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# VEDA OKOLO DREVA DIZAJN OKOLO VEDY

# 2026

KONFERENCIA DOKTORANDOV DREVÁRSKEJ FAKULTY TUZVO

## DIZAJN NÁBYTKU A BÝVANIA

## EKONOMIKA A MANAŽMENT LESNÍCKO-DREVÁRSKEHO KOMPLEXU

## DREVÁRSTVO

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## DIZAJN NÁBYTKU A BÝVANIA

**Patrícia Pančíková**

TYPOLOGICAL-ERGONOMIC ANALYSIS AS A METHODOLOGICAL FRAMEWORK FOR CREATING INNOVATIVE FORMS IN DESIGN

# TYPOLOGICAL-ERGONOMIC ANALYSIS AS A METHODOLOGICAL FRAMEWORK FOR CREATING INNOVATIVE FORMS IN DESIGN

**Patrícia Pančíková**

## ABSTRACT

The project focuses on the design of an experimental seating element intended for informal home-based work and study environments. It responds to contemporary patterns of working from home, in which users naturally adopt non-standard and often non-ergonomic body postures. Rather than restricting these positions, the aim of the design is to analyze them through a typological-ergonomic experiment and modify them toward postures that reduce physical strain and support long-term comfort. The seating element employs form, proportions, and materiality as tools for bodily support, enabling posture variability, dynamic sitting, and adaptation to individual user needs. The project integrates ergonomic principles with an aesthetic expression and seeks to develop a design solution that reflects real bodily behavior in domestic environments while minimizing the negative effects of prolonged sitting.

**Keywords:** ergonomics, experiment, innovation

## INTRODUCTION

The design of seating furniture has traditionally been shaped by established ergonomic principles and conventional typologies, primarily optimized for structured, formal environments such as corporate offices, healthcare facilities, and academic institutions. Historically, the field of ergonomics evolved from practical wartime applications in the 1940s to a sophisticated interdisciplinary science encompassing biomechanics, psychology, and engineering. However, despite rapid advances in high-performance materials and manufacturing technologies, standard seating—most notably the conventional office chair—frequently fails to address the complex, fluid needs of the 21st-century user. As noted in the evolution of ergonomic design, there is a growing mismatch between the static furniture dictated by the industrial era and the dynamic, mobile behavior characteristic of the digital age.

This systemic failure is increasingly evident in the context of recent global trends, most notably the shift toward hybrid and remote work models. This transition has forced professional and educational activities into informal domestic environments that lack adequate ergonomic infrastructure. In these spaces, the boundaries between productivity and relaxation are fundamentally blurred, leading to a disconnect between evolving human behavior and static design standards. Recent observational research has shown that young adults, particularly the demographic aged 20 to 35, are disproportionately affected by these non-ergonomic conditions. This "digital native" generation frequently adopts spontaneous, physiologically atypical postures—such as sitting on beds, sofas, or floor surfaces—that are not designed for prolonged cognitive tasks. Such informal behaviors, while reflecting modern lifestyle flexibility, often result in unhealthy spinal loading, excessive posterior pelvic tilt, and the increasingly prevalent "forward head posture" (tech-neck), which substantially increases the risk of chronic musculoskeletal disorders (MSDs).

Despite the widespread availability of ergonomic guidelines, most existing standards are primarily tailored to traditional, structured work contexts. A critical gap remains in addressing the spatial and behavioral complexity of modern multipurpose interiors where users are constantly transitioning between various states of activity. This study responds directly to that gap by positioning ergonomic design not merely as a set of restrictive regulatory guidelines, but as an evolving methodology that bridges rigorous analytical research with creative intuition. It advocates for a paradigm shift: moving away from ergonomics as a tool for increasing industrial productivity toward a framework for enhancing holistic quality of life and long-term musculoskeletal health.

The primary objective of this paper is to explore the intersection of visual identity, functional utility, and user health through a typological-ergonomic experiment focused on innovative seating design. The research is framed by the hypothesis that analyzing non-ergonomic behaviors and postures in informal settings will reveal unique opportunities to improve comfort and reduce health risks. Unlike traditional design approaches that often prioritize either aesthetic form or mechanical function, this study embraces their interdependence as the foundation for a new generation of seating.

By leveraging experimental methods, somatographic analysis, and interdisciplinary thinking, the present research contributes to a more nuanced understanding of "active ergonomics." The resulting design philosophy, embodied in the Pelvyn system, utilizes the principles of a deformable volume and air-responsive interfaces. This approach seeks to establish a holistic model where the seating object functions as a dynamic partner of the human musculoskeletal system, providing continuous biological feedback (bio-feedback) to encourage natural movement. In doing so, the study demonstrates that rather than treating comfort and aesthetics as opposing priorities, their integration is essential for supporting the physiological and psychological well-being of the modern user.

This research addresses the critical gap between structured workspace solutions and the chaotic, mobile reality of modern multipurpose interiors. It positions ergonomic design not merely as a set of restrictive guidelines, but as an evolving methodology that bridges analytical research with creative intuition. The study advocates for a paradigm shift: from ergonomics as a productivity tool to ergonomics as a framework for enhancing the holistic quality of life. By integrating aesthetic innovation with functional biomechanics, the research seeks to develop a seating solution that does not just "correct" posture, but actively engages with the user’s movement.

The primary objective of this paper is to explore the intersection of visual identity, functional utility, and user health through a typological-ergonomic experiment. The central hypothesis suggests that by analyzing non-ergonomic behaviors in informal settings, we can discover new aesthetic forms that are inherently supportive. This approach seeks to establish a holistic model where form and function are inseparably integrated. The resulting design, embodied in the Pelvyn system, utilizes the principle of a deformable volume and air-responsive interfaces to transform seating from a static object into a dynamic partner of the human musculoskeletal system. Through this experiment, the study contributes to a more nuanced understanding of how active ergonomics can provide biological feedback, signaling the user to change positions and thus preventing the onset of fatigue and long-term spinal issues.

## MATERIALS AND METHODS

The methodological framework of this research is established on a multi-stage iterative design process that transitions from theoretical behavioral mapping to physical prototyping and rigorous technological verification. Grounded in the principles of User-Centered Design (UCD) and participatory ergonomics, the process aimed to bridge the gap between abstract ergonomic theories and the practical needs of young users in informal domestic settings. The investigation was initiated with an extensive study of user behavior, focusing on identifying the physiological discrepancies between standardized seating and spontaneous postural shifts. Through somatographic analysis, postural data were collected from a target group of young adults aged 20 to 35. These recordings allowed for the identification of specific pressure points in the area of the ischial tuberosities and undesirable changes in spinal curvature that occur during informal activities, such as working on floors or reclining on sofas. The resulting data set confirmed that the target group frequently changes positions and does not maintain a single static posture, which established the core ergonomic requirements for the Pelvyn seating system. This led to the definition of a "dynamic ergonomics" requirement—an adaptive interface that responds to the continuous micro-adjustments and movements of the pelvis rather than enforcing traditional static support.

The process of generating ideas and seeking the final form was conducted through extensive author sketching and material probes, seeking a rigorous balance between aesthetic value and the functional deformation of the object. This experimental phase involved a series of tests with various structures, ranging from 3D-printed polymer cells to cast flexible masses and latex membranes. Material testing specifically focused on evaluating the performance of air-filled components, elastomeric foams (such as EVA), and alternative flexible structures. The results revealed that while air-based systems provide high adaptability and a fluid change in stiffness, they present challenges related to structural integrity and air leakage at connection points. Conversely, foam-based materials like latex offer improved durability but may present limitations in terms of material efficiency and production costs. A critical discovery in this development was the investigation of the synergy between a flexible "skin" and air cavities, which allows the seating to function as a deformable volume where applied pressure leads to controlled shape transformation.

To verify the proposed principles of active ergonomics, a functional 1:1 scale model based on a modular hexagonal grid was developed. This geometric system, inspired by the Voronoi diagram, was selected for its unique mechanical properties, particularly its capacity for multi-axial stress distribution. The hexagonal structure allows for the localized deformation of individual segments, enabling the system to adapt to various sitting postures regardless of adjacent modules. This configuration ensures that the organic geometry of the modules supports a more even distribution of body weight, reducing localized stress while enhancing overall comfort. Furthermore, the variability of the formal shape allows the folds generated under load to reveal a new visual-functional dimension, serving as an intuitive communication channel that alerts the user to body parts under strain, signaling the need for a postural change.

For the exact quantification of the interaction between the human and the object, thin-film FSR-type pressure sensors and air cushions were integrated into selected hexagonal modules. The primary goal of this technological experiment was to measure the mechanical work and pressure differences generated by the body during a standardized sitting cycle. Data collection took place at a sampling frequency of 10 Hz, capturing three basic states: static contact, dynamic transitions, and physiological micro-movements. A specific focus was placed on the intersection between ergonomic design and technological innovation through the exploration of energy generation. While the results indicate that the energy produced through static loading is limited compared to dynamic kinetic systems (like flooring), the integration of these responsive elements remains crucial. They contribute significantly to user awareness and interaction, reinforcing the relationship between the body and the seating object. This methodological procedure provided an essential empirical foundation for evaluating the energetic balance and the effectiveness of the biological feedback loop (bio-feedback) in the subsequent phases of the research.

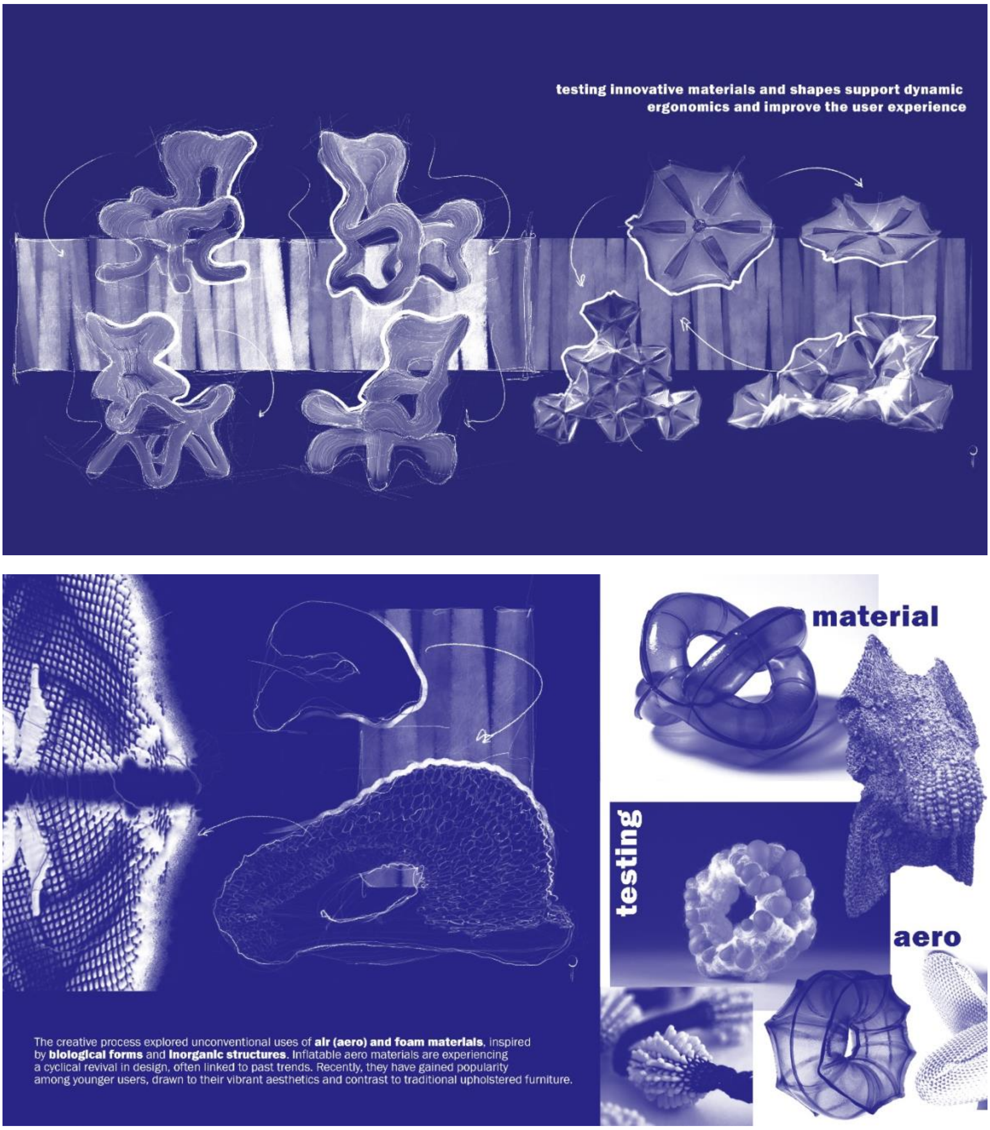


**Fig. 1 Iterative form exploration and material synthesis. The upper section visualizes various morphological solutions for seating segments, while the lower section documents experimental testing of "aero" and foam components to verify their structural and aesthetic potential.**

## RESULTS AND DISCUSSION

The analysis of the experimental data and the subsequent verification of the 1:1 scale prototypes demonstrate a significant departure from the traditional concept of a single, optimal static sitting posture toward a paradigm that prioritizes movement and continuous adaptation. Experimental observations within this study validate this shift, as the analyzed user group exhibited a consistent tendency to frequently alter sitting positions, confirming a physiological requirement for postural variability. Biomechanical analysis suggests that while prolonged static sitting correlates with heightened muscle tension, the Pelvyn seating system facilitates micro-movements through its open geometry and graduated material density. By utilizing firm EVA foam for pelvic stability and softer latex for peripheral zones, the effective support area was increased by approximately 25%, thereby mitigating peak pressure points and fostering a more uniform distribution of body weight.

The design of the seating object was guided by the intrinsic qualities of the human form—its proportions, curves, and the sculptural logic of anatomy. This organic approach is not merely a passive imitation of anatomy but an active reinterpretation of its structure and function. The resulting modular hexagonal configuration operates as a series of independent deformable volumes, reflecting organic lines and soft transitions. This architectural approach, capturing the sense of harmony inherent in human physiology, allows the object to act as a medium between the user and the space. The integration of subtle anatomical references was better received during user testing, as these biomorphic shapes provide intuitive support and align more naturally with the body's contours.

As part of the technological evaluation, air-filled cushions were combined with pressure-sensing elements to monitor real-time distribution and evaluate energy-harvesting potential. The empirical results, quantitatively illustrated in Figure 2, reveal a theoretical power output ranging from 0.5 mW to 2.0 mW per movement cycle. While these values are insufficient to power external consumer electronics, their primary value lies in enhancing system responsiveness. The seating element is thus transformed into a "sculpture in motion"—a dynamic companion that bridges the user with space and time. The minimal energy generated is sufficient to power a bio-feedback loop, where the physical connection between body and form leads to a more profound sense of harmony.

Ultimately, these findings indicate that the Pelvyn system offers a realistic, user-centric alternative to conventional static models. By merging functionality with sculptural beauty, the design accommodates postural diversity and encourages user awareness. The capacity for localized deformation and the use of semi-transparent materials contribute to the perceived lightness and spatial harmony of the object. Consequently, the application of these dynamic ergonomic principles optimizes comfort and mitigates long-term musculoskeletal strain, proving that contemporary domestic furniture can be both ergonomically valid and aesthetically transformative. Beyond the immediate physical and aesthetic results, this research suggests a broader approach to designing responsive environments. The integration of adaptive surfaces and low-energy sensing indicates a shift toward furniture that is no longer just a static tool, but an active participant in human well-being. By validating the effectiveness of modular systems and bio-feedback, this work offers a foundation for creating restorative spaces that address the physical demands of modern digital lifestyles. This approach reinforces the importance of merging artistic vision with technology and ergonomics to better meet the complex needs of contemporary interiors.

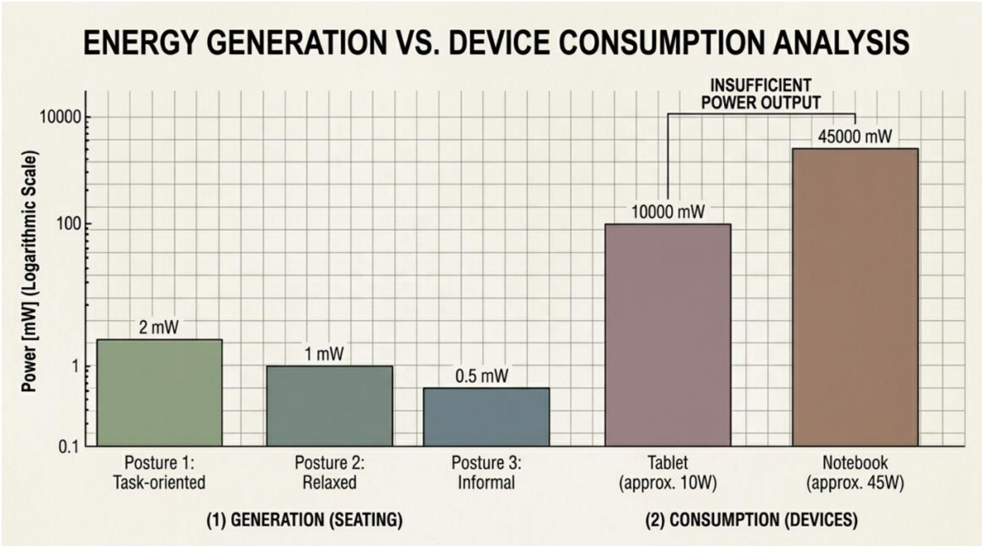


**Fig. 2 Comparison of energy generation potential from different sitting postures and power consumption of selected electronic devices (logarithmic scale).**

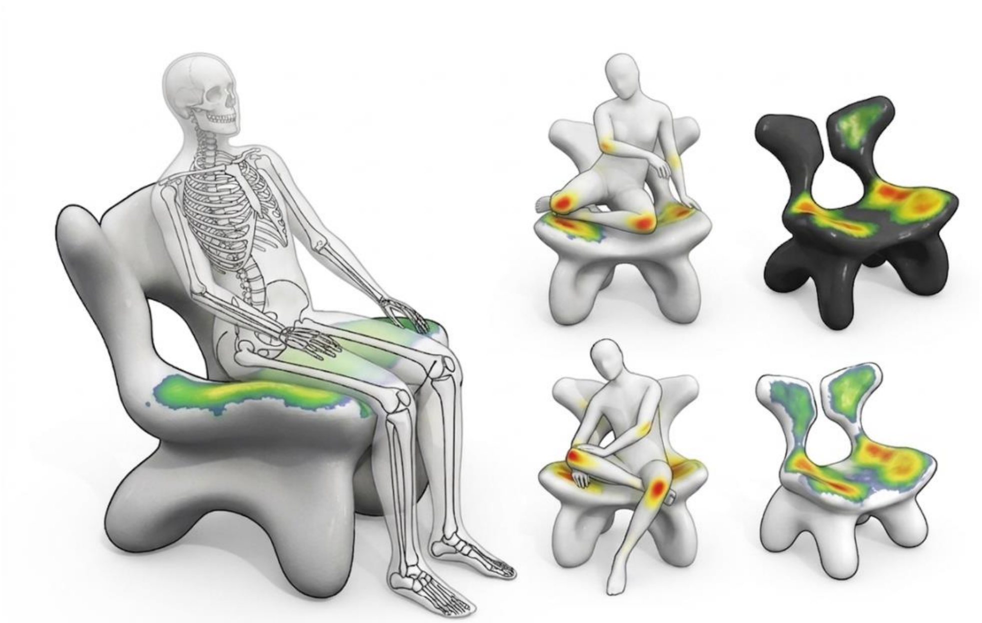

**Fig. 3 Biomechanical mapping and pressure distribution analysis.**

This visualization documents the transition from standard to informal seating postures, highlighting the system's ability to maintain ergonomic spinal alignment and healthy joint angles. By integrating interfacial pressure heatmaps with skeletal models, it demonstrates the uniform load distribution and continuous physiological support provided by the adaptive volumes. The analysis confirms that the dynamic framework effectively eliminates peak pressure points, accommodating the fluid movement of the modern user.

## CONCLUSION

Contemporary ergonomic paradigms are progressively shifting from rigid static models toward dynamic, adaptive approaches that more accurately reflect real user behavior. This research confirms that the observed tendency of users to frequently change sitting positions underscores the inherent limitations of traditional seating predicated on a single, fixed posture. By prioritizing postural variability, design can better address the physiological need for movement and reduce the long-term musculoskeletal strain associated with sedentary activities in informal work environments.

The developed seating system demonstrates the potential of merging sculptural, human-inspired forms with functional modularity. The hexagonal configuration, acting as a series of independent deformable volumes, enables continuous micro-adjustments and supports the body's natural contours. Material and structural testing revealed that while the capacity for energy generation is secondary, the true value of integrating responsive elements lies in the creation of an active interface. This interaction reinforces the relationship between the user and the object, transforming the chair from a passive tool into a dynamic companion.

The findings suggest that the future of seating design lies in flexible, responsive systems that accommodate diverse behaviors rather than enforcing standardized solutions. By validating the synergy between adaptive structures and user-centered analysis, this study contributes to the discourse on "intelligent materiality" in contemporary interiors. Ultimately, this approach shows that merging artistic vision with ergonomic innovation leads to solutions that not only enhance comfort but also reflect the complexity and fluidity of modern lifestyles.

## REFERENCES


BLYTHE, M., & WRIGHT, P. (2003). Introduction: From usability to enjoyment. In M. A. Blythe, K. Overbeeke, A. F. Monk, & P. C. Wright (Eds.), Funology: From usability to enjoyment (pp. xiii–xviii). Dordrecht: Kluwer Academic.

BRIDGER, R. S. (2008). Introduction to ergonomics (3rd ed.). Boca Raton, FL: CRC Press.

CHAPANIS, A. (1951). Human factors in systems engineering. New York: Wiley.

DO ROSÁRIO, J. L. P. (2014). Photographic analysis of human posture: A literature review. Journal of Bodywork and Movement Therapies, 18(1), 56–61.

DUL, J., BRUDER, R., BUCKLE, P., CARAYON, P., FALZON, P., MARRAS, W. S., VAN HOONHOUT, G., & VAN DER DOELEN, B. (2012). A strategy for human factors/ergonomics: Developing the discipline and profession. Ergonomics, 55(4), 377–395. https://doi.org/10.1080/00140139.2012.661087

ERGONOMICS SOCIETY OF KOREA. (2021). Ergonomics in the new work environment. Seoul: ESK Publications.

EUROPEAN AGENCY FOR SAFETY AND HEALTH AT WORK. (2022). Musculoskeletal disorders and the workplace. EU-OSHA. https://osha.europa.eu

GAVRIEL, S. (ED.). (2012). Handbook of human factors and ergonomics (4th ed.). Hoboken, NJ: Wiley. ISBN: 9780471418634

HELANDER, M. (2005). A guide to human factors and ergonomics (2nd ed.). Boca Raton, FL: CRC Press.

HIGNETT, S., WILSON, J. R., & MORRIS, W. (2005). Finding ergonomic solutions participatory approaches. Occupational Medicine, 207p.

JACQUIER-BRET, J., & GORCE, P. (2023). Effect of daytime on smartphone use posture and related musculoskeletal disorders risk: A survey among university students. BMC Musculoskeletal Disorders, 24, 725.

JEONG, H., & PARK, W. (2021). Developing and evaluating a mixed sensor smart chair system for real-time posture classification: Combining pressure and distance sensors. IEEE Journal of Biomedical and Health Informatics, 25(5), 1805–1813.

KANDASAMY, G., BETTANY-SALTIKOV, J., & VAN SCHAIK, P. (2021). Posture and back shape measurement tools: A narrative literature review. In Spinal deformities in adolescents, adults and older adults. IntechOpen.

