9
10. Handy, T. C.; Smilek, D.; Geiger, L.; Liu, C.; Schooler, J. W., 2008: ERP evidence for rapid hedonic evaluation of logos. Journal of Cognitive Neuroscience, 22: 124-138. https://doi.org/10.1162/jocn.2008.21180
11. Hughes, M., 2023: The art of woodworking: Craftsmanship meets creativity. Woodcraft Magazine.
12. Hummel, A., 2023: Exploring the strength and durability of coconut wood: A comprehensive guide. Mondoro.
13. Kasal, A.; Kuşkun, T.; Haviarova, E.; Erdil, Y. Z., 2016: Static front-to-back loading capacity of wood chairs and relationship between chair strength and individual joint strength. BioResources, 11 (4): 9359-9372. https://doi.org/10.15376/biores.11.4.9359-9372
14. Okai, R.; Frimpong-Mensah, K.; Arthu, S., 2004: Characterization of mechanical strength properties of coconut wood infested with the Cape St Paul Wilt disease. Agricultural and Food Sciences, 62: 390-392. https://doi.org/10.1007/s00107-004-0470-5
15. Rame, R.; Purwanto, P.; Sudarno, S., 2023: Transforming the furniture industry in the digital age. Jurnal Riset Teknologi Pencegahan Pencemaran Industri, 14: 53-69.
16. Schepman, A.; Rodway, P.; Kirkham, J. A.; Lambert, J.; Locke, A., 2018: Shared meaning in children's evaluations of art: A computational analysis. Psychology of Aesthetics, Creativity and the Arts, 12: 440-452. https://doi.org/10.1037/aca0000159
17. Sibley, F., 2001: Approach to Aesthetics: Collected Papers on Philosophical Aesthetics. Oxford University Press, Oxford.
18. Smardzewski, J., 2015: Furniture Design. Springer. https://doi.org/10.1007/978-3-319-19533-9
19. Uysal, M.; Haviarova, E.; Eckelman, C. A., 2015: A comparison of the cyclic durability, ease of disassembly, repair, and reuse of parts of wooden chair frames. Materials & Design, 87: 75-81. https://doi.org/10.1016/j.matdes.2015.08.009
20. Vlaović Z.; Gržan T.; Župčić I.; Domljan D.; Mihulja G., 2024: Strength, durability and aesthetics of corner joints and edge banding in furniture design: A review. Applied Sciences, 14 (22): 10285. https://doi.org/10.3390/app142210285
21. Zhu, Z.; Buck, D.; Wang, J.; Wu, Z.; Xu, W.; Guo, X., 2022: Machinability of different wood-plastic composites during peripheral milling. Materials, 15 (4): 1303. https://doi.org/10.3390/ma15041303
22. ***ASTM, 2014: ASTM D143-14: Standard Test Methods for Small Clear Specimens of Timber. ASTM International, West Conshohocken, PA, USA. https://www.astm.org/d0143-14.html (Accessed: Nov. 11, 2025).
23. ***BSI, 1999: BS 373:1957 (Reconfirmed 1999): Methods of Testing Small Clear Specimens of Timber. British Standards Institution, London. https://shop.bsigroup.com/ProductDetail/?pid=000000000000199017 (Accessed: Nov. 10, 2025).
24. ***BSI, 2012: BS EN 1728:2012: Furniture – Seating – Test Methods for the Determination of Strength and Durability. British Standards Institution, London. https://shop.bsigroup.com/ProductDetail/?pid=000000000030250413 (Accessed: Nov. 10, 2025).
25. ***CEN, 2018: EN 1022:2018 Furniture – Seating – Determination of Stability. European Committee for Standardization, Brussels, Belgium. https://standards.iteh.ai/catalog/standards/cen/5dd9a28d-52d9-4e07-b0e5-b9f-9d752a899/en-1022-2018 (Accessed: Nov. 10, 2025).
26. ***Furniture Crafters, 2022: Joinery: The heart and soul of fine woodworking.
27. ***GDS, 2024: Ghana Districts: A Repository of All Local Assemblies in Ghana. https://ghanadistricts.com (Accessed: Dec. 18, 2025).
28. ***IUCN, 2022: Mapping the health of forest reserves in Ghana. https://www.iucn.org/news/forest/201608/mapping-health-forest-reserves-ghana (Accessed: Jan. 25, 2026).

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Innovation and Competitive Characteristics in Local Forest Industry Enterprises: A Case Study

Inovacijska i konkurentska obilježja lokalnih poduzeća drvne industrije: studija slučaja

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ABSTRACT • *The forest products industry makes significant contributions to national economies in terms of basic economic indicators such as employment, expansion into rural areas, added value, investment and exports. This study aims to measure the innovation perception, awareness and competitiveness of small and medium-sized forest products enterprises operating in local areas on the basis of different variables. Within the scope of the study, a data collection tool including on-site observation, interviews and the developed scale was used on enterprises located in a local administrative region. The data obtained were subjected to hypothesis testing and correlation analysis. The findings revealed that the perception of innovation in small and medium-sized forest products industry enterprises is affected by demographic factors related to the enterprise managers, and basic factors related to the enterprise such as the number of employees, field of activity, duration of activity, annual average income, and product distribution channels. Furthermore, it has been determined that innovation awareness decreases as the scale of the enterprises shrinks. As a result, it can be said that the innovation and competition characteristics that are valid in the global and national forest products industry market are not yet fully applicable to local-scale and low-capacity enterprises.*

KEYWORDS: *products industry; innovation; small and medium-sized enterprise; competition*

SAŽETAK • *Drvna industrija znatno pridonosi nacionalnim gospodarstvima u smislu osnovnih ekonomskih pokazatelja kao što su zaposlenost, širenje u ruralna područja, dodana vrijednost, ulaganja i izvoz. Cilj ove studije bio je na temelju različitih varijabli izmjeriti percepciju inovacija, svijest i konkurentnost malih i srednjih drvnoindustrijskih poduzeća koja posluju na lokalnim područjima. U sklopu studije primijenjeni su ovi alati za prikupljanje podataka u poduzećima smještenima u lokalnoj administrativnoj regiji: izravno promatranje u poduzeću, intervjui i skala razvijenosti. Dobiveni su podatci podvrgnuti testiranju hipoteza i analizi korelacije. Rezultati su pokazali da na percepciju inovacija u malim i srednjim poduzećima u drvnoj industriji utječu demografski čimbenici povezani s menadžerima poduzeća i osnovni čimbenici povezani s poduzećem poput broja zaposlenika, područja djelovanja, trajanja djelovanja, prosječnoga godišnjeg prihoda i kanala distribucije proizvoda. Nadalje, utvrđeno je da je svijest o inovacijama razmjerna veličini poduzeća, tj. što je poduzeće manje, manja je i svijest o inovacijama.*

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Stoga se može reći da inovacijska i konkurentska obilježja koja vrijede na globalnome i nacionalnom tržištu drvne industrije još nisu u potpunosti primjenjiva na lokalna poduzeća i poduzeća malog kapaciteta.

KLJUČNE RIJEČI: *prerađivačka industrija; inovacija; malo i srednje poduzeće; konkurencija*

1 INTRODUCTION
1. UVOD

With globalization, the significant removal of trade barriers between countries has exposed enterprises to intense competitive conditions (Jovane *et al.,* 2017). On the other hand, developments in technology have emerged as an important qualitative variable in consumer demands (Kotler *et al.,* 2017; Loučanová *et al*., 2022). Global enterprises have the potential to gain a competitive advantage not only by utilizing cutting-edge technology but also through their product and cost policies (Tsai and Shih, 2004). Today, enterprises must compete under challenging conditions not only with companies producing products of the same quality but also with those producing substitute products. Enterprises have had to change their traditional products and production methods in line with changes in market conditions (Aytekin and Pekkaya, 2021; Uhan *et al*., 2023; Humaira, 2024). This process has necessitated innovations in accordance with environmental changes (Moore, 2015). Increased competition in the goods and services market has heightened the importance of the concept of innovation (Vives, 2008).

In other words, innovation is the process of taking an idea from the discovery stage to implementation. It generally includes the research, development, and production stages (Lane and Flagg, 2010). The prediction that enterprises cannot sustain competition by maintaining traditional product and service approaches in changing market conditions has led them to focus on innovation, making innovation a new competitive tool among enterprises (Pirc-Barčić and Motik, 2013). Large enterprises with strong capital structures can allocate more budget to R&D activities and leverage their innovation advantage (Shefer and Frenkel, 2005). On the other hand, large organizational structures and the inability to respond quickly to changes in demand have had a negative impact on large companies in terms of innovation. Small and medium-sized enterprises (SMEs), unlike large enterprises, have been able to achieve greater success in innovation due to their more flexible structures, their ability to maintain close communication with customers, and their capacity to adapt product and service processes to customer requirements (Allocca and Kessler, 2006).

SMEs account for a significant proportion of enterprises in national economies (Robu, 2013; Zafar and Mustafa, 2017; Ndiaye *et al.,* 2018; Barinova and Zempsov, 2019). On the other hand, it carries significant importance in terms of employment, added value, investment, exports, taxes, etc. (Sertić *et al.,* 2018). It is reported that 95 – 99 % of enterprises worldwide are SMEs, with SMEs accounting for 30 – 60 % of investments, 40 – 80 % of total employment, and 30 – 70 % of Gross Domestic Product (GDP). As of the end of 2022, it is seen that SMEs constitute 99.7 % of all enterprises in Turkey. In terms of personnel numbers, SMEs account for 70.6 % of total employment (Ketboğa, 2024). On the other hand, according to the latest statistics released in 2024, the number of personnel employed in the forest products sector in Türkiye was reported as 309,797 (SGK, 2024). This number of employees corresponds to approximately 2 % of total employment. The number of enterprises operating in the Turkish forest products industry (European Union's NACE Rev.2 statistical economic activity classifications 16, 17, and 31) is 46,550 (SGK, 2024). In 40,093 of these enterprises (86 %), the number of employees is less than 10 (SGK, 2024). The Turkish forest products sector accounts for a significant share of the country's economy, but the sector's overall structure consists of small and medium-sized enterprises.

It is clear that SMEs, which occupy an important place in the forest products industry sector, play a significant role in the distribution of capital. It is considered an inevitable necessity for these enterprises to carry out innovation-focused activities in order to maintain their existence and develop their competitive strength. The aim of this study is to determine the level of innovation awareness among local forestry industry enterprises. In this context, the key factors influencing this awareness and the differences in awareness based on these factors will be identified. Consequently, the study will highlight the areas that need to be focused on in order to improve innovation and, consequently, the competitive capabilities of enterprises in the local forestry industry sector.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research was conducted among small and medium-sized enterprises (SMEs) operating in the forest products industry within the province of Gümüşhane. In order to implement the research, it was determined that there was a total of 85 enterprises in the study area according to the records of the Chamber of Commerce and Industry, the Chamber of Tradesmen and Craftsmen in the province and districts, and the

Social Security Institution (SGK, 2024). Therefore, the study was carried out within the scope of the main sectors of “Manufacturing of wood, wood products and cork products (excluding furniture); manufacturing of articles made by weaving reeds, straw and similar materials” (NACE Rev. 2 code 16) and “Manufacturing of furniture” (NACE Rev. 2 code 31).

2.1 Data collection instrument
2.1. Instrument za prikupljanje podataka

In this study, a face-to-face interview-based survey was used as a data collection tool to determine the perception and awareness of innovation among enterprises owners and officials. The statements included in the research scale were structured according to a 5-point Likert scale. The statements were structured as follows: (1) Strongly disagree, (2) Disagree, (3) Undecided, (4) Agree, (5) Strongly agree. The research design consisted of 19 questions and 16 statements, including related sub-questions in the survey section. Different sources related to the subject were used in preparing the survey questions (Kanber, 2010; Demir, 2014; Karaman, 2019). Data was collected between April and August 2024.

2.2 Data collection
2.2. Prikupljanje podataka

In this study, conducted in enterprises engaged in wood, woodworking and furniture manufacturing within the scope of the field of work, the minimum number of participating enterprises required to reach generalizable conclusions regarding innovation was calculated using formula 1 (Baş, 2006).

$$n = (N \cdot t^2 \cdot p \cdot q) / (d^2 \cdot (N-1) + t^2 \cdot p \cdot q) \quad (1)$$

N – number of elements in the universe (total number of workplaces), n – sample size, t – confidence coefficient, p – probability of the attribute being observed in the universe, q – probability of the attribute not being observed in the universe (1-p), d – sampling error.

In the study, sampling error was included in the calculation as $t = 1.96$ for a 95 % confidence level. The variable values p and q were considered as 0.5.

Within the scope of the research area, a total of 85 enterprises were identified in the fields of tree, woodworking and furniture manufacturing (SGK, 2024). Therefore, the research population was determined to be 85. In this study, the minimum sample size required from a known population was calculated as 45. A total of 128 sector employees from 49 enterprises were reached for the study.

The reliability (internal consistency) of the data collection tool was calculated using Cronbach’s Alpha Reliability Coefficient. The suitability of the data obtained as a result of the application of the data collection tool for factor analysis was examined using Bartlett’s Sphericity test and the Kaiser-Meyer-Olkin (KMO) coefficient (Kalaycı, 2010; Baş, 2006).

2.3 Analysis of data
2.3. Analiza podataka

The scale included in the data collection instrument used in this study was developed specifically for this study. During the scale development process, a pre-test was administered to 15 participants using 20 variables. Based on the evaluation of the pre-test data, 4 variables that were found difficult for participants to understand and evaluate were removed from the scale. The final test of the study was conducted using a 16-variable scale. The data obtained were subjected to validity and reliability analyses, and these findings revealed that the data set was suitable for factor analysis (Kalaycı, 2010).

To determine the analysis method to be used in the study, Kolmogorov Smirnov and Shapiro Wilk normality tests were performed on the 16 statements included in the scale. The results obtained from both tests were significant at the $p < 0.05$ level ($p = 0.000$ for all statements), indicating that the data did not show a normal distribution (Baştürk, 2011). On the other hand, since the calculated Skewness and Kurtosis values did not fall within the range of -2 to +2 (George and Mallery, 2012), it was decided that non-parametric tests should be used in analyses based on the scale.

In order to simplify the statistical analyses to be used, the 16 variables in the scale were grouped into 4 different groups based on the main idea to be measured. These groups are new product development, market research and customer satisfaction, technological development and organizational development, new enterprises ideas, methods and information.

The study included hypothesis testing as well as correlation analysis aimed at identifying the relationship between innovation factors and research variables. In this context, SPSS version 20 statistical analysis software (IBM Corp., Armonk, NY, USA) was utilized.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In the study, a KMO validity analysis was applied to test the validity of the data and the suitability of factor analysis. As a result of the analyses, the KMO coefficient was calculated as 0.657, and the Bartlett test result was found to be significant ($p < 0.05$) with a $p = 0.000$ value. These values indicate that the data collection tool meets the KMO coefficient adequacy condition of KMO>0.500 (Kalaycı, 2010). The reliability of the data was tested using the Cronbach Alpha method, one of the most preferred methods in data collection tools (Kula Kartal and Mor Dirlik, 2016), and

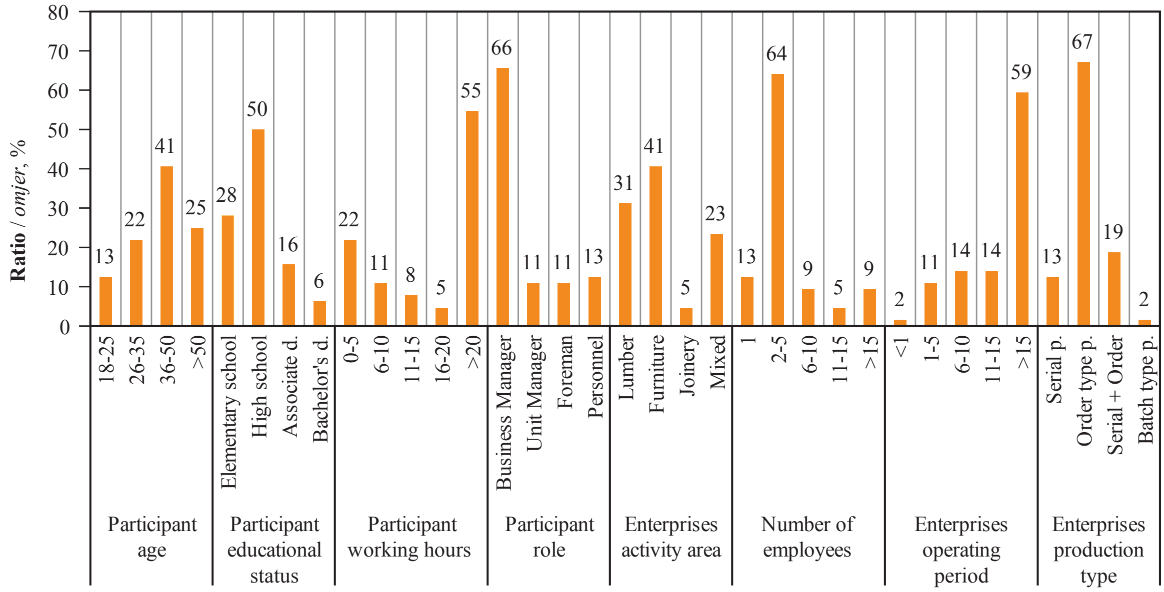

Figure 1 Distribution of participants and enterprises based on certain variables
Slika 1. Raspodjela sudionika i poduzeća na temelju određenih varijabli

the Cronbach Alpha Coefficient (α) was calculated as 0.849. The fact that the reliability coefficient meets the condition of $0.80 < \alpha < 1.00$ indicates that the data is highly reliable (Kalaycı, 2010; Yıldız and Uzunsakal, 2018).

Participants in the study were clustered as follows: 63 % were aged 26-50, 78 % had a high school education or below, 60 % had over 15 years of work experience, and 66 % were enterprises executives. On the other hand, the enterprises were clustered as follows: 41 % in the furniture sector, 77 % with 1-5 employees, 59 % operating for over 15 years, and 67 % engaged in order-type production (Figure 1).

Information regarding the enterprises examined in this study is given in Figure 2. Furniture enterprises had the highest participation rate at 45 %, while joinery enterprises had the lowest at 6 %. It was determined that 65 % of the participating enterprises had between 2 and 5 employees. 55 % of the enterprises had been operating for less than 10 years in total. 71 % of the participating enterprises carry out order-based production.

It has been observed that enterprises plans regarding innovation-driven machine renewal (5 %) and production system renewal (2 %) factors remain at a low level. On the other hand, it has been understood that plans for machine renewal are related to increasing production capacity. It has been determined that the current situation is largely considered sufficient, or that machine renewal is seen as a priority goal to ensure the

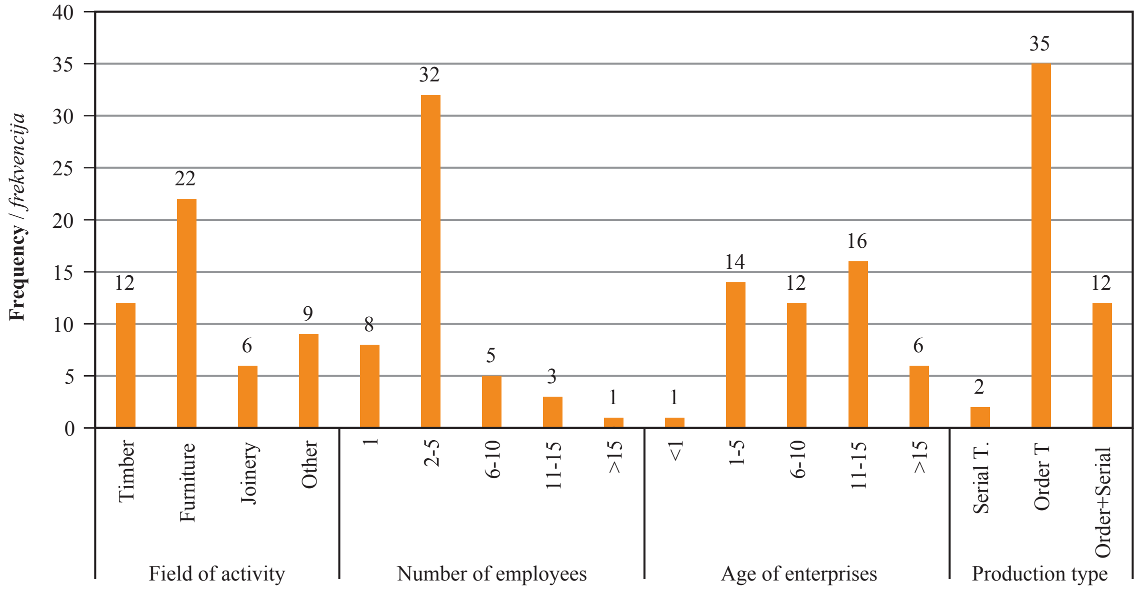

Figure 2 Distribution of participants and enterprises based on certain variables
Slika 2. Raspodjela sudionika i poduzeća na temelju određenih varijabli

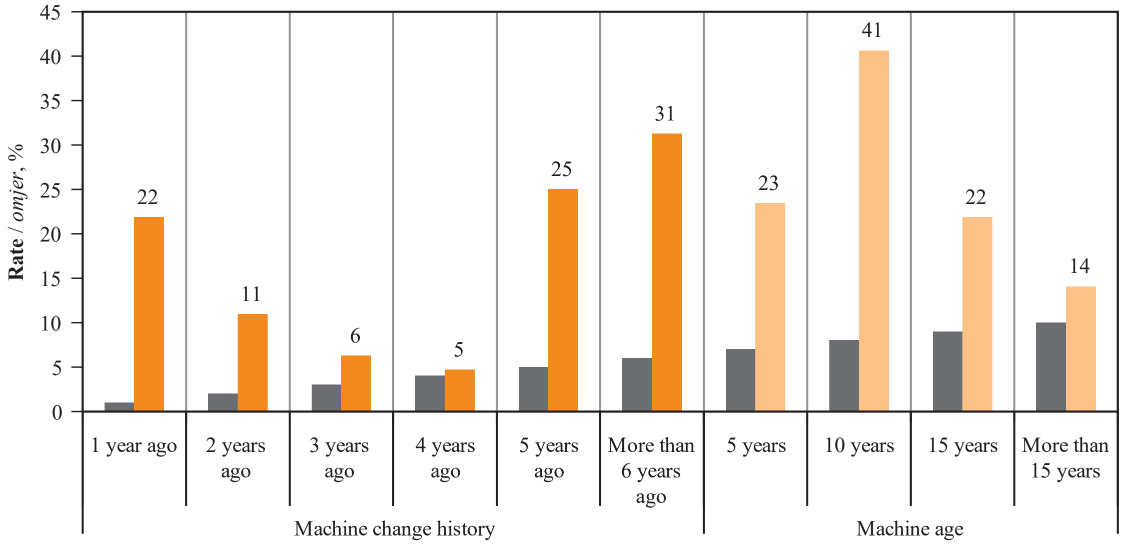

Figure 3 Machinery and equipment renewal history of enterprises
Slika 3. Povijest obnove strojeva i opreme poduzeća

employment of workers for the increase in production capacity. Similarly, in the Zambian timber industry, the Cobb-Douglas model showed that sawn timber recovery depends on operator skills, especially in non-automated machines, which are common (Mandiringana *et al.,* 2022).

Within the scope of the study, 75 % of the enterprises evaluated the use of direct sales methods, while 20 % offer their products to consumers in company-owned stores. It was found that only 5 % of enterprises use wholesaler or retailer marketing channels. On the other hand, it was determined that 63 % of enterprises do not use any product promotion method, while 37 % of enterprises engage in product promotion on a limited scale.

It was determined that 56 % of the enterprises included in the study had renewed their machinery and equipment more than five years ago, while 33 % have renewed their machinery and equipment in the last two years. Furthermore, it was found that 77 % of the existing machines in the enterprises had been in use for over 10 years (Figure 3). On the other hand, it was observed that 86 % of the enterprises have not made any changes to inputs such as raw materials or semi-finished products since their establishment.

The study found that the age of employees working in the companies included in the study was a differentiating factor in their views on innovation factors. Employees aged 18-25 were the group with the most positive attitude toward innovation factors. Employees aged 26-35, on the other hand, were found to be the group with the lowest average positive opinion overall. Statistically significant differences ($p < 0.05$) were found between the educational levels of enterprises employees and their views on innovation factors. In terms of innovation factors, it was determined that the average opinions of participants with a high school education level were generally high, while participants with a bachelor's degree had the lowest average opinions across all factors (Table 1).

Innovation factors were determined using relevant literature (Table 1) (Cao and Hansen, 2006; Çetin and Gedik, 2017; Ayşin, 2019).

The study found statistically significant differences ($p < 0.05$) between participants' views on innovation factors and their length of service in the sector. The results showed that employees with 0-5 years of work experience in the sector and participants with more than 20 years of work experience had on average the highest opinion on innovation factors. On the other hand, participants with 16-20 years of work experience had on average the lowest opinion on innovation factors. The analyses revealed differences in participants' views on the new product development innovation factor based on the average annual income levels of enterprises. It was observed that an increase in average annual income levels raised awareness of new product development in the sector (Table 2).

In the analyses based on the participants' roles within the company, statistically significant differences in opinion ($p < 0.05$) were found in market research and customer satisfaction, technological development and organizational development, and new enterprises ideas, methods, and knowledge factors. It was determined that enterprises owners had the highest level of awareness in the specified innovation factors. On the other hand, it was observed that innovation awareness among employees without administrative roles in the enterprises remained at a low level. Statistically significant differences ($p < 0.05$) were found between the opinions of participants regarding the innovation factor of new product development based on the activity area

Table 1 Kruskal-Wallis analysis results on innovation factors scale according to age and education status of employees
Tablica 1. Rezultati Kruskal-Wallisove analize inovacijskih čimbenika s obzirom na dob i razinu obrazovanja zaposlenika

Innovation factors *Inovacijski čimbenici*	**Age** *Dob*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig.** **(*p < 0.05)**	**Educational status** *Razina obrazovanja*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig.** **(*p < 0.05)**
New product development *razvoj novog proizvoda*	18-25	16	92.5	11.932	0.008*	Elementary school / *osnovna škola*	36	61.17	13.191	0.004*
	26-35	28	58.29			High school / *srednja škola*	64	73.63		
	36-50	52	63.77			Associate d. / *stručni studij*	20	55.10		
	> 50	32	57.13			Bachelor's d. / *prvostupnik*	8	30.00		
	Total *Ukupno*	128				Total / *Ukupno*	128			
Market research and customer satisfaction *istraživanje tržišta i zadovoljstvo kupaca*	18-25	16	81.63	18.014	0.000*	Elementary school / *osnovna škola*	36	71.67	22.281	0.000*
	26-35	28	43.64			High school / *srednja škola*	64	70.06		
	36-50	52	70.42			Associate d. / *stručni studij*	20	51.70		
	> 50	32	64.56			Bachelor's d. / *prvostupnik*	8	19.75		
	Total *Ukupno*	128				Total / Ukupno	128			
Technological development and organizational development *tehnološki i organizacijski razvoj*	18-25	16	61.13	10.304	0.016*	Elementary school / *osnovna škola*	36	65.94	16.728	0.001*
	26-35	28	46.21			High school / *srednja škola*	64	73,69		
	36-50	52	69.73			Associate d. / *stručni studij*	20	47.10		
	> 50	32	73.69			Bachelor's d. / prvostupnik	8	28.00		
	Total *Ukupno*	128				Total / *Ukupno*	128			
New enterprises ideas, methods, and knowledge *nove ideje, metode i znanja poduzeća*	18-25	16	70.00	10.021	0.018*	Elementary school / osnovna škola	36	68.17	17.522	0.001*
	26-35	28	45.71			High school / *srednja škola*	62	70.11		
	36-50	52	69.26			Associate d. / stručni studij	20	51.10		
	> 50	32	66.81			Bachelor's d. / *prvostupnik*	8	22.25		
	Total *Ukupno*	128				Total / *Ukupno*	126			

Table 2 Kruskal-Wallis analysis results on innovation factors scale according to enterprises annual average revenue and participants' work duration
Tablica 2. Rezultati Kruskal-Wallisove analize inovacijskih čimbenika s obzirom na prosječni godišnji prihod poduzeća i radni staž zaposlenika

Innovation factors *Inovacijski* ***čimbenici***	**Annual average income, USD**** *Prosječni godišnji prihod, USD***	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig. (*p < 0.05)**	**Working period, years** *Radni odnos, godine*	**Freq., N** *Frekv., Br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig. (*p < 0.05)**
New product development *razvoj novog proizvoda*	< 17870	34	63.62	10.896	0.028*	0-5	28	88.71	19.462	0.001*
	17870-23827	28	55.14			6-10	14	60.36		
	23827-35741	14	45.64			11-15	10	44.30		
	35741-47654	20	70.70			16-20	6	41.17		
	> 47654	32	78.00			> 20	70	60.53		
	Total	128				Total	128			
Market research and customer satisfaction *istraživanje tržišta i zadovoljstvo kupaca*	< 17870	34	68.50	4.699	0.320	0-5	28	65.57	19.288	0.001*
	17870-23827	28	68.14			6-10	14	53.36		
	23827-35741	14	51.07			11-15	10	61.70		
	35741-47654	20	57.00			16-20	6	14.17		
	> 47654	32	67.63			> 20	70	71.01		
	Total	128				Total	128			
Technological development and organizational development *tehnološki i organizacijski razvoj*	< 17870	34	64.68	6.558	0.161	0-5	28	60.86	13.010	0.011*
	17870-23827	28	78.64			6-10	14	42.36		
	23827-35741	14	63.79			11-15	10	55.70		
	35741-47654	20	59.00			16-20	6	40.83		
	> 47654	32	55.69			> 20	70	73.67		
	Total	128				Total	128			
New enterprises ideas, methods, and knowledge *nove ideje, metode i znanja poduzeća*	< 17870	34	66.74	8.147	0.086	0-5	28	66.00	20.525	0.000*
	17870-23827	28	75.71			6-10	14	49.21		
	23827-35741	14	46.93			11-15	8	53.75		
	35741-47654	18	60.28			16-20	6	11.83		
	> 47654	32	58.44			> 20	70	70.90		
	Total	126				Total	126			

**As of 10/22/2025, the exchange rate is 1USD = 41.9692 TL
**Tečaj dana 22.10.2025. 1USD = 41,9692 TL

Table 3 Kruskal-Wallis analysis results on innovation factors scale according to participants' roles and enterprises activity
Tablica 3. Rezultati Kruskal-Wallisove analize inovacijskih čimbenika s obzirom na ulogu ispitanika i aktivnosti poduzeća

Innovation factors *Inovacijski čimbenici*	**Task** *Uloga*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig.** **(*p < 0.05)**	**Field of activity** *Područje aktivnosti*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig.** **(*p < 0.05)**
New product development *razvoj novog proizvoda*	Ent. Owner / *vlasnik*	84	65.60	1.544	0.672	Lumber / *piljena građa*	40	81.70	15.229	0.002*
	Unit manager / *voditelj*	14	53.64			Furniture / *namještaj*	52	52.81		
	Foreman / *predradnik*	14	68.64			Joinery / *stolarija*	6	70.83		
	Other / *drugo*	16	64.63			Other / *ostalo*	30	60.57		
	Total / *Ukupno*	128				Total / *Ukupno*	128			
Market research and customer satisfaction *straživanje tržišta i zadovoljst-vo kupaca*	Ent. Owner *vlasnik*	84	69.76	16.557	0.001*	Lumber / *piljena građa*	40	68.05	1.425	0.700
	Unit manager / *voditelj*	14	68.36			Furniture / *namještaj*	52	61.73		
	Foreman / *predradnik*	14	63.64			Joinery / *stolarija*	6	73.50		
	Other / *drugo*	16	34.25			Other / *ostalo*	30	62.77		
	Total / Ukupno	128				Total / *Ukupno*	128			
Technological development and organizational development *tehnološki i organizacijski razvoj*	Ent. Owner / *vlasnik*	84	76.95	29,962	0,000*	Lumber / *piljena građa*	40	65.70	0.685	0.877
	Unit manager / *voditelj*	14	31.36			Furniture / *namještaj*	52	66.50		
	Foreman / *predradnik*	14	46.5			Joinery / *stolarija*	6	59.83		
	Other / *drugo*	16	43.88			Other / *ostalo*	30	60.37		
	Total / *Ukupno*	128				Total / *Ukupno*	128			
New enterprises ideas, methods, and knowledge *nove ideje, metode i znanja poduzeća*	Ent. Owner / *vlasnik*	82	72.87	19,88	0,000*	Lumber / *piljena građa*	38	58.71	5.909	0.116
	Unit manager / *voditelj*	14	49.21			Furniture / *namještaj*	52	64.54		
	Foreman / *predradnik*	14	53.5			Joinery / *stolarija*	6	94.50		
	Other / *drugo*	16	36.75			Other / *ostalo*	30	61.57		
	Total / *Ukupno*	126				Total / *Ukupno*	126			

Table 4 Kruskal-Wallis analysis results on innovation factors scale according to distribution channels of enterprises
Tablica 4. Rezultati Kruskal-Wallisove analize inovacijskih čimbenika s obzirom na distribucijske kanale poduzeća

Innovation factors *Inovacijski čimbenici*	**Distribution channels** *Distribucijski kanali*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig.** **(*p < 0.05)**
New product development *razvoj novog proizvoda*	Direct delivery / *direktna dostava*	96	66.92	2.053	0.358
	Own store / *vlastita trgovina*	26	58.96		
	Wholesale/retail / *veleprodaja/maloprodaja*	6	49.83		
	Total / Ukupno	128			
Market research and customer satisfaction *istraživanje tržišta i zadovoljstvo kupaca*	Direct deliveryd / *direktna dostava*	96	67.50	4.298	0.117
	Own store / *vlastita trgovina*	26	58.19		
	Wholesale/retail / *veleprodaja/maloprodaja*	6	43.83		
	Total / *Ukupno*	128			
Technological development and organizational development / *tehnološki i organizacijski razvoj*	Direct delivery / *direktna dostava*	96	71.52	17.403	0.000*
	Own store / *vlastita trgovina*	26	37.96		
	Wholesale/retail / *veleprodaja/maloprodaja*	6	67.17		
	Total / *Ukupno*	128			
New enterprises ideas, methods, and knowledge *nove ideje, metode i znanja poduzeća*	Direct delivery / *direktna dostava*	94	68.97	9.958	0.007*
	Own store / *vlastita trgovina*	26	45.73		
	Wholesale/retail / *veleprodaja/maloprodaja*	6	54.83		
	Total / *Ukupno*	126			

of the enterprise. Accordingly, the highest average opinion was recorded in the lumber sector, while the lowest was recorded in the furniture sector (Table 3).

Statistically significant differences in opinion were identified among enterprises based on distribution channels, technological development, and organizational development, as well as innovation factors of new enterprise ideas, methods, and knowledge. For both innovation factors, it was found that the average opinion scores of employees working for enterprises that offer their products to consumers in their own stores were the lowest, while the highest average opinion scores belonged to employees working for enterprises that deliver directly (Table 4).

Based on the total number of employees in enterprises, statistically significant differences in opinion were identified regarding the innovation factor in new product development. Analyses determined that the highest average opinion was among participants in enterprises with more than 15 employees, indicating that positive opinions regarding innovation awareness increase with enterprises scale. Based on the duration of enterprises operations, statistically significant differences in opinions were identified regarding innovation factors such as new product development, market research, and customer satisfaction. It revealed that the highest average opinion for both innovation factors was among enterprises with 6-10 years of operation. In

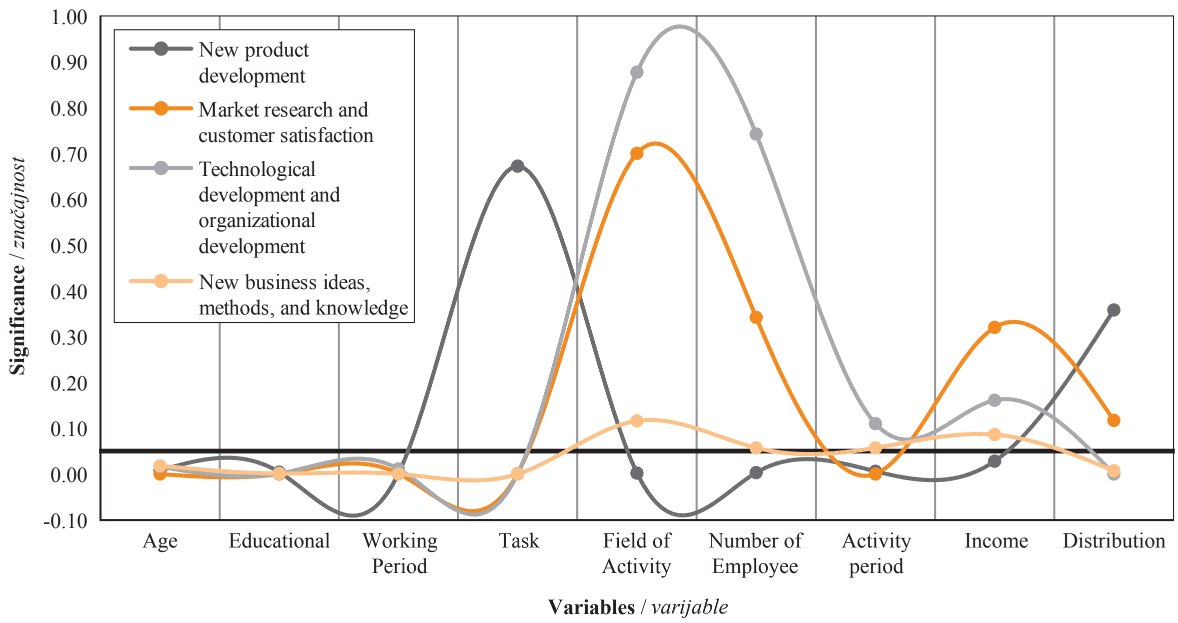

Figure 4 Statistical significance of innovation factors based on different variables
Slika 4. Statistička značajnost inovacijskih čimbenika na temelju različitih varijabli

Table 5 Kruskal-Wallis analysis results on innovation factors scale according to the number of employees and duration of operations
Tablica 5. Rezultati Kruskal-Wallisove analize inovacijskih čimbenika s obzirom na broj zaposlenika i trajanje poslovanja

Innovation factors *Inovacijski čimbenici*	**Number of employees** *Broj zaposlenika*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig. (*p < 0.05)**	**Duration of activity, years** *Trajanje aktivnosti*	**Freq., N** *Frekv., br.*	**Mean rank** *Rang srednje vrijednosti*	**Chi-Square** *hi-kvadrat*	**Sig. (*p < 0.05)**
New product development *razvoj novog proizvoda*	1	16	60.00	15.778	0.003*	< 1	2	37.50	14.277	0.006*
	2-5	82	59.72			1-5	14	65.64		
	6-10	12	56.83			6-10	18	92.83		
	11-15	6	89.83			11-15	18	61.83		
	> 15	12	98.17			> 15	76	58.92		
	Total / *Ukupno*	128				Total / *Ukupno*	128			
Market research and customer satisfaction *istraživanje tržišta i zadovoljstvo kupaca*	1	16	68.88	4.508	0.342	< 1	2	43.50	21.358	0.000*
	2-5	82	63.33			1-5	14	36.64		
	6-10	12	53.00			6-10	18	88.50		
	11-15	6	62.17			11-15	18	66.06		
	> 15	12	79.33			> 15	76	64.13		
	Total / *Ukupno*	128				Total / *Ukupno*	128			
Technological development and organizational development *tehnološki i organizacijski razvoj*	1	16	58.00	1.965	0.742	< 1	2	33.50	7.529	0.110
	2-5	82	63.01			1-5	14	56.50		
	6-10	12	73.00			6-10	18	53.39		
	11-15	6	73.17			11-15	18	80.94		
	> 15	12	70.50			> 15	76	65.53		
	Total / *Ukupno*	128				Total / *Ukupno*	128			
New enterprises ideas, methods, and knowledge *nove ideje, metode i znanja poduzeća*	1	16	73.63	9.182	0.057	< 1	2	94.50	9.155	0.057
	2-5	82	59.65			1-5	14	41.79		
	6-10	10	49.10			6-10	18	72.72		
	11-15	6	71.17			11-15	16	59.63		
	> 15	12	84.50			> 15	76	65.32		
	Total / *Ukupno*	126				Total / *Ukupno*	126			

enterprises under 5 years of operation, the average opinion remained low overall (Table 5).

Analyses conducted on the data obtained revealed that the variables of age, education, and participants' length of service caused differences in opinion among employees regarding all innovation factors. Therefore, it was understood that there is a high level of correlation between these variables and innovation factors (Figure 4).

Among the innovation factors, the highest level of opinion divergence was observed in the new product development factor. The effect of the other three innovation factors on the divergence of opinions was found to be at the same level (Figure 4). Similar to the findings of this study, a study aiming to measure the competitiveness level of forest industry enterprises concluded that enterprises considered themselves sufficient in terms of new product development (Akyüz *et al.,* 2010). Another study in the literature reports that forest industry enterprises, particularly at the SME level, predominantly use traditional production methods (Karayılmazlar *et al.,* 2008). Therefore, it can be said that innovation has emerged as an important requirement for enterprises at the SME level. On the other hand, similar to the results of this study, it has been stated that 85.5 % of SME-level forest industry enterprises in Turkey Balıkesir strive to keep up with new developments, but capital inadequacy poses a significant problem (Kalafat, 2012). Another study conducted in Turkey *İnegöl* reported that 97.4 % of enterprises follow sectoral innovations and developments (Sevim Korkut and Bozkurt Küçük, 2016).

Innovation factors and research pattern variables were examined using correlation analysis. A positive correlation was found between the ages of industry representatives and their willingness to develop technology and organization. Additionally, a negative correlation was found between the participants' education level and all innovation factors. Similarly, there is a negative correlation between the participant's length of service and the new product development factor. A negative correlation was found, indicating that interest in innovation factors increased as the participants' level of authority in the company decreased. A positive correlation was observed between the duration of the company's operations and the factors of conducting market research and considering customer satisfaction (Table 6). The main reasons for the low perception of the sector among demographic factors are the limited career development opportunities due to the dominance of family-controlled small and medium-sized enterprises (SMEs) in the sector and the discouraging attitudes of family members and friends (Ratnasingam *et al.,* 2022).

Forest industry enterprises face difficulties in obtaining capital, qualified personnel, technical equipment, and the supply of raw materials or semi-finished products of the desired quality (Karayılmazlar *et al.,* 2008). It is reported that the growth of these enterprises and their desire to expand into different markets are restricted by the large amount of capital required (Ng and Thiruchelvam, 2012; Ratnasingam *et al.,* 2018). It has been emphasized that the transition to innovative production and the creation of greater added value in these enterprises can be achieved through clustering initiatives (Şener Uzcan and Karayılmazlar, 2018; Ratnasingam *et al.,* 2018).

4 CONCLUSIONS
4. ZAKLJUČAK

This study examined the perception of innovation in local forestry industry enterprises and the individual and company-specific factors influencing these perceptions. The results showed that the enterprises are largely small-scale, have traditional production structures, and that innovation-focused investments are limited. The long frequency of machinery and production system renewals, the long-term use of existing machinery, and the lack of changes in the input structure indicate that innovation is mostly perceived as a functional element for ensuring production continuity, rather than a strategic competitive tool.

Analyses of demographic variables showed that age, education level, and length of service in the sector led to significant differences in perceptions of innovation factors. Younger employees had a more positive attitude towards innovation, while innovation awareness decreased as education level and sector experience increased.

Based on company characteristics, it was observed that awareness, particularly regarding new product development, increased with the number of employees and annual income level. This reveals that financial capacity and organizational scale are important factors supporting innovation activities. Furthermore, the fact that business owners have higher innovation awareness compared to non-managerial employees indicates that innovation knowledge has not been sufficiently disseminated within the business. Overall, the study results reveal that the level of innovation in local forestry industry enterprises is closely related to human capital characteristics, enterprise scale, and economic capacity.

In this context, strengthening access to finance for small-scale enterprises, expanding training and capacity-building programs aimed at increasing innovation awareness, and supporting organizational structures that encourage knowledge sharing can contribute

Table 6 Correlation analysis of innovation factors and research variables
Tablica 6. Korelacijska analiza inovacijskih *čimbenika* i istraživanih varijabli

Variables *Varijable*	**New product development** *Razvoj novog proizvoda*			**Market research and customer satisfaction** *Istraživanje tržišta i zadovoljstvo kupaca*			**Technological development and organizational development** *Tehnološki i organizacijski razvoj*			**New enterprises ideas, methods, and knowledge** *Nove ideje, metode i znanja poduzeća*		
	Pearson Corr.	Sig. (*$p < 0.05$)	N	Pearson Corr.	Sig. (*$p < 0.05$)	N	Pearson Corr.	Sig. (*$p < 0.05$)	N	Pearson Corr.	Sig. (*$p < 0.05$)	N
Age *dob*	-0.144	0.106	128	-0.008	0.932	128	0.192*	0.030	128	0.056	0.533	126
Educational status *razina obrazovanja*	-0.175*	0.049	128	-0.281*	0.001	128	-0.268*	0.002	128	-0.250*	0.004	126
Working period *radni odnos*	-0.186*	0.036	128	0.113	0.204	128	0.202*	0.022	128	0.098	0.273	126
Task *uloga*	-0.021	0.815	128	-0.353*	0.000	128	-0.369*	0.000	128	-0.365*	0.000	126
Field of activity *područje aktivnosti*	-0.141	0.113	128	-0.013	0.881	128	-0.063	0.483	128	-0.015	0.868	126
Number of employees *broj zaposlenih*	0.285*	0.001	128	0.034	0.702	128	0.107	0.228	128	0.092	0.306	126
Activity period *trajanje aktivnosti*	-0.155	0.08	128	0.179*	0.043	128	0.063	0.477	128	0.123	0.169	126
Income *prihod*	0.088	0.325	128	-0.011	0.903	128	-0.146	0.101	128	-0.118	0.188	126
Distribution *distribucija*	-0.069	0.442	128	-0.132	0.139	128	-0.271*	0.002	128	-0.197*	0.027	126

to increasing innovation-based competitiveness in the sector.

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5 REFERENCES
5. LITERATURA

1. Akyüz, C. K.; Gedik, T.; Akyüz, İ., 2010: Competitive strategies and quality approaches of the enterprises in Trabzon Arsin Organized Industrial Zone. International Journal of Economic and Administrative Studies, 4 (1): 65-82.
2. Allocca, M. A.; Kessler, E. H., 2006: Innovation speed in small and medium-sized enterprises. Creativity and Innovation Management, 15 (3): 279-295. https://doi.org/10.1111/j.1467-8691.2006.00389.x
3. Ayşin, A., 2019: Determining the innovation capabilities of medium and large-sized furniture enterprises: The example of Marmara, Aegean and Central Anatolia regions. PhD Thesis, Bartın University, Bartın, Türkiye.
4. Aytekin, A.; Pekkaya, M., 2021: Determining the competencies necessary for exporting in furniture industry with decision tree models. Drvna industrija, 72 (1): 13-30. https://doi.org/10.5552/drvind.2021.1952
5. Barinova, V. A.; Zempsov, S. P., 2019: International comparative analysis of the role of small and medium-sized enterprises in the national economy: A Statistical study. Voprosy Statistiki, 26 (6): 55-71. https://doi.org/10.34023/2313-6383-2019-26-6-55-71
6. Baş, T., 2006: How to Prepare a Survey? How to Administer a Survey? How to Evaluate a Survey?, 4th ed. Seçkin Publishing, Ankara (in Turkey).
7. Baştürk, R., 2011: All Aspects of Nonparametric Statistical Methods with SPSS Examples, 2nd ed. Anı Publishing, Ankara (in Turkey).
8. Cao, X., Hansen, E. N., 2006: Innovation in China's furniture industry. Forest Products Journal, 56 (11/12): 33-42.
9. Çetin Gedik, T., 2017: The factors affecting innovation in enterprises: Sample of Karaman. Journal of Management Economics and Business, ICMEB17 Special Issue: 16-172.
10. Demir, S., 2014: The role of innovation in gaining a competitive advantage for businesses and an analysis of its effects on the performance of textile firms in particular. MSc Thesis, Haliç University, Istanbul, Türkiye.
11. George, D.; Mallery, M., 2010: SPSS for Windows Step by Step: A Simple Guide and Reference, 17th ed. Boston: Pearson.
12. Humaira, J. A., 2024: Analysis of the impact of technological changes on traditional business model. Inspirat, 15 (1): 18-26.
13. Jovane, F.; Seliger, G.; Stock, T., 2017: Competitive sustainable globalization general considerations and perspectives. Procedia Manufacturing, 8: 1-19. https://doi.org/10.1016/j.promfg.2017.02.001
14. Kalafat, N., 2012: Socio-economic analysis of forest industry enterprises in Balıkesir province. MSc Thesis, Bartın University, Bartın, Türkiye.
15. Kalaycı, Ş., 2010: SPSS Applied Multivariate Statistics Techniques. Asil Publication Distribution, Ankara (in Turkey).
16. Kanber, S., 2010: Innovation in manufacturing: Examining the effects of innovation activities on innovation performance in industrial organizations. MSc Thesis, Çukurova University, Adana, Türkiye.
17. Karaman, H., 2019: The relationship between strategic innovation orientation, innovation capabilities and innovation performance. MSc Thesis, Altınbaş University, Istanbul, Türkiye.
18. Karayılmazlar, S.; Çabuk, Y.; Aşkın, A., 2008: Production and technological characteristics of Bartın forest industry enterprises, their problems and solution suggestions. Süleyman Demirel University Forestry Faculty Journal, A (1): 143-154.
19. Ketboğa, M., 2024: 2013 – 2022 Analysis of the role of SMEs in Turkey's foreign trade activities between 2013 and 2022. International Journal of Accounting and Finance Researche, 6 (2): 83-107.
20. Kurtoğlu, A.; Koç, K. H.; Erdinler, E. S.; Sofuoğlu, S. D., 2009: Structural and educational problems of the Turkish forest products industry. In: 2nd Congress on Socio-Economic Problems in Forestry, 176-186, SDÜ, Isparta, Turkey.
21. Lane, J. P.; Flagg, J. L., 2010: Translating three states of knowledge – discovery, invention, and innovation. Implementation Science, 5 (9): 1-14. https://doi.org/10.1186/1748-5908-5-9
22. Loučanová, E.; Olšiaková, M., Paluš, H., 2022: Consumers' perception of eco-services innovations related to furniture. Drvna industrija, 73 (4): 463-473. https://doi.org/10.5552/drvind.2022.2141
23. Mandiringana, M.; Matakala, M.; Mwanabute, N. P.; Ngoma, J.; Ncube, E., 2022: Analysis of the factors limiting the performance of small-to-medium scale sawmills in the Copperbelt of Zambia. BioResources, 17 (1): 369-383. https://doi.org/10.15376/biores.17.1.369-383
24. Moore, G. A., 2015: Zone to Win: Organizing to compete in an age of disruption, diversion books. https://doi.org/10.1080/10438599.2013.811936
25. Ndiaye, N.; Razak, L. A.; Nagayev, R.; Ng, A., 2018: Demystifying small and medium enterprises' (SMEs) performance in emerging and developing economies. Borsa Istanbul Review, 18 (4): 269-281. https://doi.org/10.1016/j.bir.2018.04.003
26. Ng, B. K.; Thiruchelvam, K., 2012: The dynamics of innovation in Malaysia's wooden furniture industry: Innovation actors and linkages. Forest Policy and Economics, 14: 107-118. https://doi.org/10.1016/j.forpol.2011.08.011
27. Pirc Barčić, A.; Motik, D., 2013: Innovation and innovativeness in medium-low tech/low-tech industries-wood industry. Drvna industrija, 64 (3): 247-255. https://doi.org/10.5552/drind.2013.1301
28. Robu, M., 2013: The dynamic and importance of SMEs in economy. The USV Annals of Economics and Public Administration, 13 1(17): 84-89.
29. Ratnasingam, J.; Ab Latib, H.; Liat, L. C.; Mariapan, M.; Jegatheswaran, N.; Othman, K.; Amir, M. A., 2022: Public perception of the wood products industry in Malaysia and its implication on the future workforce. BioResources, 17 (2): 2097-2115. https://doi.org/10.15376/biores.17.2.2097-2115
30. Ratnasingam, J.; Ark, C. K.; Ab Latib, H.; Subramaniam, H.; Khoo, A., 2018: Innovation in the Malaysian furniture