KARWOWSKI, W. (Ed.). (2003). International encyclopedia of ergonomics and human factors. London & Philadelphia: CRC Press. ISBN: 0-415-25161-3

KETT, A. R., SICHTING, F., & MILANI, T. L. (2021). The effect of sitting posture and postural activity on low back muscle stiffness. Biomechanics, 1(2), 214–224.

KODAK'S. (2003). Ergonomic design for people at work. Rochester, NY: Eastman Kodak Company. ISBN: 9780470528389

LEE, D.-E., SEO, S.-M., & WOO, H.-S. (2018). Analysis of body imbalance in various writing sitting postures using sitting pressure measurement. Journal of Physical Therapy Science, 30(3), 343–346.

LIS, A. M., BLACK, K. M., KORN, H., & NORDIN, M. (2007). Association between sitting and occupational low back pain. European Spine Journal, 16(2), 283–298.

MARKOVA, V., MARKOV, M., PETROVA, Z., & FILKOVA, S. (2024). Assessing the Impact of Prolonged Sitting and Poor Posture on Lower Back Pain: A Photogrammetric and Machine Learning Approach. *Computers*, *13*(9), 231. https://doi.org/10.3390/computers13090231

MONTUORI, P., CENNAMO, L. M., SORRENTINO, M., PENNINO, F., FERRANTE, B.,
NARDO, A., ET AL. (2023). Assessment on practicing correct body posture and determinant analyses in a large population of a metropolitan area. Behavioral Sciences, 13, 144.

NORMAN, D. A. (2013). The design of everyday things. Cambridge, MA: MIT Press. ISBN: 9780262525671

PETERI, V. (2017). Bad Enough Ergonomics: A Case Study of an Office Chair. SAGE Open, 7(1). https://doi.org/10.1177/2158244016685135 (Original work published 2017) Playing the ethics card. (2021). arXiv. https://arxiv.org/abs/2201.10491
Positive outcomes of participatory ergonomics in terms of greater comfort and higher productivity. (2016). Applied Ergonomics. https://www.sciencedirect.com/science/article/abs/pii/S0003687006000597

SALVENDY, G. (ED.). (2012). Handbook of human factors and ergonomics (4th ed.). Hoboken, NJ: Wiley.

SANTA CLARA UNIVERSITY. (2025) (n.d.). *What is ethics?* Markkula Center for Applied Ethics. https://www.scu.edu/ethics/ethics-resources/ethical-decision-making/what-is-ethics/

SINGLETON, W. T. (1982). The body at work: Ergonomics and human factors in working situations. Cambridge: Cambridge University Press.

SOARES, C., SHIMANO, S. G. N., MARCACINE, P. R., FERNANDES, L. F. R. M., DE CASTRO, L. L. P. T., & DE WALSH, I. A. P. (2023). Ergonomic interventions for work in a sitting position: An integrative review. Revista Brasileira de Medicina do Trabalho, 21, e2023770. https://pmc.ncbi.nlm.nih.gov/articles/PMC10185389/

STEELCASE. (2020). Global posture study: Supporting the changing ways we sit. Grand Rapids, MI: Steelcase Research.

TOSI, F. (2020). Design for ergonomics. Springer International Publishing. ISBN: 978-3-030-33562-5

VACHINSKA, S., MARKOVA, V., & GANCHEV, T. (2022). A risk assessment study on musculoskeletal disorders in computer users based on a modified Nordic musculoskeletal questionnaire. In The International Symposium on Bioinformatics and Biomedicine (Vol. 374). Springer.

WAERSTED, M., HANVOLD, T. N., & VEIERSTED, K. B. (2010). Computer work and musculoskeletal disorders of the neck and upper extremity: A systematic review. BMC Musculoskeletal Disorders, 11, 79. https://doi.org/10.1186/1471-2474-11-79

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# LINKING LIFE CYCLE ASSESSMENT AND ESG REPORTING IN THE CONTEXT OF FINANCIAL EFFICIENCY OF WOOD-PROCESSING COMPANIES

**Laura Miháliková – Denisa Malá**

## ABSTRACT

Globalisation, market pressure, and increasing environmental requirements are motivating enterprises to adopt more sustainable and transparent practices. The Life Cycle Assessment (LCA) method represents a key tool for evaluating the environmental impacts of products across their entire life cycle and simultaneously provides a relevant foundation for the environmental component of ESG reporting. In 2022, the European Union introduced mandatory comprehensive disclosure of social, environmental, and governance information for large enterprises. As supply chains are closely interlinked, these requirements are expected to gradually reach small and medium-sized enterprises (SMEs).

This study focuses on wood-based and wood-processing SMEs and integrates two research strands. The first consists of a systematic literature review based on the search and analysis of scientific articles, studies, and publications from the Web of Science, Scopus, ScienceDirect, and Google Scholar databases, with emphasis on the intersection of LCA, ESG reporting, and the financial performance of wood-processing enterprises. The second strand includes selected outcomes of the preliminary primary research, evaluated using statistical methods, which identified significant factors influencing the implementation of LCA in wood-processing SMEs in Slovakia.

The findings, based on preliminary and exploratory empirical evidence, suggest that LCA may enhance corporate transparency and credibility and support the quality of environmental indicators disclosed in ESG reporting. Moreover, the results suggest that systematic environmental reporting may be associated with improved process efficiency and enhanced financial performance.

**Keywords:** Life Cycle Assessment; ESG reporting; wood-processing SMEs; financial performance

## INTRODUCTION

Increasing regulatory pressure and stakeholder expectations are driving enterprises to adopt more transparent sustainability practices, particularly in the area of ESG reporting. The introduction of the CSRD directive expands reporting obligations, gradually affecting also wood-processing SMEs.

LCA represents a key tool for evaluating environmental impacts across the product life cycle and provides a structured basis for environmental indicators used in ESG reporting. Despite the growing research on LCA and ESG reporting, their integrated application in SMEs, particularly in relation to financial performance within the wood-processing sector, remains insufficiently explored.

The aim of this paper is to examine the relationship between LCA implementation, ESG reporting, and financial efficiency in wood-processing SMEs. The study combines a literature review with exploratory preliminary empirical research conducted among Slovak enterprises.

## LITERATURE REVIEW

### LCA and ESG Reporting in the Wood-Processing Industry

The wood-processing industry represents a key pillar of the Slovak economy and plays an important role in the economy and sustainable resource management (Dzianová *et al.,* 2025; Sedliačiková *et al.*, 2016). With increasing demand for environmentally friendly products, companies in this sector are progressively adopting sustainability-oriented approaches (Malá *et al.,* 2018). In this context, LCA has emerged as a fundamental tool for evaluating environmental impacts across the entire product life cycle, from raw material extraction to end-of-life (Ahmed *et al.,* 2025; Hauschild *et al.,* 2018).

LCA enables the identification of environmental inefficiencies and prevents the shifting of environmental burdens between life-cycle stages. Its integration into ESG reporting is particularly relevant in light of the EU Directive 2022/2464 (CSRD), which requires transparent disclosure of environmental, social, and governance information (Pantazi, 2024). LCA provides quantified and comparable environmental data, thereby improving the quality, credibility, and transparency of ESG reporting (de Salles and Brantsch, 2025; Isik and Žilka, 2023). As a result, companies can strengthen stakeholder trust and enhance their competitive position.

### The Environmental Pillar of ESG as a part of LCA and the Financial Performance of Wood-Processing Enterprises

The environmental pillar of ESG is closely linked to LCA, as it relies on measurable indicators such as emissions, energy consumption, and resource efficiency. Empirical studies show that environmental disclosure is positively associated with financial performance indicators, including return on equity (ROE), return on assets (ROA), and market value (Radzi, 2023; Alareeni and Hamdan, 2020; Buallay, 2019). These effects are primarily driven by improved resource utilisation, cost reduction, and increased investor confidence.

In this sector, efficient use of natural resources represents a key determinant of economic efficiency and long-term competitiveness. ESG reporting further enhances corporate governance, employee engagement, and stakeholder trust, contributing to improved organisational performance and market positioning (Zeng and Jiang, 2023; Khamisu *et al.,* 2023).

At the same time, sustainability investments are often evaluated based on economic criteria such as ROI and payback period, especially in SMEs, which may face barriers related to administrative burden and limited access to financial incentives (Sedliačiková *et al.,* 2025). ESG adoption is also associated with reduced operational costs, improved efficiency, and lower risk, which together contribute to long-term financial stability and profitability (Ali *et al.,* 2025; Abakwuru *et al.,* 2024; Zhao *et al.,* 2018).

## MATERIALS AND METHODS

The primary objective of this research is to examine how LCA indicators can be linked with ESG reporting practices in small and medium-sized wood-processing enterprises and to evaluate how this integration influences their financial efficiency. The study applies a two-phase research design, combining primary questionnaire-based research with a systematic literature review.

**Phase 1.** Preliminary quantitative research (October 2025 – February 2026) focused on the extent to which wood-processing enterprises integrate LCA indicators into ESG reporting. It examined the relationship between the duration of LCA/environmental measure implementation and the intensity of environmental outcomes, as well as their potential link to financial efficiency. The study also identified which benefits SMEs perceive as key drivers for LCA adoption.

**Phase 2.** The second phase consisted of a systematic literature review aimed at synthesising knowledge on the relationships between LCA, ESG reporting, and financial performance, with a focus on the wood-processing sector.

The review used databases including Scopus, Web of Science, ScienceDirect, ResearchGate, and Google Scholar (2018–2025). Keywords included "life cycle assessment", "ESG reporting", "financial performance", and "wood-processing SMEs". The review combined synthesis and analytical approaches, including backward citation tracking.

Artificial intelligence tools were used to support language refinement and clarity of presentation.

**Sample and Data Analysis**

The preliminary research focused on Slovak wood-processing enterprises. Representativeness was tested using a chi-square test ($\alpha = 0.05$). The minimum required sample size was set at 100 companies. Given the sample size, the empirical findings should be interpreted as exploratory rather than confirmatory. Data was analysed using IBM SPSS Statistics 29. Spearman's rank correlation coefficient assessed relationships between implementation duration and benefit intensity. The Friedman test evaluated differences among motivational factors, with the Wilcoxon signed-rank test used for pairwise comparisons.

**Hypotheses**

**H1**: There is a positive relationship between the duration of LCA/environmental measure implementation and the intensity of selected environmental benefits.

LCA is a process that enables enterprises to identify inefficiencies and optimise resource use across the product life cycle (Ahmed *et al.,* 2025; Hauschild *et al.,* 2018). In the wood-processing industry, its longer application improves data quality and supports reductions in emissions, waste, and resource consumption (Husgafvel *et al.,* 2013; Schaubroeck *et al.,* 2013).

**H2**: The environmental benefits resulting from the implementation of LCA/environmental measures constitute a precondition for the subsequent indirect improvement of a company's economic indicators.

Reduced energy and material consumption and waste minimisation are linked to cost reduction and operational efficiency (Abakwuru *et al*., 2024). Environmental performance within ESG reporting is further associated with improved financial indicators and investor confidence (Radzi, 2023; Alareeni and Hamdan, 2020; Buallay, 2019).

**H3:** SMEs consider those benefits of LCA adoption that are reflected immediately in the internal functioning of the enterprise to be more significant motivating factors than benefits of a reputational or market-related nature.

Due to resource constraints, wood-processing SMEs prioritise measures with immediate operational impacts, such as cost savings and efficiency gains, over long-term reputational benefits (Sedliačiková *et al.,* 2025).

## RESULTS AND DISCUSSION

This part presents the key findings of the research, followed by their interpretation in the context of existing literature.

The relationship between the length of LCA implementation, or environmental measures respectively (Question 38), and the intensity of the reported benefits (Question 39) was analyzed using Spearman's rank correlation coefficient for **Hypotheses 1** and **Hypotheses 2.**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Spearman's rho | | | o39a | o39b | o39c | o39d | o39e | o39f |
| | o38 | Correlation Coefficient | 0,328 | -0,162 | -0,278 | 0,192 | 0,286 | 0,382 |
| | | Sig. (2-tailed) | 0,101 | 0,428 | 0,169 | 0,348 | 0,157 | 0,054 |
| | | N | 26 | 26 | 26 | 26 | 26 | 26 |
| | | | o39g | o39h | o39i | o39j | o39k | o39l |
| | o38 | Correlation Coefficient | 0,153 | -0,045 | 0,125 | -0,084 | 0,041 | -0,110 |
| | | Sig. (2-tailed) | 0,457 | 0,827 | 0,542 | 0,684 | 0,843 | 0,592 |
| | | N | 26 | 26 | 26 | 26 | 26 | 26 |
| | | | o39m | o39n | o39o | o39p | o39r | o39s |
| | o38 | Correlation Coefficient | 0,183 | -0,272 | 0,314 | -0,095 | -,417* | 0,077 |
| | | Sig. (2-tailed) | 0,372 | 0,178 | 0,118 | 0,645 | 0,034 | 0,710 |
| | | N | 26 | 26 | 26 | 26 | 26 | 26 |
| | | | o39t | o39u | o39x | o39y | o39z | |
| | o38 | Correlation Coefficient | -0,032 | -0,007 | -0,295 | 0,016 | 0,043 | |
| | | Sig. (2-tailed) | 0,876 | 0,974 | 0,143 | 0,937 | 0,836 | |
| | | N | 26 | 26 | 26 | 26 | 26 | |

a. Reduced consumption of primary raw materials and resources
b. Reduced energy consumption
c. Reduced water consumption
d. Reduced heat consumption
e. Reduced volume of production waste
f. Reduced emissions released
g. Reduced total waste generation
h. Extended product lifespan
i. Greater transparency regarding the origin of materials
j. Integration of environmental criteria into decision-making processes
k. Introduction of monitoring for environmental indicators
l. Improved cooperation among different departments within the company
m. Reduced operating costs of the company
n. Increased efficiency of production processes
o. Improved waste management
p. Increased competitiveness through an environmentally responsible approach
r. Strengthened environmental awareness among employees
s. Improved corporate reputation and customer relations
t. Increased profit as a result of implementing environmental measures
u. Greater attractiveness for investors and business partners
x. Opportunity to enter new markets (e.g. better access to public funding)
y. Reduced fuel consumption
z. Reduced mileage travelled

**Fig. 1 Relationship Between the Duration of LCA Implementation and the Intensity of Reported Benefits: Spearman's Rank Correlation Results**

Given the ordinal data and small sample (N = 26), the results should be interpreted as exploratory and preliminary, and not as confirmatory statistical evidence. No statistically significant relationship was found between implementation duration and financial indicators, including operating costs (p = 0.372), production efficiency (p = 0.178), and profit (p = 0.876), nor for market-related outcomes such as competitiveness, reputation, investor attractiveness, or market expansion (p > 0.05).

However, several environmental indicators showed positive trends, particularly emission reduction (p = 0.054), reduced material consumption (p = 0.101), improved waste management (p = 0.118), and lower production waste and energy use. Although these relationships are not statistically significant, they may indicate the need for further research with larger samples.

Environmental improvements should be seen as mechanisms that can indirectly lead to economic benefits through cost reduction and efficiency gains. Hypothesis H2 cannot be statistically confirmed; however, the observed patterns may suggest a possible indirect relationship that should be tested.

This interpretation is consistent with studies highlighting LCA as a tool for improving resource efficiency and environmental performance, which are linked to better financial outcomes and stakeholder trust (Ahmed *et al.,* 2025; de Salles and Brantsch, 2025; Abakwuru *et al.*, 2024; Isik and Žilka, 2023; Alareeni and Hamdan, 2020; Buallay, 2019).

A statistically significant negative relationship was identified for employees' environmental awareness (p = 0.034), indicating stronger effects in early implementation stages.

Overall, no direct relationship was confirmed between implementation duration and financial indicators. However, positive environmental trends suggest an evolving connection between environmental and economic performance, providing only limited exploratory support for H1. This aligns with LCA as an iterative process that improves environmental outcomes over time (Dominguez-Villanueva *et al.,* 2025; Pantazi, 2024; Hauschild *et al.,* 2018; Husgafvel *et al.,* 2013; Schaubroeck *et al.,* 2013).

To assess motivating factors for LCA adoption (Question 40) in relation to **Hypothesis H3**, indicators were grouped into environmental, ESG-related, and financial-strategic categories. The Friedman test showed no significant differences within environmental indicators, suggesting they are perceived as a homogeneous set of expected benefits.

In contrast, significant differences were found among financial-strategic indicators (p < 0.001). Cost reduction was the highest-ranked motivator, followed by profit increase, investor attractiveness, and production efficiency, while reputation, competitiveness, and market expansion were rated lower. Wilcoxon tests confirmed a significant difference only between cost reduction and profit increase (p = 0.027), indicating that cost savings are perceived as a stronger and more immediate motivator.

| | o40t-o40m | o40u-o40t | o40n-o40u | o40s-o40n | o40p-o40s | o40x-o40p |
|---|---|---|---|---|---|---|
| Z | -2,205[b] | -1,324[b] | -,587[b] | -,492[c] | -,330[b] | -1,530[b] |
| Asymp. Sig. (2-tailed) | 0,027 | 0,186 | 0,557 | 0,622 | 0,741 | 0,126 |
| a. Wilcoxon Signed Ranks Test b. Based on positive ranks. c. Based on negative ranks. | | | | | | |
| m. Reduced operating costs of the company<br>n. Increased efficiency of production processes<br>p. Increased competitiveness through an environmentally responsible approach<br>s. Improved corporate reputation and customer relations<br>t. Increased profit as a result of implementing environmental measures<br>u. Greater attractiveness for investors and business partners<br>x. Reduced fuel consumption | | | | | | |

**Fig. 2 Results of the Wilcoxon Test for Financial-Strategic Indicators**

The results indicate that cost reduction is perceived as a stronger motivational factor than profit growth. Other pairwise differences within financial-strategic indicators were not statistically significant ($p > 0.05$), suggesting that while differences exist, they are not clearly pronounced. Overall, wood-processing SMEs appear to prioritise immediate and tangible benefits, while profit growth, market expansion, and reputational effects are viewed as secondary and longer-term.

Within ESG-related indicators, significant differences were identified ($p = 0.010$), with the highest rankings assigned to employees' environmental awareness and interdepartmental cooperation. However, Wilcoxon tests did not confirm significant differences between individual pairs ($p > 0.05$), indicating that variations occur at the overall priority level rather than between specific indicators.

| | o40l - o40r | o40j - o40l | o40k - o40j | o40i - o40k |
|---|---|---|---|---|
| Z | -1,438[b] | -,500[b] | -,380[c] | -1,419[b] |
| Asymp. Sig. (2-tailed) | 0,150 | 0,617 | 0,704 | 0,156 |
| a. Wilcoxon Signed Ranks Test b. Based on positive ranks. c. Based on negative ranks. | | | | |
| i. Greater transparency regarding the origin of materials<br>j. Integration of environmental criteria into decision-making processes<br>k. Introduction of monitoring for environmental indicators<br>l. Improved cooperation among different departments within the company<br>r. Strengthened environmental awareness among employees | | | | |

**Fig. 3 Results of the Wilcoxon Test for Indicators Associated with ESG Reporting**

Respondents differentiated between groups of motivators. Environmental indicators were perceived as a balanced set of expected benefits, while financial-strategic and ESG-related factors were more clearly prioritised. Cost reduction appeared as the dominant driver, confirming that SMEs favour benefits directly reflected in daily operations. Within ESG, emphasis was placed on internal factors such as employees' environmental awareness and interdepartmental cooperation, indicating that LCA is also perceived as a driver of organisational change.

This is consistent with literature showing that SMEs prioritise immediate and tangible benefits, particularly cost savings and efficiency gains (Sedliačiková *et al.,* 2025; Abakwuru *et al.,* 2024), while reputational and market-related benefits are viewed as indirect and long-term (Zeng and Jiang, 2023; Khamisu *et al.,* 2023). LCA also supports governance and decision-making through structured environmental data (de Salles and Brantsch, 2025; Pantazi, 2024).

Overall, the findings indicate that internally observable benefits play a decisive role in LCA adoption. Although preliminary, the results support Hypothesis H3, as wood-processing SMEs assign greater importance to operational benefits than to reputational or market-related outcomes.

## CONCLUSION

The exploratory study examined the relationship between LCA implementation, ESG reporting, and financial efficiency in wood-processing SMEs. The results did not confirm a statistically significant direct relationship between the duration of LCA implementation and financial performance indicators.

However, positive trends observed in environmental indicators suggest that environmental improvements may represent an indirect pathway toward economic benefits.

Reduced resource consumption, emissions, and waste can contribute to cost savings and efficiency gains over time.

From a motivational perspective, SMEs prioritise benefits that are immediately observable within internal operations. Cost reduction and process efficiency were identified as the most significant drivers of LCA adoption, while reputational and market-related benefits were perceived as less influential.

The findings also highlight the importance of internal organisational factors, particularly environmental awareness, cooperation, and the integration of environmental criteria into decision-making. This suggests that LCA plays not only a technical role but also supports organisational development.

Despite the absence of strong statistical evidence, the results support the assumption that LCA and ESG reporting may contribute to both environmental and economic performance, when implemented systematically.

The main limitation of the study is the small sample size, which limits the generalisability of the findings and reinforces their exploratory nature. Future research should extend the dataset and incorporate qualitative approaches to better understand the mechanisms behind LCA adoption and its impacts. Further work should also focus on developing practical frameworks that support the integration of LCA data into ESG reporting and enhance its usability in wood-processing SMEs‘ practice.

**REFERENCES**


Abakwuru, V., Onyena hazi, O.B., Antwi, B.O., Oyewale, K., 2024. The impact of environmental, social, and governance (ESG) reporting on corporate financial performance. International Journal of Research Publication and Reviews 5(9), 3629–3644. 10.55248/gengpi.5.0924.2710

Ahmed, S., Liscio, M.C., Sospiro, P., Voukkali, I., Zorpas, A.A., 2025. Advancing sustainable development through environmental performance monitoring: The organisational life cycle assessment. Business Strategy and the Environment 34(2), 2556–2570. https://doi.org/10.1002/bse.4115

Alareeni, B., Hamdan, A., 2020. ESG impact on performance of US S&P 500 listed firms. Corporate Governance: The International Journal of Business in Society 20(7), 1409–1428. 10.1108/CG-06-2020-0258

Ali, M.B.N., Hussin, A.A.A.H., Mohammed, F.M.H., Mohmmed, H.A.A.K., Almutiri, S.A.A., Ali, A.A., 2025. The effect of environmental, social, and governance (ESG) disclosure on the profitability of Saudi-listed firms: Insights from Saudi Vision 2030. Sustainability 17(1). https://doi.org/10.3390/su17072977

Buallay, A., 2019. Is sustainability reporting (ESG) associated with performance? Evidence from the European banking sector. Management of Environmental Quality: An International Journal 30(1), 98–115. 10.1108/MEQ-12-2017-0149

De Salles, N.C.A., Brantsch, P., 2025. How life cycle assessment supports sustainability reporting: Example from clean aviation. Engineering Proceedings 90, 56. https://doi.org/10.3390/engproc2025090056

Dominguez-Villanueva, S., Rojas-García, A.M., Sánchez-Ruíz, J.F., Hernández-Reyes, H., Cuautle-Gutiérrez, L., 2025. Life cycle analysis of waste management of a brake pad manufacturing company. Cleaner Logistics & Waste Studies 11. https://doi.org/10.1016/j.clwas.2025.100314

Dzianová, L., Parobek, J., Paluš, H., Dzian, M., 2025. The strategic potential of publishing ESG information in strengthening the competitiveness of the wood-based sector.