industry: Drivers and challenges. BioResources, 13 (3): 5254-5270. https://doi.org/10.15376/biores.13.3.5254-5270
31. Schumpeter, J., 1978: The Theory of Economic Development, 1st ed. Oxford University Press, New York.
32. Sertić, M. B.; Pirc Barčić, A.; Klarić, K., 2018: Economic determinants and analysis of the European Union wood industry SMEs employment. BioResources, 13 (1): 522-534.
33. Sevim Korkut, D.; Bozkurt Küçük, B. 2016. Structural analysis of İnegöl forest products industry enterprises. Bartın Forestry Faculty Journal, 18 (2): 107-120. https://doi.org/10.15376/biores.13.1.522-534
34. Shefer, D.; Frenkel A., 2005: R&D, firm size and innovation: an empirical analysis. Technovation, 25 (1): 25-32. https://doi.org/10.1016/S0166-4972(03)00152-4
35. Şener Uzcan, G.; Karayılmazlar, S., 2018: Cluster analysis of the forest products industry in the TR81 Level 2 region. Bartın Faculty of Forestry Journal, 20 (2): 239-251.
36. Tsai, M. T.; Shih, C. M., 2004: The impact of marketing knowledge among managers on marketing capabilities and business performance. International Journal of Management 21 (4): 524-530.
37. Uhan, Z.; Malovrh, S. P.; Jost, M., Remic, K., 2023: Integration of sustainable development goals in higher education and research processes related to forestry and wood science. Drvna industrija, 75 (1): 87-98. https://doi.org/10.5552/drvind.2024.0120
38. Vives, X., 2008: Innovation and competitive pressure. The Journal of Industrial Economics, 56: 419-469. https://doi.org/10.1111/j.1467-6451.2008.00356.x
39. Yıldız, D.; Uzunsakal, E., 2018: Comparison of reliability tests in field research and an application on agricultural data. Journal of Applied Social Sciences, 2 (1): 14-28.
40. Zafar, A.; Mustafa, S., 2017: SMEs and its role in economic and socio-economic development of Pakistan. International Journal of Academic Research in Accounting, 6 (4): 1-16.
41. ***SGK, 2024: Social Security Institution Statistical Yearbooks. https://www.sgk.gov.tr/Istatistik/Yillik/fcd5e59b-6af9-4d90-a451-ee7500eb1cb4/ (Accessed: May 24, 2024).

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Effect of Wood Ash and Boron Salts on Hygroscopicity of Sawdust Composites Bonded with Wheat Protein

Utjecaj drvnog pepela i soli bora na higroskopnost kompozita od piljevine lijepljenih pšeničnim proteinom

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ABSTRACT • *Bio-based wood composites bonded with wheat protein represent a sustainable alternative to conventional formaldehyde-based panels; however, their high moisture sensitivity limits dimensional stability and functional reliability. This study comparatively evaluated the effect of incorporating equivalent low dosages (5 wt.% dry basis) of wood ash and boron salts on the hygroscopic behavior of sawdust composites manufactured under identical formulation and processing conditions. By maintaining constant raw material, adhesive system, and consolidation parameters, the experimental design enabled direct assessment of additive performance within the same lignocellulosic matrix. Hygroscopic response was characterized through short-term water immersion tests, analyzing density, hygroexpansion, and water absorption index. Relative to the unmodified control, both additives produced statistically significant improvements with large effect sizes. Wood ash increased bulk density and markedly reduced water uptake, indicating microstructural modification and partial pore blocking. Boron salts achieved the greatest reduction in hygroexpansion, suggesting chemical stabilization of cell-wall polymers. The results demonstrate that even low mineral additions can substantially modify short-term moisture response without compromising adhesive consolidation. These findings provide controlled comparative evidence supporting the use of low-cost inorganic additives to enhance the dimensional stability of sustainable wood composites intended for interior applications.*

KEYWORDS: *dimensional stability; moisture sensitivity; inorganic additives; hygroexpansion; water absorption*

SAŽETAK • *Biokompoziti od drva lijepljeni pšeničnim proteinom održiva su alternativa konvencionalnim pločama na bazi formaldehida. Međutim, njihova visoka osjetljivost na vlagu utječe na njihovu dimenzijsku stabilnost i funkcionalnost. U ovoj studiji usporedno je procijenjen utjecaj dodavanja ekvivalentnih niskih doza (5 %-tni*

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maseni udio suhe tvari) drvenog pepela i soli bora na higroskopnost kompozita od piljevine proizvedenih s istom formulacijom ljepila i u jednakim uvjetima prešanja. Održavanjem konstantnog sastava sirovine, sustava ljepila i parametara konsolidacije eksperiment je omogućio izravnu procjenu učinkovitosti aditiva unutar iste lignocelulozne matrice. Higroskopnost je proučavana kratkotrajnim testovima uranjanja u vodu, analiziranjem gustoće, promjenom dimenzija i indeksa upijanja vode. U odnosu prema nemodificiranome kontrolnom uzorku, aditivi su znatno poboljšali svojstva kompozita. Drveni je pepeo povećao gustoću i znatno smanjio upijanje vode, što upućuje na mikrostrukturnu modifikaciju i djelomično zapunjavanje pora. Dodavanjem soli bora postignuta je najbolja dimenzijska stabilnost, što upućuje na kemijsku stabilizaciju polimera staničnih stijenki. Rezultati pokazuju da čak i niski dodatci minerala mogu znatno promijeniti kratkotrajni odgovor na vlagu bez ugrožavanja konsolidacije ljepila. Ti rezultati daju kontrolirane usporedne dokaze koji podupiru upotrebu jeftinih anorganskih aditiva za poboljšanje dimenzijske stabilnosti održivih drvenih kompozita namijenjenih za unutarnju primjenu.

KLJUČNE RIJEČI: *dimenzijska stabilnost; osjetljivost na vlagu; anorganski aditivi; promjene dimenzija; upijanje vode*

1 INTRODUCTION
1. UVOD

Wood particle composite materials are a fundamental axis in the valorization of lignocellulosic waste for applications in furniture and interior components (Iždinský *et al*., 2020). However, composites made with natural adhesives, such as wheat protein, exhibit marked hygroscopicity, which translates into dimensional instability and a reduction in their service life (Ferdosian *et al*., 2017). Water-material interaction dominates the hygroscopic behavior and, consequently, the mechanical strength and durability of these systems, with moisture variations being responsible for hygroexpansion and losses of stiffness (Thybring *et al*., 2022).

Recent studies indicate that sorption and hysteresis determine the hygroscopic equilibrium, especially under fluctuating conditions (Fredriksson *et al*., 2023; Thybring *et al*., 2022). Consequently, current research in wood technology is oriented towards the incorporation of sustainable mineral or ionic additives to mitigate hygroscopicity in lignocellulosic composites (Gonçalves *et al*., 2021).

In the development of sustainable composites, protein adhesives derived from wheat gluten have been established as bio-based alternatives to synthetic resins that release formaldehyde in particleboards (Raydan *et al*., 2021). Various studies have shown that gluten dispersions, especially when modified or cross-linked, can achieve adequate bond strength and dimensional stability for interior applications, provided pressing conditions are optimized (Aluvihare Gedara *et al*., 2021; Calvez *et al*., 2024).

In this sense, protein denaturation and chemical modification can alter the accessibility and reactivity of polar groups, and in some cases reduce net water sorption by promoting intra- and intermolecular crosslinks that reduce chain mobility and porosity; however, the net effect depends on the denaturation method and on crosslink density (Aluvihare Gedara *et al*., 2021; Calvez *et al*., 2024). Consequently, the use of wheat protein as a sustainable adhesive provides an ideal basis for analyzing the comparative influence of inorganic additives, such as wood ash and boron salts, on the hygroscopicity of bio-based lignocellulosic matrices (Raydan *et al*., 2021).

Wood ash, composed mainly of mineral oxides, has been used as a pozzolanic additive and alkalizing agent in cemented wood composites, due to its influence on the reactivity and stability of the matrix (Teker Ercan *et al*., 2023). Research on wood-cement boards with partial substitution of cement by ash shows a progressive increase in absorption capacity by increasing its fraction, identifying an optimal range of 10-30 % to balance mechanical and physical properties (Vu *et al*., 2019). The effects of ash on hygroscopicity derive from multiple interrelated mechanisms: modification of pH and local ionic strength, alteration of porosity and effective surface area by the incorporation of fine particles, and the presence of soluble fractions (alkaline salts, carbonates) that regulate capillary absorption and vapor sorption (Sigvardsen, 2019; Teker Ercan *et al*., 2023; Vu *et al*., 2019).

Although the use of wood ash has been predominantly investigated as a pozzolanic additive in wood-cement composites, its role in matrices bonded with bio-based adhesives remains insufficiently explored. In cement-based systems, ash fractions between 10-30 % have been observed to increase absorption capacity, an effect attributed to the modification of porosity and the presence of soluble salts. However, in a protein matrix such as the one proposed in the present study, it is postulated that the ash acts primarily as an inorganic filler, modifying the capillary network of the composite (Mwango and Kambole, 2019; Martínez-García *et al*., 2022). This raises the question of whether, at low concentrations, it can physically hinder water diffusion pathways without compromising the integrity of the adhesive, a mechanism fundamentally different from that reported in inorganic matrices.

Boron compounds, mainly boric acid (H_3BO_3) and borax ($Na_2B_4O_7 \cdot 10H_2O$), are traditionally used as low-toxicity preservatives in lignocellulosic products, providing protection against wood-destroying organisms. In addition to their biocidal action, various studies have shown that boron salts influence the hygroscopic and dimensional properties of wood composites, depending on their form, concentration, and method of incorporation (Khademibami and Bobadilha, 2022).

Impregnation tests with concentrations of 1-8 % boron have shown significant reductions in equilibrium moisture content and hygroexpansion, as in clones of *Eucalyptus* spp. treated with 4 % solutions (Baraúna *et al*., 2020). This effect is attributed to the ability of borates to form complexes with hydroxyl groups of polysaccharides, their own intrinsic hygroscopicity, and their influence on the pH and curing reactions in adhesives (Ayrilmis, 2020; Khademibami and Bobadilha, 2022).

Thus, empirical evidence supports the effectiveness of boron compounds, such as boric acid and borax, in reducing hygroexpansion in wood. However, most of this research uses vacuum-pressure impregnation methods on solid wood, achieving significant reductions in equilibrium moisture content. This approach differs from that proposed in the present investigation, which evaluates the direct addition of borates into the sawdust matrix before pressing. Consequently, it is expected that the dominant mechanisms not only include the formation of complexes with polysaccharides, but also the alteration of the adhesive rheology and the interfacial properties between particles, an aspect not yet clarified in the literature.

The literature review shows that both ashes and borates have been widely studied, although generally in matrices, concentrations, and incorporation methods that are not comparable (Ayrilmis, 2020; Teker Ercan *et al*., 2023; Vu *et al*., 2019). While cemented boards use ash fractions between 10-30 % and boron treatments are usually applied by impregnation in ranges of 1-8 %, there are few studies that evaluate both additives in the same lignocellulosic matrix under homogeneous experimental conditions. Direct comparisons using a low dosage (5 % w/w on dry mass) of wood ash and boron salts in systems bonded with bio-based adhesives have barely been explored (Baraúna *et al*., 2020; Khademibami and Bobadilha, 2022; Vu *et al*., 2019). This experimental gap limits the understanding of their relative effectiveness in reducing hygroscopicity in composites made with sawdust.

Despite the industrial relevance of controlling moisture absorption in lignocellulosic composites, the literature lacks comparative studies that evaluate, in the same matrix and with the same natural wheat protein adhesive, the effects of homogeneous and low additions of wood ash or boron salts on the material's hygroscopicity. This lack of evidence generates uncertainty regarding the relative efficacy of these inorganic additives in mitigating the hygroscopic instability of these bio-composites.

The research hypothesis proposes that the incorporation of 5 % by mass of ash or boron salts will reduce the hygroscopicity of the wood sawdust composites compared to the control composite without additives. Consequently, the present research aims to quantitatively determine and compare the effect of adding 5 % ash or 5 % boron salts on the hygroscopicity of wood sawdust composites, through an experimental design that allows contrasting their effects under identical composition and processing conditions.

The concentration of 5 % by weight was strategically selected as a low and constant dosage for both additives. This choice allows a direct comparison of their efficacy, avoiding the adhesive dilution effects or alterations in composite density that would be observed with larger additions. In this way, the experimental design focuses on elucidating whether, at this level of addition, the hygroscopic benefits outweigh any possible compromise in the functional properties of the final composite.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials and board manufacture
2.1. Materijali i proizvodnja ploča

Three types of wheat protein–bonded sawdust composites were prepared under controlled laboratory conditions. The control formulation consisted of sawdust from Mexican white pine (*Pinus pseudostrobus* Lindl. var. *pseudostrobus*) (Figure 1) with a defined

Figure 1 Micrograph (10x magnification) of *P. pseudostrobus* particles from the fraction retained on a 850 µm sieve
Slika 1. Mikrografija (uz uvećanje od 10 puta) čestica drva *P. pseudostrobus* iz frakcije zadržane na situ od 850 µm

particle size distribution: > 850 μm (50 %), 425–850 μm (25 %), 250–425 μm (12.5 %) and < 250 μm (12.5 %). Prior to blending, the sawdust was oven-dried at (103 ± 2) °C to constant mass (mass variation < 0.1 % between two measurements separated by 2 h) to obtain absolute dry material. All formulation proportions were calculated on an oven-dry sawdust basis.

The adhesive was prepared from commercial wheat flour (10 % protein content), following the protein quality characteristics described by Moreno-Araiza *et al*. (2020). The formulation consisted of 30 wt.% wheat flour and 200 wt.% distilled water, both expressed relative to the oven-dry mass of sawdust. The high-water content was required to ensure adequate protein gelatinization and homogeneous dispersion within the sawdust matrix. The mixture was stirred continuously for 2 min and heated to 98–100 °C until gelatinization occurred and a homogeneous, high-viscosity paste was obtained.

Two modified formulations were produced by incorporating inorganic additives at 5 wt.% relative to the oven-dry mass of sawdust (dry/dry basis). In the second composite (MC Ash), wood ash obtained from controlled combustion of *P. pseudostrobus* residues at 600 °C for 4 h (ISO 18122:2022) was incorporated. In the third composite (MC Boron), a mixture of boric acid (H_3BO_3, 39.4 %) and sodium borate ($Na_2B_4O_7 \cdot 10H_2O$, 60.6 %) was added. In all cases, the dry components were blended prior to adhesive addition to ensure homogeneous distribution.

The furnish was manually pre-formed and subsequently compacted in a steel mold (2 cm × 17 cm × 17 cm) using a laboratory hydraulic press at 2.5 MPa for 5 min to minimize void formation and improve thickness uniformity (Figure 2). The wet plates were subjected to a stepped thermal schedule to promote adhesive gelation and moisture removal: 65 °C for 24 h, followed by 85 °C for 24 h, and finally 103 °C for 24 h.

Figure 2 Composite material specimens during the drying process in an oven at 103 °C
Slika 2. Uzorci kompozitnih materijala tijekom procesa sušenja u sušioniku na 103 °C

After drying, twelve specimens (2 cm × 2 cm × 5 cm) were cut from each board. The specimens were subsequently oven-dried at (103 ± 2) °C to constant mass, defined as a mass variation of less than 0.1 % between two consecutive measurements separated by 2 h. This condition was considered the oven-dry reference state (MC ≈ 0 % on a wet basis), and all subsequent moisture contents were calculated relative to this oven-dry mass.

The complete formulation and manufacturing parameters are summarized in Table 1.

2.2 Methods
2.2. Metode

The absorption tests started with the specimens in oven-dry condition. These were immersed in water at a temperature of 20 °C and, at time intervals (t) of 10 minutes up to 120 minutes. Moisture content was determined using ISO 13061-1:2014. Short-term water uptake was measured by immersing specimens in deionized water at (20 ± 1) °C; at each time point specimens were removed, surface water was removed by gentle blotting with a damp lint-free cloth, and the sample was immediately weighed (balance accuracy ± 0.01 g). The 120-minute interval was selected to simulate short-term exposure and identify initial absorption differences between treatments. Density (ρ_{MC}) was calculated according to standard ISO 13061-2:2014. Weight and volume were determined by direct measurement at each time interval, considering the total expansion of the specimen. The wood ash was prepared according to standard ISO 18122:2022.

Hygroexpansion was calculated with Eq. 1 (Fu *et al*., 2019):

$$\alpha = \left(\frac{v_s - v_i}{v_i} \right) \cdot 100 \qquad (1)$$

Where α – hygroexpansion (%), v_s – volume corresponding to t = 120 min (m^3), v_i – initial volume corresponding to t = 0 min (m^3).

The water absorption index was calculated using Eq. 2 (Yang and Liu, 2020):

$$WAI = \left(\frac{w_s - w_i}{w_i} \right) \cdot 100 \qquad (2)$$

Where WAI – water absorption index (%), w_s – weight corresponding to t = 120 min (g), w_i – weight corresponding to t = 50 min (g).

2.3 Experimental design
2.3. Postavke eksperimenta

A completely randomized experiment was designed. The composite formulation was considered with the variation factor at three levels: Control (base formulation), Ash (formulation with 5 % ash) and Boron (formulation with 5 % boron salts). The total number of units was 36 (3 treatments × 12 independent

Table 1 Composition and manufacturing parameters of wheat protein–bonded sawdust composites
Tablica 1. Sastav i parametri proizvodnje kompozita od piljevine lijepljenih pšeničnim proteinom

Parameter *Parametar*	**MC Control** *Uzorak za kontrolu sadržaja vode*	**MC Ash (5 wt.%)** *Sadržaj vode uzorka s dodatkom pepela (5 %-tni maseni udio)*	**MC Boron (5 wt.%)** *Sadržaj vode uzorka s dodatkom soli bora (5 %-tni maseni udio*
Wood species *vrsta drva*	*Pinus pseudostrobus* Lindl. var. *pseudostrobus*	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Sawdust condition svojstva piljevine	Oven-dry ((103 ± 2) °C, constant mass) *sušenje u sušioniku (103 ± 2 °C, konstantna masa)*	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Particle size distribution *distribucija veličine čestica*	> 850 µm (50 %); 425 – 850 µm (25 %); 250–425 µm (12.5 %); < 250 µm (12.5 %)	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Adhesive type *vrsta ljepila*	Wheat flour (10 % protein) *pšenično brašno (10 % proteina)*	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Adhesive formulation[1] *formulacija ljepila*[1]	30 wt.% flour + 200 wt.% water *30 masenih postotaka brašna + 200 masenih postotaka vode*	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Additive type *vrsta dodataka*	—	Wood ash / *drvni pepeo*	Boric acid + sodium borate *borna kiselina + natrijev borat*
Additive dosage[2] *količina aditiva*[2]	—	5 wt.%	5 wt.%
Ash preparation *priprema pepela*	—	600 °C, 4 h (ISO 18122:2022)	—
Mat forming *formiranje tepiha*	Manual pre-forming	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Pressing conditions *parametri prešanja*	2.5 MPa, 5 min	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Plate dimensions *dimenzije ploče*	2 cm × 17 cm × 17 cm	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Drying schedule *raspored sušenja*	65 °C × 24 h → 85 °C × 24 h → 103 °C × 24 h	Same as control *jednako kao u kontrolnom uzorku*	Same as control *jednako kao u kontrolnom uzorku*
Specimen dimensions *dimenzije uzoraka*	2 cm × 2 cm × 5 cm	Same as control *jednako kao u kontrolnom uzorku*	Same as control jednako kao u kontrolnom uzorku
Number of specimens (n) *broj uzoraka (n)*	12	12	12

[1]Expressed relative to oven-dry sawdust mass / *u odnosu prema masi piljevine osušene u sušioniku*
[2]Expressed on oven-dry sawdust basis (dry/dry) / *u odnosu prema masi piljevine osušene u sušioniku (suho/suho)*

replicates). The response variables were density ρ_{MC} (kg/m³), hygroexpansion α (%) and water absorption index WAI (%).

Descriptive statistics mean (μ), standard deviation (σ) and coefficient of variation ($CV = \sigma/\mu$) were calculated. The assumptions of normality (Shapiro-Wilk): evaluated individually by group ($p > 0.05$ indicates normal distribution); and homoscedasticity (Levene): verification of equality of variances between groups ($p > 0.05$ indicates homogeneity) were verified. One-way analyses of variance (ANOVA) were performed, when the ANOVA was significant ($p < 0.05$), as well as multiple comparisons with Tukey's Honestly Significant Difference (HSD) tests. In the case of hygroexpansion (α), the data did not meet the parametric assumptions. Therefore, the analysis of hygroexpansion (α %) was conducted using Welch's ANOVA followed by the Games-Howell post-hoc test. Effect sizes (η^2 and ω^2) and power ($1 - \beta$) were calculated from the observed effect size ($\eta^2 \rightarrow f$), the total sample size and for $\alpha = 0.05$. Adequate power was considered when $1-\beta \geq 0.80$.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The physical properties of the wheat protein–bonded sawdust composites are summarized in Table 2. Results are expressed as mean ± standard deviation (n = 12). Statistically significant differences among formulations are indicated by superscript letters ($\alpha = 0.05$).

Regarding density, the ash-modified composite exhibited the highest mean value (435 kg/m³), differing significantly from both the control and the boron-modified composite, which did not differ from each other. The relatively low dispersion values indicate consistent manufacturing across treatments. The significant F-value (27.93, $p < 0.001$) confirms that composite formulation influenced bulk density. The effect size ($\eta^2 = 0.629$) indicates that approximately 63 % of total density variance is attributable to additive incorporation, evidencing a strong structural impact of ash addition.

For hygroexpansion, the control composite showed the highest volumetric swelling (21.7 %), whereas both modified composites presented significantly lower values (14.9 % for ash and 13.0 % for boron), without statistical difference between them. The overall model was significant (Welch-adjusted $F = 18.19$, $p < 0.001$). The effect size ($\eta^2 = 0.524$) reveals that more than half of the variability in swelling behavior is governed by formulation, demonstrating that both additives substantially improve dimensional stability relative to the unmodified matrix.

In the case of water absorption index, all formulations differed significantly, following the order Control > Ash > Boron. The control composite exhibited the highest short-term water uptake (177 %), while the boron-modified composite showed the lowest value (148 %). The large F-statistic (96.80, $p < 0.001$) and very high effect size ($\eta^2 = 0.854$) indicate that formulation explains more than 85 % of the variance in water absorption. This represents the strongest treatment effect among the evaluated properties and confirms the dominant role of additive incorporation in regulating short-term capillary water uptake.

Overall, the consolidated presentation integrates descriptive and inferential statistics in a single table, providing a concise yet statistically rigorous evaluation of treatment effects. The magnitude of the observed effect sizes demonstrates that even a low additive dosage (5 wt.% dry basis) produces substantial and practically meaningful modifications in the hygroscopic performance of wheat protein–bonded sawdust composites under short-term immersion conditions.

Hygroscopicity is a decisive factor in the durability and dimensional stability of lignocellulosic composite materials, as moisture variations cause volumetric deformations and reduce mechanical performance. According to the experimental results, the MC control, without additives, showed the highest hygroexpansion and water absorption index, in addition to high variability, which reflects its sensitivity to moisture. The statistical significance of the analysis of variance confirms that the differences between the groups are due to the modifications introduced (Rahim *et al*., 2024). Likewise, the incorporation of 5 % ash or boron salts was compatible with the wheat protein adhesive, allowing adequate consolidation of the material. Consequently, the effects on hygroscopic properties are attributed to the additives, consolidating their role in improving the stability and functionality of sawdust composites.

The effect of wood ash on hygroscopicity is complex and depends on the balance between pore filling and the introduction of hygroscopic soluble salts. The results of this study (Table 2) show that, with a low concentration of 5 %, the ash had a positive effect. The ash-modified composite showed a significant and important reduction in hygroexpansion compared to the control, as well as in the water absorption index. The significant difference in the density of the composite containing ash, compared to the control and the composite containing boron, supported by the Tukey HSD test, suggests a modification in the microstructure of the composite. This modification may be due to an improvement in

Table 2 Physical properties of wheat protein–bonded sawdust composites (mean ± SD, n = 12)
Tablica 2. Fizička svojstva kompozita od piljevine lijepljenih pšeničnim proteinom (srednja vrijednost ± SD, n = 12)

Property *Svojstvo*	**MC control** *Kontrolni uzorci*	**MC ash (5 wt.%)** *Uzorci s dodatkom drvnog pepela*	**MC boron (5 wt.%)** *Uzorci s dodatkom soli bora*	**F**	**p-value**	η^2
Density, kg/m³ / *gustoća,* kg/m³	414 ± 12.9^b	435 ± 13.5^a	408 ± 17.5^b	27.93	< 0.001	0.629
Hygroexpansion, % *promjene dimenzija,* %	21.7 ± 6.4^a	14.9 ± 2.7^b	13.0 ± 2.2^b	18.19*	< 0.001	0.524
Water absorption index, % *indeks upijanja vode,* %	177 ± 1.5^a	160 ± 1.4^b	148 ± 0.8^c	96.80	< 0.001	0.854

Notes: Different superscript letters within the same row indicate statistically significant differences at α = 0.05; Density and WAI were analyzed by one-way ANOVA followed by Tukey's HSD test; Hygroexpansion was analyzed using Welch's ANOVA and Games–Howell post-hoc test due to heteroscedasticity; η^2 = proportion of total variance explained by formulation (effect size).
Napomena: Različita slova u natpisu brojeva unutar istog retka označavaju statistički značajne razlike pri α = 0,05; gustoća i indeks upijanja vode analizirani su jednosmjernom ANOVA-om, nakon čega je slijedio Tukeyjev HSD test; promjene dimenzija su zbog heteroskedastičnosti analizirane Welchovom ANOVA-om i Games-Howell post-hoc testom; η² = udio ukupne varijance objašnjen formulacijom (veličina učinka).

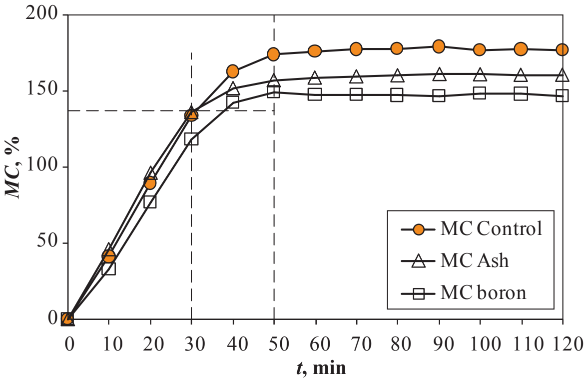

Figure 3 Variation of moisture content (*MC*) as a function of immersion time (*t*), each point represents mean ± standard deviation ($n = 12$)

Slika 3. Varijacija sadržaja vode (*MC*) kao funkcija vremena uranjanja (*t*); svaka točka predočuje srednju vrijednost ± standardnu devijaciju ($n = 12$)

compaction or a change in particle distribution, which in turn contributes to the reduction in water absorption.

The composite containing boron showed the greatest decrease in hygroexpansion, and this difference is statistically significant compared to the control. This supports the idea that borates can work well with the lignocellulosic matrix to limit hygroexpansion (Ayrilmis, 2020; Teker Ercan *et al*., 2023; Vu *et al*., 2019). However, its performance in water absorption was intermediate, notably higher than that of ash and notably lower than that of the control. This result indicates a dual behavior: while borates are effective in restricting hygroexpansion caused by moisture adsorbed in the cell wall, their hygroscopic nature could be favoring the retention of a greater amount of liquid water in the material, which is reflected in a water absorption index higher than that observed in the case of ash.

The moisture content of the three analyzed composites showed an evolution as a function of the immersion time, evidencing a general trend of rapid increase in the initial stages of exposure (0-50 minutes), followed by a stabilization phase between 50 and 120 minutes (Figure 3). The profile of these trends resembles that documented by Fu *et al*. (2019) for *Pinus radiata* D. Don wood, with immersion periods of 300 hours, and that reported by Widiastuti *et al*. (2023) for wood-plastic composites, with periods of 240 hours. The materials analyzed and the immersion times in water documented by the authors cited differ from those examined in the present investigation. The current study employed a 120-minute immersion to investigate short-term capillary uptake and near-surface saturation, thus limiting comparisons with multi-day immersion studies; nonetheless, the early uptake kinetics is similar in structure and permit inferences about initial sorption mechanisms (capillarity versus cell-wall sorption). Nonetheless, the trends in hygroscopic behavior are analogous and corroborate the interpretation of Figure 3.

4 CONCLUSIONS
4. ZAKLJUČAK

This study comparatively evaluated the effect of low and equivalent dosages (5 wt.% dry basis) of wood ash and boron salts on the hygroscopic performance of wheat protein–bonded sawdust composites manufactured under identical formulation and processing conditions. By controlling all other variables, the experimental design allowed a direct assessment of the relative efficacy of both inorganic additives within the same lignocellulosic matrix.

The unmodified control composite exhibited pronounced hygroexpansion and water absorption, confirming the inherent moisture sensitivity of protein-bonded systems. In contrast, both modified composites showed statistically significant improvements, supported by large effect sizes. Wood ash incorporation increased bulk density and markedly reduced water absorption, indicating a predominantly microstructural mechanism associated with partial pore filling and modification of capillary pathways. Boron salts produced the greatest reduction in hygroexpansion, suggesting that chemical interactions with hydroxyl groups in the cell-wall polymers contributed to restricting moisture-induced dimensional changes.

The results demonstrate that even at a relatively low concentration (5 wt.%), mineral additives can substantially modify short-term moisture response without impairing adhesive consolidation. The distinct yet complementary mechanisms identified for ash and boron highlight that additive selection can be tailored depending on whether the primary objective is to reduce water uptake or to minimize dimensional instability.

Although the findings are limited to one species, one adhesive system, a single additive concentration, and short-term immersion conditions, they provide controlled comparative evidence supporting the feasibility of low-cost inorganic additives as functional modifiers in sustainable, bio-based wood composites intended for interior applications.

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5 REFERENCES
5. LITERATURA

1. Aluvihare Gedara, A. K.; Chianella, I.; Bhattacharyya, D.; Endrino, J. L.; Zhang, Q., 2021: Alkali-treated wheat gluten cross-linked with sodium alginate as a bio-based

wood adhesive for interior grade particleboard. BioResources, 16 (4): 7916-7934. https://doi.org/10.15376/biores.16.4.7916-7934
2. Ayrilmis, N., 2020: Effect of boron and phosphorus compounds on fire and technological properties of oriented strandboard. Materials International, 2: 117-122. https://doi.org/10.33263/Materials22.117122
3. Baraúna, E. E. P.; Paes, J. B.; Christoforo, A. L.; Lahr, F. A. R., 2020: Influence of the impregnation with boron compounds on the physical properties of Eucalyptus wood. Scientia Forestalis, 48 (128): e3383. https://doi.org/10.18671/scifor.v48n128.09
4. Calvez, I.; Pizzi, A.; Amirou, S.; Mansouri, H. R., 2024: Recent advances in bio-based adhesives and formaldehyde-free technologies for wood-based panel manufacturing. Current Forestry Reports, 10 (5): 386-400. https://doi.org/10.1007/s40725-024-00227-3
5. Ferdosian, F.; Pan, Z.; Gao, G.; Zhao, B., 2017: Bio-based adhesives and evaluation for wood composites application. Polymers, 9 (2): 70. https://doi.org/10.3390/polym9020070
6. Fredriksson, M.; Thybring, E. E.; Zelinka, S. L., 2023: Water sorption in wood cell walls – data exploration of the influential physicochemical characteristics. Cellulose, 30: 1857-1871. https://doi.org/10.1007/s10570-022-04973-0
7. Fu, Z.; Zhou, Y.; Gao, L.; Zhao, R.; Tu, D., 2019: Changes of water related properties in radiata pine wood due to heat treatment. Construction and Building Materials, 227: 116692. https://doi.org/10.1016/j.conbuildmat.2019.116692
8. Gonçalves, D.; Paiva, N.; Ferraz, J. M.; Martins, J.; Magalhães, F. D.; Carvalho, L. H., 2021: Non-formaldehyde, bio-based adhesives for use in wood-based panel manufacturing industry – A review. Polymers, 13 (23): 4086. https://doi.org/10.3390/polym13234086
9. Iždinský, J.; Vidhodlová, Z.; Reinprecht, L., 2020: Particleboards from recycled wood. Forests, 11 (11): 1166. https://doi.org/10.3390/f11111166
10. Khademibami, L.; Bobadilha, G. S., 2022: Recent developments studies on wood protection research in academia: A review. Frontiers in Forests and Global Change, 5: 793177. https://doi.org/10.3389/ffgc.2022.793177
11. Martínez-García, R.; Alaejos, P.; Vegas, I.; Frías, M., 2022: The present state of the use of waste wood ash as an eco-efficient construction material: A review. Materials, 15 (15): 5349. https://doi.org/10.3390/ma15155349
12. Moreno-Araiza, O.; López, A.; Ramírez, J.; Rodríguez, M., 2020: Protein quality in roller-milling fractions of wheat (Triticum aestivum) at a commercial scale. Biotecnia, 22 (3): 53-60. https://doi.org/10.18633/biotecnia.v22i3.1201
13. Mwango, A.; Kambole, C., 2019: Engineering characteristics and potential increased utilisation of sawdust composites in construction – A review. Journal of Building Construction and Planning Research, 7: 59-88. https://doi.org/10.4236/jbcpr.2019.73005
14. Rahim, N. L.; Hassan, M. F.; Zain, M. F. M.; Abdullah, S.; Ismail, N., 2024: Development of eco-friendly particleboard composite using fly ash. E3S Web of Conferences, 589: 04002. https://doi.org/10.1051/e3sconf/202458904002
15. Raydan, N. D. V.; Silva, R. A.; Oliveira, J. R.; Santos, L. M., 2021: Recent advances on the development of protein-based adhesives for wood composite materials – A review. Molecules, 26 (24): 7617. https://doi.org/10.3390/molecules26247617
16. Sigvardsen, N. M.; Jensen, P. A.; Dam-Johansen, K.; Ahrenfeldt, J., 2019: Impact of production parameters on physicochemical characteristics of wood ash for possible utilisation in cement-based materials. Resources, Conservation and Recycling, 145: 230-240. https://doi.org/10.1016/j.resconrec.2019.02.034
17. Teker Ercan, E. E.; Kaya, A.; Yilmaz, H.; Demir, I., 2023: Wood ash as sustainable alternative raw material for the production of concrete – A review. Materials, 16 (7): 2557. https://doi.org/10.3390/ma16072557
18. Thybring, E. E.; Fredriksson, M.; Engelund, E. T., 2022: Water in wood: A review of current understanding and knowledge gaps. Forests, 13 (12): 2051. https://doi.org/10.3390/f13122051
19. Vu, V.-A.; Nguyen, T. H.; Tran, Q. T.; Pham, D. H., 2019: The effect of wood ash as a partial cement replacement material for making wood-cement panels. Materials, 12 (17): 2766. https://doi.org/10.3390/ma12172766
20. Widiastuti, I.; Suryanegara, L.; Hadi, Y. S.; Santoso, A., 2023: Optimizing the water absorption behaviour and natural weathering resistance of compatibilized iron-wood-based recycled polypropylene composites. Composites. Part C: Open Access, 12: 100423. https://doi.org/10.1016/j.jcomc.2023.100423
21. Yang, L.; Liu, H.-H., 2020: Effect of a combination of moderate-temperature heat treatment and subsequent wax impregnation on wood hygroscopicity, dimensional stability and mechanical properties. Forests, 11 (9): 920. https://doi.org/10.3390/f11090920
22. ***ISO 13061-1, 2014: Wood – Physical and mechanical properties of wood. Test methods for small clear wood specimens. Part 1: Determination of moisture content for physical and mechanical tests. International Organization for Standardization, Geneva.
23. ***ISO 13061-2, 2014: Wood – Physical and mechanical properties of wood. Test methods for small clear wood specimens. Part 2: Determination of density for physical and mechanical tests. International Organization for Standardization, Geneva.
24. ***ISO 18122, 2022: Solid biofuels – Determination of ash content. International Organization for Standardization, Geneva.

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Comparative Study of Thermal Aging Effects on Old Newspaper Pulps Bleached with Different Chemicals

Komparativna studija utjecaja toplinskog starenja na papirnu pulpu od starih novina izbijeljenu različitim kemikalijama

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ABSTRACT • *This study investigates the influence of different bleaching systems on the thermal aging behavior of old newspaper pulps (ONP) under controlled laboratory conditions. Hydrogen peroxide, sodium dithionite, and formamidine sulfinic acid (FAS) were applied at their respective optimum dosages, and the resulting pulps were subjected to accelerated aging at (103 ± 2) °C for up to 240 h. Aging was evaluated as a multidimensional process rather than being limited to brightness changes. Optical properties were assessed together with mechanical strength retention and structural modifications associated with hornification and pore evolution. Brightness, whiteness, yellowness, and color difference (ΔE) were measured alongside breaking length, burst index, Cobb water absorption, and air permeability to characterize the overall response of the fiber network during thermal exposure. Statistical analysis was performed using one-way ANOVA followed by Duncan's multiple range test. Distinct differences were observed among the bleaching systems. Peroxide-treated pulps maintained relatively stable optical and mechanical performance during aging. In contrast, dithionite-bleached samples showed pronounced color reversion and a reduction in strength. FAS-treated pulps exhibited intermediate behavior. The results indicate that initial brightness gain alone is insufficient to predict long-term performance, emphasizing the need to consider durability under thermal conditions when selecting bleaching strategies for recycled paper.*

KEYWORDS: *newspaper; aging; bleaching; stability; durability*

SAŽETAK • *U studiji je istražen utjecaj različitih sustava izbjeljivanja na toplinsko starenje papirne pulpe od starih novina (ONP) u kontroliranim laboratorijskim uvjetima. Vodikov peroksid, natrijev ditionit i formamidinsulfonska kiselina (FAS) primijenjeni su u optimalnim dozama, a dobivena pulpa podvrgnuta je ubrzanom starenju na 103 ± 2 °C tijekom 240 sati. Evaluacija starenja nije bila ograničena samo na promjenu svjetline nego je ono promatrano kao višedimenzionalni proces. Optička svojstva istražena su usporedno sa zadržavanjem mehaničke čvrstoće i strukturnim modifikacijama povezanima s hornifikacijom i razvojem pora. Mjereni su svjetlina, bjelina, žućenje i razlika u boji (ΔE), kao i duljina loma, indeks pucanja, upijanje vode prema Cobbu i propusnost zraka kako bi se upotpunio ukupni odgovor mreže vlakana tijekom toplinskog izlaganja pulpe. Statistička analiza provedena je primjenom jednosmjerne ANOVA-e, a zatim Duncanova testa višestrukog raspona. Uočene su znatne razlike među sustavima za izbjeljivanje. Naime, pulpe tretirane peroksidom održale su relativno stabilna optička i*

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mehanička svojstva tijekom starenja. Nasuprot tome, uzorci izbijeljeni ditionitom pokazali su izrazito veliku promjenu boje i smanjenje čvrstoće. FAS-om tretirana pulpa pokazala je srednje promjene svojstava. Rezultati upućuju na to da početno postizanje bjeline nije dovoljno za predviđanje dugoročnih svojstava, što nameće potrebu upoznavanja trajnosti u toplinskim uvjetima izbijeljenoga recikliranog papira.

KLJUČNE RIJEČI: *novine; starenje; izbjeljivanje; stabilnost; trajnost*

1 INTRODUCTION
1. UVOD

Recycling of waste paper, and especially old newspaper pulp (ONP), plays a major role in today's pulp and paper industry. Increasing pressure to use sustainable raw materials, reduce dependence on virgin fibers, and limit the environmental burden of conventional pulping has strengthened the importance of recovered paper streams (Nestor, 1994; Kumar *et al.,* 2020). Within these streams, ONP represents a considerable fraction. However, its high lignin content, together with residual printing inks and various additives from offset and gravure processes, restricts both optical and mechanical performance (Çiçekler and Tutuş, 2025). Compared with many other recovered grades, ONP-derived pulps are more vulnerable to discoloration and strength loss during storage or thermal exposure. The presence of lignin-derived chromophores and printing-related contaminants contributes to reduced stability over time. For this reason, improving the durability of ONP requires bleaching and stabilization approaches that not only account for initial brightness improvement but also for long-term aging behavior.

Bleaching of recycled fibers follows a different logic than bleaching of virgin chemical pulps. In recycled systems, the goal is generally not extensive delignification. Instead, the focus is on improving brightness and visual appearance by modifying existing chromophoric groups and removing residual ink components, while preserving fiber integrity as much as possible. Maintaining mechanical performance during this process is critical, since recycled fibers are already subjected to previous drying and reprocessing cycles that may have weakened their structure (Aguilar-Rivera, 2021; Zeb *et al.,* 2021; Tofani *et al.,* 2022). In recycled fiber processing, hydrogen peroxide (H_2O_2), sodium dithionite ($Na_2S_2O_4$), and formamidine sulfinic acid (FAS) are commonly used bleaching chemicals (Koshitsuka, 2002; Bajpai, 2014; Saad *et al.,* 2020; Sepahvand *et al.,* 2025). Hydrogen peroxide is widely used because of its strong oxidative action and its capacity to permanently modify lignin-derived chromophoric structures. It is also generally considered more environmentally acceptable than many alternative bleaching agents (Asha and Badamali, 2020; Miglbauer *et al.,* 2020; Tofani *et al.,* 2021). However, the efficiency of peroxide bleaching depends strongly on process conditions. Parameters such as pH, temperature, and the presence of transition metal ions must be carefully controlled, since unfavorable conditions can lead to cellulose oxidation or subsequent brightness reversion. (Zeb *et al.,* 2021). Sodium dithionite is a reducing bleaching agent that has been widely used in the deinking and brightness enhancement of ONP. Its continued use is largely related to its relatively low cost and its effectiveness in reducing conjugated chromophoric groups (Carreira *et al.,* 2012; Krishnan *et al.,* 2020). However, several studies have shown that dithionite does not permanently remove chromophoric structures. Instead, it reduces them to colorless forms without destroying the underlying conjugated systems. As a result, the chemical stability of the pulp remains limited, and noticeable brightness reversion may occur during storage or thermal aging (Pemberton *et al.,* 1995; Lennholm and Iversen, 1998). To overcome these limitations, formamidine sulfinic acid (FAS) has been introduced as a more stable reductive bleaching option. Compared with dithionite, FAS is reported to provide better resistance to oxidative reversion and to present a comparatively lower environmental impact (Choi and Kim, 2006; Sepahvand *et al.,* 2025). Earlier studies indicate that FAS can reach brightness values similar to those obtained with dithionite, while preserving acceptable initial strength properties in recycled pulps (Choi and Kim, 2006; Yun and He, 2011; Bajpai, 2014; Zeb *et al.,* 2021). However, most of these studies concentrate primarily on short-term optical results, while the long-term durability of FAS-treated pulps under aging conditions has received comparatively little attention.

In addition to initial bleaching efficiency, the aging behavior of recycled pulps is an important performance parameter. Paper products are often exposed to storage over long periods or to elevated temperatures during use, which can gradually affect their properties. For this reason, thermal aging tests are commonly applied to simulate natural degradation processes. These processes typically involve cellulose depolymerization, oxidation of residual lignin components, and a gradual weakening of inter-fiber bonding within the sheet structure (Małachowska *et al.,* 2021a; Ornaghi *et al.,* 2020; Kaszonyi *et al.,* 2022). The type of bleaching chemistry used can significantly influence these degradation processes, since oxidative and reductive agents alter fiber chemistry through fundamentally different reaction mechanisms (Bajpai, 2014; Li *et al.,* 2020; Pydimalla and Reddy, 2020). Earlier studies have largely addressed aging-related optical variations in bleached recycled pulps. In peroxide-bleached systems, brightness reversion has been linked to residual chromophores and oxidation reactions promoted by trace metal ions (Liu, 2003; Rundlöf *et al.,* 2006; Jiao *et al.,* 2020; Kyene *et al.,* 2019). In contrast, dithionite-bleached pulps tend to lose their initial optical improvement more rapidly under thermal conditions, mainly because the reduced chromophoric structures can be easily re-oxidized (Pemberton *et al.,* 1995; Lennholm and Iversen, 1998; Carreira *et al.,* 2012; Krishnan *et al.,* 2020). While FAS has been reported to improve optical stability compared with dithionite, comprehensive assessments under well-controlled thermal aging conditions remain scarce, and most investigations focus primarily on optical properties without extending to mechanical or physical performance (Choi and Kim, 2006; Sepahvand *et al.,* 2025).

Most of the available literature addresses aging primarily from an optical standpoint. In contrast, the simultaneous changes in mechanical performance and physical structure during aging have received comparatively less attention (Lennholm and Iversen, 1998; Choi and Kim, 2006; Yun and He, 2011; Carreira *et al.,* 2012; Saad *et al.,* 2020). Aging-related changes such as fiber hornification, rearrangement of pore structure, and reduction of inter-fiber bonding area can directly affect tensile strength, burst resistance, water absorption, and air permeability. However, these structural and mechanical consequences are rarely examined together with the type of bleaching chemistry applied (Youssef *et al.,* 2017; Jiao *et al.,* 2020; Chen *et al.,* 2024; Sepahvand *et al.,* 2025; Sevastyanova *et al.,* 2025). Although many studies have investigated bleaching strategies for recycled fibers (Lennholm and Iversen, 1998; Koshitsuka, 2002; Choi and Kim, 2006; Yun and He, 2011; Bajpai, 2014; Saad *et al.,* 2020; Zeb *et al.,* 2021; Sepahvand *et al.,* 2025), a direct and systematic comparison of hydrogen peroxide, sodium dithionite, and formamidine sulfinic acid (FAS) under the same thermal aging conditions has not been thoroughly addressed. In particular, studies using identical raw material and controlled aging parameters for all three systems remain limited.

The present study aims to fill this gap through a controlled comparison of the thermal aging behavior of ONP bleached with hydrogen peroxide, sodium dithionite, and FAS. All three systems were evaluated under identical conditions in order to allow a direct assessment of their performance. In addition to optical stability parameters such as brightness, whiteness, yellowness, and color difference, mechanical properties including breaking length and burst index were examined. Physical changes related to hornification and pore structure development were also considered through Cobb water absorption and air permeability measurements. By combining these parameters, the study seeks to provide a broader understanding of how bleaching chemistry influences long-term durability. Particular attention is given to the relationship between initial property improvement and subsequent stability during thermal exposure. The findings are expected to contribute to more informed selection of bleaching strategies in recycled newspaper processing and to support the optimization of sustainable paper production practices.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Old newspaper dated January 1 2023 was used as the raw material in this study. To ensure consistency among the experimental runs, the same type and number of pages were selected for each trial. Care was taken to avoid variations that could influence bleaching performance. Hydrogen peroxide (H_2O_2), sodium dithionite ($Na_2S_2O_4$), and formamidine sulfinic acid (FAS) were used as bleaching agents. Additional chemicals required during bleaching were applied as specified in the experimental design. All reagents were of analytical grade and obtained from MERCK. Deionized water was used throughout the study to prevent possible interference from dissolved ions or impurities.

2.1 Recycling and pulping of old newspaper (ONP)
2.1. Recikliranje i priprema papirne pulpe od starih novina (ONP)

The old newspapers were manually cut into pieces of approximately 2 cm × 2 cm, following the recommendations of the International Association of the Deinking Industry (INGEDE, Method 11p – 5.5) to maintain uniformity. The prepared samples were placed in sealed polyethylene bags and stored away from light and heat until use.

Pulping was carried out using a Hobart-type laboratory pulper. The ONP samples were pre-soaked at 10 % consistency for 10 minutes and then pulped at 10 % consistency for 22 minutes at speed level 1 – 2. During pulping, the chemical formulation recommended in INGEDE Method 11p – 4.2 was applied. The mixture consisted of 0.6 % sodium hydroxide (NaOH), 0.7 % hydrogen peroxide (H_2O_2), 1.8 % sodium silicate (Na_2SiO_3), and 0.8 % oleic acid, calculated on an oven-dry pulp basis.

After pulping, the recycled pulp was thoroughly washed and dewatered to a solids content of approximately 20 – 25 %. The pulp was then stored in sealed polyethylene bags at +4 °C until bleaching experiments were conducted.

2.2 Bleaching procedure
2.2. Postupak izbjeljivanja

The bleaching conditions used in this study are presented in Table 1. All bleaching trials were carried out under controlled and constant conditions. Temperature, reaction time, and pulp consistency were kept the same for all treatments to allow direct comparison between the bleaching systems. When required, auxiliary chemicals such as NaOH, EDTA, $MgSO_4$, and sodium silicate were added to improve process stability and to reduce possible side reactions.

All bleaching experiments were carried out in an electrically heated water bath with a temperature control accuracy of ± 0.5 °C. The recycled ONP and the calculated amounts of chemicals were placed in sealed polyethylene bags. The bags were manually mixed to ensure uniform distribution of the chemicals within the pulp and then immersed in the water bath for the specified reaction time. Each bleaching condition was repeated three times in order to improve reliability and reduce possible experimental variation.