Hauschild, M.Z., Rosenbaum, K.R., Olsen, I.S., 2018. Life Cycle Assessment: Theory and Practice. Springer, Cham. ISBN 978-3-319-56475-3. https://doi.org/10.1007/978-3-319-56475-3

Husgafvel, R., Watkins, G., Linkosalmi, L., Dahl, O., 2013. Review of sustainability management initiatives within Finnish forest products industry companies—Translating EU level steering

into proactive initiatives. Resources, Conservation and Recycling 7, 1–11. https://doi.org/10.1016/j.resconrec.2013.04.006
Isik, B., Žilka, M., 2023. Life cycle assessment integration to improve ESG reporting: A path to sustainable decision-making and stakeholder confidence. In: Proceedings of KNOWCON 2023 Knowledge on Economics and Management. Olomouc. 10.5507/ff.23.24463902
Khamisu, S.M., Paluri, A.R., Sonwaney, V., 2023. Environmental social and governance (ESG) disclosure motives for environmentally sensitive industry: An emerging economy perspective. Cogent Business & Management 11(1). https://doi.org/10.1080/23311975.2024.2322027
Malá, D., Sedliačiková, M., Benčíková, D., 2018. How customers of small and medium wood-processing Slovak enterprises perceive a green product. Bioresources 13(1), 1930–1950.
Pantazi, T., 2024. The introduction of mandatory corporate sustainability reporting in the EU and the question of enforcement. European Business Organization Law Review. 25. 509-532. https://doi.org/10.1007/s40804-024-00320-x
Radzi, H., 2023. An overview of environmental, social and governance (ESG) and company performance. In: Proceedings of the International Conference in Technology, Humanities and Management. 10.15405/epsbs.2023.11.90
Sedliačiková, M., Hajdúchová, I., Krištofík, P., Viszali, I., 2016. Improving the performance of small and medium wood-processing enterprises. Bioresources 11(1), 439–450. 10.15376/biores.11.1.439-450
Sedliačiková, M., Kostúr, M., Osvaldová, M., 2025. Proposing green growth indicators for enterprises in the woodworking and furniture industry. Forests 16(11). https://doi.org/10.3390/f16111629
Schaubroeck, T., Alvarenga, R.A.F., Verheyen, K., Muys, B., Dewulf, J., 2013. Quantifying the environmental impact of an integrated human/industrial-natural system using life cycle assessment: A case study on a forest and wood processing chain. Environmental Science & Technology 47(23), 13578–13586. https://doi.org/10.1021/es4046633
Zeng, L., Jiang, X., 2023. ESG and corporate performance: Evidence from agriculture and forestry listed companies. Sustainability 15(8). https://doi.org/10.3390/su15086723
Zhao, C., Guo, Y., Yuan, J., Wu, M., Li, D., Zhou, Y., Kang, J., 2018. ESG and corporate financial performance: Empirical evidence from China's listed power generation companies. Sustainability 10(8). https://doi.org/10.3390/su10082607

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# POTENTIAL OF FACILITY MANAGEMENT IN CRAFT FAMILY BUSINESSES

**Martin Synák-Varga – Mariana Sedliačiková – Denis Pinka**

## ABSTRACT

The management of support processes is a key strategic factor for companies in ensuring their long-term competitiveness and sustainability in a rapidly changing business environment. Facility management plays a crucial role in this context by coordinating support activities that enable the effective functioning of core business processes. It takes on particular significance in the family business segment, which is characterized by specific management and work organization characteristics. Family businesses in the field of craft production of specialty wood products form a distinct group. These businesses utilize wood as a renewable natural resource while emphasizing artisanal production, originality, and a personalized approach to the customer. The main scientific objective of this study was to analyze the theoretical foundations of facility management in the context of family businesses in the craft sector, with a focus on the production of specialty wood products. The research objective was achieved through a detailed analysis of secondary sources focusing on the topics of facility management, family businesses, craft businesses, and the production of specialty wood products. In the presented study, relevant professional sources by reputable authors, published primarily in licensed scientific databases, were utilized. The analysis of the issues was conducted using scientific methods such as description, analogy, summarization, and synthesis of knowledge and information. Based on the findings, recommendations are formulated for theory, science, and practice, focused on the effective use of facility management in family businesses in the field of craft wooden product manufacturing. The conclusion of the study also suggests possible directions for further research in this area.

**Keywords:** facility management; family business; craft; specialty wood products.

## INTRODUCTION

Matos *et al.* (2023) argue that facility management (FM) involves the planning, organizing, and controlling of activities related to the operation and maintenance of buildings and technical equipment. FM is an integrated approach to managing people, processes, and the physical environment with the aim of supporting the effective functioning of an organization (ISO 41011, 2017). From the perspective of current trends, FM can be viewed as a dynamic managerial function that responds to changing user needs, technological developments, and growing demands for service quality, while contributing to organizational performance even under conditions of increasing operational complexity (Ismaeil, 2024).

Family businesses (FBs) constitute an exceptionally significant group of entities in both European and global economies, whose activities have a fundamental impact on wealth creation, employment, and regional development. They act as a stabilizing force in the economic environment thanks to the integration of business objectives with family values and a long-term decision-making horizon (Nyabakora, 2024). Birdthistle and Hales (2024) emphasize that FBs are among the most important job creators in the labor market, significantly contribute to economic growth, and contribute to social sustainability and community development. Zajkowski *et al.* (2022) argue that the combination of family ownership, managerial influence, and intergenerational business succession creates the unique character of FB. Amore *et al.* (2022) also demonstrated that FBs with higher levels of family involvement exhibit greater resilience during crises, stemming from a long-term orientation and a willingness to sacrifice profits in favor of long-term stability.

Craft entrepreneurship represents a specific business model based on the combination of manual production, artisanal know-how, and an individualized approach to product creation. Unlike industrial production, craft entrepreneurship is characterized by small-batch production, a high proportion of manual labor, and often significant involvement of the entrepreneur themselves in the production process (Ganzin *et al*., 2024). The process-oriented nature of craft entrepreneurship reinforces consumers' perception of the uniqueness and authenticity of products. Consumers place high value on the story behind a product's creation, the craft techniques used, and the maker's identity (Downey, 2024). This approach allows businesses to differentiate themselves from mass production and create emotional bonds with customers, but at the same time limits the possibilities for rapidly increasing production capacity (Pine & Gilmore, 2020). The essence of artisanal production is characterized by the fact that the product's value is created gradually through manual labor, craftsmanship, and the maker's creative decisions (Smagina & Ludviga, 2020). In this context, the finished product is perceived not only as a functional object but also as a bearer of culture, aesthetics, and the producer's personal identity (Luckman, 2015). This business model is characterized by a distinct logic of value creation that is not based on production volume, but on the authenticity, originality, and cultural significance of the products (Solomon & Mathias, 2020; Dobrev & Verhaal 2024).

Wood is one of the oldest materials used in human economic activity and continues to play a significant role in the production of high-value-added products. (Schubert *et al.,* 2022). In the wood-based products industry, wood serves as a material that combines technical, environmental, and emotional values, and its processing significantly influences the perceived quality and long-term durability of products (Duan *et al*., 2023; Ross, 2021). Current literature does not provide a uniform definition of the term "special wood products" (SWPs), but they can be defined based on product characteristics, function, and method of use. In general, SWPs can be understood as wood products with higher added value, which differ from basic products primarily through a higher degree of processing and the enhancement of material properties (Calvano *et al*., 2025). The category of SWPs includes a wide range of products with various uses, particularly those intended for household, leisure, and cultural purposes, such as kitchenware, musical instruments, or decorative items that go beyond the basic material utilization of wood (Hetemäki et al., 2023; de Araujo *et al*., 2017). In these products, wood is processed into a final form intended for the end customer, with design, quality of workmanship, and the product's functional properties playing a key role (Suandi *et al*., 2022). The successful production of SWPs requires not only a high level of craftsmanship but also the ability to systematically manage production processes and workmanship quality, as defects have a direct impact on the functional and aesthetic properties of the final product (Zhao et al., 2021; Yaghoubi *et al.,* 2024).

Family-owned craft businesses (FOCBs) generally do not have systematic energy consumption monitoring in place or defined energy efficiency targets. Electricity, gas, or heat consumption is monitored primarily through billing data, while a more detailed analysis of energy-intensive processes and equipment is lacking. This situation significantly increases the businesses' vulnerability to rising energy prices and limits their ability to actively respond to changes in their cost structure (Baniya, 2023). Energy inefficiency is often closely linked to the technical condition of production facilities and infrastructure. Many craft businesses use facilities that were not designed with current energy efficiency requirements in mind. Inadequate thermal insulation, outdated lighting, or inefficient technical equipment lead to energy losses that directly translate into rising operating costs (Altwassi et al., 2024; Vitkova & Vitasek, 2024). The underestimation of preventive maintenance poses a significant problem for operational management, as maintenance of buildings and technical equipment is often carried out only after a failure has occurred (Matos et al., 2023). While a reactive approach to maintenance is characterized by lower initial costs, it leads to unplanned downtime and higher long-term repair costs, which negatively impacts overall operational efficiency (Gholipour et al., 2025). Another significant limiting factor is the absence of systematic planning and tracking of operating costs. Energy, maintenance, and FM costs account for a significant portion of total building operating costs, and their effective management requires systematic data collection and analysis (Moghadam & Besiktepe, 2025). The lack of structured and detailed cost data limits the company's ability to identify key cost drivers and make effective decisions regarding operational optimization and investments in technical modernization or energy efficiency (Alrubaidi, 2024). Based on a synthesis of the above findings from the literature, key operational issues and their impact in FOCBs can be identified, which are systematically summarized in Table 1.

**Tab. 1 Operational challenges and their impact on family-owned craft businesses**

| Management area | Problem | Impact on the business |
|---|---|---|
| production management | intuitive decision-making | ineffective cost and investment planning |
| energy management | lack of energy consumption monitoring | increased sensitivity to rising energy prices |
| maintenance of buildings and facilities | irregular maintenance instead of preventive maintenance | malfunctions, downtime, and higher repair costs |
| work organization | the owner's time constraints | reduced management efficiency and risk of errors |
| workplace safety | inadequate established safety procedures | increased operational and health risks |

Source: authors' own elaboration based on Baniya, 2023; Matos et al., 2023; Gholipour et al., 2025; Solomon and Mathias, 2020; Dixit et al., 2021.

The operational and organizational management of FOCBs is often characterized by a lack of flexibility, a reactive approach, and limited strategic planning, which restricts the businesses' ability to respond effectively to changing conditions (Sedhom et al., 2024). In the context of growing demands for energy efficiency and sustainability, the absence of systematic operations and maintenance management poses a significant risk to the long-term stability and performance of these businesses. Identifying these weaknesses provides a starting point for considering the use of facility services as a tool for the systematic management of operations, energy, and costs (Shohet, 2025).

Current literature focuses primarily on FM in large enterprises, while its application in small and specific segments, such as FOCBs producing SWPs, remains under-researched.

This gap limits our understanding of the possibilities for systematically managing support processes in the context of craft production.

The segment of FOCBs producing SWPs is of research interest due to the interplay of family management, the artisanal nature of production, and the growing importance of wood as a high-value-added material, while these businesses often operate without formalized management approaches.

The contribution of this study is the creation of a theoretical framework for the application of FM in this segment, supplemented by an implementation model and recommendations for practice, with the aim of supporting the efficiency and sustainability of these businesses.

*The main scientific goal of this study is to analyze the theoretical foundations of FM in the context of FBs engaged in the craft production of SWPs and to assess its potential as a tool for enhancing the operational efficiency and long-term sustainability of these enterprises; the study also includes a proposal for a model example of its practical application.*

## MATERIALS AND METHODS

To ensure a clear structure and systematic treatment of the subject matter, the methodology of this paper was divided into three interconnected stages. The study focuses on a theoretical analysis of the subject matter. In the first stage, an in-depth analysis of secondary sources focused on FM, FBs, craft businesses, and SWPs was conducted. As part of the analysis, the selection of sources focused on foreign scientific studies published in licensed databases such as Web of Science, Scopus, ScienceDirect, and ProQuest. The analysis was conducted by comparing the approaches of individual authors and identifying common and differing characteristics of the subject matter. In the second stage, a synthesis of the acquired knowledge was performed, which involved integrating partial findings into a comprehensive concept for the application of FM in the context of FOCBs. The synthesis was based on a logical-systematic approach, with individual findings organized according to the functional areas of FM and subsequently transformed into proposed solutions reflecting the specifics of craft production. Subsequently, a model example of a FOCB was created, which serves as an illustrative tool for the practical application of the identified principles of FM. The model example was chosen due to the lack of empirical data, and its purpose is to demonstrate the practical feasibility of the proposed solutions, identify key operational issues, and illustrate possible solutions under the real-world conditions of a small business. The concluding section of the study is based on the methods of analogy, synthesis, deduction, and summarization, where the summary of conclusions is subsequently strategically supplemented by a systematic approach that enables the formulation of the future direction of the presented research.

## RESULTS AND DISCUSSION

The following section of this study focuses on analyzing the potential for utilizing facility services in the context of FOCBs specializing in the production of SWPs. The focus is on assessing how facility services can contribute to enhancing competitiveness and ensuring the long-term sustainability of these businesses.

### The strategic potential of facility management in family-owned craft businesses producing specialty wood products

In FOCBs producing wooden goods, operations tend to expand gradually, with production areas, warehouses, auxiliary workspaces, and administrative facilities growing without a unified planning framework (Matos et al., 2023). This development can lead to unclear processes, conflicts between activities, and inefficient use of space, which negatively impacts production flow and the quality of the work environment (Nota et al., 2021). The implementation of FM provides tools for analyzing operational processes and infrastructure utilization, thereby contributing to a more effective alignment of production and support activities. It is of particular importance in the context of enterprise asset lifecycle management, which encompasses planning, maintenance, and infrastructure renewal (Alkhard, 2024). In practice, we often encounter an insufficiently systematic approach to asset management and problems with data integration, which can lead to inefficient use of resources and increased maintenance costs. Implementing FM principles enables better planning of renewal, investments, and maintenance, thereby supporting the efficiency and stability of business processes (Ehab et al., 2025). A key area where FM adds value is the management of operational risks associated with the handling of hazardous materials and waste. Failure to adequately follow procedures and guidelines can lead to risks to employee health, environmental hazards, and violations of legal requirements. A systematic approach to managing these processes, including the implementation of standardized procedures, regular training, and inspections, is essential for minimizing risks and ensuring safe operations (Dixit et al., 2021). From an organizational perspective, facility services serve as an important tool for reducing a company's dependence on a single individual. In a FOCB, the owner is often the holder of key knowledge and decision-making authority, and their personal involvement and value orientation significantly influence the company's operations (Solomon & Mathias, 2020). This concentration of knowledge also increases the company's vulnerability in the event of the owner's prolonged absence or generational transition. The formalization of support processes, documentation of procedures, and systematic asset management therefore contribute to greater organizational stability and facilitate the transfer of know-how within the business (Pipatanantakurn, 2022). FM also supports the ability of FOCBs to respond to market growth and changes. Changes in the scale of production or the organization of operations place increased demands on logistics, spatial layout, and support processes. Without systematic management of these areas, resources may be used inefficiently and the quality of services provided may decline. The implementation of FM enables improved planning, organization, and maintenance of infrastructure, thereby supporting the efficient operation of the business without disrupting the artisanal nature of production (Simpeh et al., 2023; Baniya, 2023). As previously mentioned, a significant trend in FM is the gradual digitization of support processes, which may also be relevant for FOCBs. Even simple digital tools for asset tracking, maintenance planning, or monitoring operations and costs increase transparency and support economic and managerial decision-making (Ismaeil, 2024). The digitization of FM increases management efficiency even in small FOCBs, provided it is tailored to their capacity (Nota et al., 2021).

Based on the above, the management process of a FOCBs can be understood as a continuous and interconnected cycle of support and production activities, which is systematically influenced by the implementation of facility services. In this context, FM serves as a strategic framework that links planning, day-to-day operations, the execution of production processes, regular maintenance of buildings and equipment, as well as modernization and improvement activities aimed at ensuring the company's stability and greater competitiveness in the market. This cyclical nature of management demonstrates that the individual phases are interdependent and form a logical sequence of activities leading to the long-term stability and competitiveness of a FOCB. These interconnections imply that FM does not merely fulfill an operational support function but serves as an integrating element of the enterprise's life cycle management, as schematically illustrated in Fig. 1.

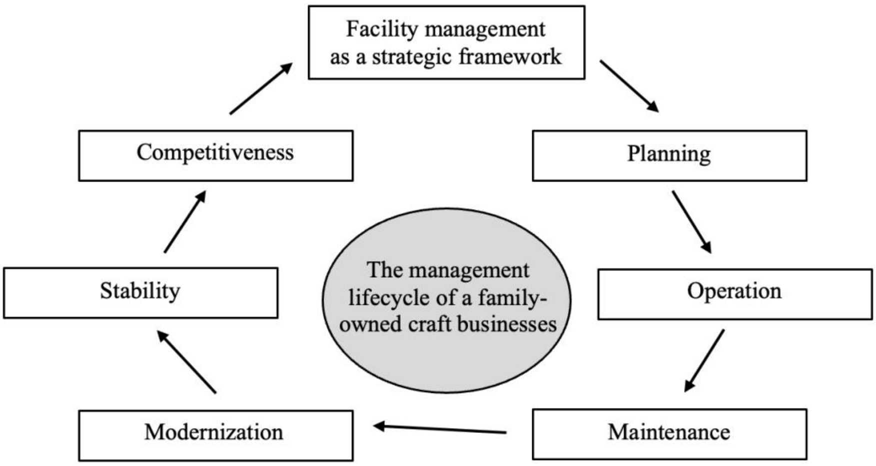


**Fig. 1 The management lifecycle of a family-owned craft businesses**
Source: authors' own elaboration based on Matos et al. (2023); Ismaeil (2024); Baniya (2023); Simpeh et al. (2023); Alkhard (2024)

In the long term, FM in FOCBs specializing in specialty wood products can be viewed as a tool to support their competitiveness and sustainability. Systematic management of facilities, processes, and infrastructure creates stable conditions for the long-term development of craft production, reduces operational risks, and supports business continuity over time. FM thus need not pose a threat to the traditional character of craft production, but can be understood as a logical complement to it in the context of growing market demands and regulation (Baniya, 2023; Okoro, 2023).

**A case study of the use of facility services in a family-owned craft business specializing in specialty wood products**

As a practical example of facility services, we can consider a small family workshop specializing in the craft production of SWPs. This business operates out of a small production facility that was created by gradually converting former farm buildings into a workshop and warehouse. The business specializes in the production of wooden toys, designer kitchen accessories, and smaller custom decorative items, with each product undergoing multiple manual operations - from material selection, through machining, sanding, and finishing, to packaging. Production is small-batch and heavily dependent on the craftsmanship of family members, who participate in individual production phases according to their abilities. The company's organizational structure is very simple and informal. The owner handles production management, customer communication, material procurement, and technical management of the workshop, while other family members are primarily involved in manual production operations and product packaging. This arrangement allows for a flexible response to individual orders and maintains a high degree of product authenticity, but at the same time makes the operation heavily dependent on a single key person. Decisions regarding work organization, equipment maintenance, and investments in equipment are made intuitively based on experience and current needs, without systematic planning of support processes. The company's production facilities are divided into a woodworking zone, a product finishing area, and a small warehouse for materials and finished products. However, the individual workstations were created gradually in response to expanding production needs, leading to a confusing flow of materials and frequent movement of products between operations. In the craft production of SWPs, which require precise manual processing and multiple inspection steps, these spatial constraints result in increased labor time and more complicated organization of production processes. The workshop's technical equipment consists of a combination of basic woodworking machines, hand tools, and auxiliary devices for sanding and finishing products. Maintenance of this equipment is primarily performed on an ad hoc basis, that is, in response to a problem that has arisen or reduced machine functionality. Preventive inspections are conducted on an irregular basis and are not systematically documented. A similar situation is evident in the area of building and workplace management, where minor technical issues are addressed on an ad hoc basis, but without a long-term strategic plan for the company's development. From an occupational safety perspective, the production of SWPs involves handling sharp tools, rotating machine parts, and chemical agents used in surface treatments. Safety measures are based primarily on the family members' experience and long-term practice, while formal risk assessment procedures or regular workplace inspections are not fully developed. While this approach is consistent with the nature of a small family workshop, it may pose a significant operational risk as the business grows, production volumes increase, or new workers are hired.

In this model craft business, facility services could be introduced gradually and to an extent commensurate with its size, financial resources, and time constraints.

- As a first step, it would be advisable to systematically map out the support activities related to workshop management, workstation organization, equipment maintenance, and workplace safety. Such an analysis would make it possible to identify specific areas where makeshift solutions are affecting the smooth flow of SWPs production and increasing the owner's workload.
- In terms of organizing production spaces, facility services could focus on optimizing the layout of workstations according to the logical sequence of production operations typical of craft woodworking. For products that undergo multiple manual processing steps, it is important to ensure a smooth flow of materials from initial processing through to final quality control. A better arrangement of work zones would reduce the need for repeated movement of products, facilitate quality control, and simultaneously create a safer working environment.
- In the area of equipment maintenance, it would be advisable to implement a simple schedule of preventive inspections for machines used in woodworking and sanding, as these machines have a key impact on product quality and precision. Regular inspections of the technical condition would reduce the risk of breakdowns during production peaks

and ensure more stable production conditions, which are important in small-batch production.

- Facility services could also be beneficial in systematizing safety measures tailored to the nature of woodworking. The implementation of simple checklists for workstations and clear labeling of storage areas would help reduce the risk of workplace accidents without creating an excessive administrative burden.
- The most relevant facility services for a small craft family workshop include the management and organization of production spaces, preventive maintenance of equipment, record-keeping of operational documents, monitoring of energy consumption, and the systematization of safety procedures. As supplementary practical tools, FOCBs can utilize simple and affordable solutions, such as cloud storage for recording service interventions, inspections, machine operating manuals, warranty documents, and safety procedures. Simple measuring devices, such as meters for electricity consumption, humidity, temperature, or dust levels, can also be useful in identifying energy-intensive activities, unsuitable wood storage conditions, safety risks, and the need for preventive equipment maintenance. Implementing these measures can contribute to better workplace organization, a lower risk of unplanned downtime, improved workplace safety, and greater operational transparency for a family-run craft business.

The expected benefits of implementing facility services in a model family workshop would be reflected primarily in improved organization of production processes, greater operational transparency, and reduced dependence of the business on a single individual. The owner would gain a better overview of the condition of workstations, equipment, and risks, which would allow them to focus more on developing new products. At the same time, the systematization of support processes would create more stable conditions for the long-term operation of the business and its potential expansion with new employees.

The risks of implementing facility services lie primarily in the time-consuming nature of the process and the limited financial resources of a small FOCB. Therefore, it is necessary for the scope of facility services to be tailored to the specific needs of SWPs manufacturing and not to reduce the flexibility that is key to a craft business.

Based on the identified operational shortcomings and the proposed measures for implementing FM, we can understand the transformation process of a FOCB as a systematic transition from intuitive management to a process-oriented management model. This transition involves changes in the organization of production processes, maintenance management, and occupational safety, as well as in the level of transparency and operational control. The comprehensive interconnection of these changes and their impact on the company’s operations is schematically illustrated in Fig. 2.

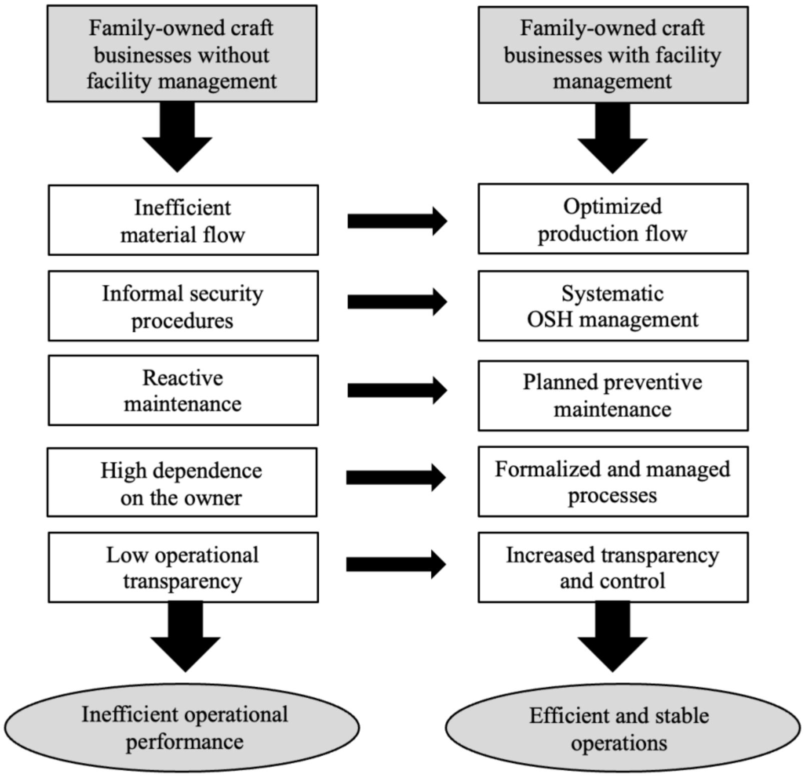


**Fig. 2 Transformation of a family-owned craft businesses through the implementation of facility management**

Source: authors' own elaboration based on insights from Matos et al. (2023); Gholipour et al. (2025); Baniya (2023); Ismaeil (2024); Dixit et al. (2021); Solomon and Mathias (2020)

Fig. 2 presents a synthetic summary of the transformation mechanism for a FOCB resulting from the implementation of FM as an integrating management framework. The initial state of the business is characterized by the absence of systematic management of support processes, which leads to inefficiency, increased risks, and high dependence on the owner. The implementation of FM connects individual activities, thereby creating a coordinated management system based on planning, control, and process optimization. The transformation includes the optimization of material flows, the introduction of preventive maintenance, the systematization of safety procedures, and increased operational transparency. At the same time, personnel dependency is reduced and the company's organizational stability is strengthened. The resulting state represents a more efficient, stable, and better-managed business environment capable of responding to growth opportunities and changing market conditions.

Fig. 2 confirms that FM in FOCBs does not merely serve a supportive role, but rather represents a key integrative management tool that enables the systematic development of the business, improves its performance, and ensures long-term sustainability.

When interpreting the proposed model example, its limitations must also be taken into account. The model is based on a theoretical synthesis of knowledge and has not been empirically tested on a specific FOCB. At the same time, it reflects a specific type of small craft family workshop focused on the production of SWPs; therefore, its application in other types of FBs may require adaptation based on the size of the operation, technical equipment, and nature of production processes. From a practical standpoint, it is recommended that FOCBs begin implementing FM gradually, starting with simple inventory of technical equipment, planning preventive maintenance, and basic tracking of operating costs. At the same time, it is advisable to implement simple safety and organizational procedures that will not increase the administrative burden but will promote transparency, safety, and stability in day-to-day operations.

The study's findings confirm the understanding of FM as an integrative function that connects processes, people, and the physical environment to support organizational performance, as noted by Ismaeil (2024). They also align with the conclusions of Sedhom et al. (2024), who emphasize the importance of flexibility and adaptability in FM when aligning it with organizational requirements. In the context of FOCBs, this need is particularly evident in the fact that support processes must be managed more systematically, yet without compromising the flexibility and artisanal nature of production. These findings can be further interpreted in light of Solomon and Mathias (2020), who point to the tension between the growth of craft businesses and the preservation of their value-oriented character. The results of this study suggest that FM can serve as a supportive tool in the context of FOCBs for systematizing selected operational activities without directly interfering with the artisanal nature of production. In this context, FM does not act as a tool for excessive formalization, but rather as a means of improving operational organization, workplace safety, and quality consistency. From the perspective of digitalization, the findings align with technology-oriented approaches in FM that emphasize the importance of integrating data and digital tools into operations management (Altwassi et al., 2024; Alrubaidi, 2024). However, unlike solutions designed for larger and more complex organizations, this study shows that in the context of small FOCBs, a more appropriate approach is the gradual implementation of simple and affordable tools for equipment inventory, maintenance planning, energy consumption monitoring, and operational cost control. The results are also consistent with those of Matos et al. (2023), who emphasize the importance of preventive maintenance in managing the technical condition of buildings and the need for a systematic approach to maintenance. This view is complemented by the findings of Gholipour et al. (2025), according to whom the transition from reactive to preventive maintenance contributes to reducing breakdowns, unplanned downtime, and long-term costs. However, in the context of FOCBs producing SWPs, preventive maintenance also has qualitative significance, as the technical condition of equipment can affect not only operating costs but also machining precision, the smoothness of production operations, and the quality of the final product. This perspective is further explored in a study by Vitková and Vítášek (2024), who emphasize the importance of systematic cost and technology management throughout a building's life cycle. The present study extends this approach to the specific context of FOCBs, where support and production processes are closely intertwined. The specific nature of this segment lies primarily in its low degree of formalization, high dependence on the owner, and the direct impact of operating conditions on the quality of the final product - factors that traditional FM models have not yet taken into account.

## CONCLUSION

The issue of FM in the FM segment of the SWPs craft industry represents a significant area in terms of enhancing operational efficiency, stability, and the ability to respond to changing conditions in the business environment. The specific nature of these businesses, stemming from the intertwining of family relationships, artisanal production, and an intuitive management style, creates conditions for operational inefficiencies, inadequate planning, and increased dependence of the business on a single individual. In this context, FM represents not only an operational management tool but also a strategic approach enabling the systematization of support processes, more efficient use of resources, and the reduction of operational risks.

Based on the analysis conducted, three key findings can be identified. First, family-owned craft businesses are characterized by the absence of systematic management of support processes, which leads to inefficient use of resources and increased operational costs. Second, the business's high dependence on a single individual poses a significant organizational risk, particularly from the perspective of business continuity. Third, the implementation of FM has the potential to significantly improve the transparency, stability, and efficiency of management without disrupting the artisanal nature of production.

From a practical standpoint, several recommendations can be made for FOCBs specializing in SWPs. The implementation of a systematic approach to operations management should be carried out gradually and in line with the company's capacity. Key measures include, in particular:

- implementation of a monthly preventive maintenance schedule for equipment,
- creation of a simple energy consumption tracking system,
- optimizing the layout of production areas according to the flow of production operations,
- implementing basic records of operating costs,
- formalizing simple safety procedures,
- using simple digital tools for asset and maintenance tracking,
- delegating support activities to other employees within the company.

The implementation of these measures enables a shift from intuitive management to a systematic approach that increases transparency, reduces risks, and supports the long-term sustainability of the business. A limitation of this study is its theoretical focus and the lack of empirical validation of the proposed approaches. Future research should focus on empirically verifying the benefits of FM in this segment, particularly in terms of its impact on performance, cost-effectiveness, and risk management. At the same time, it is necessary to identify specific tools and models for implementing FM that are practically feasible and financially accessible for small FBs.

### REFERENCES

Alkhard, A., 2024. Enhancing Asset Management Through Integrated Facilities Data, Digital Asset Management, and Metadata Strategies. Construction Economics and Building 24(3), 76–94. https://doi.org/10.5130/AJCEB.v24i3.8741

Alrubaidi, M., 2024. Evaluating the effects of digital transformation on facilities management projects in Saudi Arabia: Overcoming challenges and seizing opportunities. Open Journal of Civil Engineering 14, 536–569. https://doi.org/10.4236/ojce.2024.144030

Altwassi, E.J., Aysu, E., Ercoskun, K., Abu Raed, A., 2024. From Design to Management: Exploring BIM's Role across Project Lifecycles, Dimensions, Data, and Uses, with Emphasis on Facility Management. Buildings 14, 611. https://doi.org/10.3390/buildings14030611

Amore, M.D., Bennedsen, M., Larsen, B.M., 2022. The resilience of family firms during crises: Evidence from the COVID-19 pandemic. Journal of Corporate Finance 74, 102219. https://doi.org/10.1016/j.jcorpfin.2022.102219

Baniya, B., 2023. Circularity in facility management: Conceptualisation and potential areas for circularity-oriented actions. Sustainability 15, 8460. https://doi.org/10.3390/su15118460

Besiktepe, D., Ozbek, M.E., Atadero, R.A., 2021. A multi-criteria decision-making approach for building maintenance strategy selection using choosing by advantages. Journal of Facility Management Education and Research 5(1), 1–12. https://doi.org/10.22361/2474-6630-5.1.1

Birdthistle, N., Hales, R., 2024. Attaining the 2030 Sustainable Development Goal of Sustainable Cities and Communities. Emerald Publishing Limited, Bingley. https://doi.org/10.1108/978-1-80455-836-220231001

Calvano, S., Negro, F., Blanc, S., Bruzzese, S., Brun, F., Zanuttini, R., 2025. Adding value to wood-based products: A systematic literature review on drivers. Forests 16, 590. https://doi.org/10.3390/f16040590

de Araujo, V.A., Vasconcelos, J., Lahr, F.A.R., Christoforo, A.L., 2022. Timber forest products: A way to intensify global bioeconomy from bio-materials. Acta Facultatis Xylologiae Zvolen 64(1), 99–111. https://doi.org/10.17423/afx.2022.64.1.09

Dixit, A.M., Bansal, P., Jain, P., Bajpai, P.K., Rath, R.S., Kharya, P., 2021. Assessment of biomedical waste management in health facilities of Uttar Pradesh: An observational study. Cureus 13(12), e20098. https://doi.org/10.7759/cureus.20098

Dobrev, S.D., Verhaal, J.C., 2024. Organizational authenticity: How craft-based ventures manage authentic identities and audience appeal. Strategic Entrepreneurship Journal 1–30. https://doi.org/10.1002/sej.1496

Downey, H., McAdam, M., Crowley, C., 2024. Authenticity and craft entrepreneurship: The interplay of passion and place. Entrepreneurship & Regional Development 36(9–10), 1275–1293. https://doi.org/10.1080/08985626.2024.xxxxx

Duan, Z.Y., Liu, Y., Li, J., 2023. Crafting a place-based souvenir for sustaining cultural heritage: The role of perceived value. Heliyon 9, e19687. https://doi.org/10.1016/j.heliyon.2023.e19687

Ehab, A., Mahdi, M.A., El-Helloty, A., 2025. Enhancing facility maintenance using knowledge-based BIM and IoT integration. Scientific Reports. https://doi.org/10.1038/s41598-025-30057-7

Ganzin, M., Chirico, F., Kroezen, J.J., Dacin, M.T., Sirmon, D.G., Suddaby, R., 2024. Craft and strategic entrepreneurship: Exploring and exploiting materiality, authenticity and tradition in craft-based ventures. Strategic Entrepreneurship Journal 18(4), 671–685. https://doi.org/10.1002/sej.1528

Gholipour, Y., Zare, M., Vazirisereshk, M., Gholipour, Y., 2025. A comprehensive review of maintenance strategies: From reactive to proactive approaches. Central Asia and the Caucasus 26(1), 70–83. https://doi.org/10.61841/ca-c.70-83

Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahí, M., Trasobares, A., 2023. Forest bioeconomy and the role of wood-based products in sustainable development. Nature Reviews Earth & Environment 4, 123–136. https://doi.org/10.1038/s43017-022-00380-0

International Organization for Standardization, 2017. Facility management – Vocabulary (ISO 41011). ISO, Geneva.

Ismaeil, K., 2024. Asset Information Model Management-Based GIS/BIM Integration in Facility Management Contract. Sustainability 16(6), 2495. https://doi.org/10.3390/su16062495

Luckman, S., 2015. Craft and the Creative Economy. Palgrave Macmillan, London. ISBN 978-1-137-39968-7.

Matos, R., Rodrigues, H., Costa, A., Requejo, C., Rodrigues, F., 2023. Facility manager perspectives on building condition assessment for Portuguese higher education institutions. Building Research & Information 51(8), 949–964. https://doi.org/10.1080/09613218.2023.2204415

Nota, G., Peluso, D., Toro Lazo, A., 2021. The contribution of Industry 4.0 technologies to facility management. International Journal of Engineering Business Management 13, 1–14. https://doi.org/10.1177/18479790211024131

Nyabakora, W.I., 2024. The Contribution of Family Businesses to Economic Growth: A Bibliometric Review. SAGE Open 14(4), 1–16. https://doi.org/10.1177/21582440241301423

Okoro, C.S., 2023. Sustainable Facilities Management in the Built Environment: A Mixed-Method Review. Sustainability 15(4), 3174. https://doi.org/10.3390/su15043174

Pine, B.J., Gilmore, J.H., 2020. The Experience Economy. Updated edition. Harvard Business Review Press, Boston. ISBN 978-1-63369-797-6.

Pipatanantakurn, K., Ractham, V.V., 2022. The role of knowledge creation and transfer in family firm succession. Sustainability 14(10), 5845. https://doi.org/10.3390/su14105845

Ross, R.J., 2021. Wood handbook—wood as an engineering material. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. URL https://research.fs.usda.gov/treesearch/62200

Schubert, M., Panzarasa, G., Burgert, I., 2022. Sustainability in Wood Products: A New Perspective for Handling Natural Diversity. Chemical Reviews 123(5), 1889–1924. https://doi.org/10.1021/acs.chemrev.2c00360

Simpeh, F., Mavangwa, G.M., Wentzel, L., 2023. Strategies to overcome barriers to public facilities management. Property Management 41(3), 365–380. https://doi.org/10.1108/PM-03-2022-0016

Suandi, M.E.M., Amlus, M.H., Hemdi, A.R., Abd Rahim, S.Z., Ghazali, M.F., Rahim, N.L., 2022. A review on sustainability characteristics development for wooden furniture design. Sustainability 14, 8748. https://doi.org/10.3390/su14148748

Sedhom, I., Khodeir, L.M., Fathy, F., 2024. Integrated agile facility management model for improving performance in construction projects. Innovative Infrastructure Solutions 9, 171. https://doi.org/10.1007/s41062-024-01475-9

Shohet, I.M., Levi, S., Zeibak-Shini, R., Shahin, F., 2025. Performance-based maintenance and operation of multi-campus critical infrastructure facilities using supply chain multi-choice goal programming. Applied Sciences, 15(20), 11161. https://doi.org/10.3390/app152011161

Smagina, A., Ludviga, I., 2020. Craft entrepreneurship and created value. Rural Environment. Education. Personality 13, 366–376. https://doi.org/10.22616/REEP.2020.044

Solomon, S.J., Mathias, B.D., 2020. The artisans' dilemma: Artisan entrepreneurship and the challenge of firm growth. Journal of Business Venturing 35, 106044. https://doi.org/10.1016/j.jbusvent.2020.106044

Vitkova, A., Vitasek, S., 2024. A case study on sustainable technologies in residential buildings from a life cycle cost analysis (LCC) perspective. Sustainability 16, 10892. https://doi.org/10.3390/su162410892

Yaghoubi, S., Rabiei, F., Seidi, M., 2024. A comprehensive assessment on surface quality of machined wooden products via Box–Behnken design method. Wood Material Science & Engineering 19(4), 896–905. https://doi.org/10.1080/17480272.2023.2290212

Zajkowski, R., Safin, K., Stańczyk, E., 2022. The success factors of family and non-family firms: Similarities and differences. Entrepreneurial Business and Economics Review 10(3), 51–72. https://doi.org/10.15678/EBER.2022.100304

Zhao, G., Liu, C., Qiu, Z., Deng, Z., Gong, J., 2021. 3D morphology of internal defects in wooden products based on computed tomography. BioResources 16(3), 6267–6280. https://doi.org/10.15376/biores.16.3.6267-6280

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# APPLICATION OF COMPUTED TOMOGRAPHY FOR ASSESSING DEFECTS IN SAWN BEECH TIMBER

**Branislav Priadka – Rastislav Lagaňa – Barbora Herdová – Radovan Gracovský – Tomáš Gergeľ**

## ABSTRACT

This research focuses on the use of computed tomography (CT) to develop, implement and evaluate a method for detecting selected quality parameters of unedged beech timber (Fagus sylvatica L.). In response to the increasing demand for hardwoods in load-bearing applications, a methodology was created that allows non-invasive identification of internal imperfections, including knots, cracks and fibre deviation. CT scanning was proved capable of capturing local variations in density that correspond to the presence of these defects. Calibration performed on seven wood species with different density levels demonstrated a strong linear correlation between CT image intensity and material density ($r = 0.998$). The findings indicate that CT technology can be effectively used not only for sorting roundwood but also for assessing sawn boards after processing, supporting production optimisation and enhancing the added value of wood products. Density-based detection of defects further opens new possibilities for automated grading supported by machine-learning techniques.

**Keywords:** automated grading beech timber, computed tomography (CT), timber quality, wood density

## INTRODUCTION

Climate change is reshaping forest species composition. European beech (Fagus sylvatica L.), widely distributed across western and central Europe, has been traditionally utilized primarily in furniture manufacturing; however, its application in load-bearing structural elements is now receiving increasing attention (Aicher et al., 2014, Ehrhart et al., 2016, Pramreiter, Grabner, 2023).

Computed tomography (CT) enables detailed visualization of the internal structure of wood, allowing the detection of defects such as knots, cracks, and decay, as well as the assessment of local density and moisture distribution (Davis, Wells, 1992). As positive attributes cannot be directly assigned to wood, its evaluation must rely on negative characteristics, specifically the presence of defects (Gejdoš et al., 2021). The market value of sawn timber is primarily determined by surface-visible defects, particularly knots, notches, and others (Stängle et al. 2015). The application of CT scanning for log analysis and subsequent cutting-plan optimization has been shown to increase yield by up to 20% (Stängle et al., 2015; Rais et al., 2017).

CT images are typically presented as two-dimensional representations of attenuation coefficients arranged on a square grid. Each grid element, referred to as a pixel, is assigned a grey value corresponding to the calculated mean attenuation coefficient of the respective area within the cross-section of the object. Materials with lower density are depicted by darker grey tones, whereas higher densities appear as lighter shades. Variations in wood density related to annual ring structure and the presence of quality-related features, such as knots, cracks, and decay, can therefore be clearly identified (Davis, Wells, 1992; Gejdoš et al., 2023). X-ray attenuation is governed by the atomic composition of the examined material and the energy of the X-ray radiation. To ensure comparability of images acquired using different scanners, for instance those operating at varying X-ray energies, a standardized normalized unit has been introduced. Hounsfield units (HU) or indexes (H) or CT numbers are normalized to the X-ray attenuation of water as follows:

$$HU = 1000(\mu_{\text{pixel}} - \mu_{\text{water}})/\mu_{\text{water}} \tag{1}$$

where: HU Hountsfield unit (-)
$\mu_{\text{pixel}}$ linear attenuation coefficient of pixel ($mm^{-1}$)
$\mu_{\text{water}}$ linear attenuation coefficient of water ($mm^{-1}$)

Manufacturers of commercial CT scanners supply calibration procedures, typically based on standardized water-filled samples, which must be performed regularly to ensure that Hounsfield units are set to HU = 0 for water and HU = −1000 for air, independent of the X-ray energy applied (Davis, Wells, 1992; Parr et al., 2004).

Nevertheless, the assessment of CT-based quality in beech wood remains insufficiently resolved, as the standards for visual strength grading were originally developed for coniferous species and subsequently adopted for hardwoods, where they do not fully reflect their specific characteristics (Plos et al., 2018). Moreover, as highlighted by Frühwald and Schickhofer (2005), the correlation between strength and density in hardwood timber is relatively low, reaching only about 16 %. In contrast, local features that negatively affect the strength performance of timber can be detected through density variations. Consequently, the application of CT scanning is more appropriate for identifying local density heterogeneity rather than for determining the average density of the timber.

The objective of this study was to develop, implement, and evaluate a methodology for assessing selected qualitative characteristics of unedged beech timber. The main contribution of the research lies in the application of CT scanning as a non-contact approach for wood growth defects identification and visual wood grading aimed at the production of wood products with higher added value.

## MATERIALS AND METHODS

A beech log (Fig. 1) classified as quality class 3.B according to STN 48 0056:2007 was used in the analysis. The log had a length of 5700 mm, with end diameters of 370 mm and 400 mm, respectively. It was felled in September 2023 and scanned after two months of storage in an outdoor log yard.

**Fig. 1 Frontal view of analysed log prepared for CT scanning and followed cutting**

In January 2024, live sawn timber with a thickness of 55 mm was produced. The live sawing pattern was chosen as it is the most commonly applied method in studies utilizing CT scanning of sawn timber (Chang, Gazo, 2009; Stängle et al., 2015). Nevertheless, several authors have reported lower qualitative and quantitative yields of this cutting method compared to alternative sawing patterns (Popadić et al., 2014; Vilkovský et al., 2023). Following sawing, the logs were reassembled from individual boards. During reassembly, spruce spacers with dimensions of 2 × 3 cm were placed between the boards, and each reconstructed log was secured with a clamping strap to ensure shape stability during the drying process. The moisture content of the boards immediately after sawing ranged from 39% to 45% and was measured using a GMH 3851 (Greisinger, Regenstauf, Germany) moisture meter for solid materials. The prepared samples were air-dried for 21 months under covered and dry conditions while being secured with clamping straps. The ambient temperature in the storage area varied seasonally. Prior to CT scanning, the moisture content of the individual boards was measured, with an average value of 16%. During the reassembly of the logs, each board was marked for identification purposes (Fig. 2).

**Fig. 2 Labelling of sawn timber from a beech log prior to CT scanning**

The boards were arranged to approximate the original log geometry and secured using plastic clip strapping. The scanning procedure and methodological framework have been described in detail by Gejdoš et al., (2023). Prior to image analysis, Hounsfield units were converted into an 8-bit intensity scale (digital numbers) ranging from 0 to 255.

Image processing was performed using the open-source software 3D Slicer version 5.6.2 (Fedorov et al., 2012). As an initial step a region of interest (ROI) with dimensions of 200 × 2000 mm, as specified by STN EN 975-1:2009, and with a height exceeding the board thickness, was defined and inserted into the image (Fig. 3 and Fig. 4). For each board, the most favourable position of the ROI was selected (Fig. 4). The occurrence of selected defects, namely knots, cracks, and fibre deviation, was then identified within the ROI on both the upper and lower board surfaces in accordance with STN EN 975-1:2009. Knots were detected by segmentation based on density differences between the knot tissue and the surrounding wood.

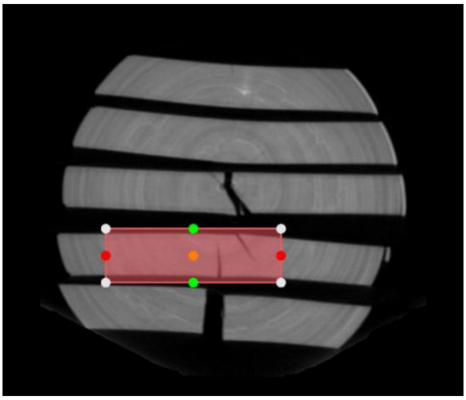

**Fig. 3 Cross-sectional view of the selected area of interest**

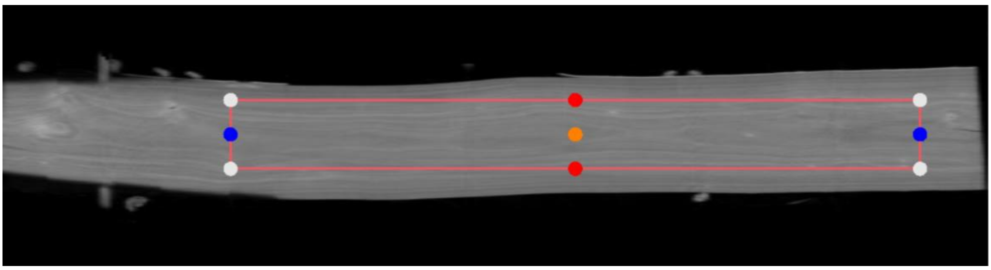

**Fig. 4 Longitudinal section view of the selected area of interest**

To verify the relationship between CT image intensity and material density, device calibration was required. Seven wood species with densities ranging from 300 to 800 kg·m$^{-3}$ were used, all conditioned to a moisture content of 12%. The calibration set included samples of paulownia, willow, aspen, pine, birch, beech, and ash. The samples had dimensions of 700 × 16 × 100 mm (length × thickness × width). Initially, an individual segment was created for each calibration sample, after which the corresponding CT image intensity was determined using the Segment Statistics function.