After bleaching, the pulps were diluted to 1 % consistency and formed into standard laboratory handsheets using a Rapid-Köthen RK-21 sheet former in accordance with ISO 5269-2. The target basis weight of the sheets was approximately 70 g/m². For each bleaching condition, ten handsheets were prepared. The sheets were dried under standard laboratory conditions and then conditioned at 23 °C and 50 % relative humidity for 24 hours before testing.

2.3 Thermal aging procedure
2.3. Postupak toplinskog starenja

The prepared handsheets were subjected to accelerated thermal aging according to ISO 5630-1:1991 to evaluate long-term stability. Only the sheets produced under the optimum bleaching conditions for each chemical were used in the aging tests. Samples were placed in a forced-air oven and aged at (103 ± 2) °C for 72, 120, 168, and 240 hours. During aging, all samples were positioned to allow uniform heat exposure.

At the end of each aging period, the corresponding set of handsheets was removed from the oven and allowed to cool to room temperature. The sheets were then conditioned at 23 °C and 50 % relative humidity before optical and mechanical testing.

2.4 Test methods
2.4. Ispitne metode

Optical and mechanical properties of the handsheets were measured in accordance with the relevant ISO standards. Brightness was determined according to ISO 2470-1:2016. Whiteness and yellowness indices were measured based on ISO 11475:2017 and ISO 11476:2016, respectively. Opacity was evaluated according to ISO 2471:2008, and CIE $L^*a^*b^*$ color coordinates were determined following ISO 5631-1:2015.

Color changes after thermal aging were assessed using the ΔE parameter, which represents the overall difference between two color measurements. The ΔE value was calculated using Eq. (1).

$$\Delta E = \sqrt{(L2 - L1)^2 + (a2 - a1)^2 + (b2 - b1)^2} \quad (1)$$

Mechanical properties were evaluated by measuring tensile strength (breaking length) according to ISO 1924-2:2008 and bursting strength in accordance with ISO 2758:2014. Surface wettability was assessed using the Cobb water absorption test (ISO 535:2014), and air permeability was measured following ISO 5636-5:2013 (Gurley method).

All tests were performed under standard laboratory conditions of (23 ± 1) °C and (50 ± 2) % relative humidity, as specified in ISO 187:1990. For each parameter and experimental condition, a minimum of five replicates was tested.

Statistical analysis was conducted using one-way ANOVA, followed by Duncan's multiple range test at a 95 % confidence level. Each bleaching system was analyzed separately to evaluate the effects of chemical dosage and aging time.

Table 1 Process conditions for bleaching experiments
Tablica 1. Parametri procesa izbjeljivanja

Parameters *Parametri*	**Hydrogen peroxide (H_2O_2)** *Vodikov peroksid (H_2O_2)*	**Sodium dithionite ($Na_2S_2O_4$)** *Natrijev ditionit ($Na_2S_2O_4$)*	**Formamidine sulfinic acid (FAS)** *Formamidinsulfonska kiselina (FAS)*
Reagent charge, % / *udio reagensa,* %	3 – 5 – 7	0.5 – 1.0 – 1.5	0.5 – 1.0 – 1.5
NaOH, %	H_2O_2/0.75	–	0.25 – 0.5 – 0.75
pH	10.9	5.5	–
Temperature, °C / *temperatura,* °C	70	65	65
Time, min / *vrijeme,* min	60	60	60
Pulp consistency, % / *konzistencija,* %	12	5	5
EDTA, %	0.5	-	-
$MgSO_4$, %	0.5	–	–
Sodium silicate, % / *natrijev silikat,* %	2.0	–	–

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Determination of optimum dosages for different bleaching agents
3.1. Određivanje optimalnih doza različitih izbjeljivača

To identify the most suitable bleaching dosage for each chemical, the optical and mechanical properties of the handsheets were evaluated statistically. One-way ANOVA was applied, followed by Duncan's multiple range test to compare group means. The analyses were performed separately for hydrogen peroxide, sodium dithionite, and formamidine sulfinic acid (FAS), so that the effect of the dosage could be examined within each bleaching system.

In the Duncan test, mean values sharing the same letter were considered not significantly different at the 95 % confidence level. The average results for all measured parameters, together with their statistical groupings, are given in Table 2.

Among the peroxide treatments, the 3 % dosage provided the highest whiteness (59.50 %) and brightness (47.27 %), and the differences were statistically significant ($p < 0.05$). At this level, mechanical properties were also maintained at acceptable values, with a breaking length of 3.83 km and a burst index of 2.60 kPa·m²/g. Increasing the peroxide dosage to 5 % and 7 % did not lead to a meaningful improvement in brightness. In fact, whiteness decreased slightly, and a noticeable reduction in breaking length was observed at 7 %. When optical results are considered together with mechanical performance, chemical consumption, and process practicality, the 3 % peroxide treatment appears to offer the most balanced outcome.

Sodium dithionite treatment led to moderate increases in optical properties, but tensile strength gradually decreased as the dosage increased. At 1 %, whiteness (43.71 %) and brightness (39.56 %) were significantly higher than those of the unbleached pulp, while the corresponding strength values remained within an acceptable range. Increasing the dosage beyond 1 % resulted in only slight additional improvements in optical properties. However, these limited gains were accompanied by higher chemical usage and a potential increase in effluent load. Considering both performance and process efficiency, the 1 % dosage appears to represent a reasonable balance for dithionite bleaching.

In the case of FAS, optical properties increased gradually with higher dosages. The highest whiteness (48.33 %) and brightness (40.99 %) were obtained at 1.5 %. However, statistical analysis showed that the differences between 1 % and 1.5 % FAS were not significant for several parameters. Although the 1.5 % dosage provided slightly higher optical values, the improvement was limited. Considering the additional chemical consumption and its potential impact on process cost and environmental load, the 1 % dosage appears to provide a more practical balance between optical enhancement and preservation of mechanical properties.

Based on the statistical results, and taking into account economic and environmental aspects, the most suitable dosages were 3 % for hydrogen peroxide, 1 % for sodium dithionite, and 1 % for formamidine sul-

Table 2 Optical and mechanical properties of ONP bleached with hydrogen peroxide, sodium dithionite, and FAS at different dosages
Tablica 2. Optička i mehanička svojstva ONP-a izbijeljenoga različitim dozama vodikova peroksida, natrijeva ditionita i FAS-a

	%	**Breaking L., km** *Duljina loma,* km	**Burst In., kPa·m²/g** *Indeks loma,* kPa m²/g	**Whiteness (ISO), %** *Bjelina (ISO), %*	**Brightness (ISO), %** *Svjetlina (ISO), %*	**Yellowness (E313)** *Žućenje (E13)*	**Opacity (ISO) %** *Prozirnost (ISO), %*	*L**	*a**	*b**
UBP**	0	3.80a*	2.28b	42.85c	38.63b	14.57a	99.12a	71.5b	-0.54c	6.29a
Per	3	3.83a	2.60a	59.50a	47.27a	19.92b	98.11ab	81.6a	-1.47a	13.9d
Per	5	3.92a	2.36ab	56.07b	46.80a	20.87b	95.89c	81.6a	-1.13b	9.55c
Per	7	3.40b	2.49ab	54.88b	46.92a	15.27a	96.47bc	82.1a	-0.54c	7.43b
FAS	0.5	2.94b	2.42a	44.19c	38.73b	16.98b	98.90ab	72.3b	-0.90a	7.75b
FAS	1	2.90b	2.25a	46.14b	39.10b	19.50c	98.95ab	73.2c	-0.61b	8.85c
FAS	1.5	2.73b	2.22a	48.33a	40.99a	21.14d	98.35b	74.3d	-0.50c	9.33d
Dit	0.5	3.00b	1.85b	43.43b	39.20c	13.78a	99.10a	71.9b	-1.01b	6.29a
Dit	1	2.70c	1.78b	43.71b	39.56b	13.63a	98.12b	72.1b	-1.10ab	6.19a
Dit	1.5	2.41d	1.75b	45.01a	40.70a	14.11ab	97.61b	72.9a	-1.18a	6.54a

*Mean values with the same lower-case letters are not significantly different at the 95 % confidence level according to Duncan's mean separation test. **UBP refers to unbleached pulp.
**Srednje vrijednosti označene istim malim slovima ne razlikuju se značajno na razini pouzdanosti od 95 % prema Duncanovu testu. **UBP se odnosi na nebijeljenu pulpu.*

finic acid. The final selection was therefore not determined solely by statistical differences. Chemical consumption, possible environmental effects, and practical applicability in industrial conditions were also considered in the evaluation.

3.2 Optical stability and color reversion
3.2. Optička stabilnost i promjena boje

Changes in optical properties during accelerated thermal aging varied depending on the bleaching agent used (Table 3). Statistical analysis carried out separately for each bleaching system showed that aging time had a significant effect on several optical parameters. However, the magnitude of these changes and their statistical significance differed among the bleaching treatments.

The peroxide-treated samples showed the most stable optical behavior during aging. Whiteness decreased slightly from 61.90 % ISO to 61.16 % ISO after 240 h. Although this change was statistically significant (p = 0.0079), the difference was small in practical terms. Duncan's test indicated considerable overlap between aging periods, suggesting a gradual change rather than a sharp decline. Brightness and yellowness were more affected by thermal exposure. Both parameters changed significantly over time (p = 0.0000 and p = 0.0003, respectively). However, even in these cases, the overall variation remained relatively moderate compared with the other bleaching systems.

The total color difference (ΔE^*) increased gradually from 0.94 at 72 h to 2.14 at 240 h. Despite this upward trend, the effect of aging time on ΔE within the peroxide group was not statistically significant (p = 0.8512). This suggests that color change occurred in a steady manner rather than through distinct stages. The relatively low ΔE^* values observed for peroxide-treated samples indicate a higher resistance to thermally induced color reversion compared with the other bleaching systems.

These results can be explained by the oxidative mechanism of hydrogen peroxide. Peroxide is known to break down conjugated chromophoric structures, especially those associated with lignin-derived functional groups (Liu, 2003; Rundlöf *et al.,* 2006; Jiao *et al.,* 2020; Li *et al.,* 2020). In contrast to reductive bleaching systems, peroxide modifies or removes these chromophores rather than simply converting them into temporarily colorless forms. As a result, the fiber structure tends to remain more chemically stable, which may contribute to the lower degree of brightness reversion observed during thermal aging (Chen *et al.,* 2015).

By contrast, dithionite-treated samples showed a more pronounced decline in optical stability during thermal aging. Aging time did not significantly affect whiteness (p = 0.5941), but clear changes were observed in brightness and yellowness (p = 0.0003 and p = 0.0000, respectively). In particular, yellowness increased from 10.24 at the beginning of the test to 17.80 after 240 h, which corresponds to an increase of nearly 95 %. Duncan's test separated the longer aging periods into distinct statistical groups, indicating that optical deterioration became more evident with extended exposure.

Table 3 Optical properties of bleached pulps during thermal aging
Tablica 3. Optička svojstva izbijeljene pulpe tijekom toplinskog starenja

Group *Grupa*	**Duration, h** *Trajanje,* h	**Whiteness (ISO), %** *Bjelina (ISO), %*	**Brightness (ISO), %** *Svjetlina (ISO), %*	**Yellowness (E313)** *Žućenje (E13)*	**ΔE**
Peroxide	0	61.90[ab*]	50.86[c]	26.74[c]	0.00[c]
	72	62.76[b]	50.04[bc]	27.22[bc]	0.94[bc]
	120	62.88[b]	50.20[bc]	27.82[bc]	0.96[bc]
	168	62.08[ab]	49.04[ab]	28.64[ab]	1.30[ab]
	240	61.16[a]	47.92[a]	29.80[a]	2.14[a]
	p values	0.0079	0.0000	0.0003	0.8512
FAS	0	56.20[ab]	48.54[a]	18.88[d]	0.00[e]
	72	55.98[b]	47.98[ab]	20.32[c]	1.04[d]
	120	56.84[a]	48.22[a]	20.94[c]	1.38[c]
	168	56.42[ab]	46.92[bc]	22.78[b]	2.08[b]
	240	56.44[ab]	46.20[c]	24.46[a]	3.00[a]
	p values	0.5430	0.0004	0.0000	0.8505
Dithionite	0	50.76[ab]	47.14[a]	10.24[e]	0.00[e]
	72	50.92[a]	46.50[ab]	12.36[d]	1.10[d]
	120	50.34[b]	45.48[bc]	13.80[c]	1.56[c]
	168	50.50[ab]	44.70[cd]	15.32[b]	2.72[b]
	240	50.44[ab]	44.06[d]	17.80[a]	3.52[a]
	p values	0.5941	0.0003	0.0000	0.3254

*Mean values followed by the same lowercase letter within the same column are not significantly different at the 95 % confidence level according to one-way ANOVA and Duncan's multiple range test
**Srednje vrijednosti označene istim malim slovom unutar istog stupca ne razlikuju se značajno na razini pouzdanosti od 95 % prema jednosmjernoj ANOVA-i i Duncanovu testu višestrukih raspona.*

The ΔE values also increased noticeably during aging, reaching an average of 3.52 at 240 h. In some cases, individual measurements were as high as 4.40. Although the differences between aging periods were not statistically significant (p = 0.3254), the overall Δ*E* values were clearly higher than those measured for peroxide- and FAS-treated samples. This higher color difference suggests that dithionite-bleached pulps experienced more pronounced optical changes during thermal exposure.

The observed trend is consistent with the chemical action of sodium dithionite. As a reducing agent, dithionite converts chromophoric groups into colorless forms but does not eliminate the underlying conjugated structures (Carreira *et al.,* 2012; Krishnan *et al.,* 2020). These reduced structures can be unstable under thermal or oxidative conditions and may revert to their original-colored state. This explains the rapid increase in yellowness and color difference during aging. Similar patterns have been described in earlier studies on dithionite-bleached mechanical and recycled pulps, where low initial yellowness was followed by pronounced thermal yellowing and brightness reversion (Friman *et al.,* 2004; Boeva and Radeva, 2014; El-Sakhawy *et al.,* 2021; Vaysi and Ebadi, 2021).

FAS-treated samples showed optical behavior that fell between peroxide and dithionite systems. Aging time did not have a significant effect on whiteness (p = 0.5430), suggesting that overall perceived whiteness remained relatively stable throughout the aging period. However, brightness and yellowness were affected by thermal exposure (p = 0.0004 and p = 0.0000, respectively). The changes were gradual, and although deterioration was evident over time, it was less pronounced than in the dithionite-treated samples.

The Δ*E* values increased from 1.04 at 72 h to 3.00 at 240 h. As observed in the other bleaching systems, aging time did not lead to statistically significant differences among ΔE values (p = 0.8505). Nevertheless, the overall ΔE levels measured for the FAS-treated samples were consistently lower than those of the dithionite group. This suggests that FAS provides better resistance to thermal color reversion compared with conventional dithionite bleaching.

This trend is consistent with previous reports suggesting that FAS behaves as a more stable reducing agent than dithionite. Earlier studies have indicated that FAS can delay oxidative reversion while still providing the benefits associated with reductive bleaching systems (El-Sakhawy, 2002; Yun and He, 2011; Fišerová *et al.,* 2018; Paranjape and Athalye, 2024).

Although one-way ANOVA did not show statistically significant differences in Δ*E* values over time within each bleaching group ($p > 0.05$), this does not contradict the general optical trends observed. The Δ*E* parameter represents the combined change in *L**, *a**, and *b** values. When color variation progresses gradually and continuously, it may not produce clearly separated statistical groups, even though a steady shift is present. Similar observations have been reported in other accelerated aging studies, where Δ*E* increased over time without distinct statistical separation.

In the present case, Δ*E* is more useful as a comparative indicator between bleaching systems rather than as a precise marker of aging stages. Based on overall Δ*E** levels, peroxide-treated samples showed the most stable optical behavior, whereas dithionite-treated pulps experienced faster and more pronounced color change. FAS-treated samples displayed intermediate performance, performing better than dithionite but not reaching the stability observed with peroxide treatment.

3.3 Mechanical strength and durability
3.3. Mehanička čvrstoća i trajnost

Accelerated thermal aging led to a general reduction in the mechanical properties of the bleached pulps. This decline can be related to gradual weakening of inter-fiber bonding and cellulose chain degradation, as reported in previous studies (Hirn and Schennach, 2017; Fišerová *et al.,* 2018; Małachowska *et al.,* 2021b; Paranjape and Athalye, 2024). The extent of this reduction, however, varied depending on the bleaching system used (Table 4). Statistical analysis conducted separately for each group showed that aging time had a significant effect on some mechanical parameters, while others changed more gradually without reaching statistical significance. These patterns suggest a progressive deterioration process rather than a sudden loss of mechanical integrity.

Among the tested systems, peroxide-treated samples showed the most stable mechanical behavior during thermal aging. The breaking length decreased from 3.80 km to 3.33 km after 240 h, which corresponds to a reduction of about 12 %. Although aging time had a statistically significant effect (p = 0.031), the overlap observed in Duncan's test suggests that the decline occurred gradually rather than in clearly separated stages.

The burst index followed a similar trend. After 240 h of aging, it decreased slightly from 2.28 to 2.12 kPa·m²/g and remained within the same statistical group as some intermediate aging periods. These results indicate that peroxide bleaching helps maintain fiber bonding and sheet integrity more effectively under thermal exposure compared with the reductive systems.

The mechanical stability observed in peroxide-treated samples can be related to its oxidative action on lignin-derived structures. By irreversibly modifying these chromophoric groups, peroxide reduces the number of thermally reactive sites that may contribute to

Table 4 Mechanical properties of bleached pulps during thermal aging
Tablica 4. Mehanička svojstva izbijeljene pulpe tijekom toplinskog starenja

Group *Grupa*	**Duration, h** *Trajanje,*h	**Breaking length, km** *Duljina loma,* km	**Burst index, kPa·m²/g** *Indeks loma,* kPa·m²/g
Peroxide	0	3.80[a*]	2.28[a]
	72	3.54[ab]	1.91[b]
	120	3.53[b]	2.20[a]
	168	3.25[b]	2.12[ab]
	240	3.33[b]	2.12[ab]
	p-value	0.031	0.018
FAS	0	3.47[a]	2.39[a]
	72	3.27[ab]	1.77[c]
	120	3.39[a]	1.85[bc]
	168	3.49[a]	1.94[b]
	240	3.27[b]	1.76[c]
	p-value	0.214	0.000
Dithionite	0	3.64[a]	2.30[a]
	72	3.45[ab]	1.75[c]
	120	3.54[ab]	1.71[c]
	168	3.53[ab]	1.86[b]
	240	3.42[b]	1.81[bc]
	p-value	0.047	0.000

*Mean values followed by the same lowercase letter within the same column are not significantly different at the 95 % confidence level according to one-way ANOVA and Duncan's multiple range test
**Srednje vrijednosti označene istim malim slovom unutar istog stupca ne razlikuju se značajno na razini pouzdanosti od 95 % prema jednosmjernoj ANOVA-i i Duncanovu testu višestrukih raspona.*

further degradation during aging (Chen *et al.,* 2015; Fišerová *et al.,* 2018; Jiao *et al.,* 2020; Zeb *et al.,* 2021). With fewer reactive groups present, secondary reactions during thermal exposure are limited. This may help slow down hornification and preserve inter-fiber bonding, which in turn supports better mechanical retention over time. Similar trends have been described in previous studies on peroxide-treated recycled and mechanical pulps.

FAS-treated samples showed relatively stable tensile behavior during thermal aging. The breaking length decreased only slightly from 3.47 km to 3.27 km after 240 h, and the effect of aging time was not statistically significant ($p = 0.214$). This suggests that FAS bleaching is able to maintain tensile load-bearing capacity to a certain extent under thermal exposure. The burst index, however, responded more sensitively to aging. It declined from 2.39 to 1.76 kPa·m²/g, corresponding to a strength reduction of approximately 26 %, and the effect of aging time was statistically significant ($p < 0.001$). Duncan's test distinguished early and late aging periods, indicating a progressive weakening of inter-fiber bonding. Although FAS is often regarded as more stable than conventional dithionite, the present results indicate that extended thermal exposure still leads to noticeable bonding deterioration. In this respect, FAS appears to offer improved tensile stability compared with dithionite, but it does not match the mechanical retention observed for peroxide-treated samples.

Dithionite-treated pulps showed the most pronounced mechanical decline during aging. The breaking length decreased from 3.64 km to 3.42 km, with a statistically significant effect of aging time ($p = 0.047$). While the tensile reduction remained moderate, the burst index dropped more markedly, from 2.30 to 1.81 kPa·m²/g ($p < 0.001$). The decrease in burst strength points to progressive loss of inter-fiber bonding and sheet integrity. Duncan analysis separated longer aging durations into lower statistical groups, confirming continued mechanical deterioration over time. After 240 h, the burst index of dithionite-treated samples remained clearly lower than that of peroxide-treated pulps under the same conditions.

The mechanical trend observed for dithionite-treated samples can be related to its reductive bleaching mechanism. Dithionite reduces chromophoric groups to colorless forms but does not eliminate the underlying conjugated structures (Pemberton *et al.,* 1995; Lennholm and Iversen, 1998; El-Sakhawy *et al.,* 2021; Vaysi and Ebadi, 2021). Under thermal conditions, these reduced structures may be re-oxidized. Such reactions can generate reactive species that contribute to cellulose chain scission, increased fiber brittleness, and gradual loss of bonding strength. Similar behavior has been described in previous studies on recycled and mechanical pulps, where dithionite bleaching was associated with accelerated mechanical deterioration under thermal or oxidative stress (Małachowska *et al.,* 2021b; Vaysi and Ebadi, 2021; Kaszonyi *et al.,* 2022; Chen *et al.,* 2024; Sevastyanova *et al.,* 2025).

In some cases, particularly for breaking length, aging time did not lead to statistically distinct groups ($p > 0.05$). However, this does not mean that degradation was absent. Thermal aging generally progresses through gradual microstructural changes rather than sudden strength failure. Processes such as hornification, reduced fiber swelling, and a slow decrease in bonding area develop progressively over time (Hirn and Schennach, 2017; Zhao *et al.,* 2022; Sjöstrand *et al.,* 2023; Hashemzehi *et al.,* 2024). As these changes occur continuously, strength values measured at different aging intervals may still overlap statistically, even though a practical decline is present. Therefore, the absence of clear statistical separation should be interpreted cautiously in the context of long-term material performance.

For this reason, the mechanical results in the present study should be evaluated not only in terms of statistical significance but also through direct comparison among bleaching systems. When the overall trends are considered, peroxide-treated samples showed the most stable mechanical behavior during aging. In contrast, dithionite-treated pulps experienced a more pronounced decline in strength properties. FAS-treated samples displayed intermediate performance. Tensile strength was relatively well preserved, whereas burst strength showed greater sensitivity to prolonged thermal exposure. These differences highlight the influence of bleaching chemistry on long-term mechanical stability.

3.4 Physical properties and surface characteristics
3.4. Fizička svojstva i svojstva površine

Accelerated thermal aging led to noticeable changes in the physical properties of the bleached pulps. These changes are associated with modifications in fiber surface characteristics, pore structure, and inter-fiber contact within the sheet. The degree of variation differed depending on the bleaching system used (Table 5). Statistical analysis conducted separately for each group showed that aging time had a significant effect on Cobb water absorption and air permeability. However, the extent and consistency of these changes were not the same for all bleaching treatments.

Peroxide-treated samples showed relatively stable physical behavior during thermal aging. Air permeability changed only slightly, decreasing from 21.72 s to 21.46 s after 240 h. Duncan's test grouped early and late aging periods together, indicating that pore structure and overall sheet compactness were largely maintained.

Table 5 Physical properties of bleached pulps during thermal aging
Tablica 5. Fizička svojstva izbijeljene pulpe tijekom toplinskog starenja

Group *Grupa*	**Duration, h** *Trajanje,* h	**Cobb, g/m²**	**Air permeability, s** *Propusnost zraka,* s
Peroxide	0	162.0^{a*}	21.72^{a}
	72	162.2^{a}	18.94^{b}
	120	144.8^{b}	18.64^{b}
	168	145.0^{b}	20.60^{ab}
	240	145.0^{b}	21.46^{a}
	p-value	0.000	0.021
FAS	0	162.8^{a}	14.70^{a}
	72	138.0^{b}	11.92^{b}
	120	128.8^{c}	12.24^{b}
	168	137.2^{b}	11.50^{b}
	240	140.8^{b}	11.12^{b}
	p-value	0.000	0.000
Dithionite	0	161.2^{a}	15.12^{a}
	72	137.2^{b}	15.02^{a}
	120	113.2^{c}	13.34^{b}
	168	109.8^{c}	11.64^{c}
	240	95.2^{d}	12.00^{bc}
	p-value	0.000	0.000

*Mean values followed by the same lowercase letter within the same column are not significantly different at the 95 % confidence level according to one-way ANOVA and Duncan's multiple range test
**Srednje vrijednosti uz koje stoji isto malo slovo unutar istog stupca ne razlikuju se značajno na razini pouzdanosti od 95 % prema jednosmjernoj ANOVA-i i Duncanovu testu višestrukih raspona.*

Cobb values decreased from 162.0 g/m² to about 145.0 g/m² ($p < 0.001$). This reduction suggests limited hornification and a moderate decrease in fiber swelling capacity. However, the magnitude of change remained controlled, implying that peroxide treatment helps preserve fiber surface characteristics and pore structure during thermal exposure. Similar observations have been reported in earlier studies, where peroxide bleaching was associated with reduced pore collapse and more stable sheet morphology.