## RESULTS AND DISCUSSION

The relationship between CT image intensity expressed as digital numbers (DN) and wood density exhibited a linear correlation (Fig. 5). Using seven wood species with different density levels, a correlation coefficient of 99.8% was achieved (Freyburger et al., 2009; Wei et al., 2011; Wang et al., 2019). The established relationship between density (kg·m$^{-3}$) and

CT image intensity, represented by DN values indicating the numerical intensity of the reflected or emitted signal in individual image pixels, is specific to the CT device used in this study. Provided that the scanning conditions remain constant, the derived linear equation can be applied to subsequently estimate the density of unedged timber.

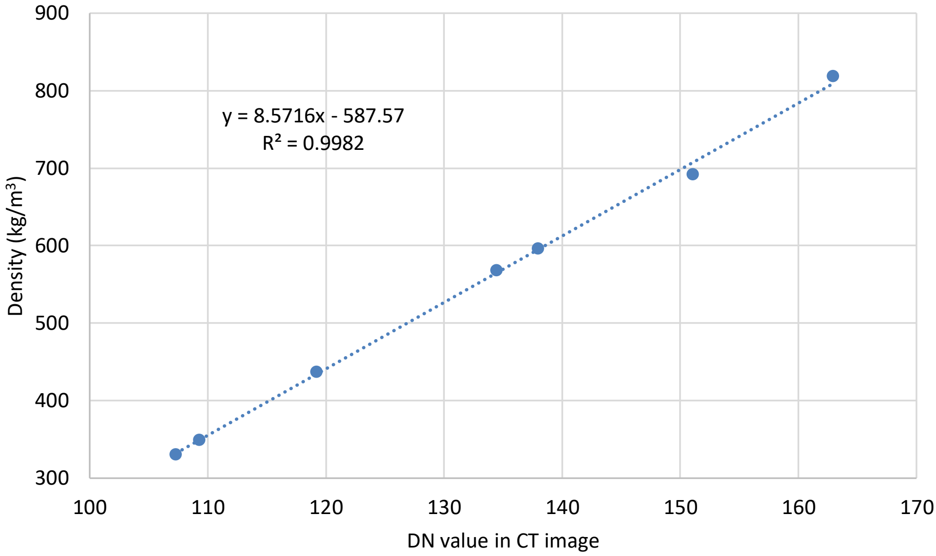


**Fig. 5 Graph showing the relationship between average segment density and average density of calibration samples**

Within the defined ROI, knot identification was straightforward (Fig. 6). Defects can be detected not only in sawn timber but also during the cutting preparation stage, where the positioning of knots within the board can be influenced (Beaulieu, Dutilleul 2019; Gejdoš et al. 2023).

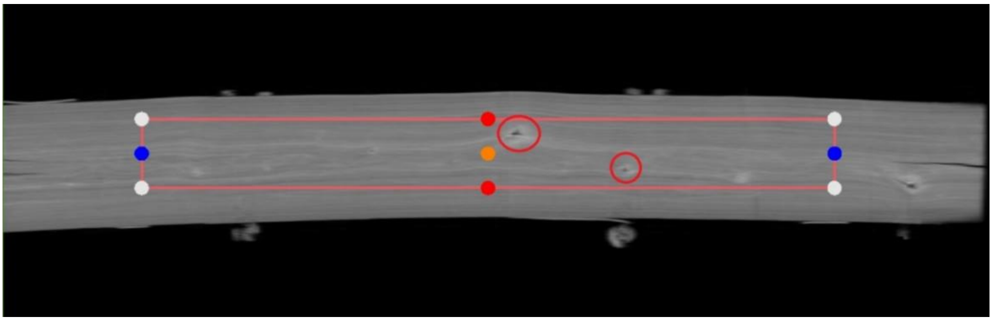

**Fig. 6 Identified knots on the longitudinal section**

When processing dried timber, cracks can be readily identified (Fig. 7) and are most commonly located in the vicinity of the sapwood (Bhandarkar et al., 2005; Wei et al., 2011; Gejdoš et al., 2023). In the case of log-level analysis, a substantially larger number of cross-sections would need to be evaluated to obtain sufficient data for the development of a predictive model capable of forecasting the formation of drying cracks in wood.

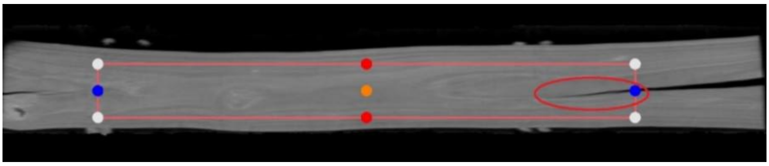

**Fig. 7 Identified cracks on longitudinal section**

Fibre deviation represents the most challenging defect to identify using CT scanning. In the case of beech wood, the assessment of fibre deviation is generally problematic, and visual evaluation methods are considered unreliable. The only dependable approach for determining fibre deviation in beech timber is the measurement of the fracture angle after destructive testing (Aicher et al., 2001; Frühwald, Schickhofer, 2005; Westermayr et al., 2018). However, when employing a live sawing pattern, it can be assumed that fibre deviation largely corresponds to the natural taper and convergence of the roundwood. An additional influencing factor may be spiral grain around the pith, which varies radially and can currently be resolved by CT technology only at ultra-high imaging resolutions (Hu et al., 2022).

The analysis was carried out on 11 boards produced from two sections of a single log. Table 1 shows that the occurrence of cracks was increased in the central zone, which we attribute to the presence of wood rays. The occurrence of knots and cracks was identified on 4 boards, representing 36 %. Fibre deviation was identified visually on 2 boards, representing 18 %. For this reason, we would classify both cuts as quality class F-S3 according to the STN EN 975-1:2009. The density of individual boards in an air-dry state ranged from 695 to 734 kg/m3, with an average density of 719 kg/m3. Our density values are between those reported in the literature, where Lagaňa and Babiak (2012) report a density of 680 kg/m3 for beech, and Gryc et al. (2008) report values ranging from 736 to 768 kg/m3.

**Tab. 1 Table showing the occurrence of defects in individual boards**

| Log | Part | Board | Knots | Cracks | Fibre deviation | CT image intensity | Density (kg/m$^3$) |
|---|---|---|---|---|---|---|---|
| 8 | TL | 1 | ✓ | ✓ | × | 151 | 704 |
| 8 | TL | 2 | × | × | × | 154 | 721 |
| 8 | TL | 3 | ✓ | ✓ | × | 154 | 728 |
| 8 | TL | 4 | × | × | × | 154 | 726 |
| 8 | TL | 5 | × | × | ✓ | 150 | 695 |
| 8 | BL | 1 | × | × | ✓ | 154 | 734 |
| 8 | BL | 2 | × | ✓ | × | 154 | 730 |
| 8 | BL | 3 | ✓ | ✓ | × | 153 | 724 |
| 8 | BL | 4 | ✓ | × | × | 154 | 728 |
| 8 | BL | 5 | × | × | × | 153 | 721 |
| 8 | BL | 6 | × | × | × | 150 | 700 |

Legend: ✓ - the selected error was found in the board, × - the selected error was not found in the board
TL , Top log, thinner part of the trunk, BL – Butt log, thicker part of the log, Board number – number of the board in the reassembled log from sawn boards

## CONCLUSION

Within the framework of the study, a comprehensive methodology was developed and implemented to assess selected qualitative attributes of unedged beech timber through computed tomography (CT). Each methodological stage was examined individually, and its influence on the overall outcome was systematically evaluated. The results confirmed that the use of CT scanning allows for reliable evaluation of the qualitative characteristics of beech timber, both prior to and following the cutting process.

The analysis further revealed a statistically significant linear relationship between CT image intensity and wood density. These findings underscore the potential for broader implementation of CT technology in the assessment of sawn timber, offering prospects for optimizing wood processing workflows and facilitating the production of higher value-added products.

Recent study points to the future research focusing on extending CT-based quality assessment from logs to construction timber, thereby broadening the technology's applicability. Additional efforts will include expanding the calibration dataset and examining the influence of moisture content on CT image intensity.

**REFERENCES**


Aicher, S., Höfflin, L., Behrens, W., 2001. A study on tension strength of finger joints in beech wood laminations. Otto-Graf-Journal 12, 169-186.

Aicher, S., Christian, Z., Dill-Langer, G., 2014. Hardwood glulams – Emerging timber products of superior mechanil properties, in: Proceedings WCTE 2014 – World Conference on Timber Engineering. Quebec City, pp 287-296. https://doi.org/10.13140/2.1.5170.1120

Beaulieu, J., Dutilleul, P., 2019. Application of computed tomography (CT) scanning technology in forest research: a timely update and review. Canadian Journal of Forest Research 49, 1173-1188. https://doi.org/10.1139/cjfr-2018-0537

Bhandarkar, M.S., Luo, X., Daniels, R., Tollner, E.W., 2005. Detection of cracks in computed tomography images if logs. Pattern Recognition Letters 26, 2282-2294. https://doi.org/10.1016/j.patrec.2005.04.004

Davis, J., Wells, P., 1992. Computed tomography measurements on wood. Industrial Metrology 2, 195-218. https://doi.org/10.1016/0921-5956(92)80004-D

Ehrhart, T., Fink, G., Steiger, R., Frangi, A., 2016. Strength grading of European beech timber for the production of GLT & CLT, in: Proceedings Meeting 49 of International Network on Timber Engineering Research. Graz, pp 29-44. https://doi.org/10.3929/ethz-a-010795316

Fedorov, A., Beichel, R., Kalpathy-Cramer, J., Finet, J., Fillion-Robin, J., Pujol, S., Bauer, Ch., Jennings, D., Fennessy, F., Sonka, M., Buatti, J., Aylward, S., Miller, J.V., Pieper, S., Kikinis, R., 3D Slicer as an Image Computing Platform for the Quantitative Imaging Network. Magnetic Resonance Imaging 30, 1323-1341. https://doi.org/10.1016/j.mri.2012.05.001

Freyburger, Ch., Longetaud, F., Mothe, F., Constant, F., Leban, J., 2009. Measuring wood density by means of X-ray computer tomography. Annals of Forest Science 66, 804. https://doi.org/10.1051/forest/2009071

Frühwald, K., Schickhofer, G., 2005. Strength grading of hardwoods, in: Proceedings 14th International Symposium on Nondestructive Testing of Wood. Eberswalde, pp 199-210. ISBN 3-8322-3949-9.

Gejdoš, M., Gergeľ, T., Michajlova, K., Bucha, T., Gracovský, R., 2023. The Accuracy of CT Scanning in the Assessment of the Internal and External Qualitative Features of Wood Logs. Sensors 23, 8505. https://doi.org/10.3390/s23208505

Gejdoš, M., Suchomel, J., Danihelová, Z., 2021. Analysis of Qualitative Features of Beech and Oak Trunks as a Determinant of the Quality Assessment. Forests 12, 15. https://doi.org/10.3390/f12010015

Gryc, V., Vavrčík, H., Gomola, Š., 2008. Selected properties of European beech (Fagus sylvatica L.). Journal of Forest Science, 54. 418-425. https://doi.org/10.17221/59/2008-334
Hu, M., Olsson, A., Hall, S., Seifert, T. 2022. Fibre directions at a branch-stem junction in Norway spruce: a microscale investigation using X-ray computed tomography. Wood Science and Technology, 56. 147-169. https://doi.org/10.1007/s00226-021-01353-y
Chang, S., Gazo, R., 2009. Measuring the effect of internal log defect scanning on the value of lumber produced. Forest Products Journal 59, 56-59. https://doi.org/10.13073/0015-7473-59.11.56
Lagaňa, R., Babiak, M., 2012. Quality of Beech Standing Trees Related to Properties of Structural Timber, in: Proceedings 55th International Convention of Society of Wood Science and Technology. Beijing, pp 347-352. ISBN ISBN 978-0-9817876-3-3.
Parr, D., Stoel, B., Stolk, J., Nightingale, P.G., Stockley, R.A., 2004. Influence of Calibration on Densitometric Studies of Emphysema Progression Using Computed Tomography. American Journal of Respiratory and Critical Care Medicine 170, 883-890. https://doi.org/10.1164/rccm.200403-326OC
Plos, M., Fortuna, B., Šuligoj, T., Turk, G., 2018. Beech as construction wood, in: Proceedings Common Foundations 2018 - uniSTem: 6th Congress of Young Researchers in the Field of Civil Engineering and Related Sciences. Split, pp 180-185. https://doi.org/10.31534/CO/ZT.2018.25
Popadić, R., Šoškić, B., Milić, G., Todorovič, N., Furtula, M., 2014. Influence of the Sawing Method on Yield of Beech Logs with Red Heartwood. Drvna industrija 65, 35-42. https://doi.org/10.5552/drind.2014.1312
Pramreiter, M., Grabner, M., 2023. The Utilization of European Beech Wood (Fagus sylvatica L.) in Europe. Forests 14, 1419. https://doi.org/10.3390/f14071419
Rais, A., Ursella, E., Vicario, E., Giudiceandrea, F., 2017. The use of the first industrial X-ray CT scanner increases the lumber recovery value: case study on visually strength-graded Douglas-fir timber. Annals of Forest Science 74, 28. https://doi.org/10.1007/s13595-017-0630-5
Stängle, S.M., Brüchert, F., Heikkila, A., Usenius, T., Usenius, A., Sauter, U.H., 2015. Potentially increased sawmill yield from hardwoods using X-ray computed tomography for knot detection. Annals of Forest Science 72, 57–65. https://doi.org/10.1007/s13595-014-0385-1
STN 48 0056, 2007. Qualitative classification of hardwood round timber. Slovak Office of Standards, Metrology and Testing.
STN EN 975-1, 2009. Sawn Timber. Appereance grading of hardwoods. Part 1: Oak and beech. Slovak Office of Standards, Metrology and Testing.
Vilkovský, P., Klement, I., Vilkovská, T., 2023. The Impact of the Log-Sawing Patterns on the Quantitative and Qualitative Yield of Beech Timber (Fagus sylvatica L.). Applied Sciences 13, 8262. https://doi.org/10.3390/app13148262
Wang, Q., Liu, X., Yang, S., Jiang, M., Cao, J., 2019. Non-destructive detection of density and moisture content of heartwood and sapwood based on X-ray computed tomography (X-CT) technology. European Journal of Wood and Wood Products 77, 1053–1062. https://doi.org/10.1007/s00107-019-01459-y
Wei, Q., Leblon, B., La Rocque, A., 2011. On the use of X-ray computed tomography for determining wood properties: a review. Canadian Journal of Forest Research 41, 2120–2140. https://doi.org/10.1139/x11-111
Westermayr, M., Stapel, P., van de Kuilen, J.W., 2018. Tensile Strength and Stiffness of 380 Low Quality Beech (Fagus Sylvatica) Sawn Timber, in: Proceedings WCTE 2018 World Conference on Timber Engineering. Seoul. https://pure.tudelft.nl/ws/portalfiles/portal/47891668/4.pdf

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# EFFECT OF SELECTED 3D PRINTING PARAMETERS ON THE MECHANICAL PROPERTIES OF FURNITURE JOINTS

**Šimon Beliansky – Jozef Fekiač – Nadežda Langová**

## ABSTRACT

This study focuses on the design and experimental verification of a 3D-printed connector based on a modified dovetail geometry intended for furniture frame corner joints. PLA-wood material was used for the fabrication of the connectors, and the influence of selected 3D printing parameters, namely infill density (20%, 30%, and 40%) and perimeter thickness expressed by the number of perimeters (1P, 3P, and 5P), on mechanical properties and material consumption was analyzed. Test specimens were incorporated into beech wood corner joints and subjected to compression testing in the angular plane according to applicable testing procedures. The results demonstrated that increasing infill density from 20% to 40% led to a 7–17% increase in load-bearing capacity, depending on the number of perimeters, while increasing the number of perimeters from 1P to 5P resulted in a 28–43% increase in load-bearing capacity. At the same time, perimeter thickness was confirmed to have a greater influence on material consumption than infill density, with connector weight increasing by up to 70% when changing from 1P to 5P. Based on the evaluation of weight-specific load-bearing capacity, it was found that configurations with the highest absolute load-bearing capacity did not represent the most efficient solution in terms of strength-to-material consumption ratio. Variants 3P20 to 3P30 were identified as optimal configurations, providing the most favorable compromise between load-bearing capacity, material consumption, and manufacturing efficiency. The results confirm the importance of optimizing 3D printing parameters in the design of additively manufactured connectors for furniture constructions.

**Keywords:** 3D printing; furniture joints; connector; additive manufacturing; mechanical properties

## INTRODUCTION

The dovetail joint is among the most historically significant form-fitting joints in wood processing, with its use dating back to ancient civilizations, where it was applied in furniture production and wooden structural elements. Its long-term use is attributed to its favorable mechanical properties, high dimensional stability, and ability to create a strong connection without the need for additional fastening elements.

Joints represent a critical structural component of furniture, as they significantly influence load-bearing capacity, stiffness, stability, service life, and assembly requirements. Therefore, the development of joint types capable of efficiently transferring loads, being technologically feasible, and meeting aesthetic and economic production requirements has long been an important objective in furniture engineering. Among traditional and proven solutions is the dovetail joint, which is widely applied in furniture manufacturing due to its favorable geometry based on the mechanical restriction of the degrees of freedom of connected elements. Previous studies have confirmed that the geometry of dovetail and related form-fitting joints significantly affects joint stiffness, strength, and stability, while an appropriately designed shape improves load transfer and contact interaction between connected components (Kamboj *et al*., 2020; Tannert *et al*., 2016; Wu *et al*., 2024).

The dovetail joint is also advantageous because its geometry naturally provides a self-locking effect, thereby reducing the need for additional fastening elements and contributing to precise positioning of components during assembly. Its mechanical properties are influenced not only by the existence of the mechanical interlock itself, but also by the contact surface area, manufacturing tolerances, and degree of compression between the connected parts (Kamboj *et al*., 2020; Wu *et al*., 2024). In furniture constructions, dovetail joints are valued for their ability to create compact and dimensionally stable nodes with favorable load transfer in corners and intersections of components.

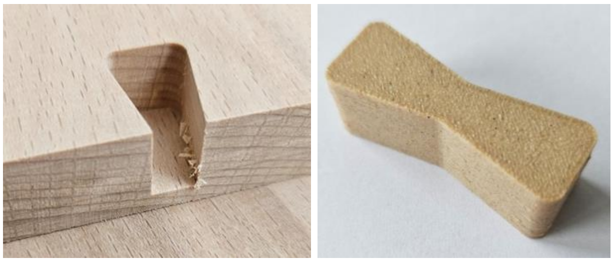
The development of additive manufacturing technologies opens new possibilities in the design of furniture joints. 3D printing enables the production of non-standard, shape-optimized connectors tailored to specific structural requirements, which is particularly advantageous in prototyping and small-batch production. The dovetail principle appears to be a suitable basis for the design of 3D-printed connectors, as it combines mechanical interlocking with the possibility of parametric geometry modification. Previous studies have shown that 3D-printed connectors can achieve favorable mechanical properties, while their behavior is significantly influenced by printing parameters such as material type, infill density, print orientation, and perimeter thickness (Nicolau *et al*., 2022; Nicolau *et al*., 2025; Mazlan *et al*., 2023).

Based on the above, the dovetail geometry can be considered a suitable design principle for the development of new 3D-printed connectors for furniture constructions. Therefore, the present study is based on a modified dovetail-shaped connector and investigates the effect of selected 3D printing parameters on the mechanical performance of a furniture joint.

## MATERIALS AND METHODS

### Construction Materials

The design of the experimental joining system considered the joint type, the characteristics of the connected elements, the material of the joined parts, and the material of the 3D-printed connector. Beech wood (*Fagus sylvatica* L.) was selected as the base material for the test corner joints due to its common use in furniture structures and favorable mechanical properties. PLA-wood filament manufactured by AzureFilm, containing approximately 40% wood particles, was used for the fabrication of the 3D-printed connectors. The material was selected because of its good printability, wood-like aesthetic appearance, and potential applicability in furniture production. The slot in the beech elements was designed with respect to the geometry of the modified dovetail connector and the technological possibilities of its machining. Machined connector slots (Fig. 1a) were produced by milling on an SCM TECH Z5 CNC machining center using a spiral end mill with a diameter of 5 mm. The geometry of the connector is shown in Fig. 1b.



**a)** **b)**

**Fig. 1 Machined slot (a) for connector insertion and geometry (b) of the dovetail-shaped connector.**

### 3D Printing Parameters

Prior to the fabrication of test specimens, printing parameters were optimized based on the filament manufacturer's recommendations and preliminary prototype testing. The filament was dried for 8 h at 55 °C before printing. The connectors were manufactured using FDM technology on a Bambu Lab X1C 3D printer equipped with a 0.4 mm nozzle. The nozzle temperature was set to 220 °C and the textured PEI build plate temperature to 55 °C. The layer height was 0.2 mm. The printing speed of the first layer was set to 50 $mm \cdot s^{-1}$ for the perimeter walls and 105 $mm \cdot s^{-1}$ for the infill, while the remaining layers were printed at 60 $mm \cdot s^{-1}$ for the perimeter walls and 270 $mm \cdot s^{-1}$ for the infill.

The print orientation was selected so that the primary layer deposition direction corresponded to the anticipated loading direction of the connector in order to minimize interlayer weakening. A monotonic infill pattern was used for the three bottom and three top shell layers. The orientation of the printing paths was set at an angle of 45° relative to the longitudinal axis of the connector. In the middle layer, the orientation of the printing paths was rotated by 90° relative to the first and third layers. The print preparation was performed in Bambu Studio software. Two main 3D printing parameters were analyzed in the experiment:

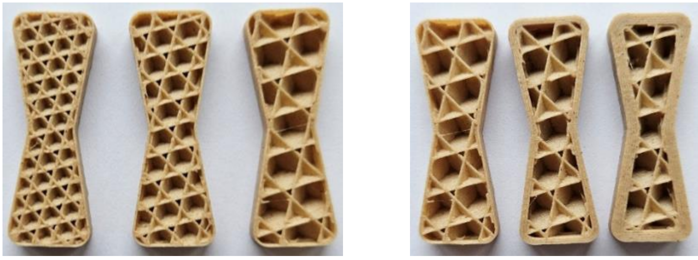
– infill density: 20%, 30%, and 40% (Fig. 2a)
– perimeter thickness / number of perimeters: 1P, 3P, and 5P (Fig. 2b)

The perimeter parameter represents the number of outer walls forming the external shell of the printed component. When using a 0.4 mm nozzle, the corresponding approximate perimeter thicknesses were 0.4 mm for 1P, 1.2 mm for 3P, and 2.0 mm for 5P.

Plné

### Connector Infill

Cubic infill was selected as the internal infill pattern based on its assumed favorable mechanical behavior under multidirectional loading. Infill density was analyzed at three levels: 20%, 30%, and 40%. The selection of cubic infill was based on the requirement to ensure sufficient load-bearing capacity of the connector while simultaneously optimizing material consumption.

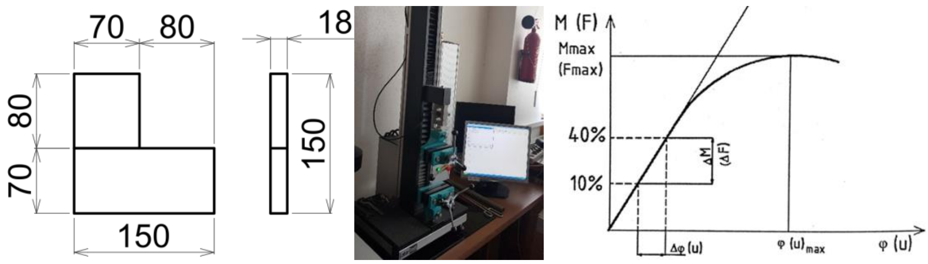


a) b)

**Fig. 2 Visual representation of the analyzed 3D printing parameters of the connectors: (a) cubic infill densities of 40%, 30%, and 20% (from left to right); (b) number of perimeters, perimeter thickness corresponding to 1P, 3P, and 5P (from left to right).**

### Determination of Mechanical Properties of Frame Corner Joints

Mechanical tests were performed using a universal testing machine, LabTest 4.050, by loading the test specimens in compression in the angular plane (Fig. 3). The test specimens consisted of frame corner joints made of beech wood with a thickness of 18 mm, into which 3D-printed connectors of the individual variants were inserted. Six replicates were tested for each variant, resulting in a total of 54 measurements.




a) b) c)

**Fig. 3 Geometry and dimensions of the test specimen (a), testing setup and determination of load-bearing capacity of the tested joints using the LabTest 4.050 machine (b), representative force–deformation diagram of the test procedure (c) (Beliansky, 2024).**

### Determination of Mechanical Characteristics

The load-bearing capacity of the corner joint $M_u$ was calculated according to Equation (1):

$$M_u = F_{max} \cdot l \text{ (N·mm)} \tag{1}$$

where: $F_{max}$ – maximum force at joint failure (N)
$l$ – joint arm length (mm)

The weight-specific load-bearing capacity of the connector was calculated according to Equation (2):

$$M_{u,s} = \frac{M_u}{m} \text{ (N·mm/g)} \tag{2}$$

where: $M_{u,s}$ – weight-specific load-bearing capacity of the connector (N.mm/g)

$M_u$ – load-bearing capacity of the joint (N.mm)

$m$ – connector weight (g)

All printing parameters other than infill density and perimeter thickness were kept constant throughout the experiment.

## RESULTS AND DISCUSSION

The results of experimental testing of the mechanical properties and weight of the 3D-printed connectors are presented in Table 1. In addition to the average load-bearing capacity, the specific load-bearing capacity was calculated for each variant, defined as the ratio of achieved load-bearing capacity to connector weight. This parameter expresses the efficiency of material utilization and enables a more comprehensive evaluation of 3D printing parameter optimization, as it considers not only the mechanical performance of the connector but also the material demands of its production.

**Tab. 1 Mechanical Properties and Material Efficiency of Tested Connectors**

| Variant | Infill Density *(%)* | Perimeter | Average Load-Bearing Capacity $M_u$ *(N·mm)* | Weight *(g)* | Specific Load-Bearing Capacity $M_{u,s}$ *(N·mm/g)* |
|---|---|---|---|---|---|
| 1P20 | 20 | 1P | 12377 | 2.56 | 4835 |
| 1P30 | 30 | 1P | 13576 | 3.15 | 4310 |
| 1P40 | 40 | 1P | 14535 | 3.74 | 3886 |
| 3P20 | 20 | 3P | 16225 | 3.49 | 4649 |
| 3P30 | 30 | 3P | 17139 | 3.95 | 4339 |
| 3P40 | 40 | 3P | 17441 | 4.41 | 3955 |
| 5P20 | 20 | 5P | 17725 | 4.36 | 4065 |
| 5P30 | 30 | 5P | 17326 | 4.74 | 3655 |
| 5P40 | 40 | 5P | 19864 | 5.08 | 3910 |

### Effect of Infill Density and Number of Perimeters on Joint Load-Bearing Capacity

The results showed that increasing both infill density and the number of perimeters generally led to an increase in joint load-bearing capacity. Increasing the infill density from 20% to 40% resulted in a load-bearing capacity increase of 17% for the 1P variant, 7% for the 3P variant, and 12% for the 5P variant. At the same time, increasing the number of perimeters from 1P to 5P led to an increase in load-bearing capacity of 43% at 20% infill, 28% at 30% infill, and 37% at 40% infill.

These results confirm that both analyzed parameters significantly affect the mechanical properties of the connector, with a more pronounced influence observed for the number of perimeters. This phenomenon can be explained by the fact that the perimeter wall represents the primary load-bearing part of an FDM-printed component and transfers load more efficiently than the internal infill. The outer shell of the printed part consists of continuous layers deposited along the perimeter of the component, creating a more compact and mechanically efficient structure than the internal infill. In contrast, the infill consists of a discontinuous internal geometry, whereas the perimeter provides a more continuous material connection in the loading direction and improves stress transfer between individual layers.

An additional important factor is the adhesion between deposited filaments, which significantly influences the mechanical properties of FDM-printed parts. The quality of bonding between adjacent deposited filaments is generally higher in the outer perimeter walls than in the internal infill regions, further increasing their contribution to load transfer. Similar conclusions were reported by Mazlan et al. (2023), who stated that perimeter thickness has a greater influence on the mechanical response of FDM-printed parts than infill density alone. Figure 4 shows the typical failure modes of the tested connectors under mechanical loading.


a) b)

**Fig. 4 Typical failure modes of the tested connectors: (a) failure across the entire connector cross-section for the 1P configuration; (b) failure of the specimen arm without connector failure for the 3P configuration.**

In the 1P configuration, failure occurred across the entire cross-section of the connector (Fig. 4a). In contrast, for the 3P configuration, no failure of the connector itself was observed instead, failure occurred in the arm of the test specimen against which the connector was supported (Fig. 4b). This indicates that increasing the number of perimeters substantially improves the mechanical resistance of the connector and shifts the critical failure location outside the connector body.

**Effect of Printing Parameters on Material Consumption**

The weight of the connectors increased with increasing infill density and number of perimeters, while the perimeter had a more pronounced effect on material consumption. Changing the perimeter from 1P to 5P resulted in a weight increase of up to 70% at 20% infill density, whereas increasing infill density from 20% to 40% caused a maximum weight increase of 46%. These results indicate that increasing the number of perimeters is more material-intensive than increasing infill density, which should be taken into account when optimizing printing parameters.

**Evaluation of Weight-Specific Load-Bearing Capacity**

Maximum load-bearing capacity alone does not represent a sufficient indicator of the technical efficiency of the connector, as it does not account for the amount of material required to achieve the given strength. For this reason, weight-specific load-bearing capacity was also evaluated to assess material utilization efficiency. The highest weight-specific load-bearing capacity was achieved by variant 1P20 (4835 N·mm/g), followed by variant 3P20 (4649 N·mm/g), while the lowest value was recorded for variant 5P30 (3655 N·mm/g).

These results indicate that configurations with the highest absolute load-bearing capacity were not necessarily the most efficient in terms of material consumption. Although variant 5P40 achieved the highest absolute load-bearing capacity, its weight-specific load-bearing capacity was lower than that of several lighter configurations. This suggests that further increases in infill density and number of perimeters lead to diminishing efficiency, where the increase in material consumption exceeds the gain in mechanical resistance.

Although variant 1P20 achieved the highest weight-specific load-bearing capacity, its absolute load-bearing capacity was substantially lower than that of the 3P variants. Therefore, from a practical engineering perspective, variants 3P20 to 3P30 can be considered optimal, as they provide the most favorable compromise between load-bearing capacity, weight, and material efficiency.

The obtained results are consistent with previous studies dealing with 3D-printed connectors and furniture joints. Krzyżaniak *et al.* (2021) reported that the mechanical properties of 3D-printed fastening elements are significantly influenced by connector geometry and material properties, while optimization of geometric and structural parameters is essential for achieving the required joint strength. Similarly, Smardzewski *et al.* (2016) confirmed that properly designed 3D-printed connectors can achieve sufficient strength and stiffness for application in furniture structures, with geometry and structural design remaining critical factors.

## CONCLUSION

Based on the design, fabrication, and experimental verification of the 3D-printed connector derived from a modified dovetail geometry, the following conclusions can be drawn:

- It was confirmed that the selected 3D printing parameters significantly influence the mechanical properties of 3D-printed connectors applied in furniture frame corner joints.
- Increasing the infill density from 20% to 40% resulted in a 7–17% increase in joint load-bearing capacity, depending on the number of perimeters.
- Increasing the number of perimeters from 1P to 5P led to a 28–43% increase in load-bearing capacity, confirming the greater influence of perimeter thickness on the strength properties of the connector compared to infill density.
- At the same time, it was demonstrated that increasing the number of perimeters had a greater impact on material consumption than increasing infill density, with connector weight increasing by up to 70% in some variants.
- Evaluation of weight-specific load-bearing capacity showed that configurations with the highest absolute load-bearing capacity did not represent the most efficient solution in terms of strength-to-material consumption ratio.
- Configurations 3P20 to 3P30 were identified as optimal variants from a techno-economic perspective, providing the most favorable compromise between load-bearing capacity, material consumption, and manufacturing efficiency.
- The results confirm that 3D-printed connectors based on modified dovetail geometry represent a promising solution for application in furniture constructions, while their mechanical properties can be effectively optimized through appropriate selection of printing parameters.

## REFERENCES

KAMBOJ, G. – GAFF, M. – SMARDZEWSKI, J. – HAVIAROVÁ, E. – BORŮVKA, V. – SETHY, A. K. 2020. Numerical and experimental investigation on the elastic stiffness of glued dovetail joints. Construction and Building Materials. 263, 120652.

KASAL, A., SMARDZEWSKI, J., KUŞKUN, T., GÜRAY, E., 2023. Analyses of L-type corner joints connected with auxetic dowels for case furniture. Materials 16(13), 4547. https://doi.org/10.3390/ma16134547

KRZYZANIAK, Ł., KUŞKUN, T., KASAL, A., SMARDZEWSKI, J., 2021. Analysis of internal mounting forces and strength of newly designed fastener to joints wood and wood-based panels. Materials 14(23), 7119. https://doi.org/10.3390/ma14237119

MAZLAN, M. A. – ANAS, M. A. – NOR IZMIN, N. A. – ABDULLAH, A. H. 2023. Effects of Infill Density, Wall Perimeter and Layer Height in Fabricating 3D Printing Products. Materials. 16(2), 695.

NICOLAU, A. – CROITORU, C. – ROȘCA, I. C. et al. 2022. 3D Printing Application in Wood Furniture Components Assembling. Materials. 15(8), 2907.

NICOLAU, A. et al. 2025. Evaluation of 3D-Printed Connectors in Chair Construction: A Comparative Study with Traditional Mortise-and-Tenon Joints. Materials. 18(1), 201.

SMARDZEWSKI, J., RZEPA, B., KILIÇ, H., 2016. Mechanical properties of externally invisible furniture joints made of wood-based composites. BioResources 11(1), 1224–1239.

TANNERT, T. – LAM, F. – TESFAMARIAM, S. – KALESNIKOFF, C. – ENDACOTT, B. 2016. Improved performance of reinforced rounded dovetail joints. Construction and Building Materials. 116, pp. 228–234.

WU, W. – XU, W. – WU, S. 2024. Mechanical Performance Analysis of Double-dovetail Joint Applied to Furniture T-Shaped Components. BioResources. 19(3), pp. 5862–5879.

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# EFFECT OF FEED RATE AND DEPTH OF CUT ON SURFACE UNEVENNESS OF NORWAY SPRUCE DURING FACE MILLING ON A SINGLE-SPINDLE THICKNESS PLANER

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## ABSTRACT

Surface integrity, expressed through surface irregularities, is a key indicator of wood machining quality. This study analysed the influence of feed rate and depth of cut on surface unevenness of Norway spruce (*Picea abies* L.) during face milling on a thickness planer Robland D630 EL equipped with a spiral cutter block. Surface quality was evaluated using roughness (*R*a) and waviness (*W*a) parameters, measured with a Keyence VHX-7000 digital microscope according to ISO 21920 standards. A full-factorial design with three levels of depth of cut and ten feed rate levels was applied at constant spindle speed. Two-way ANOVA revealed a significant effect of feed speed and a significant interaction between feed speed and depth of cut. Surface roughness increased with feed speed, and a similar trend was observed for waviness. Increasing feed speed from the lowest to the highest level resulted in a 33% increase in roughness and a 76% increase in waviness. Post-hoc tests showed significant differences between the highest and lowest feed speed levels, while adjacent levels often did not differ significantly. Depth of cut alone was not significant.

**Key words:** feed speed; depth of cut; Norway spruce; thickness planer; surface roughness; surface waviness

## INTRODUCTION

The surface quality of machined wood is a key indicator of machining performance and significantly affects subsequent processing, functional properties, and the aesthetic appearance of wood products (Kvietková et al. 2015; Novák et al. 2011). In wood machining practice, surface quality is commonly evaluated using surface roughness and surface waviness, which describe different scales of surface irregularities resulting from the interaction between the cutting tool, machining conditions, and the anatomical structure of wood (Hernández et al. 2014). In chip-forming wood machining processes, particularly face milling on a thickness planer, the surface is generated by the periodic cutting action of the rotating tool combined with the linear feed motion of the workpiece. Surface roughness, typically characterized by the parameter *R*a, is mainly associated with short-wavelength irregularities such as tool marks, chip formation, and local fiber damage (Angelescu et al. 2025; Keturakis et al. 2017). In contrast, surface waviness, expressed by the parameter *W*a, represents longer-wavelength surface undulations related to dynamic effects in the machine–tool–workpiece system, system stiffness, and material inhomogeneity (Raja et al. 2002).

Norway spruce (*Picea abies, L.*) is one of the most widely processed softwood species in Central Europe but presents specific technological challenges due to the pronounced contrast between earlywood and latewood, the low density of earlywood, and its susceptibility to fiber pull-out, fuzziness, and waviness formation (Wang and Yang 2025). These effects are particularly evident during roughing operations, where higher feed rates and greater depths of cut are applied to achieve high material removal rates.

Experimental studies consistently indicate that feed rate is one of the most influential parameters affecting wood surface quality. Increasing feed rate generally leads to greater chip thickness, higher mechanical loading of wood fibres, and deterioration of the surface roughness parameter *R*a, while simultaneously promoting higher surface waviness (*W*a) (Piernik et al. 2023; Novák et al. 2011). The depth of cut influences surface quality mainly through its effect on cutting forces and process stability, with a more pronounced impact when combined with higher feed rates (Qi et al. 2023; Pakzad et al. 2023).

Available literature further suggests that surface roughness and waviness do not respond identically to changes in machining parameters. While roughness is closely related to cutting geometry and feed per tooth, waviness is more strongly influenced by process dynamics, system stiffness, and the anisotropic structure of wood. Therefore, evaluating surface quality solely based on roughness parameters may be insufficient, particularly under roughing conditions (Ruzova a Haddadi 2025).

Surface topography can be understood as a combination of irregularities occurring at different wavelengths, while the quality of the generated surface refers to the magnitude of deviations (irregularities) of the real surface from an ideal, perfectly smooth surface (Adamčík et al. 2024). Roughness is associated with short-wavelength irregularities, whereas waviness represents those with longer wavelengths (Khazaeian 2006).

The aim of this study is to analyze the effect of feed rate and depth of cut on surface roughness (*R*a) and surface waviness (*W*a) of Norway spruce wood during face milling on a thickness planer. The investigation focuses on roughing conditions, where technological and material-related factors are expected to have a more pronounced impact on surface formation, contributing to improved understanding and optimization of machining parameters with respect to productivity and surface quality.

## MATERIALS AND METHODS

*Sample Preparation and Milling*

Spruce wood (*Picea abies* L.) samples were prepared from radial defect-free boards (without knots, cracks, resin pockets, or visible fiber deviations). The material was first cross-cut and ripped into test specimens with dimensions 500 mm × 65 mm × 20 mm (length × width × thickness). The boards were kiln-dried and subsequently stored under controlled conditions to maintain an equilibrium moisture content of w = 8 ± 2 %, minimizing moisture-related variability prior to machining.

Thickness planing (longitudinal - face milling) was performed on a single-spindle thickness planer Robland D630 EL (Robland NV, Brugge, Belgium) equipped with a spiral cutter block. The experiment followed a full-factorial design with three levels of depth of cut ($a_e$ = 1 mm, 2 mm, and 3 mm) and ten feed speed levels ($v_f$0–vf9). The spindle speed was kept constant (6 000 rpm) throughout the experiment.

The feed speed levels were distributed evenly across the selected range. The increment between consecutive levels was calculated as (22 − 5) / 9, corresponding to a constant step of 1.89 m·min$^{-1}$:

**Tab. 1 Feed speed levels and corresponding feed speed values used in the experiment**

| Feed speed level | Feed speed ($v_f$) [m·min$^{-1}$] |
|---|---|
| vf0 | 5.0 |
| vf1 | 6.9 |
| vf2 | 8.8 |

| Feed speed level | Feed speed ($v_f$) [m·min$^{-1}$] |
|---|---|
| vf3 | 10.7 |
| vf4 | 12.6 |
| vf5 | 14.4 |
| vf6 | 16.3 |
| vf7 | 18.2 |
| vf8 | 20.1 |
| vf9 | 22.0 |

Each specimen was machined using the selected combination of depth of cut and feed rate, generating surfaces intended for subsequent roughness (*R*a) and waviness (*W*a) evaluation.

*Measurement of Surface Roughness and Waviness with Microscopic Analysis*

Measurements were performed using a Keyence VHX-7000 digital microscope (Keyence Corporation, Osaka, Japan), which was used for both roughness measurement and microscopic analysis. Roughness was measured on the radial surface of the samples. The measurement was carried out over an evaluation length of 12.5 mm, with a lateral resolution of 0.1 μm to ensure sufficient accuracy. Surface roughness was defined using an L-filter cutoff wavelength ($\lambda_c$) of 2.5 mm and an S-filter ($\lambda_s$) of 8 μm, in accordance with the ISO 21920 (2021) series of standards. Among the available roughness parameters, *R*a (arithmetical mean height) was selected, as it is the most widely used parameter and allows comparison with results from other studies. Surface waviness was also evaluated using the parameter *W*a with an L-filter cutoff wavelength ($\lambda_c$) of 2.5 mm and an F-filter ($\lambda_f$) of 8 μm.

*Statistical Evaluation*

The measured dataset was subsequently analyzed using the statistical software STATISTICA 14 (TIBCO Software Inc., Palo Alto, California, USA). Prior to performing the analysis of variance (ANOVA), the assumptions required for its application were verified. The normality of the data distribution for all combinations of machining parameters was tested using the Shapiro–Wilk test, which confirmed that the measured values followed a normal distribution. The homogeneity of variances was evaluated using Levene's test. Although the equality of variances was not fully satisfied, which may be attributed to the natural heterogeneity of the wood surface, ANOVA was applied because the method is considered sufficiently robust to moderate violations of this assumption. The independence of observations was ensured by the experimental design and verified by logical evaluation.

To evaluate the combined effect of the two investigated factors, a two-way analysis of variance (ANOVA) was applied. The results of the ANOVA indicated that both factors had a statistically significant individual effect on surface roughness, as well as a significant interaction effect ($p < 0.001$).

## RESULTS AND DISCUSSION

The obtained results are further interpreted in relation to the applied machining parameters and compared with findings reported in previous studies.

The ANOVA results (Tab. 2) show that feed rate ($v_f$) significantly affects surface roughness ($F = 8.581$, $p < 0.001$). In contrast, depth of cut ($a_e$) was not significant ($p = 0.229$)

and had a negligible effect (partial $\eta^2 = 0.012$). The interaction between $v_f$ and $a_e$ was significant ($p = 0.003$). Overall, the results clearly demonstrate that feed rate is the key parameter controlling surface roughness, while depth of cut has a minor direct effect but contributes through interaction. However, other studies suggest that depth of cut may become significant under specific conditions or in combination with other parameters (Hernández et al. 2014).

**Tab. 2 Two-way ANOVA for surface roughness (*R*a)**

| **Source of variation** | sum of squares | mean square | F statistic | P – level | Partial $\eta^2$ |
|---|---|---|---|---|---|
| $a_e$ | 2.906 | 1.453 | 1.481 | 0.229 | 0.012 |
| $v_f$ | 75.772 | 8.419 | 8.581 | <0.001 | 0.243 |
| $a_e$*$v_f$ | 39.572 | 2.198 | 2.241 | 0.003 | 0.144 |

According to Tab. 3, both roughness (*R*a) and waviness (*W*a) showed an overall increasing trend with feed rate, although the relationship was not strictly linear. Roughness values increased from 2.61–3.19 µm at the lowest feed speed ($v_f = 5.0$ m·min⁻¹) to 4.08–4.98 µm at higher feed speeds ($v_f = 18.2$–$20.1$ m·min⁻¹). In contrast, waviness showed a more pronounced increase, from 1.31–1.80 µm to 2.70–3.99 µm over the same feed speed range. The development of *R*a was non-linear, with local maxima occurring at intermediate feed rates, such as 5.49 µm at $v_f = 6.9$ m·min⁻¹ ($a_e = 1$ mm), indicating the influence of material heterogeneity. In contrast, *W*a increased more consistently, reaching maximum values at $v_f = 22.0$ m·min⁻¹ for all depth of cut levels. No consistent trend was observed for depth of cut. However, differences between depth levels became more pronounced at higher feed rates. For example, at $v_f = 22.0$ m·min⁻¹, waviness increased from 2.70 µm ($a_e = 1$ mm) to 3.99 µm ($a_e = 3$ mm), confirming an interaction effect. Roughness showed a similar but less pronounced pattern, ranging from 4.08 to 4.98 µm at higher feed speeds.

**Tab. 3 Surface parameters *R*a and *W*a across the full feed rate range ($v_f0$ - $v_f9$) for each depth of cut**

| **Parameter** | **Depth of cut [mm]** | **Minimum [µm]** | **Maximum [µm]** | **Increase [µm]** | **Increase (%)** |
|---|---|---|---|---|---|
| ***Ra*** | 1 | 2.66 ($v_f5$) | 5.49 ($v_f2$) | 2.83 | 106.5 |
| | 2 | 2.61 ($v_f1$) | 4.98 ($v_f7$) | 2.38 | 91.2 |
| | 3 | 2.33 ($v_f2$) | 4.55 ($v_f9$) | 2.22 | 95.4 |
| ***Wa*** | 1 | 1.31 ($v_f1$) | 2.70 ($v_f9$) | 1.39 | 106.3 |
| | 2 | 1.72 ($v_f1$) | 2.91 ($v_f9$) | 1.19 | 69.2 |
| | 3 | 1.80 ($v_f1$) | 3.99 ($v_f9$) | 2.19 | 121.7 |

The relatively high variability of the measured values can be attributed to the heterogeneous structure of wood, particularly the contrast between earlywood and latewood (Gurău et al. 2021). In the case of Norway spruce, this behaviour is further associated with its relatively low density, which promotes the formation of protruding fibres on the machined surface. During milling, these fibres are not always completely separated and tend to remain partially attached, creating surface fuzziness, which contributes to increased roughness (Carll a Wiedenhoeft 2009; Adamčík et al. 2024). A similar tendency has been reported by Landry et al. (2013), who observed a higher propensity for fuzziness formation in low-density wood species. Conversely, increasing wood density leads to a reduction in surface fuzziness, as reported by Evans et al. (2017), which explains the higher susceptibility of spruce to surface irregularities.