FAS-treated pulps displayed intermediate behavior. Cobb values declined from 162.8 g/m² to 140.8 g/m² ($p < 0.001$), corresponding to roughly a 13 % decrease. Air permeability also decreased from 14.70 s to 11.12 s ($p < 0.001$), indicating changes in pore connectivity and some loss of compactness. Compared with peroxide-treated sheets, FAS samples showed a greater tendency toward structural rearrangement during aging.

Dithionite-treated pulps experienced the most pronounced changes. Cobb values dropped from 161.2 g/m² to 95.2 g/m² after 240 h, and statistical analysis clearly separated aging stages. This substantial reduction points to marked hornification and reduced swelling ability. Air permeability likewise decreased significantly, suggesting progressive alteration of sheet structure under thermal stress.

The lower physical stability observed in dithionite-treated pulps is likely related to its reductive bleaching mechanism. As dithionite does not eliminate lignin-derived structures, certain reactive components remain within the fiber matrix. During thermal aging, these structures may contribute to surface oxidation, pore rearrangement, and gradual fiber embrittlement, which in turn affect both hydrophilicity and porosity. Similar trends have been reported for dithionite-bleached mechanical and recycled pulps exposed to thermal or oxidative conditions (Zhu *et al.,* 2018).

Although all bleaching systems showed statistically significant changes in Cobb and air permeability values ($p < 0.05$), these results should be interpreted in light of the continuous nature of physical aging. Processes such as hornification, pore collapse, and redistribution of surface energy develop progressively rather than abruptly. For this reason, gradual but consistent changes can be practically relevant even when numerical differences appear moderate. When the overall trends are considered, peroxide-treated samples maintained the most stable surface and pore structure during aging. Dithionite-treated pulps exhibited more pronounced physical alteration, while FAS-treated samples showed intermediate behavior under prolonged thermal exposure.

3.5 Evaluation of aging performance across bleaching systems

3.5. Evaluacija utjecaja starenja u sustavima izbjeljivanja

To strengthen the statistical interpretation of the data, a two-way ANOVA was performed to evaluate the individual and interactive effects of bleaching agent and aging time on optical, mechanical, and physical properties. The analysis revealed that both bleaching agent ($p < 0.05$) and aging time ($p < 0.001$) had significant effects on the evaluated properties. More importantly, a statistically significant interaction between bleaching agent and aging time was observed ($p < 0.05$), indicating that the influence of bleaching treatment varies depending on the duration of thermal aging. This finding confirms that different bleaching chemistries exhibit distinct degradation behaviors across optical, mechanical, and physical performance over time.

Accelerated thermal aging led to noticeable changes in the physical properties of the bleached pulps. These changes are associated with modifications in fiber surface characteristics, pore structure, and inter-fiber interactions. The degree of variation differed depending on the bleaching system used (Figure 1). Statistical analysis conducted separately for each bleaching group showed that aging time had a significant effect on Cobb water absorption and air permeability. However, the extent and consistency of these changes were not the same for all bleaching treatments.

Figure 1 presents an integrated visualization of aging performance by combining optical, mechanical, and physical stability within a unified framework. The radar chart is based on normalized values derived from experimental measurements, enabling direct comparison between bleaching systems despite differences in parameter scales. Rather than replacing statistical analysis, it provides a visual synthesis of multi-parameter behavior and highlights the balance between different performance aspects during aging. This approach demonstrates that bleaching chemistry not only affects individual properties but also their combined contribution to long-term stability, indicating that evaluations based solely on initial optical improvement may be insufficient for selecting appropriate bleaching strategies.

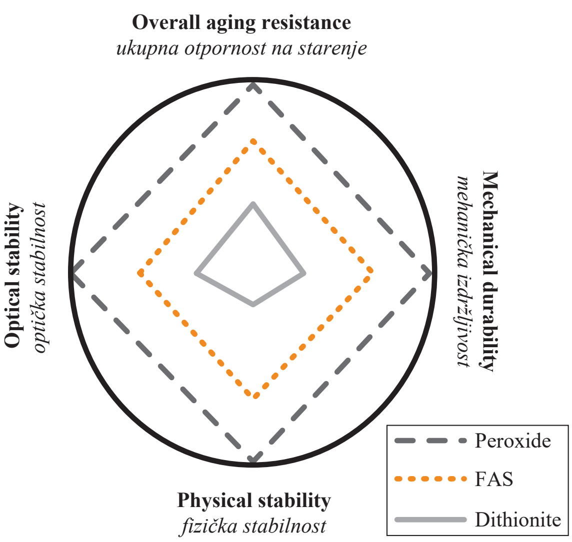

Figure 1 Aging performance comparison of differently bleached ONP

Slika 1. Usporedba utjecaja starenja na različito izbijeljenu papirnu pulpu od starih novina

Peroxide-treated pulps showed stable behavior across the optical, mechanical, and physical parameters evaluated in this study. This trend can be related to the oxidative action of hydrogen peroxide, which modifies lignin-derived chromophoric structures and reduces the number of thermally reactive sites within the fiber matrix (Choi and Kim, 2006; Li *et al.,* 2020; Miglbauer *et al.,* 2020; Zeb *et al.,* 2021). With fewer reactive groups remaining, peroxide-treated fibers tend to display lower brightness reversion, more gradual mechanical decline, and relatively stable surface characteristics during aging. Similar findings have been reported in earlier studies, where peroxide bleaching was associated with improved resistance to thermal and oxidative aging in recycled and mechanical pulps, largely due to the stabilization of residual lignin components (Liu, 2003; Fišerová *et al.,* 2018; Kyene *et al.,* 2019; Jiao *et al.,* 2020; Vaysi and Ebadi, 2021).

FAS-treated pulps showed aging behavior that can be described as intermediate between peroxide and dithionite systems. Optical properties remained relatively stable, but mechanical and physical parameters were more sensitive to prolonged thermal exposure. Although FAS is generally considered more stable than sodium dithionite, it still operates through a reductive mechanism and does not completely remove chromophoric structures from the fiber matrix. As aging progresses, gradual oxidative reactions may continue, influencing fiber bonding and pore structure. Similar observations have been reported in earlier studies comparing FAS and dithionite treatments, where FAS was found to slow down aging-related degradation but not fully prevent losses in strength-related properties (Lennholm and Iversen, 1998; Choi and Kim, 2006; Carreira *et al.,* 2012; Hirn and Schennach, 2017; Peşman and Laloğlu, 2018).

Dithionite-treated pulps showed a less stable aging response compared with the other systems. Although the initial optical values were satisfactory, more pronounced changes were observed in mechanical and physical properties during thermal exposure. The reductive action of sodium dithionite converts chromophores into colorless forms but does not eliminate their conjugated structures (Carreira *et al.,* 2012; Vaysi and Ebadi, 2021). As a result, these structures may be re-oxidized during aging, contributing to progressive hornification, pore modification, and weakening of interfiber bonding. This sequence of changes can lead to a gradual decline in both functional and structural paper properties. Similar trends have been reported in previous studies on reductively bleached recycled fibers subjected to thermal or oxidative conditions.

Figure 1 is therefore not only a visual summary but also an interpretive tool that supports the statistical findings by revealing system-level differences in aging behavior. The combined evaluation clearly indicates that peroxide-treated pulps provide the most balanced and stable performance, followed by FAS and dithionite systems.

4 CONCLUSIONS
4. ZAKLJUČAK

This study compared the optical, mechanical, and physical behavior of ONP bleached with hydrogen peroxide, FAS, and sodium dithionite under accelerated thermal aging at 103 ± 2 °C. The results show that bleaching chemistry has a clear influence on the long-term stability of recycled paper properties. From an optical standpoint, peroxide-treated pulps displayed higher initial brightness and whiteness and maintained these properties relatively well during aging. Dithionite-treated pulps, although characterized by low initial yellowness, exhibited a more pronounced increase in yellowness and color difference over time. This suggests that initial optical improvement alone is not sufficient to predict aging performance. Mechanical and physical results followed a similar pattern. While all samples experienced some reduction in strength and changes in surface-related properties, peroxide-treated sheets showed a more gradual decline. Dithionite-treated pulps were more sensitive to aging, particularly in terms of burst strength and water absorption behavior. FAS-treated pulps showed intermediate performance. Overall, the findings indicate that bleaching agent selection plays an important role in balancing initial quality with long-term durability in recycled paper applications.

Disclosure of GenAI usage – Izjava o primjeni generativne umjetne inteligencije

The authors confirm that no artificial intelligence (AI) tools were used in the design of the study, data collection, data analysis, interpretation of results, or preparation of scientific conclusions. AI-based language tools were used only for limited language editing and stylistic refinement to improve clarity and readability of the manuscript. All scientific content, interpretations, and final decisions remain the sole responsibility of the authors.

5 REFERENCES
5. LITERATURA

1. Aguilar-Rivera, N., 2021: Emerging technology for sustainable production of bleached pulp from recovered cardboard. Clean Technologies and Environmental Policy, 23 (9): 2575-2588. https://doi.org/10.1007/s10098-021-02171-3
2. Asha, K.; Badamali, S. K., 2020: Highly efficient photocatalytic degradation of lignin by hydrogen peroxide under visible light. Molecular Catalysis, 497: 111236. https://doi.org/10.1016/j.mcat.2020.111236
3. Bajpai, P., 2014: Bleaching of Secondary Fibres. In: Recycling and Deinking of Recovered Paper, pp. 155-180, Elsevier. https://doi.org/10.1016/B978-0-12-416998-2.00009-X
4. Boeva, R.; Radeva, G., 2014: Kinetic analysis of the effect of bleaching and temperature increase on the ageing of a chemical-mechanical pulp derived from poplar wood. Cellulose Chemistry and Technology, 48 (7-8): 703-711.
5. Carreira, H. J. M.; Loureiro, P. E. G.; Carvalho, M. G. V. S.; Evtuguin, D. V., 2012: Reductive degradation of residual chromophores in kraft pulp with sodium dithionite. TAPPI Journal, 11 (3): 59-67. https://doi.org/10.32964/TJ11.3.59
6. Chen, S.; Zhu, J., Yu, M.; Jin, C.; Huang, C., 2024: Effect of aging and bleaching on the color stability and surface roughness of a recently introduced single-shade composite resin. Journal of Dentistry, 143: 104917. https://doi.org/10.1016/j.jdent.2024.104917
7. Chen, Y.; Wan, J.; Ma, Y.; Dong, X.; Wang, Y.; Huang, M., 2015: Fiber properties of de-inked old newspaper pulp after bleaching with hydrogen peroxide. BioResources, 10 (1): 1857-1868. https://doi.org/10.15376/biores.10.1.1857-1868
8. Choi, W. J.; Kim, H. J., 2006: Studies on the bleaching efficiency in newsprint using formamidine sulfinic acid. In: Proceedings of the Korea Technical Association of the Pulp and Paper Industry Conference, 381-386.
9. Çiçekler, M.; Tutuş, A., 2025: Cellulose nanofibers (cnf) and cellulose nanocrystals (cnc) as high-performance fillers improving the mechanical, optical and surface properties of recycled newspaper. Turkish Journal of Forest Science, 9 (1): 122-140. https://doi.org/10.32328/turkjforsci.1587158
10. El-Sakhawy, M., 2002: Innovative approaches in bleaching of lignocelluloses – A review. Indian Pulp & Paper Technical Association, 14 (2): 69-84.
11. El-Sakhawy, M.; Abd El-Kader, A. H.; Fahmy, T. Y. A.; Abd El-Sayed, E. S.; Kassem, N. F., 2021: Optimization of dithionite bleaching of high yield bagasse pulp. Cellulose Chemistry and Technology, 55 (5-6): 667-673. https://doi.org/10.35812/CelluloseChemTechnol.2021.55.55
12. Fišerová, M.; Opálená, E.; Gigac, J.; Stankovská, M., 2018: Oxidative and reductive bleaching of deinked pulp. Wood Research, 63 (4): 639-654.
13. Friman, L.; Höglund, H.; Agnemo, R., 2004: Tannin-iron impregnated thermomechanical pulp. Part II: Bleachability and brightness reversion. Nordic Pulp & Paper Research Journal, 19 (4): 525-531. https://doi.org/10.3183/npprj-2004-19-04-p525-531
14. Hashemzehi, M.; Sjöstrand, B.; Håkansson, H.; Henriksson, G., 2024: Degrees of hornification in softwood and hardwood kraft pulp during drying from different sol-

vents. Cellulose, 31 (3): 1813-1825. https://doi.org/10.1007/s10570-023-05657-z
15. Hirn, U.; Schennach, R., 2017: Fiber-Fiber Bond Formation and Failure: Mechanisms and Analytical Techniques. In: Trans. of the XVI[th] Fund. Res. Symp. Oxford, 839-863. Fundamental Research Committee (FRC), Manchester. https://doi.org/10.15376/frc.2017.2.839
16. Jiao, J.; Fang, G.; Liang, F.; Deng, Y.; Shen, K.; Tian, Q.; Han, S.; Zhu, B., 2020: Bleachability improvement of eucalypt mechanical pulps using hydrogen peroxide in ethanol-water media. BioResources, 15 (1): 1370-1383. https://doi.org/10.15376/biores.15.1.1370-1383
17. Kaszonyi, A.; Izsák, L.; Králik, M.; Jablonsky, M., 2022: Accelerated and natural aging of cellulose-based paper: Py-GC/MS method. Molecules, 27 (9): 2855. https://doi.org/10.3390/molecules27092855
18. Koshitsuka, T., 2002: Foundation of recycled pulp bleaching technology. Japan Tappi Journal, 56 (7): 963-975. https://doi.org/10.2524/jtappij.56.963
19. Krishnan, J.; Sunil Kumar, S.; & Krishna Prasad, R., 2020: Characterization of kraft pulp delignification using sodium dithionite as bleaching agent. Chemical Engineering Communications, 207 (6): 837-846. https://doi.org/10.1080/00986445.2019.1630391
20. Kumar, V.; Kalra, J. S.; Verma, D.; Gupta, S., 2020: Process and environmental benefit of recycling of waste papers. International Journal of Recent Technology and Engineering, 8 (2S12): 104-106. https://doi.org/10.35940/ijrte.B1020.0982S1219
21. Kyene, S.; Ventorim, G.; Silva Camargo, B.; De Carvalho Araújo, C. K.; Araújo, C. K. D. C.; Ribas De Lima Soares, L.; Almeida Ferraz, A. P., 2019: Ultraviolet resonance Raman spectroscopy analysis of carbonyl groups present after different bleaching stages for various bleach sequences. BioResources, 14 (1): 1915-1927. https://doi.org/10.15376/biores.14.1.1915-1927
22. Lennholm, H.; Iversen, T., 1998: Pulp bleaching with dithionite: Brightening and darkening reactions. Journal of Pulp and Paper Science, 24 (8): 254-259.
23. Li, M.; Yin, J.; Hu, L.; Chen, S.; Min, D.; Wang, S.; Luo, L., 2020: Effect of hydrogen peroxide bleaching on anionic groups and structures of sulfonated chemo-mechanical pulp fibers. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 585: 124068. https://doi.org/10.1016/j.colsurfa.2019.124068
24. Liu, S., 2003: Chemical kinetics of alkaline peroxide brightening of mechanical pulps. Chemical Engineering Science, 58 (11): 2229-2244. https://doi.org/10.1016/S0009-2509(03)00089-7
25. Małachowska, E.; Dubowik, M.; Boruszewski, P.; Przybysz, P., 2021a: Accelerated ageing of paper: Effect of lignin content and humidity on tensile properties. Heritage Science, 9 (1): 132. https://doi.org/10.1186/s40494-021-00611-3
26. Małachowska, E.; Pawcenis, D.; Dańczak, J.; Paczkowska, J.; Przybysz, K., 2021b: Paper ageing: The effect of paper chemical composition on hydrolysis and oxidation. Polymers, 13 (7): 1029. https://doi.org/10.3390/polym13071029
27. Miglbauer, E.; Gryszel, M.; Głowacki, E. D., 2020: Photochemical evolution of hydrogen peroxide on lignins. Green Chemistry, 22 (3): 673-677. https://doi.org/10.1039/C9GC04324A
28. Nestor, D. V., 1994: Issues in the design of recycling policy: The case of old newspapers. Journal of Environmental Management, 40 (3): 245-256. https://doi.org/10.1006/jema.1994.1018
29. Ornaghi, H. L.; Ornaghi, F. G.; Neves, R. M.; Monticeli, F.; Bianchi, O., 2020: Mechanisms involved in thermal degradation of lignocellulosic fibers: A survey based on chemical composition. Cellulose, 27 (9): 4949-4961. https://doi.org/10.1007/s10570-020-03132-7
30. Paranjape, M.; Athalye, A., 2024: Eco-friendly polyester reduction clearing: Examining cutting-edge approaches. Advance Research in Textile Engineering, 9 (3): 1103.
31. Pemberton, R. S.; Depew, M. C.; Heitner, C.; Wan, J. K. S., 1995: Some mechanistic insights into a model bleaching process of quinones by bisulfite and dithionite: An ESR-CIDEP study. Journal of Wood Chemistry and Technology, 15 (1): 65-83. https://doi.org/10.1080/02773819508009500
32. Peşman, E.; Laloğlu, S., 2018: Recycling of colored office paper. Part I: Pre-bleaching with formamidine sulfinic acid at pulper. BioResources, 13 (2): 3949-3957. https://doi.org/10.15376/biores.13.2.3949-3957
33. Pydimalla, M.; Reddy, K., 2020: Effect of pulping, bleaching and refining process on fibers for paper making – A review. International Journal of Engineering Research & Technology, 9 (12): 310-316. https://doi.org/10.17577/IJERTV9IS120143
34. Rundlöf, E. S.; Zhang, E.; Zhang, L.; Gellerstedt, G., 2006: The behavior of chromophoric structures in softwood mechanical pulp on bleaching with alkaline hydrogen peroxide. Nordic Pulp & Paper Research Journal, 21 (3): 359-364. https://doi.org/10.3183/npprj-2006-21-03-p359-364
35. Saad, A.; Owda, M.; Ibrahim, A.; Bassiouni, M., 2020: Effect of deinking and peroxide bleaching on the physical properties of recycled newspapers. Al-Azhar Bulletin of Science, 31 (2): 9-18. https://doi.org/10.21608/absb.2020.35942.1070
36. Sepahvand, S.; Akbarpour, I.; Ashori, A., 2025: Optimizing mixed waste paper properties through formamidine sulfinic acid bleaching and cationic additive treatments. Journal of Polymers and the Environment, 33 (1): 29-50. https://doi.org/10.1007/s10924-024-03411-5
37. Sevastyanova, Y.; Shcherbak, N.; Konshina, K.; Potashev, A.; Palchikova, E.; Makarov, I.; Kalimanova, D.; Sakipova, L.; Kareshova, Z.; Balabekova, S.; Shambilova, G.; Vinogradov, M.; Novikov, E., 2025: Study of the change in properties by artificial aging of eco-papers. Processes, 13 (6): 1750. https://doi.org/10.3390/pr13061750
38. Sjöstrand, B.; Karlsson, C.-A.; Barbier, C.; Henriksson, G., 2023: Hornification in commercial chemical pulps: Dependence on water removal and hornification mechanisms. BioResources, 18 (2): 3856-3869. https://doi.org/10.15376/biores.18.2.3856-3869
39. Tofani, G.; Cornet, I.; Tavernier, S., 2021: Estimation of hydrogen peroxide effectivity during bleaching using the Kappa number. Chemical Papers, 75 (11): 5749-5758. https://doi.org/10.1007/s11696-021-01756-y
40. Tofani, G.; Cornet, I.; Tavernier, S., 2022: Multiple linear regression to predict the brightness of waste fibres mixtures before bleaching. Chemical Papers, 76 (7): 4351-4365. https://doi.org/10.1007/s11696-022-02181-5
41. Vaysi, R.; Ebadi, S. E., 2021: Thermal yellowing of hornbeam chemi-mechanical pulps bleached with hydrogen peroxide and sodium dithionite. BioResources, 16 (4): 7635-7647. https://doi.org/10.15376/biores.16.4.7635-7647

42. Youssef, A.; Rushdy, A.; Noshy, W., 2017: Influence of bleaching materials on mechanical and morphological properties for paper conservation. Egyptian Journal of Chemistry, 60 (5): 893-903. https://doi.org/10.21608/ejchem.2017.1288.1073
43. Yun, N.; He, B. H., 2011: Study on bleaching of de-inked pulp. Advanced Materials Research, 236-238: 1224-1228. https://doi.org/10.4028/www.scientific.net/AMR.236-238.1224
44. Zeb, H.; Hussain, M. A.; Ahmed, I.; Akram, M. S.; Haider, B.; Haider, R.; Babar, Z. B.; Saleem, R. M.; Ahsan, A.; Aziz, I.; Arif, M., 2021: Study of bleaching of old newsprint recycled paper: Reproduction of newspaper material. Materials Research Express, 8 (8): 085305. https://doi.org/10.1088/2053-1591/ac1ca9
45. Zhao, L.; Jiang, W.; Wang, Y.; Wang, Z.; Wang, Y., 2022: Study on micro topography of thermal aging of insulation pressboard based on image processing. Energies, 15 (17): 6317. https://doi.org/10.3390/en15176317
46. Zhu, M.; Chen, Y.; Gu, C.; Zhu, W.; Ma, X.; Wang, X., 2018: Effect of thermal aging on the properties of insulating paper. In: Proceedings of the 4th Annual International Conference on Material Engineering and Application (ICMEA 2017), pp. 122-124. https://doi.org/10.2991/icmea-17.2018.28

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Energy Efficiency of Industrial Wood Drying: Comparative Analysis of Convective and Vacuum Drying Based on an Operational Case Study

Energetska učinkovitost industrijskog sušenja drva: komparativna analiza konvektivnoga i vakuumskog sušenja na temelju studije slučaja iz prakse

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ABSTRACT • *Artificial wood drying is an energy-intensive industrial process with major economic and environmental implications. This study evaluates the energy performance of convective and vacuum drying in a Hungarian wood-processing plant, with separate analysis of one summer and one winter convective cycle. For convective drying, measured energy use was compared with literature-based theoretical estimates. The measured thermal demand exceeded the theoretical estimate by approximately 17 % in winter, whereas the summer deviation remained within ± 4 %. Electrical demand was markedly lower in summer; however, as only full-kiln electrical data were available, this difference is interpreted cautiously as the combined effect of fan duty, cycle duration, moisture condition, and seasonal operating context rather than as a direct fan-level effect. On an annual total basis, the vacuum dryer consumed only about one-quarter to one-fifth as much energy as the convective system, but on a specific volume basis it showed substantially higher electrical demand. The results indicate that industrial wood-drying energy performance may be improved through heat recovery, improved thermal insulation, and more adaptive fan-control strategies. As the convective analysis was based on only two industrial cycles, the findings should be interpreted as site-specific evidence rather than generally transferable performance relationships.*

KEYWORDS: *wood drying; energy efficiency; convective drying; vacuum drying; industrial case study*

SAŽETAK • *Umjetno sušenje drva energetski je intenzivan industrijski proces s velikim ekonomskim i ekološkim učincima. U ovoj se studiji procjenjuju energetska svojstva konvektivnoga i vakuumskog sušenja u pogonu za preradu drva u Mađarskoj, s odvojenom analizom jednoga ljetnog i jednoga zimskog konvektivnog ciklusa. Za konvektivno je sušenje izmjerena potrošnja energije uspoređena s teorijskim procjenama utemeljenima na literaturi. Izmjerena po-*

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treba toplinske energije premašila je teorijsku procjenu za otprilike 17 % zimi, dok je ljetno odstupanje ostalo unutar ± 4 %. Potreba za električnom energijom bila je znatno niža ljeti. Međutim, zbog dostupnosti podataka o električnoj energiji samo za punu sušaru, ta se razlika oprezno tumači kao kombinirani učinak rada ventilatora, trajanja ciklusa, sadržaja vode i sezonske prirode rada, a ne kao izravan učinak rada ventilatora. Na godišnjoj razini vakuumska je sušara približno potrošila samo jednu četvrtinu do jednu petinu energije koju je potrošio konvektivni sustav, ali ako se računa na temelju specifičnog volumena, pokazala je znatno veću potrošnju električne energije. Rezultati pokazuju da se energetska učinkovitost industrijskog sušenja drva može poboljšati povratom topline, poboljšanom toplinskom izolacijom i prilagodljivijim strategijama upravljanja ventilatorima. Budući da je konvektivna analiza bila utemeljena samo na dva industrijska ciklusa, rezultate treba shvatiti kao specifične dokaze za istraživanu lokaciju, a ne kao općenito prenosive odnose svojstava konvektivnoga i vakuumskog sušenja drva.

KLJUČNE RIJEČI: *sušenje drva; energetska učinkovitost; konvektivno sušenje; vakuumsko sušenje; studija industrijskog slučaja*

1 INTRODUCTION
1. UVOD

Wood drying is a fundamental prerequisite for the quality of sawn timber, as insufficiently dried wood is prone to warping, cracking, and increased susceptibility to biological degradation (Faipar, n.d.). Although natural air drying requires no direct energy input, it is slow and demands extensive storage space. Consequently, various artificial drying methods have become widespread in modern wood processing, including convective, condensation (heat-pump), vacuum, microwave, and radio-frequency drying. While all technologies aim to reduce wood moisture content to a target level, their energy efficiency and environmental impacts differ substantially. Artificial wood drying is a process with high thermal energy demand. In industrial practice, actual energy consumption is often substantially higher than the theoretical minimum required for water evaporation, due to the high initial moisture content of green wood and additional heat losses associated with kiln operation (Simpson, 1991). Convective dryers remove moisture through continuous air exchange, resulting in considerable energy consumption, whereas heat-pump-based systems can recover a large proportion of heat from circulating air, achieving savings of up to 50–70 % (Faipar, n.d.). Vacuum drying has been widely discussed in the literature as an alternative drying technology that operates under reduced pressure and may provide shorter drying times and gentler treatment, particularly for hardwoods and higher value-added products (Espinoza and Bond, 2016). At the same time, commercial implementation requires careful consideration of equipment costs, electricity demand, and process applicability under industrial conditions (Espinoza and Bond, 2016; Lyon *et al.*, 2021). The annual drying volume of the Hungarian sawmilling industry is estimated at approximately 1.1 – 1.3 million m³/year (KSH, 2023; FAGOSZ, 2023). Since about 90 – 95 % of industrial drying relies on convective technology, an average volume of 1.2 million m³/year was considered for national-scale evaluation. Based on operational experience, the average specific energy demand is approximately 2000 MJ/m³ of thermal energy and 112 kWh/m³ of electrical energy (≈ 403 MJ/m³), corresponding at national scale to roughly 2400 TJ/year of heat and 134.4 GWh/year (≈ 484 TJ/year) of electricity consumption. Approximately two-thirds of the thermal demand is typically covered by wood-based by-products, while the remaining share is supplied by natural gas. Assuming an emission factor of 56.26 kg carbon dioxide equivalent (CO_2eq)/GJ for natural gas (IPCC, 2021) and a boiler efficiency of 90 %, emissions related to heat production amount to approximately 50 kt CO_2 eq/year. Electricity consumption, calculated using the Hungarian annual average grid carbon intensity of 0.243 kg CO_2 eq/kWh for 2024, based on Electricity Maps yearly data (Electricity Maps, n.d.), contributes an additional ~32.7 kt CO_2 eq/year. The applied factor was used as an attributional average electricity-emission indicator rather than as a marginal emission factor. Accordingly, total annual emissions from wood drying in Hungary are estimated at approximately 82.5 kt CO_2 eq, corresponding to about 69 kg CO_2 eq/m³. Energy demand in wood drying is influenced by factors such as wood species, thickness, initial and target moisture content, and equipment design. In conventional convective kiln drying, seasonal ambient conditions can substantially influence thermal energy demand. This is because total kiln energy consumption is not limited to moisture evaporation but also includes the heating of kiln structures and incoming air, ventilation-related losses, thermal transmission through the kiln envelope, and air leakage losses (Elustondo and Oliveira, 2009). Accordingly, colder winter operation generally requires more heat than summer operation due to the larger temperature difference between kiln and ambient air. Experimental observations by Meng *et al.* (2019) showed that, although less fresh air may be needed in winter, more energy is required to heat the colder incoming air, resulting in higher kiln heating demand under winter conditions. Likewise, annual simulations by Lamrani *et al.* (2021) confirmed that climate has a pronounced effect on wood-dryer energy performance and that cold-climate operation is associated with a stronger thermal-energy penalty than hot-climate operation. This literature background supports the expectation that winter heat demand may substantially exceed summer heat demand under industrial convective drying conditions. Consequently, industrial boiler systems are typically sized to meet peak winter loads.

This study presents an industrial case study based on high-resolution energy measurements in a Hungarian wood-processing plant. It compares one summer and one winter convective drying cycle, evaluates the energy-consumption structure of convective and vacuum drying, and identifies practical opportunities for improving industrial energy efficiency. The focus is on seasonal and technology-related energy-use patterns under real operating conditions rather than on statistically generalized conclusions.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Experimental site and equipment
2.1. Eksperimentalna lokacija i oprema

The investigation was carried out at the drying facility of a Hungarian wood-processing company operating a sawmill; the company name is not disclosed at the operator's request. The plant operates six conventional convective drying chambers and one vacuum dryer under industrial conditions. The convective chambers are Mühlböck ZLSM units, each with an effective stack capacity of approximately 90 – 100 m³. The vacuum dryer is a WTT 151031 system with a net capacity of about 7 – 8 m³, primarily used for drying smaller volumes of higher value-added products. The convective chambers are heated via hot-water heat exchangers supplied by a central boiler system. The vacuum dryer also uses a water-based heating system; however, during winter operation, capacity limitations of the central boiler require periodic support from a local auxiliary boiler. Any such auxiliary-boiler support was supplied through the same heating circuit and was therefore included in the measured thermal energy delivered to the vacuum dryer. All chambers are equipped with circulation fans driven by variable frequency drives (VFD), enabling automatic adjustment of air-circulation intensity according to process conditions such as temperature and moisture content.

2.2 Description of the applied measurement system
2.2. Opis primijenjenoga mjernog sustava

The supervisory and data acquisition system implemented in the industrial test environment was designed for the continuous monitoring and centralized recording of thermal and electrical energy consumption in the drying chambers (Figure 1). This setup enabled a high time-resolution comparative analysis of convective and vacuum drying technologies under real industrial operating conditions. Thermal energy consumption was measured using LOW USFL-400 Engelmann ultrasonic flow meters combined with SensoStar2C evaluation units. Heat energy was calculated from the mass flow rate of the heating circuit water and the temperature difference between supply and return lines and expressed in MWh. As heat metering was performed at the dryer-side heating circuit, the measured thermal values represent the total heat actually supplied to the chamber, irrespective of whether it originated from the central boiler or from auxiliary winter support. Data transmission was performed via the M-Bus protocol. Electrical energy consumption was recorded using Schneider Electric PM710 power meters with current transformers. Voltage, current, and power parameters of the three-phase system were collected at one-minute intervals via Modbus RTU over an RS-485 communication line. Interoperability between protocols was ensured by an EGX100 Modbus/Ethernet gateway and an M-Bus/RS-232 converter. System control was provided by a Twido PLC, while aggregated data were processed using PowerLogic™ ION Enterprise™ 6.0 software, allowing real-time visualization, archiving, and automated reporting. Energy consumption data from both convective and vacuum chambers were collected by a central acquisition unit, ensuring consistent measurement-based evaluation throughout the investigated period. The reported electrical energy consumption values were based on full-kiln electricity metering. Accordingly, the measured values represent the total electrical consumption registered for the drying chamber within the applied measurement boundary, rather than a fan-only sub-metered value. In practical terms, the dominant electrical load was the kiln air-circulation system, while additional auxiliary electrical loads may also have been included where they were connected within the same chamber-level metering scope. However, detailed sub-metered data for individual consumers such as fans, dampers, pumps, or control units were not available in the processed industrial dataset. For the convective chambers, both the summer and winter cycles were carried out with VFD-controlled circulation fans. Thus, frequency-controlled fan operation was present in both analyzed runs, although the available industrial dataset did not include motor-level time series suitable for a direct reconstruction of phase-specific fan-power demand. To improve interpretability of the chamber-level electrical measurements, the circulation-fan system consisted of six fans with an installed power of approximately 3 – 4 kW per fan, corresponding to a total installed fan power of approximately 18 – 24 kW. These values are re-

Figure 1 Thermal and electrical energy monitoring and data acquisition setup for convective (left) and vacuum (right) drying systems
Slika 1. Instalacija za praćenje potrošnje toplinske i električne energije i prikupljanje podataka za konvektivne (lijevo) i vakuumske (desno) sustave sušenja

ported as engineering boundary conditions to support physical interpretation of the measured electricity demand, rather than as a disclosure of the complete proprietary equipment specification. According to manufacturer specifications, the Schneider Electric PM710 meter used for electrical energy recording conforms to Class 1 active-energy accuracy, while the thermal-energy metering chain was based on industrial ultrasonic heat-metering components designed for standardized heat-accounting applications; therefore, the instrumental uncertainty of measured energy values is expected to be moderate relative to the broader process variability of industrial drying.

2.3 Drying cycles and calculation methods
2.3. Ciklusi sušenja i metode izračuna

In the convective test chamber, one complete summer and one complete winter drying cycle were analyzed under industrial operating conditions. The summer cycle was carried out between 11 July and 30 July 2024, while the winter cycle took place between 26 January and 19 February 2024. In both cases, oak sawn timber (28 mm thickness) was dried from an initial moisture content of approximately 45 % (summer) and 55 % (winter) to a target final moisture content of 10 %. The convective dataset therefore represents a clearly defined product group, namely 28 mm oak sawn timber dried to a target final moisture content of 10 % under routine industrial kiln operation. By contrast, the vacuum-drying evaluation presented later in the paper is based on the annual operating dataset of the vacuum system as used in the investigated plant, where the technology is applied primarily to smaller batches and products with higher quality-related processing requirements. Accordingly, the convective and vacuum results should be interpreted as technology-level industrial reference cases within the same plant, rather than as a strictly matched one-to-one experimental comparison of identical charges. The reported moisture content values used for process characterization were obtained from the kiln control system based on in-kiln moisture probes. In the present study, the initial moisture contents of approximately 45 % in summer and 55 % in winter were therefore interpreted as charge-level operational values derived from kiln monitoring rather than from a separate laboratory-based sampling campaign. The convective cycles were operated under industrial kiln-control schedules in which the control settings changed by process stage. Accordingly, the value of approximately 60 °C should be interpreted as a characteristic temperature level of the main drying phase rather than as a constant set-point applied throughout the entire cycle. Due to a confidentiality agreement with the industrial partner, the complete time-resolved commercial drying schedule, including stage-wise dry-bulb and wet-bulb or EMC/RH set-points, fan-control settings, and end-stage treatments, cannot be disclosed in full. Nevertheless, in order to improve process interpretability, approximate operating ranges are provided for the principal stages of the convective schedule. For the investigated 28 mm oak charges, the schedule started under relatively mild initial conditions, typically with a dry-bulb temperature in the range of approximately 40 – 45 °C and an EMC of approximately 12 – 15 %, followed by a gradual increase in drying intensity as the timber moisture content decreased. The main drying stage was characterized by a temperature level of about 60 °C. In the final drying stage, the operating conditions typically approached approximately 60 – 65 °C with an EMC of approximately 6 – 8 %, consistent with industrial kiln drying of oak to a target final moisture content of 10 %. Equalization and/or mild conditioning were applied at the end of the process as part of routine industrial kiln operation; however, their detailed stepwise parameters also form part of the confidential commercial schedule. For interpretative purposes, these end-stage treatments may be characterized as short final adjustments carried out approximately within the range of 60 – 65 °C and about 8 – 12 % EMC in order to reduce within-charge moisture gradients and residual drying stresses before unloading. These values should be interpreted as approximate industrial operating ranges describing the principal boundary conditions of the analyzed kiln runs rather than as a fully disclosed stage-by-stage drying schedule.

Climatic conditions differed considerably, with an average outdoor temperature of about 22 °C in summer and -12 °C in winter. For each cycle, total thermal energy consumption (MWh) and electrical energy demand (kWh) were determined, together with specific values per unit volume of dried wood (MJ/m³, kWh/m³). The calculations were intentionally simplified in order to obtain an engineering estimate suitable for comparison with measured industrial energy consumption. Accordingly, minor contributions from humidification, air leakage, short transient control phases, and local inhomogeneities of airflow and moisture distribution within the stack were neglected. The simplified theoretical model did not include a separate latent heat of fusion term for possible thawing of frozen water in the wood charge; such effects were implicitly absorbed into the general heating demand and may therefore contribute to underestimation under severe winter conditions. Material properties were taken from literature data representative of oak drying, including an oven-dry density of approximately 650 kg/m³, an effective specific heat capacity of approximately 2.5 kJ/kg·K, and a latent heat of evaporation of approximately 2500 kJ/kg. Correlation-based heat-loss estimation followed the simplified approach reported by Konopka *et al.* (2021), adapted to the measured industrial chamber dimensions and seasonal temperature conditions. Literature on conventional kiln drying consistently shows that total energy demand is dominated by thermal energy, whereas electricity is mainly associated with circulation fans and auxiliary equipment; reported practice-based proportions can be expressed approximately as 80 – 90 % thermal and 10 – 20 % electrical energy (Elustondo and Oliveira, 2009; Andersson, 2014; Konopka *et al*., 2021; Lamrani *et al*., 2021). Therefore, the 88 % thermal and 12 % electrical split applied in this study should be interpreted as a practical engineering assumption within that range, in accordance with Hungarian industrial experience and expert consultation.

Vacuum drying was also evaluated under the same industrial conditions. The vacuum dryer is mainly used for rapid drying of smaller volumes of high value-added products, processing approximately 200 – 300 m³ annually (2 – 3 cycles per month, 7 – 8 m³ per cycle). For comparability, the same wood species and thickness (oak, 28 mm) were analyzed for both technologies. Vacuum dryer energy demand was assessed exclusively from continuous measurement data, as no generally accepted theoretical correlation is available in the literature; therefore, the analysis focused on the measured energy consumption structure (thermal versus electrical share). Time-resolved chamber-pressure data were not available in the processed project database; therefore, vacuum drying was evaluated here on the basis of measured thermal and electrical energy consumption rather than by correlating energy demand with detailed pressure profiles. For consistency throughout the manuscript, thermal energy is reported primarily in MJ (or MJ/m³), while electrical energy is reported primarily in kWh (or kWh/m³), where direct comparison between energy forms is relevant, and electrical values are additionally expressed in MJ using the conversion 1 kWh = 3.6 MJ.

2.3.1 Calculation framework for theoretical thermal energy demand

2.3.1. Okvir za izračun teorijske potrebe za toplinskom energijom

The theoretical thermal energy demand of the convective drying cycles was estimated by a simplified charge-level heat balance. The calculation was structured around three main components: (i) sensible heat required to increase the temperature of the wood substance and its moisture content, (ii) latent heat required for water evaporation, and (iii) heat losses associated with kiln operation. In this way, the total theoretical thermal energy demand was expressed as:

$$Q_{th,total} = Q_{heat} + Q_{evap} + Q_{loss} \tag{1}$$

Where $Q_{th,total}$ is the total theoretical thermal energy demand (MJ), Q_{heat} is the sensible heat demand for heating the wood-water system (MJ), Q_{evap} is the latent heat demand of moisture removal (MJ), and Q_{loss} represents the estimated heat losses of the kiln system (MJ). The oven-dry wood mass was determined from the loaded timber volume and the oven-dry density of oak:

$$m_0 = V \cdot \boldsymbol{\rho}_0 \tag{2}$$

Where m_0 is the oven-dry wood mass (kg), V is the timber volume loaded into the kiln (m³), and ρ_0 is the oven-dry density of oak (kg/m³).

The initial and final water masses in the charge were determined from the corresponding moisture contents on a dry basis:

$$m_{w,i} = m_0 \cdot MC_i \tag{3}$$

$$m_{w,f} = m_0 \cdot MC_f \tag{4}$$

Where $m_{w,i}$ and $m_{w,f}$ are the initial and final water masses (kg), and MC_i and MC_f are the initial and final moisture contents expressed on a dry basis (kg water/kg oven-dry wood). Accordingly, the mass of removed water was calculated as:

$$m_{evap} = m_{w,i} - m_{w,f} \quad (5)$$

For comparability, the energy results were expressed using multiple functional units. In addition to the conventional volume-based indicator (MJ/m³ of dried timber), the study also used moisture-normalized and dry-matter-normalized indicators, namely MJ/kg of removed water and MJ/kg of oven-dry wood. These were calculated as:

$$SEC_V = Q / V \quad (6)$$

$$SEC_W = Q / m_{evap} \quad (7)$$

$$SEC_{OD} = Q / m_0 \quad (8)$$

Where SEC_V is the specific energy consumption per unit volume of dried timber, SEC_W is the specific energy consumption per kilogram of removed water, SEC_{OD} is the specific energy consumption per kilogram of oven-dry wood, Q is the relevant measured or calculated energy value, m_{evap} is the mass of removed water. The sensible heat demand was estimated as:

$$Q_{heat} = m_0 \cdot c_{wd} \cdot (T_d - T_0) + m_{w,avg} \cdot c_w \cdot (T_d - T_0) \quad (9)$$

Where c_{wd} is the specific heat capacity of oven-dry wood, c_w is the specific heat capacity of water, T_0 is the initial timber temperature, T_d is the characteristic drying temperature, and $m_{w,avg}$ is the average water mass considered during heating.

The latent heat demand of evaporation was estimated as:

$$Q_{evap} = m_{evap} \cdot h_{fg} \quad (10)$$

Where h_{fg} is the latent heat of evaporation of water at the applied drying-temperature range. The heat-loss term was treated as an aggregate operational loss term that includes, in simplified form, the effects of heat transmission through the kiln envelope and other process-related thermal losses during the cycle:

$$Q_{loss} = Q_{trans} + Q_{other} \quad (11)$$

Where Q_{trans} represents conductive heat loss through the kiln structure and Q_{other} represents additional operational losses not explicitly resolved in the available industrial documentation. As the full time-resolved kiln schedule and ventilation history were confidential, the calculation was intentionally formulated as a simplified cycle-level engineering estimate using the same structure for both seasonal cases, rather than as a transient stage-resolved process model.

2.4 Nature, limitations and uncertainties of the measurement database

2.4. Priroda, ograničenja i nesigurnosti baze podataka mjerenja

The present study is an industrial case study based on the energy analysis of two complete convective drying cycles (one summer and one winter) and on the continuous annual operational measurement database of the investigated drying facility collected during the 2024 project period. The effective monitoring period was limited to one year, because the preceding project phase focused on installation and commissioning of the industrial test environment, while the subsequent phase was dedicated to data processing and evaluation.

The convective-drying analysis was intentionally restricted to two complete industrial cycles representing contrasting seasonal conditions. The aim was not to derive statistically averaged values from repeated runs, but to evaluate seasonal differences in energy demand under real industrial conditions and to compare measured convective energy consumption with simplified literature-based theoretical estimates. Representativeness is partially supported by the use of typical production material (oak, 28 mm thickness), a target final moisture content of 10 %, and routine industrial kiln operation. However, as the complete time-resolved industrial drying schedule is subject to confidentiality restrictions, detailed process-level comparability remains limited. To improve interpretability, the revised manuscript reports approximate operating ranges for the principal initial, main, and final stages of the convective drying schedule, including the general presence of end-stage equalization/conditioning treatments. Since replicated convective cycles under identical conditions were not available, repeatability-based statistical descriptors such as coefficients of variation were not considered methodologically robust. The conclusions should therefore be interpreted primarily within the context of the investigated equipment, operating conditions, raw material, and measurement period. Electrical parameters were recorded at one-minute intervals, providing tens of thousands of data points per cycle and enabling high time-resolution analysis. However, the available electrical dataset represented total chamber electricity consumption and did not permit separate reconstruction of fan-specific duty cycles, full-load operating fractions, or other component-level load profiles. Electrical energy was measured with Schneider Electric PM710 meters, specified by the manufacturer as Class 1 active-energy instruments. Thermal energy was recorded by an ultrasonic heat-metering chain; although the exact calibration certificate of the installed configuration was not evaluated in this paper, comparable Engelmann ultrasonic heat-metering systems are designed for standardized industrial heat accounting. Accordingly, direct metering uncertainty is unlikely to be the dominant source of deviation.

A more important source of uncertainty is associated with moisture-content determination and model simplification. The initial moisture contents used in the theoretical calculations were derived from in-kiln moisture-probe readings and interpreted as charge-level average operational values rather than as results of a separate destructive laboratory sampling campaign. Consequently, within-stack moisture heterogeneity, particularly in the winter charge, may have influenced the calculated heat demand through both the estimated evaporated water mass and the assumed heating requirement. The differences between calculated and measured values should therefore be interpreted as the combined effect of metering uncertainty, sampling uncertainty, and simplifying assumptions in the theoretical model, rather than as a single-source discrepancy.

No dedicated comparative dataset was available on drying quality, defect formation, or internal stress development for the two technologies. Quality-related statements in this paper should therefore be interpreted as technology-related practical considerations rather than as directly measured comparative results. The observed trends, particularly the higher winter thermal demand and the potentially lower electrical demand under VFD-controlled summer operation, are consistent with broader industrial expectations, but the present dataset is not sufficient for broad quantitative generalization.

The vacuum-drying evaluation was based on a complete annual measurement dataset. No theoretical energy calculation was applied, because no uniformly accepted correlation for vacuum-drying energy demand is available in the literature. Vacuum-related results should therefore be interpreted primarily as a measurement-based comparison and as an illustration of energy-consumption structure (thermal versus electrical share). In addition, time-resolved vacuum-pressure data were not available in the analyzed dataset; therefore, the present study does not establish a direct relationship between chamber pressure and energy demand, but rather provides a measurement-based comparison of the overall thermal and electrical consumption structure.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Energy demand of summer and winter convective drying cycles
3.1. Potrošnja energije konvektivnog sušenja u ljetnim i zimskim ciklusima

During the summer convective drying cycle (11 July – 30 July 2024), thermal energy consumption amounted to 25.60 MWh (92160 MJ) for drying 84.66 m³ of oak timber, corresponding to a specific demand of approximately 1089 MJ/m³. Electrical energy consumption was 905.7 kWh (3260 MJ), i.e. about 10.7 kWh/m³ (≈38.5 MJ/m³). In the winter cycle (26 January – 19 February 2024), 90 m³ of oak timber was dried with a measured thermal energy consumption of 57.80 MWh (208080 MJ), corresponding to about 2312 MJ/m³. Electrical demand reached 5045 kWh (18162 MJ), corresponding to approximately 56.1 kWh/m³ (≈ 202 MJ/m³). The total summer cycle duration was 20 days according to production records, referring to the full industrial kiln cycle. The corresponding winter cycle duration was 25 days, likewise referring to the full industrial cycle rather than only to a selected active drying sub-phase. Measured energy data were compared with theoretical heat balance estimates. For the summer cycle, the calculated thermal demand was 95711 MJ, exceeding measurements by only 3.7 %, indicating close agreement. In contrast, the winter cycle showed a calculated demand of 173000 MJ versus a measured value of 208080 MJ, corresponding to an approximately 17 % higher real industrial energy requirement. For electrical energy, the summer cycle exhibited a major deviation from the literature-based benchmark estimate (≈ 3190 kWh), with a measured value of only 905.7 kWh. In the winter cycle, measured electricity demand was 5045 kWh. This corresponds to an approximately 5.6-fold difference between the two analyzed industrial cycles, whereas the cycle duration differed only from 20 to 25 days. Accordingly, the seasonal gap in measured electricity use cannot be interpreted as a simple consequence of cycle length alone. The large seasonal difference observed in chamber-level electricity demand should therefore be interpreted with caution. The applied electrical measurement boundary covered the full kiln electrical consumption rather than a fan-only sub-metered load. Within this boundary, the dominant consumer was the air-circulation system; however, detailed sub-metered records for individual fans and other auxiliary electrical components were not available. Consequently, the present dataset does not permit a direct fan-level decomposition or a time-resolved verification of fan-duty profiles. In both analyzed convective cycles, the circulation fans were operated by variable-frequency drives. Thus, a difference in fan-control strategy or duty profile between summer and winter is a technically plausible contributor to the observed electricity gap, but it cannot be isolated quantitatively from the available data. The convective chamber was equipped with six circulation fans rated at approximately 3 – 4 kW each, corresponding to a total installed fan power of approximately 18 – 24 kW. Relative to this installed capacity, the measured chamber-level electricity demand corresponds to an average equivalent electrical load of about 1.9 kW over the 20-day summer cycle and about 8.4 kW over the 25-day winter cycle. Although these average values cannot be interpreted as direct fan-only power levels, they indicate that the seasonal difference is physically consistent with markedly different effective fan-duty conditions within a VFD-controlled kiln system. Although exact time-resolved fan-frequency data cannot be published, the operating concept in both cycles can be described indicatively as follows: higher fan frequencies were used in the earlier, wetter stages of drying, while reduced frequencies were applied in later stages as the timber moisture content decreased and the required circulation intensity was lower. In this sense, the summer cycle can be interpreted as having operated for a larger share of the process under reduced effective fan-speed conditions, whereas the winter cycle likely required a higher average effective circulation level over a longer fraction of the cycle. Therefore, the more appropriate interpretation is that the winter – summer difference in measured electricity use was most likely the combined result of several interacting factors: different fan-duty conditions under VFD control, a longer cycle duration, a higher initial moisture content in winter, and the overall harsher winter operating context. As the present dataset does not contain motor-level time series, these results should not be interpreted as a direct quantitative proof of fan-specific optimization performance, but rather as an industrial case-based indication that chamber-level electricity demand can vary substantially between seasonal operating conditions. In conventional kiln drying, total process demand includes not only moisture evaporation but also the heating of the wood charge and kiln structure, heat losses through the kiln envelope, and ventilation- and air-leakage-related losses. Under winter conditions, the larger temperature gradient between the kiln and ambient air increases transmission and infiltration losses, while colder incoming air requires more heat input during operation. In addition, the winter charge had a higher average initial stack moisture content (≈ 55 % vs. ≈ 45 % in summer), implying a greater moisture removal requirement. Frozen water may also have been present in part of the load during the initial phase, which would further increase the thermal burden associated with thawing and subsequent heating. To separate, at least partly, the effect of differing initial moisture contents from that of seasonal operating conditions, the energy results were also interpreted per kilogram of removed water. On this basis, the measured thermal energy demand for evaporation-related drying was approximately 4.3 MJ/kg of removed water in the summer cycle and 6.9 MJ/kg in the winter cycle. As the winter cycle remained more energy-intensive even after normalization by removed water mass, the difference between the two cycles cannot be attributed solely to the higher initial moisture content of the winter charge. Instead, the results suggest that the larger moisture removal requirement and the more severe winter heat-loss conditions acted simultaneously. Overall, thermal energy closely matched theoretical expectations in summer, whereas winter operation resulted in significantly higher measured heat consumption. Electrical energy demand remained below calculated estimates in both cycles, particularly during summer operation. The comparison of measured and calculated energy consumption values is summarized in Table 1. In addition to the conventional volume-specific indicators (MJ/m³, kWh/m³), Table 1 also presents the thermal energy demand per kilogram of removed water, which provides a more moisture-normalized basis for comparing the summer and winter convective cycles. Additionally, the table includes the specific thermal energy demand per kilogram of oven-dry wood, providing a dry-matter-based normalization of the measured and calculated thermal demand. In the summer cycle, thermal energy demand deviated from the theoretical estimate by only 3.7 %, while electrical consumption was approximately 72 % lower than the literature-based proportion. In the winter cycle, meas-

Table 1 Comparison of calculated and measured energy demands for summer and winter convective drying cycles (oak, 28 mm; MC: 45 – 55 % → 10 %; characteristic main-phase temperature ≈ 60 °C)
Tablica 1. Usporedba izračunanih i izmjerenih energetskih potreba za ljetni i zimski ciklus konvektivnog sušenja (hrast, 28 mm; MC: 45 – 55 % → 10 %; karakteristična temperatura glavne faze ≈ 60 °C)

Energy parameter *Energetski parametar*	**Summer cycle (calculated)** *Ljetni ciklus (izračunano)*	**Summer cycle (measured)** *Ljetni ciklus (izmjereno)*	**Winter cycle (calculated)** *Zimski ciklus (izračunano)*	**Winter cycle (measured)** *Zimski ciklus (izmjereno)*
Total thermal energy demand for drying, MJ *ukupna potrebna toplinska energija za sušenje,* MJ	95711	92160	173000	208080
Total electrical energy demand for drying, kWh *ukupna potrebna električna energija za sušenje,* kWh	3190 (11484 MJ)	905.7 (3260 MJ)	5767 (20762 MJ)	5045 (18162 MJ)
Total energy demand (thermal + electrical), MJ *ukupna potrebna energija (toplinska + električna),* MJ	107195	95420	193762	226242
Specific drying energy demand, MJ/m³ *specifična potrebna energija za sušenje,* MJ/m³	1266	1127	2153	2514
Thermal energy demand for evaporation of 1 kg of water, MJ/kg / *potrebna toplinska energija za isparavanje 1* kg *vode,* MJ/kg	4.5	4.3	5.7	6.9
Specific thermal energy demand per kg oven-dry wood, MJ/kg / *specifična potrebna toplinska energija po* kg *suhog drva,* MJ/kg	1.6	1.5	2.6	3.1
Electrical-to-thermal energy ratio, % *omjer električne i toplinske energije,* %	12 %	3.5 %	12 %	8.7 %

ured heat demand exceeded the theoretical value by about 17 %, whereas electrical energy consumption remained around 12 % below the calculated estimate. Accordingly, the electrical share of total energy demand was only 3.5 % in summer and 8.7 % in winter, compared with the assumed ~12 % proportion. These findings indicate that under real industrial operating conditions, the relative contribution of electrical energy may be lower than expected from general literature estimates, as further discussed in the Conclusions section.