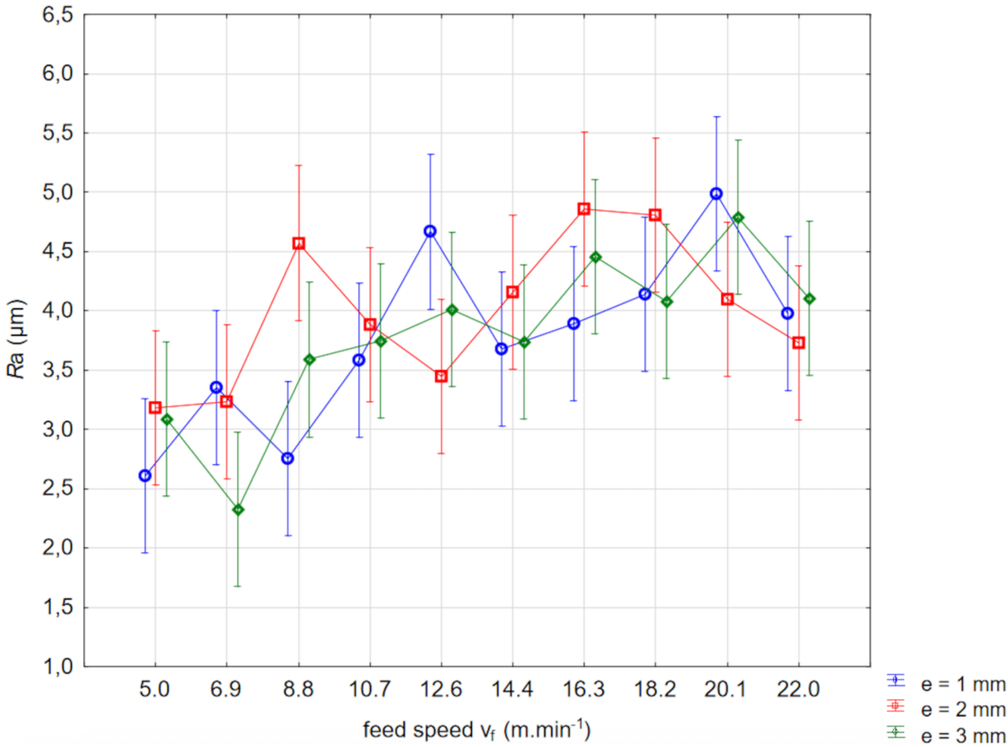


**Fig. 1 Parameter *R*a with varying rotational speed 95 % confidence intervals for population means, spindle speed 6000 rpm**

Surface roughness (*R*a) showed an overall increasing trend with feed speed, rising from approximately 2.5–3.2 µm at 5 m·min⁻¹ to about 4.0–5.0 µm at higher feed speeds (Fig. 1). Duncan's post hoc test confirmed statistically significant differences ($p < 0.05$) mainly between low ($v_f0$–$v_f1$) and high feed speeds, while adjacent levels often did not differ significantly. The influence of cutting depth was less consistent, with $a_e$ = 2 mm exhibiting the highest variability and local extremes, while $a_e$ = 1 mm and $a_e$ = 3 mm showed more gradual changes. Despite these trends, the substantial overlap of standard deviations suggests limited statistical significance between several parameter combinations. The observed variability can be attributed to the heterogeneous anatomical structure of wood, particularly the earlywood–latewood contrast.

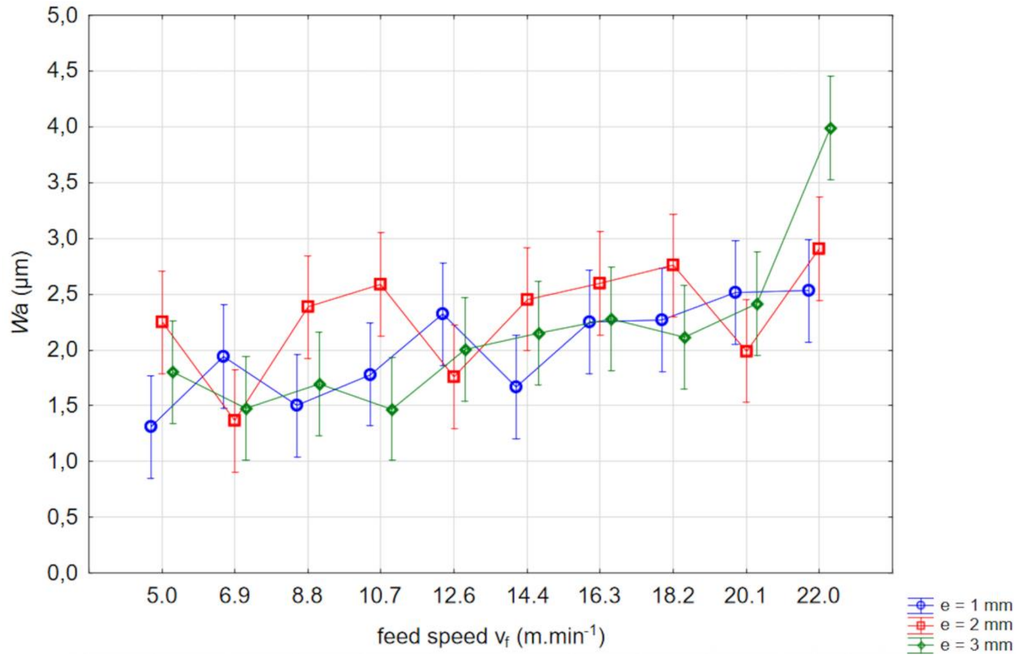


**Fig. 2 Parameter *W*a with varying rotational speed 95 % confidence intervals for population means, spindle speed 6000 rpm**

The waviness parameter (*W*a) exhibited a slight increasing trend with feed speed, rising from approximately 1.3 - 2.2 µm at lower feed rates to about 2.5 - 4.0 µm at the highest values. The highest *W*a values were observed at $v_f9$ (22.0 $m.min^{-1}$), particularly for $a_e$ = 3 mm, indicating a stronger effect of cutting depth at extreme conditions. However, considerable overlap of standard deviations (in Tab.3 - 5) suggests limited statistical differences between most parameter combinations. This behaviour is consistent with previous findings of Kuljich et al. (2013), where surface quality parameters were shown to be influenced not only by machining conditions but also by cutting mechanics, including chip formation and tool - wood interaction. Higher depths of cut can lead to increased cutting forces and instability in the cutting process, which may contribute to greater waviness (Hernández et al. 2010). Eliminating these wave patterns, which indicate the tool's movement across the surface, is important. Particularly to ensure better conditions for subsequent sanding operations (Adamčík et al. 2024).

## CONCLUSIONS

Feed rate ($v_f$) was identified as the dominant factor influencing surface quality, with a statistically significant effect on surface roughness (*R*a) ($p < 0.001$), while depth of cut ($a_e$) showed no significant main effect but contributed through interaction. Both *R*a and waviness (*W*a) generally increased with increasing feed rate, although *R*a exhibited a non-linear development with local extremes, whereas *W*a showed a more consistent upward trend. High variability and overlapping standard deviations indicate that the influence of machining parameters is partially masked by the heterogeneous anatomical structure of wood. The formation of surface irregularities, including fuzziness and waviness, is further associated with low density of spruce wood and the mechanics of chip formation during milling. From a practical perspective, minimizing feed rate is essential for achieving lower surface roughness and waviness, thereby improving the suitability of the surface for subsequent sanding operations. It should be noted that an “optimal” level of surface irregularity cannot be defined universally, as it depends on the intended application and subsequent processing requirements.

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### REFERENCES

ADAMČÍK, Lukáš, Richard KMINIAK a Adrián BANSKI, 2024. Comparison of the Roughness of the CNC Milled Surface of Selected Wood Species. *Acta Facultatis Xylologiae* [online]. 2024, zv. 66, s. 61–74. Dostupné na: doi:10.17423/afx.2024.66.2.06

ADAMČÍK, Lukáš, Veronika ŠUGÁROVÁ, Richard KMINIAK, Jarmila SCHMIDTOVÁ, Adrián BANSKI a Peter GALAJDA, 2025. Optimization of technological parameters of CNC milling of plywood depending on surface roughness. *European Journal of Wood and Wood Products* [online]. 2025, zv. 83. Dostupné na: doi:10.1007/s00107-025-02272-6

ANGELESCU, Ana-Maria, Lidia GURAU a Mihai ISPAS, 2025. Surface Quality of CNC Face-Milled Maple (Acer pseudoplatanus) and Oak (Quercus robur) Using Two End-Mill Tool Types and Varying Processing Parameters. *Applied Sciences* [online]. 2025, zv. 15, č. 13, s. 6975. ISSN 2076-3417. Dostupné na: doi:10.3390/app15136975

CARLL, Charles a Alex WIEDENHOEFT, 2009. Moisture-Related Properties of Wood and the Effects of Moisture on Wood and Wood Products. 2009.

EVANS, Philip, Ian CULLIS, Joseph KIM, Lukie LEUNG, Siti HAZNEZA a Roger HEADY, 2017. Microstructure and Mechanism of Grain Raising in Wood. *Coatings* [online]. 2017, zv. 7, č. 9, s. 135. ISSN 2079-6412. Dostupné na: doi:10.3390/coatings7090135

GURĂU, L., C. COŞEREANU a I. PAIU, 2021. Comparative Surface Quality of Larch (Larix Decidua Mill.) Fretwork Patterns Cut through by CNC Routing and by Laser. *Applied Sciences* [online]. 2021, zv. 11, 6875. Dostupné na: doi:10.3390/app11156875.

HERNÁNDEZ, Roger E., Svetka KULJICH a Ahmed KOUBAA, 2010. Effect of Cutting Width and Cutting Height on the Surface Quality of Black Spruce Cants Produced by a Chipper-Canter. *Wood and Fiber Science*. 2010, s. 273–284. ISSN 0735-6161.

HERNÁNDEZ, Roger, Angela LLAVÉ a Ahmed KOUBAA, 2014. Effects of cutting parameters on cutting forces and surface quality of black spruce cants. *Holz als Roh- und Werkstoff* [online]. 2014, zv. 72. Dostupné na: doi:10.1007/s00107-013-0762-8

KETURAKIS, Gintaras, Regita BENDIKIENE a Antanas BALTRUŠAITIS, 2017. Tool wear evolution and surface formation in milling various wood species. *BioResources* [online]. 2017, zv. 12, s. 7943–7954. Dostupné na: doi:10.15376/biores.12.4.7943-7954

KHAZAEIAN, A., 2006. 3D Characterization of wood surface quality: measurement strategy, influence of species and machining parameters. *Ph.D. Dissertation (in French)*. 2006.

KULJICH, Svetka, Roger E. HERNÁNDEZ, Angela M. LLAVÉ a Ahmed KOUBAA, 2013. Effects of Cutting Direction, Rake Angle, and Depth of Cut on Cutting Forces and Surface Quality during Machining of Balsam Fir. *Wood and Fiber Science*. 2013, s. 195–205. ISSN 0735-6161.

KVIETKOVÁ, Monika, Milan GAFF, Miroslav GAŠPARÍK, Lukáš KAPLAN a Štefan BARCÍK, 2015. Surface Quality of Milled Birch Wood after Thermal Treatment at Various Temperatures. *BioResources* [online]. 2015, zv. 10, č. 4, s. 6512–6521. ISSN 1930-2126. Dostupné na: doi:10.15376/biores.10.4.6512-6521

LANDRY, Véronic, Pierre BLANCHET a Lyne M. CORMIER, 2013. Water-Based and Solvent-Based Stains: Impact on the Grain Raising in Yellow Birch. *BioResources* [online]. 2013, zv. 8, č. 2, s. 1997–2009. ISSN 1930-2126. Dostupné na: doi:10.15376/biores.8.2.1997-2009

NOVÁK, Vít, Miroslav ROUSEK a Zdeněk KOPECKÝ, 2011. Assessment of Wood Surface Quality Obtained During High Speed Milling by Use of Non-Contact Method. *Drvna industrija* [online]. 2011, s. 105–113. ISSN 00126772, 18471153. Dostupné na: doi:10.5552/drind.2011.1027

PAKZAD, Sajjad, Siamak PEDRAMMEHR a Mahsa HEJAZIAN, 2023. A Study on the Beech Wood Machining Parameters Optimization Using Response Surface Methodology. *Axioms* [online]. 2023, zv. 12, č. 1, s. 39. ISSN 2075-1680. Dostupné na: doi:10.3390/axioms12010039

PIERNIK, Magdalena, Grzegorz PINKOWSKI a Andrzej KRAUSS, 2023. Effect of chip thickness, wood cross-sections, and cutting speed on surface roughness and cutting power during up-milling of beech wood. *BioResources* [online]. 2023, zv. 18, s. 6784–6801. Dostupné na: doi:10.15376/biores.18.4.6784-6801

QI, Xiao, Yunyue SHANG, Zijian DING a Weihua WEI, 2023. Particularities and research progress of the cutting machinability of wood-plastic composites. *Materials Today Communications* [online]. 2023, zv. 37, s. 106924. ISSN 2352-4928. Dostupné na: doi:10.1016/j.mtcomm.2023.106924

RAJA, J., B. MURALIKRISHNAN a Shengyu FU, 2002. Recent advances in separation of roughness, waviness and form. *Precision Engineering* [online]. 2002, zv. 26, č. 2, s. 222–235. ISSN 0141-6359. Dostupné na: doi:10.1016/S0141-6359(02)00103-4

RUZOVA, T. A. a B. HADDADI, 2025. Surface roughness and its measurement methods - Analytical review. *Results in Surfaces and Interfaces* [online]. 2025, zv. 19, s. 100441. ISSN 2666-8459. Dostupné na: doi:10.1016/j.rsurfi.2025.100441

# TYPOLOGICAL AND STRUCTURAL ANALYSIS OF THE TRUSS OF THE CHURCH OF ST. ELIZABETH IN ZVOLEN

**Zuzana Števková – Martin Čulík**

## ABSTRACT

This paper examines the historic roof structure of the Church of St. Elizabeth in Zvolen, Slovakia, in the broader context of Central European timber roof construction, with the aim of determining its typological classification, construction characteristics, and probable dating. The study is based on field documentation, visual survey, and structural analysis of the timber framework, focusing on the truss system, carpentry joints, assembly marks, and selected construction details, which are interpreted alongside available historical sources and comparative examples of analogous roof structures. The analysis indicates that the roof can be associated with construction traditions characteristic of the 17th century, supported by both typological comparison and the historical context of the monument. The identified structural features reflect established regional carpentry practices and contribute to understanding the development and transformation of historic roof systems. The study demonstrates that typological and material analysis can provide valuable evidence for dating, interpretation, and preservation of significant timber heritage structures.

**Keywords:** historical truss, catholic church, timber structures

## INTRODUCTION

Historic timber roof structures represent a significant part of architectural heritage, preserving evidence of past construction knowledge, regional carpentry traditions, and technological development. As primary load-bearing systems, roof trusses are important not only from a structural point of view, but also as valuable sources for understanding building chronology, construction phases, and historical craftsmanship. Their study has become an established field within building archaeology, timber engineering research, and heritage conservation.

Research on historic roof structures has received considerable attention in several European countries, where systematic documentation and analysis have produced important research frameworks and databases. Examples include the Vienna *Dachkataster*, the Czech *Atlas historických krovů*, and the documentation and public presentation of the historic roof structures in Cheb. A notable recent example demonstrating the contemporary relevance of traditional timber construction is the reconstruction of the roof structure of Notre-Dame de Paris, where historical carpentry knowledge played a central role in the design of the replica. These examples highlight the growing recognition of historic roof structures as important subjects of both scientific research and cultural heritage preservation.

In Slovakia, however, systematic research in this field remains comparatively limited. Significant contributions have been made by Ľubor Suchý, Daniela Zacharová, and Karol Ďurian through their dissertation research, which resulted from extensive investigation of historic roof structures and later contributed to the methodological publication *Metodika identifikácie a výskumu historických krovov*. Despite these important contributions, many historic roof structures in Slovakia remain insufficiently documented and studied, particularly in relation to typological classification and comparative analysis.

The Church of St. Elizabeth in Zvolen represents an important historical monument whose roof structure has not yet been comprehensively analyzed from a typological and constructional perspective. The aim of this paper is to analyze this roof structure, classify it within the framework of Central European roof truss typology, evaluate selected construction details, and discuss its probable dating in relation to comparative examples and historical context. Particular attention is given to the potential of typological and material analysis as a tool for interpreting and preserving historic timber structures.

## MATERIALS AND METHODS

The research is based on three principal groups of source materials: historical-construction evidence, direct field documentation, and comparative material.

Based on available historical sources and previous investigations, the Church of St. Elizabeth in Zvolen underwent several major construction phases. The original single-nave church was established in the mid-13th century, documented by a charter of King Béla IV and represented by the preserved early Gothic southern portal. In the 14th century, the church was enlarged by the construction of the present sacristy with adjoining chapel and a Gothic charnel chapel. In the 15th century, additional northern structures, including a royal oratory and town hall connection, were added. Significant interventions occurred during the 16th century, when side galleries were introduced, the nave was vaulted, and the western tower was probably constructed. In the 17th century, the southern chapel was added, while early 18th-century reconstruction following damage caused by the forces of Francis II Rákóczi resulted in a Baroque upper structure of the tower (Kresánek *et al.,* 2009).

These phases provide the historical framework for interpreting the existing roof structures.

### Relevant typological types of historical roof structures

One of the relevant typological types for the investigated object is represented by collar-beam roofs with a central frame and lateral queen post frames. In structures of larger span, these roofs are characterized by a developed longitudinal binding system formed by a combination of a central frame below the ridge and lateral queen post trusses. The central frame and queen post frames are braced by systems of stiffening members, including upward braces, downward braces and St. Andrew’s crosses. Vertical posts are stabilized by horizontal struts or purlins, which may occur at one or several height levels. In roof structures with larger spans, the number of lateral standing trusses may increase and may also occur in higher parts of the roof structure, often between collar beams.

Full trusses alternate with reduced intermediate trusses, which generally lack vertical posts and more substantial bracing members. Roofs of this type belong among the most complex historical timber roof structures and are generally associated with late medieval and early modern construction of the 15th and 16th centuries. Characteristic roof pitches range approximately between 58° and 68°.

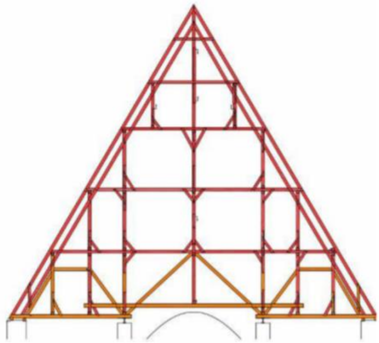

**Fig. 1 Truss of St. Martin's Cathedral (Krušinský, 2010)**

Another relevant typological group is represented by roof structures with longitudinal binding by *Liegender Stuhl,* occurring from the 16th to the first half of the 19th century. Their principal structural element is the *Liegender Stuhl*, forming a self-supporting spatial frame situated in full transverse trusses between rafters and collar beams. In transverse section, the system is formed by inclined posts connected by a horizontal strut and stabilized by diagonal braces. In the longitudinal direction, the structure is braced by St. Andrew's crosses, upward braces or downward braces.

Early forms of *Liegender Stuhl*, generally associated with the 16th and 17th centuries, are characterized by four-sided purlin profiles, frequent absence of a sill beam, offset positioning of the horizontal strut relative to the collar beam, and upward braces passing through multiple structural elements simultaneously, connecting them by lap joints. Developed forms, typical mainly of the 17th to early 19th centuries, are characterized by the horizontal strut placed directly beneath the collar beam, simplified wind bracing connecting only the *Liegender Stuhl* frame, five-sided purlins, and more regularized carpentry jointing (Suchý *et al*., 2018a).

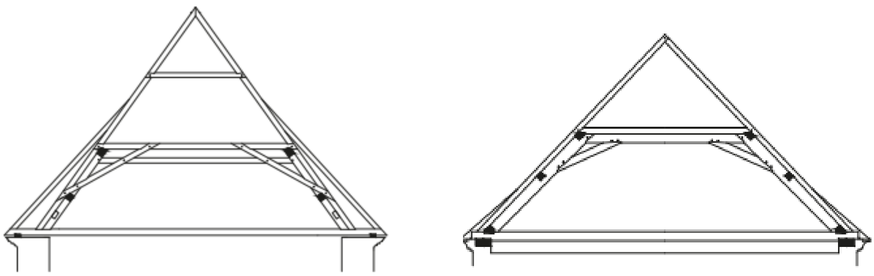

**Fig. 2 Types of Liegender Stuhl (Suchý, 2018)**

These two typological groups represent the principal structural groups relevant to the investigated roof structures.

## RESULTS AND DISCUSSION

### Structural characteristics of the roof structure

The roof structure above the nave and presbytery of the church, originally dating from the mid-13th century and later significantly rebuilt in the late 14th century, is a historic two-tier collar-beam system with a reduced ridge configuration (ridge beam positioned below the upper collar beam) and high queen post side frames. The principal trusses consist of a lower and upper collar beam system and rafters connected to the ends of tie beams by mortice and tenon.

High queen posts are tenoned into the tie beams and terminated by purlins beneath the collar beams. Between these purlins, horizontal straining beams are inserted and braced with diagonal struts using dovetailed lap joints. The queen posts are also braced by downward beams connected to tie beams.

**Fig. 3 Truss above the nave of church of St. Elizabeth (Pauer, 2026)**

A central post connects the lower collar beam and straining beam system, while the upper part is stabilized by symmetric diagonal braces. The main trusses are further stiffened by intersecting struts forming St. Andrew's crosses between the tie beams and lower collar beams. Intermediate trusses consist of simplified tie beam–collar beam systems without full bracing. The central truss is also brace by St. Andrew's crosses in the longitudinal direction in the section above the lower collar beam.

The side stools are formed by vertical posts embedded into transverse tie beams and closed by purlins. These are stabilized by diagonal braces and short struts. Every other post is reinforced by full-height diagonal bracing member intersecting the post in the middle and connecting to the queen truss purlins on the upper end and longitudinal header beam (perpendicular and connected to the tie beams) on the lower end (Suchý *et al.*, 2018b).

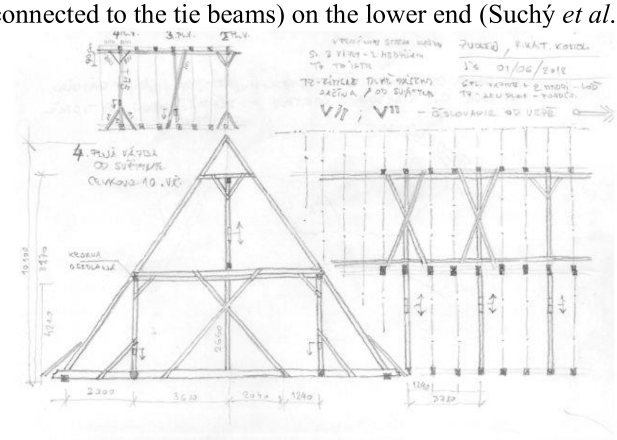

**Fig. 4 Field notes of the truss (Suchý, 2018)**

The roof structure above the southern chapel consists of a younger-type *Liegender Stuhl* truss, exhibiting several atypical features (Bláha *et al.,* 2020). The purlin has a four-sided profile and is positioned below the level of the transverse strut. Inclined braces are tenoned into the lying posts and the transverse strut. The collar beam is situated directly above the transverse strut. In the longitudinal direction, the truss is braced by a system of double St. Andrew's crosses. The roof structure also incorporates the construction of a sanctus turret, formed by a hanging-post (suspension) structure. The tie beams embedded in the masonry are made of oak.

**Fig. 5 Truss above the southern chapel, Liegender Stuhl**

## Typological and constructional particularities

A remarkable and relatively rare feature within historic roof structures is the placement of longitudinal header beams between tie beams beneath the bases of the side posts. Another notable detail is the decorated profile of tie beam ends, indicating a high level of carpentry refinement.

The roof comprises alternating full and intermediate trusses, with two intermediate trusses between each full truss. The overall span of the roof is approximately 12 m with a height of about 10 m.

## Assembly marks and carpentry technique

The roof structure is constructed using traditional hewn timber elements from Fir (Tiralová *et al.,* 2005) with predominantly halved dovetail joints, supplemented by mortise-and-tenon connections in key load-bearing areas. Assembly marks are present in the form of incised Roman numerals, exhibiting a relatively archaic execution. Numbering begins from the tower side and continues consistently across both principal trusses and queen post trusses, including posts, braces, struts, and purlins

**Evidence of Repairs and Construction Phases**

The roof structure has undergone several construction phases and repair interventions. The most recent documented intervention was carried out in 2012. During this reconstruction, an inclined truss was inserted into the roof over the southern chapel, while several timber side-plates and replacements were executed in the nave roof. Laths and shingles were also renewed.

Earlier repairs can be attributed to the 19th and 20th centuries, when interventions were carried out mainly on rafters and longitudinal header beams in the roof over the nave. Evidence of an earlier construction phase is also legible in the roof structure, particularly in carpentry joints preserved on the wall plate, indicating reuse or modification of older structural arrangements.

Although the roof structures above the nave and the presbytery are typologically identical, differences were identified in carpenters' assembly marks and in the execution of individual carpentry joints, for example in the scarfing of the foot braces (Fig. 6). This suggests that both roofs were likely constructed within the same general period, but possibly by different carpentry teams or in a short chronological sequence.

**Fig. 6 Different details of upward braces**

At the junction where the roof over the southern chapel connects to the roof over the nave, several hand-hewn battens have been preserved, representing additional evidence of earlier construction fabric.

**Chronological interpretation of the roof structures**

Based on typological analysis and comparison with Central European analogies, both the roof over the nave/presbytery and the roof over the southern chapel can most plausibly be associated with a single construction phase connected with the addition of the southern chapel, generally dated to the 17th century.

Although the roof structures differ in their detailed execution and structural arrangement, these differences do not necessarily indicate a significant chronological gap. Instead, they may reflect variation in carpentry practice, different execution teams, or adjustments to local spatial and structural conditions within one construction campaign.

The nave roof represents a modified continuation of a late medieval collar-beam system with a central frame and lateral standing trusses, a type that remained in use and was structurally adapted well into the early modern period. The structures in Central Europe, such as the roof over the monastic Church of St. Peter of Alcantara in Okoličné (1489/1490) and the Chapel of the Zápolský family in Spišská Kapitula (1490/1491), represent more archaic forms of this typological group, reflecting its earlier developmental stage (Zacharová, 2016).

Within this broader typological framework, a closer structural and chronological correspondence to the analysed nave roof is provided by the roof structure of the Church of Saint Cosmas and Damian in Háj (1692) (Suchý, 2008), and Church of St. Xaver in Leoben (1661–1662) (Caston, 2006) (Fig. 7), which constitutes a more directly comparable example of a similarly developed and later form of the same construction tradition.

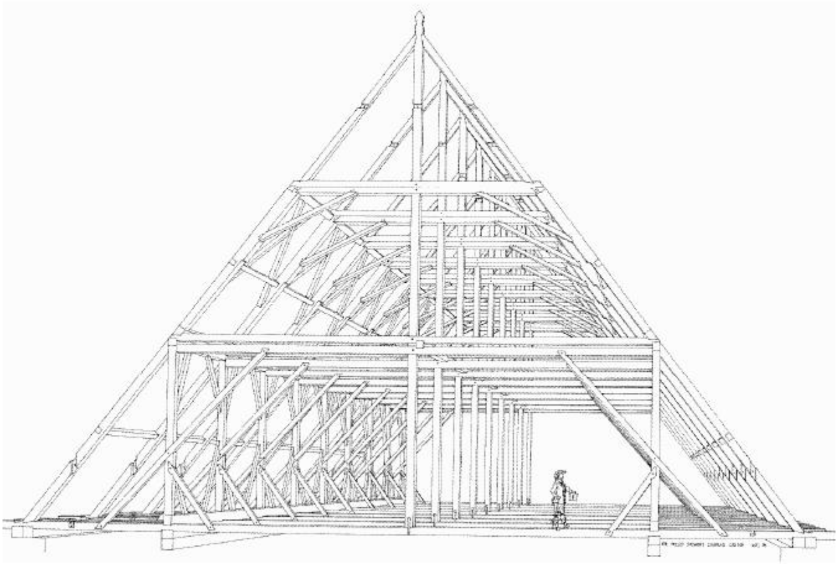

**Fig. 7 Leoben, St. Xavier (Caston, 1998)**

The roof over the southern chapel corresponds to a developed form of the Liegender Stuhl system, which is typically dated from the second half of the 17th century onwards. Despite some atypical structural features, its construction logic and longitudinal bracing system are consistent with early developed forms of this typology.

Taken together, the typological characteristics and comparative evidence suggest that both roof structures were likely executed within a single construction episode in the 17th century, corresponding to the building phase of the southern chapel. The observed differences are therefore interpreted as variations within one building campaign rather than indicators of separate chronological stages.

## CONCLUSION

The analysis of the roof structures of the Church of St. Elizabeth in Zvolen has demonstrated that both the nave/presbytery roof and the southern chapel roof can be interpreted within a single broader construction phase associated with the 17th-century building development of the monument. Despite their typological differences, the structural systems show sufficient continuity in execution logic, carpentry techniques, and construction context to exclude a significantly different chronological origin.

Comparative analysis indicates that the nave roof preserves an older structural tradition of a collar-beam system with a central frame and lateral standing trusses, which represents a conservative and regionally adapted continuation of late medieval construction principles. In this respect, it shows closer affinity to developed early modern examples such as the roof structure of the Church of St. Xaver in Leoben (1661–1662), rather than to earlier medieval prototypes from Okoličné or Spišská Kapitula, which represent more archaic stages of the same typological group.

The southern chapel roof corresponds to a developed form of the Liegender Stuhl system, consistent with its general chronological range from the second half of the 17th century. Although it exhibits several atypical features, these are interpreted as local or workshop-specific variations rather than indicators of a different period of construction.

Overall, the study confirms that typological and constructional analysis, supported by comparative examples, provides a reliable framework for relative dating and interpretation of historic timber roof structures. The results contribute to a better understanding of the construction history of the monument and highlight the importance of detailed structural documentation for the study and preservation of timber architectural heritage.

## ACKNOWLEDGEMENTS

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## REFERENCES

Bláha, J., Buzek, J., Kyncl, T., 2020. Historických krovů České republiky. ÚTAM AV ČR, Telč.

Caston, P., 2006. Historic Roof Trusses between 1500 and 1700 in German-speaking Central Europe: Documentation, Analysis and Development. Proceedings of the Second International Congress on Construction History, 1, 579–597.

Güntherová, A. et al., 1968. Súpis pamiatok na Slovensku 1. Obzor, Bratislava.

Gajdoš, M., 2002. Kostol sv. Alžbety vo Zvolene. Self-published, Sliač.

Kresánek, P. et al., 2009. Slovensko. Ilustrovaná encyklopédia pamiatok. Simplicissimus, Bratislava.

Slávik, J., 1921. Dejiny Zvolenského evanjelického a. v. bratstva a seniorátu. Banská Štiavnica.

Suchý, Ľ., Krušinský, P., Babjaková, Z., Ďurian, K., 2008. Historické krovy sakrálnych stavieb Turca. Žilinská univerzita v Žiline, Žilina.

Suchý, Ľ., Zacharová, D. et al., 2018a. Metodika identifikácie a výskumu historických krovov. Pamiatkový úrad Slovenskej republiky, Bratislava.

Suchý, Ľ., Krušinský, P., Ďurian, K., 2018b. Prieskum krovových konštrukcií na vybraných kultúrnych pamiatkach v územnej pôsobnosti KPÚ Banská Bystrica a pracovísk Banská Štiavnica, Lučenec. Kurz „Dokumentace a průzkumy historických krovů". Banská Štiavnica.

Tyralová, Z., Kotlínová, M. et al., 2005. Poškození zpracovaného dřeva houbami a hmyzem.
Odborný seminář. Česká zemědelská univerzita, Praha. ISBN 80-213-1374-9.

Vaníková, V. et al., 1993. Zvolen – monografia k 750. výročiu obnovenia mestských práv. Gradus, Martin.

Zrebený, A., 1986. Zvolen do roku 1526. Stredné Slovensko 5, 1986.

Zacharová, D., 2016. Historicko-typologický vývoj barokových krovových konštrukcií na území Slovenska. Dizertačná práca, Fakulta architektúry, Slovenská technická univerzita v Bratislave, Bratislava

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# STIFFNESS-BASED GRADING OF THERMALLY MODIFIED BEECH TIMBER FOR STRUCTURAL APPLICATIONS

**Filip Valko – Jarmila Schmidtová – Tomáš Andor – Barbora Herdová – Rastislav Lagaňa**

## ABSTRACT

Thermally modified wood is mainly used in exterior applications because thermal treatment improves dimensional stability and resistance to biological degradation, but the associated loss of strength still limits structural use. This condensed paper summarizes an experimental study on structural-size European beech timber thermally modified at 190 °C in an oxidizing atmosphere. Timber from 32 beech logs was visually graded according to DIN 4074-5:2003, evaluated by acoustic non-destructive methods (NDT), and tested in four-point bending according to EN 408:2011. Mechanical properties, density and characteristic values were determined and grading models based on modulus of elasticity were assessed. Thermal modification reduced mean bending strength by about 17 % and increased strength variability, whereas static and dynamic stiffness remained statistically unchanged. The characteristic bending strength fell below the lowest EN 338:2016 hardwood class. Global MOE was the best single predictor of bending strength, while stiffness prediction improved markedly when local and acoustic moduli were combined. The results confirm the potential of thermally modified beech for stiffness-controlled applications, but also its clear limitations in strength-controlled design.

**Keywords:** thermally modified wood; beech; structural timber; bending strength; non-destructive testing

## INTRODUCTION

In Europe, hardwood species are receiving growing attention in structural applications because softwood resources are under increasing pressure, while beech remains widely available and is expected to gain importance in mixed and climate-resilient forests (Pramreiter and Grabner, 2023). At the same time, the construction sector is looking for materials with higher added value and broader utilization potential. European beech (Fagus sylvatica L.) is therefore a logical candidate for further structural use, especially in applications where its high stiffness and favourable mechanical performance can be exploited.

Thermal modification is already well established as a treatment that improves dimensional stability, lowers equilibrium moisture content, increases resistance to biological degradation, and gives wood a darker and more uniform appearance (Hodžić and Bahmani, 2023). These advantages explain why thermally modified wood is commonly used in exterior cladding and other non-load-bearing applications. The main limitation is that the treatment can alter mechanical behaviour in a species-dependent way. Earlier studies showed that thermally modified beech may retain stiffness relatively well, but bending strength, toughness, and reliability can decrease substantially, particularly under more severe treatment regimes (Widmann *et al*., 2012; van Blokland, 2020; Al-Musawi *et al.*, 2023).

This creates a serious challenge for structural design. Conventional grading systems such as EN 338:2016 and EN 384:2016+A2:2022 assume stable relationships between density, modulus of elasticity, and strength, but these assumptions are not fully valid for heavily modified wood. As a result, visually graded thermally modified beech may appear satisfactory in terms of stiffness, while still failing to achieve the strength requirements expected for structural members. Non-destructive testing methods based on dynamic or static stiffness have already been studied for untreated timber and for selected thermally modified softwoods, yet comparable models for structural-size thermally modified beech remain limited (van Blokland *et al.*, 2019; van Blokland, 2020; Azzi *et al.*, 2025).

The present study addresses this gap by evaluating structural-size European beech timber thermally modified in an oxidizing atmosphere at 190 °C. The work focuses on the comparison of untreated and treated boards, the determination of characteristic mechanical properties, and the assessment of grading models based on stiffness-related indicator properties.

## MATERIALS AND METHODS

Stems from 16 beech trees harvested in the Zvolen district, Slovakia, were sawn into boards, air-dried, visually graded according to DIN 4074-5:2003, and paired so that neighboring boards could be compared before and after thermal modification. Industrial thermal modification was carried out in an oxidizing air atmosphere at 190 °C for 3.5 h. Material selection and adjacent-board pairing are shown in Fig. 1.

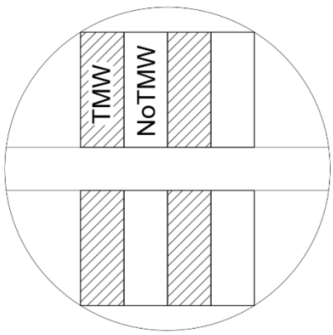


**Fig. 1 Segmental sawing pattern and adjacent-board pairing for TMW and NoTMW.**

NDT evaluation used ultrasound and natural frequency measurements to derive dynamic modulus of elasticity. Afterwards, four-point bending tests according to EN 408:2011 were performed on boards re-sized to 50 × 150 × 3100 mm. Moisture content, density, modulus of elasticity (local and global) and modulus of rupture were determined; characteristic values were calculated according to EN 384:2016+A2:2022 and EN 14358:2016.

Paired t-tests were used to compare treated and untreated boards, whereas linear and multiple regression models were applied to investigate the prediction of bending strength and stiffness from NDT indicators. The analysis focused on identifying practically usable grading variables and on assessing whether multivariable models improve the strength–stiffness description of TMW beech.

## RESULTS AND DISCUSSION

The paired comparison showed that thermal modification significantly reduced moisture content, density and bending strength, while the measured elastic moduli did not differ significantly between untreated timber and TMW (Tab. 1, Fig. 2). Treated timber reached an equilibrium moisture content of about 6 %, compared with roughly 15 % for untreated timber. The mean bending strength of the paired boards decreased significantly, confirming that heat treatment weakened the material even when the same log source was considered.

**Tab. 1 Results of paired sample t-test (NoTMW versus TMW treatment). Probabilities of significant differences are marked in bold.**

| Explanatory variable | N | t-Test | Df | p-Level |
|---|---|---|---|---|
| $f_{m,h150}$ | 34 | −3.41 | 33 | **0.002** |
| $MOE_{sylv,ref\ w}$ | 31 | 0.52 | 30 | 0.605 |
| $MOE_{MTG,ref\ w}$ | 33 | 0.78 | 32 | 0.440 |
| $MOE_{l,ref\ w}$ | 34 | 0.34 | 33 | 0.734 |
| $MOE_{g,ref\ w}$ | 34 | 0.36 | 33 | 0.720 |
| $\rho_{408,ref\ w}$ | 34 | −6.35 | 33 | **0.000** |
| MC | 34 | −40.20 | 33 | **0.000** |

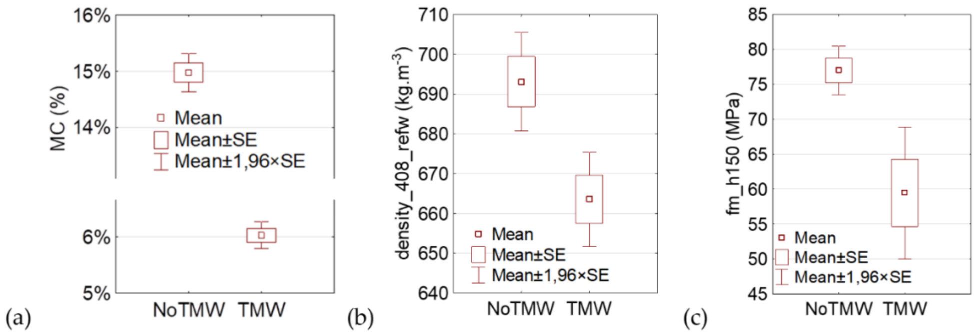


**Fig. 2 Box plot—95% confidence intervals for significantly different means between treated (TMW) and untreated (NoTMW) paired boards: (a) moisture content; (b) density at reference MC; (c) height corrected bending strength at reference MC. SE stands for standard error.**

The complete dataset confirmed the same trend. Thermally modified boards showed a mean bending strength of 63.33 MPa, versus 76.31 MPa for untreated boards, corresponding to a reduction of about 17 %, whereas mean moduli remained at a similar level and density decreased by about 5 % (Tab. 2). The strength distribution of TMW became broader and less uniform than in untreated timber, which points to greater scatter and to a stronger influence of defects after modification (Fig. 3).

**Tab. 2 Descriptive statistics of the entire set of samples (N = 53).**

| Property (unit) | TMW Mean | TMW CV* (%) | NoTMW Mean | NoTMW CV* (%) | Difference (%) |
|---|---|---|---|---|---|
| $f_{m,h150}$ (MPa) | 63.33 | 45% | 76.31 | 14% | −17% |
| $MOE_{sylv,w}$ (GPa) | 20.05 | 8% | 20.01 | 7% | 0% |
| $MOE_{MTG,w}$ (GPa) | 17.91 | 7% | 17.38 | 9% | 3% |
| $MOE_{l,ref\ w}$ (GPa) | 16.00 | 12% | 15.67 | 10% | 2% |
| $MOE_{g,ref\ w}$ (GPa) | 14.92 | 10% | 14.61 | 8% | 2% |
| $\rho_{408,ref\ w}$ ($kg.m^{-3}$) | 663.1 | 5% | 694.5 | 5% | −5% |
| MC (%) | 6.09 | 11% | 14.93 | 7% | −59% |

* Coefficient of variation.

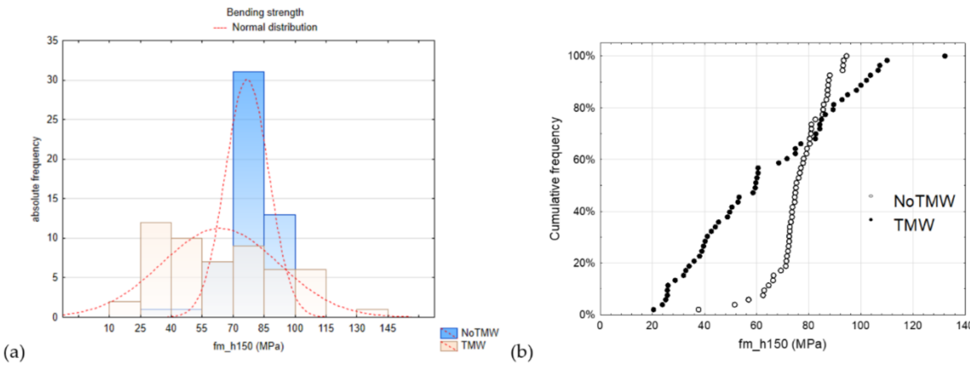


**Fig. 3 Histogram (a) and cumulative relative frequency diagram (b) of bending strength for treated (TMW) and untreated beech timber (NoTMW). The dashed lines show estimated normal distributions.**

The characteristic values highlight the main structural limitation of the treated material. The characteristic bending strength $f_{m,k}$ reached only 17.27 MPa, i.e. below the lowest deciduous strength class D18, even though mean modulus and density remained comparatively high (Tab. 3). In practical terms, thermally modified beech may appear sufficiently stiff, but its strength level and especially its variability remain unfavorable for standard structural classification.

**Tab. 3 Characteristic values of TMW timber.**

| $f_{m,05}$ (EN 14358) | $f_{m,k}$ (EN 384) | $E_{m,0,mean}$ (EN 384) | $E_{m,0,k}$ (EN 384) | $\rho_k$ | $\rho_{mean}$ | $\rho_{05}$ |
|---|---|---|---|---|---|---|
| 24.68 | 17.27 | 13.62 | 11.44 | 526.9 | 632.3 | 598.8 |

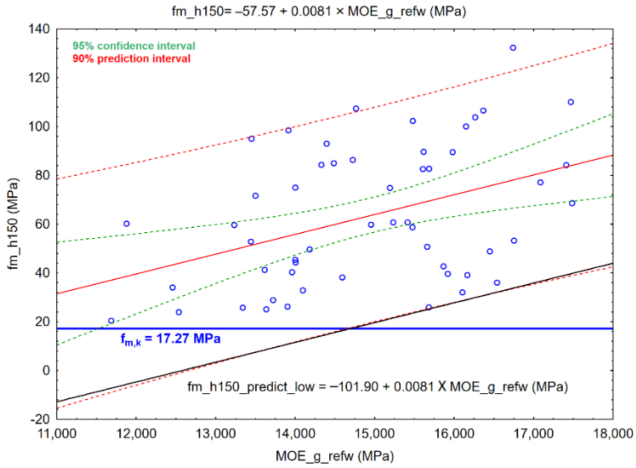


**Fig. 4 Relationship of characteristic strength with global MOE for heat-treated beech timber. The black line represents the prediction of the fifth percentile boundary; horizontal blue lines represent characteristic values fm,k; the solid red line is the regression line.**

Regression analysis showed that global MOE was the best single predictor of bending strength, but the relationship remained weak, explaining only about 17 % of strength variability. Adding further NDT indicators increased the coefficient of determination only marginally, to approximately 19 %. By contrast, stiffness prediction was much better: combining local and acoustic moduli explained about 76 % of the variation in bending stiffness. The grading relationship between characteristic strength and global MOE is summarized in Fig. 4.

These findings are consistent with previous studies reporting that thermally modified beech often preserves stiffness better than strength and becomes more brittle after treatment (Widmann *et al.*, 2012; Hodžić and Bahmani, 2023; Al-Musawi *et al.*, 2023). The present results also support the view that standard grading rules developed for untreated hardwoods cannot be transferred directly to TMW beech (Widmann *et al.*, 2012; van Blokland, 2020; Al-Musawi *et al.*, 2023). From a structural-design perspective, the material seems more suitable for stiffness-controlled or low-stress applications than for members in which bending strength governs. For practice, milder treatment regimes and enhanced grading models incorporating knot geometry or fibre orientation should be preferred.

## CONCLUSION

The study confirmed that structural-size beech timber thermally modified at 190 °C retains static and dynamic stiffness but loses part of its bending strength and becomes markedly more variable. Because the characteristic bending strength fell below EN 338:2016 class D18, direct use of conventional hardwood grading rules is unreliable. Global MOE can be used as a first grading indicator, yet strength prediction remains weak; stiffness prediction is substantially better when local and acoustic moduli are combined. Thermally modified beech therefore has structural potential only under conservative design assumptions and with improved, material-specific grading procedures.

## REFERENCES

Al-Musawi, H., Manni, E., Stadlmann, A., Ungerer, B., Hassan Vand, M., Lahayne, O., Nobile, R., Baumann, G., Feist, F., Müller, U., 2023. Characterisation of thermally treated beech and birch by means of quasi-static tests and ultrasonic waves. Scientific Reports 13, 6348. https://doi.org/10.1038/s41598-023-33054-w

Azzi, Z., Al Sayegh, H., Metwally, O., Eissa, M., 2025. Review of nondestructive testing (NDT) techniques for timber structures. Infrastructures 10, 28. https://doi.org/10.3390/infrastructures10020028

DIN 4074-5, 2003. Sortierung von Holz nach der Tragfähigkeit—Teil 5: Laubschnittholz. Deutsches Institut für Normung, Berlin.

EN 338, 2016. Structural Timber—Strength Classes. CEN, Brussels.

EN 384:2016+A2:2022, 2022. Structural Timber—Determination of Characteristic Values of Mechanical Properties and Density. CEN, Brussels.

EN 408:2011, 2011. Timber Structures—Structural Timber and Glued Laminated Timber—Determination of Some Physical and Mechanical Properties. CEN, Brussels.

EN 14358:2016, 2016. Timber Structures—Calculation and Verification of Characteristic Values. CEN, Brussels.

Hodžić, A., Bahmani, M., 2023. Physical and mechanical changes in thermal modified wood: A review. Zastita Materijala 64, 314–326. https://doi.org/10.5937/zasmat2303314H

Pramreiter, M., Grabner, M., 2023. The utilization of European beech wood (Fagus sylvatica L.) in Europe. Forests 14, 1419. https://doi.org/10.3390/f14071419

van Blokland, J., 2020. Thermally Modified Timber: Novel Aspects of Bending Behaviour Towards Grading and Structural Applications. PhD Thesis, Linnaeus University, Växjö, Sweden.

van Blokland, J., Olsson, A., Oscarsson, J., Adamopoulos, S., 2019. Prediction of bending strength of thermally modified timber using high-resolution scanning of fibre direction. European Journal of Wood and Wood Products 77, 327–340. https://doi.org/10.1007/s00107-019-01388-w

Widmann, R., Fernández-Cabo, J.L., Steiger, R., 2012. Mechanical properties of thermally modified beech timber for structural purposes. European Journal of Wood and Wood Products 70, 775–784. https://doi.org/10.1007/s00107-012-0615-x

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