Based on the summer cycle, about half of the total thermal energy demand was related to moisture evaporation, while the remaining share originated from system heating and heat losses (air exchange and transmission). In winter, losses were considerably higher: transmission losses were estimated to approach 20 %, compared with approximately 11 % in summer. Consequently, total measured energy consumption in the winter cycle was about 2.23.

3.2 Energy demand of vacuum drying and comparison with convective drying

3.2. Potrošnja energije vakuumskog sušenja i usporedba s konvektivnim sušenjem

In the investigated plant, vacuum drying is mainly applied for smaller volumes of high value-added products with increased quality requirements (e.g., oak parquet or ash decking). Its main practical advantage is faster and potentially gentler moisture removal, which according to industrial experience and literature may reduce internal stresses and improve product quality; however, the present study did not include a separate quantitative evaluation of drying quality or defect formation for the two technologies. The plant produces approximately 200–300 m³ of vacuum-dried timber annually. The six convective chambers have an installed maximum capacity of about 8000 m³/year, while the actual measured annual processed volume of the test chamber considered in the present 2024 energy evaluation was approximately 1000–1200 m³. Based on measured operational data from 2024, the annual thermal energy demand of the vacuum dryer was approximately 250000 MJ/year, while electrical consumption reached about 44000 kWh/year (158400 MJ/year). The reported annual thermal-energy value for the vacuum dryer includes all measured heat supplied through its heating circuit, including the periodic auxiliary-boiler support required during winter operation. In comparison, the convective system exhibited an annual thermal demand of around 1717560 MJ/year and electrical consumption of about 50000 kWh/year (180000 MJ/year). As the annual processed wood volume differed substantially between the two technologies, the comparison should primarily be interpreted on a specific energy basis rather than from absolute annual totals. Convective drying showed a specific electrical demand of about 45 kWh/m³ (≈ 162 MJ/m³), while the vacuum dryer required about 176 kWh/m³ (≈ 634 MJ/m³), i.e. approximately four times more electrical energy per unit volume of dried wood. This distinction is crucial, because the apparent advantage of vacuum drying in annual total energy use merely reflects its much lower processed volume, not superior overall energy efficiency. In the present comparison, CO_2 eq emissions related to electricity use were calculated using a Hungarian annual average grid carbon intensity factor of 0.243 kg CO_2 eq/kWh for 2024, obtained from Electricity Maps yearly data. This factor was interpreted as an average attributional indicator of the electricity mix available on the grid, not as a marginal emission factor. As vacuum drying is much more electricity-intensive, its operating cost is expected to be more sensitive to electricity prices. By contrast, the economic performance of convective drying depends more strongly on the cost of process heat, which may vary substantially depending on whether the thermal energy is supplied by natural gas, biomass, or a mixed heat system. In European non-household energy markets, electricity is generally priced higher per unit of delivered energy than natural gas, while the competitiveness of biomass-based heat depends strongly on local fuel availability, transport distance, and site-specific fuel handling conditions. Therefore, the economic ranking of vacuum and convective drying cannot be assessed solely from energy quantities; it is also influenced by the local energy-price structure and plant-specific infrastructure. Overall, vacuum drying energy use is largely associated with maintaining vacuum conditions and internal heat transfer, whereas convective drying mainly consumes heat for air heating and circulation. Although detailed chamber-pressure profiles were not available for direct analysis, the measured energy pattern suggests that the high electrical intensity of vacuum drying was related to the continuous demand of vacuum generation and auxiliary equipment throughout the cycle. For completeness, annual total energy use is also reported in Table 2; however, these totals mainly reflect the strongly different annual throughput of the two technologies and should not be interpreted as direct indicators of relative process efficiency.

Within the technological and energy-supply context of the investigated plant, shifting the approximately 250 m³/year currently processed by vacuum drying toward convective drying would be associated with lower calculated electricity-related CO_2 eq emissions under the applied Hungarian average grid-mix assumption. On this indicative basis, convective drying showed a specific CO_2eq value approximately 31.73 kg CO_2 eq/m³ lower than vacuum drying, corresponding to about 7.93 t CO_2 eq/year for the currently vacuum-

Table 2 Comparison of specific and annual energy consumption and CO_2eq emissions of convective and vacuum drying systems based on 2024 industrial operating data
Tablica 2. Usporedba specifične i godišnje potrošnje energije i emisija CO_2eq konvektivnih i vakuumskih sustava sušenja na temelju industrijskih operativnih podataka iz 2024.

Parameter *Parametar*	**Convective drying** *Konvektivno sušenje*	**Vacuum drying** *Vakuumsko sušenje*	**Remarks** *Napomena*
Specific indicators / *Specifični pokazatelji*			
Specific thermal energy demand, MJ/m³ *specifična potreba za toplinskom energijom,* MJ/m³	~ 1560	~ 1000	Calculated using average annual processed volume *izračunano na temelju prosječnoga godišnjeg obrađenog volumena*
Specific electrical energy demand, kWh/m³ *specifična potreba za električnom energijom,* kWh/m³	45	176	Calculated using average annual processed volume *izračunano na temelju prosječnoga godišnjeg obrađenog volumena*
Specific electrical energy demand, MJ/m³ *specifična potreba za električnom energijom,* MJ/m³	162	633.6	Electrical energy converted using 1 kWh = 3.6 MJ *električna energija pretvorena primjenom odnosa* 1 kWh = 3,6 MJ
Specific total energy demand, MJ/m³ *specifična ukupna potreba za energijom,* MJ/m³	~ 1600 – 1900	~ 1400 – 2000	Calculated based on the minimum and maximum annual quantities *izračunano na temelju minimalnih i maksimalnih godišnjih količina*
Specific CO_2 eq emissions (kg/m³) from electricity consumption *specifične emisije CO_2 eq* (kg/m³) *iz potrošnje električne energije*	11.04	42.77	0.243 kgCO_2 eq/kWh (Electricity Maps, n.d.)
Difference (vacuum − convective) *razlika (vakuumsko − konvektivno)*			+31.73 kgCO_2 eq/m³
Annual totals / *Godišnji iznosi*			
Annual volume of dried wood, m³/year *godišnji volumen osušenog drva,* m³/god.	1000 – 1200	200 – 300	
Annual thermal energy consumption, MJ/year *godišnja potrošnja toplinske energije,* MJ/god.	1717560	250000	
Annual electrical energy consumption, kWh/year *godišnja potrošnja električne energije,* kWh/god.	50000	44000	
Annual electrical energy consumption, MJ/year *godišnja potrošnja električne energije,* MJ/god.	180000	158400	
Annual total energy consumption, MJ/year *ukupna godišnja potrošnja energije,* MJ/god.	1897560	408400	
Average share of electrical energy in total drying energy, % *prosječni udio električne energije u ukupnoj energiji sušenja,* %	~ 10%	~ 39%	
Annual CO_2 eq emissions (t/year) from electricity consumption *godišnje emisije CO_2 eq* (t/god.) *od potrošnje električne energije*	12.15	10.69	0.243 kgCO_2 eq/kWh (Electricity Maps, n.d.)

Note: Electrical energy was converted using 1 kWh = 3.6 MJ. CO_2eq values related to electricity consumption were calculated using the Hungarian annual average grid carbon intensity of 0.243 kg CO_2 eq/kWh for 2024, based on Electricity Maps yearly data. The applied factor represents an average attributional electricity-mix indicator rather than a marginal emission factor. Biogenic CO_2 from biomass combustion was excluded, in line with common greenhouse gas accounting practice, under which biomass-combustion CO_2 is treated separately from fossil-energy-related emissions (IPCC, 2021). The reported CO_2 eq values therefore mainly reflect differences in electrical intensity.
Napomena: Električna energija pretvorena je primjenom odnosa 1 kWh = 3,6 MJ. Vrijednosti CO_2 eq povezane s potrošnjom električne energije izračunane su korištenjem prosječnoga godišnjeg intenziteta ugljika u mađarskoj mreži od 0,243 kg CO_2 eq/kWh za 2024. godinu, na temelju godišnjih podataka objavljenih u Electricity Maps. Primijenjeni faktor prosječni je pokazatelj atribucijskog miksa električne energije, a ne granični faktor emisije. Biogeni CO_2 iz izgaranja biomase isključen je u skladu s uobičajenom računovodstvenom praksom stakleničkih plinova, prema kojoj se CO_2 iz izgaranja biomase tretira odvojeno od emisija povezanih s fosilnom energijom (IPCC, 2021.). Stoga prijavljene vrijednosti CO_2 eq uglavnom odražavaju razlike u električnom intenzitetu.

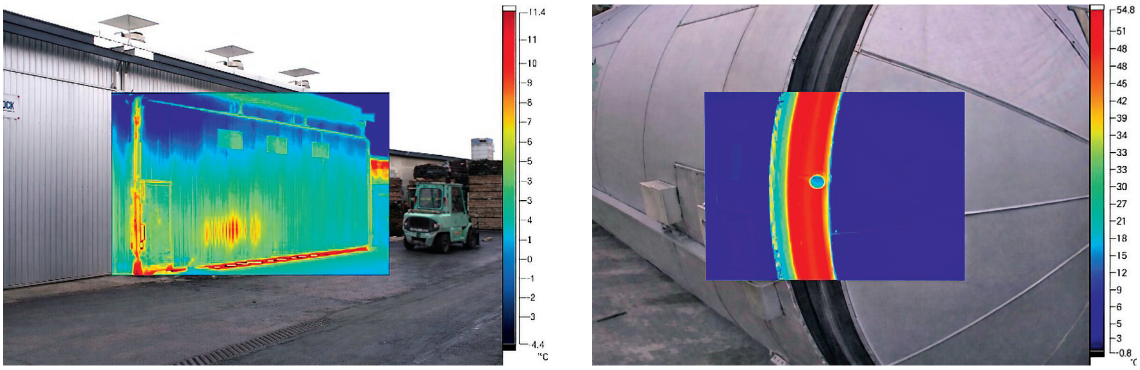

Figure 2 Thermographic visualization of winter heat transfer losses in the convective dryer (left) and vacuum dryer (right)
Slika 2. Termografska vizualizacija gubitaka topline zimi u konvektivnoj sušari (lijevo) i u vakuumskoj sušari (desno)

dried volume. However, this comparison should be interpreted strictly as case-study evidence, because it reflects the measured operating conditions, throughput structure, and energy supply of the investigated plant rather than a universally applicable technology ranking. The relative environmental outcome would also change under different electricity carbon intensities, alternative heat-supply configurations, or different product-quality requirements. If the grid carbon intensity decreases in the future due to a higher share of low-carbon generation, the CO_2 eq disadvantage associated with the higher electricity demand of vacuum drying will also decrease; conversely, under a more carbon-intensive electricity mix, the relative carbon burden of vacuum drying would become even more pronounced. The thermal energy demand of the summer drying cycle was well described by the theoretical model, with only ~ 4 % deviation between calculated and measured values. In contrast, winter heat consumption exceeded the theoretical estimate by approximately 17 %, likely due to combined industrial factors. Moisture content in certain zones of the winter load may have been higher than assumed, and drying control is typically adjusted to the wettest stack sections. In addition, the large winter temperature gradient (≈ 60–70 °C) increased transmission heat losses through chamber walls and structural interfaces, as confirmed by thermographic inspections (Figure 2). The color scale indicates transmission heat losses. The redder the color, the greater the transmission heat loss directed outward from the chamber. A further contributing factor may have been the colder, and possibly partly frozen, condition of the winter wood charge at the beginning of drying; since the latent heat of fusion was not treated as a separate term in the simplified model, this effect may also have contributed to the underestimation of measured winter heat demand.

Operational factors may also have influenced actual energy consumption, including suboptimal boiler performance or additional heating phases. Therefore, the ~17 % deviation between calculated and measured winter heat demand may partly reflect the safety margins and control reserves typical of industrial operation. Measured electrical energy consumption in the summer cycle was significantly lower than the benchmark estimate. This difference is consistent with the expected effect of VFD-controlled fan operation under favorable summer climatic conditions, when reduced air circulation may be sufficient for maintaining the required drying performance. However, as the present study did not include a separate time-resolved analysis of fan-specific power profiles, this interpretation should be regarded as an operationally plausible explanation rather than a direct component-level verification. Under favorable summer climatic conditions, the measured electrical share accounted for only ~ 3.5 % of total energy demand, compared with the assumed benchmark value of 12 %, which suggests that actual air-circulation demand in this cycle was substantially lower than indicated by the general literature-based proportion. In winter, measured electrical consumption remained about 12 % below the benchmark estimate. This may also reflect reduced fan speeds during certain drying phases; however, the present dataset does not allow direct decomposition of the total electrical demand into fan-level operating profiles. Vacuum drying offers substantially shorter process times (4 – 5 days versus 20 – 25 days for convective drying), but requires a much higher electrical input. Although thermal energy demand scales with processed volume (vacuum: ~ 250000 MJ vs. convective: ~ 1717560 MJ annually), electrical consumption remains of similar magnitude in both systems due to the continuous power requirement of vacuum pumps and auxiliary equipment. In contrast, fan energy demand in convective drying can be reduced as drying progresses. From the perspective of the present case study, the higher electrical intensity of vacuum drying resulted in a less favorable electricity-related CO_2 eq profile under the applied Hungarian grid-mix assumption. This observation should, however, be interpreted as conditional on the plant configuration and energy context investigated, not as a generally valid conclusion for all industrial drying applications.

4 CONCLUSIONS
4. ZAKLJUČAK

This study evaluated the energy efficiency of industrial wood drying in a Hungarian facility, focusing on seasonal differences in convective drying and on the comparison between convective and vacuum technologies. The main conclusions are:

- Seasonal effect: Winter operation required about 2.23 times more total energy than summer drying, mainly due to higher heating demand and increased transmission heat losses. Thus, winter peak-load conditions are decisive for dryer and boiler system dimensioning.
- Measured vs. calculated demand: Thermal energy estimates matched measurements closely in summer, while an approximately 17 % deviation was observed in winter. Electrical consumption was substantially lower than literature-based benchmark expectations in the summer cycle and remained moderately below the benchmark range in winter. However, as the available electrical data were recorded at full-kiln level and did not include fan-level sub-metering or time-resolved motor-power records, the observed seasonal difference in electricity use cannot be attributed quantitatively to fan control alone. Rather, the results indicate that chamber-level electrical demand in industrial convective drying can vary strongly between seasonal operating conditions, most likely due to the combined influence of VFD-controlled air-circulation duty, cycle duration, product moisture condition, and winter-related operational load.
- Convective vs. vacuum drying: In the investigated industrial case, vacuum drying was substantially faster (4 – 5 days vs. 20 – 25 days), but exhibited a markedly higher specific electrical demand (176 kWh/m³ compared to 45 kWh/m³ for convective drying). At the same time, the specific thermal energy requirement of vacuum drying was lower by approximately 30 – 35 % under the analyzed operating conditions. Accordingly, the present results suggest that in this case study the main difference between the two technologies lies in their energy structure: vacuum drying reduced thermal demand but required substantially higher electrical intensity. Under the applied Hungarian average electricity-mix assumption, this led to a less favorable electricity-related carbon profile for vacuum drying in the investigated plant. However, these findings should be interpreted as indicative evidence from a site-specific industrial case study rather than as a universally applicable comparison between drying technologies, particularly because only two convective drying cycles were analyzed and no direct quantitative quality comparison was included.
- Efficiency improvement potential: Literature on industrial kiln operation indicates that fan-speed optimization by variable-frequency control can reduce electrical energy consumption substantially under appropriate operating conditions. In the present case study, however, the analyzed chamber-level electricity data do not permit a direct quantitative optimization assessment at fan level. Therefore, any further electricity-saving potential related to fan-control optimization should be interpreted as a literature-supported technological opportunity rather than as a directly verified numerical result of the two analyzed seasonal cycles. In addition, heat recovery, condensation-based systems, and improved chamber insulation could significantly reduce thermal demand, especially in winter. Renewable energy integration (PV, wind, biomass by-products) may further decrease emissions and improve energy independence.
- Environmental impact: Under the investigated Hungarian electricity mix and the applied annual average grid-emission assumption, in this case study the convective system showed lower calculated electricity-related specific CO_2 eq emissions than the vacuum system by approximately 31.73 t CO_2 eq per 1000 m³. For the currently vacuum-dried annual volume in the investigated plant, this corresponds to an indicative difference of about 8 t CO_2 eq/year. This result should not be generalized without caution, because it depends on the analyzed throughput, the local energy mix, and the plant-specific technological configuration.

4.1 Practical recommendations
4.1. Praktične preporuke

- In convective kiln drying, priority should be given to reducing winter heat losses through improved insulation of chamber walls, doors, and structural thermal bridges, because seasonal heat demand is strongly influenced by ambient temperature conditions.
- Retrofitting or optimizing variable frequency drive (VFD) control of circulation fans may be considered a high-priority measure, because literature and the present chamber-level observations together suggest that favorable operating conditions may allow lower electrical demand; however, the current dataset does not permit a direct fan-level quantification of this effect.
- When evaluating heat-recovery systems, selection should be based on the expected seasonal temperature regime, because the highest thermal savings are likely to be achieved under winter operation with large kiln-to-ambient temperature differences.
- Technology selection between convective and vacuum drying should not be based solely on annual total

energy use or on simplified cross-technology comparison of non-identical product groups. Specific energy demand, electricity intensity, product quality requirements, target moisture content, batch strategy, and the local energy-price structure should all be considered simultaneously.

- Vacuum drying may remain justified for high value-added products with strict quality requirements, whereas convective drying may offer advantages where lower electricity intensity and biomass-based heat integration are available.
- For industrial plants planning modernization, measurement-based energy monitoring at high time resolution is recommended before major investment decisions, as simplified benchmark assumptions may not accurately reflect actual fan operation, seasonal effects, or dryer-specific energy structure.

Overall, the present results provide indicative industrial evidence that wood-drying energy performance can be improved through technological development and operational optimization. However, broader generalization would require analysis of a larger number of drying cycles under more diverse conditions. The study also shows that volume-based indicators alone are insufficient for comparing cycles with different moisture loads; moisture-normalized indicators, especially per kilogram of removed water, provide a more robust basis for interpretation. In the investigated plant, the combined evaluation of measured and calculated data proved useful for identifying potentially more energy-efficient drying strategies. Future development may also include RF–vacuum drying.

5 NOMENCLATURE
5. NOMENKLATURA

Symbols and variables – Simboli i varijable

$Q_{th,total}$ – total theoretical thermal energy demand
Q_{heat} – sensible heat demand for heating the wood-water system
Q_{evap} – latent heat demand of moisture removal
Q_{loss} – estimated total heat losses during kiln operation
Q_{trans} – conductive heat loss through the kiln structure
Q_{other} – additional operational heat losses not explicitly resolved in the simplified model
m_0 – oven-dry wood mass
$m_{w,i}$ – initial water mass in the wood charge
$m_{w,f}$ – final water mass in the wood charge
$m_{w,avg}$ – average water mass considered during heating
m_{evap} – mass of removed water
V – timber volume loaded into the kiln
ρ_0 – oven-dry density of wood
MC_i – initial moisture content on a dry basis
MC_f – final moisture content on a dry basis
c_{wd} – specific heat capacity of oven-dry wood
c_w – specific heat capacity of water
T_0 – initial timber temperature
T_d – characteristic drying temperature
h_{fg} – latent heat of evaporation of water
Q – relevant measured or calculated energy value
SEC_V – specific energy consumption per unit volume of dried timber
SEC_W – specific energy consumption per kilogram of removed water
SEC_{OD} – specific energy consumption per kilogram of oven-dry wood

Abbreviations – Kratice

VFD – variable frequency drive
CO_2 eq – carbon dioxide equivalent
MC – moisture content

6 REFERENCES
6. LITERATURA

1. Andersson, J.-O., 2014: Energy and resource efficiency in convective drying systems in the process industry. PhD Thesis, Luleå University of Technology. ISBN 978-91-7439-873-1
2. Elustondo, D. M.; Oliveira, L., 2009: Model to assess energy consumption in industrial lumber kilns. Maderas. Ciencia y Tecnología, 11 (1): 33-46. https://doi.org/10.4067/S0718-221X2009000100003
3. Espinoza, O.; Bond, B., 2016: Vacuum drying of wood – State of the art. *Current Forestry Reports*, 2 (4): 223-235. https://doi.org/10.1007/s40725-016-0045-9
4. Konopka, A.; Barański, J.; Orłowski, K. A.; Mikielewicz, D.; Dzurenda, L., 2021: Mathematical model of the energy consumption calculation during the pine sawn wood (*Pinus sylvestris* L.) drying process. *Wood Science and Technology,* 55: 741-755. https://doi.org/10.1007/s00226-021-01276-8
5. Lamrani, B.; Kuznik, F.; Ajbar, A.; Boumaza, M., 2021: Energy analysis and economic feasibility of wood dryers integrated with heat recovery unit and solar air heaters in cold and hot climates. Energy, 228, 120598. https://doi.org/10.1016/j.energy.2021.120598
6. Lyon, S.; Bowe, S.; Wiemann, M., 2021: Understanding vacuum drying technologies for commercial lumber (General Technical Report FPL-GTR-287). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. https://doi.org/10.13140/RG.2.2.34731.57123
7. Meng, Y.; Chen, G.; Hong, G.; Wang, M.; Gao, J.; Chen, Y., 2019: Energy efficiency performance enhancement of industrial conventional wood drying kiln by adding forced ventilation and waste heat recovery system: A comparative study. Maderas. Ciencia y Tecnología, 21 (4): 545-558. https://doi.org/10.4067/S0718-221X2019005000410
8. Simpson, W. T., 1991: Dry kiln operator's manual (Agriculture Handbook No. 188). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
9. ***Electricity Maps, n.d.: Hungary: Yearly carbon intensity for all technologies. https://app.electricitymaps.com/zone/HU/all/yearly (Accessed: Nov. 16, 2025).
10. ***FAGOSZ, 2023: Log consumption of the Hungarian sawmilling industry, 2021 – 2023. National Association

of the Hungarian Timber Industry. https://fataj.hu (Accessed: Nov. 15, 2025).
11. ***Faipar, n.d.: Energy saving and environmental protection in wood drying. https://faipar.hu/cikkek/kapcsolodo-technologia/3034/energiamegtakaritas-es-koernyezetvedelem-a-szaritasban (Accessed: Nov. 15, 2025).
12. ***Intergovernmental Panel on Climate Change (IPCC), 2021: Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896
13. ***Központi Statisztikai Hivatal (KSH), 2023: Total sawn timber production, 2017 – 2023. https://www.ksh.hu (Accessed: Nov. 15, 2025).

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HRVATSKA KOMORA
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I DRVNE TEHNOLOGIJE

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