Zagreb, 7th – 8th December

ICWST 2023

32nd International Conference on Wood Science and Technology

Unleashing The Potential of Wood-based Materials

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32nd International Conference on Wood Science and Technology (ICWST)

UNLEASHING THE POTENTIAL OF WOOD-BASED MATERIALS

PROCEEDINGS

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The CIP record for this publication is available in the catalogue of the National and University Library in Zagreb under number: **001206196.**

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Faculty of Forestry and Wood Technology, University of Zagreb, Croatia

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Edition:
200 copies

ISBN: 978-953-292-083-3

FOREWORD

Welcome to the 32nd International Conference on Wood Science and Technology – ICWST 2023, themed "Unleashing the Potential of Wood-Based Materials." As we embark on this annual gathering, it is with great excitement that we delve into a rich tradition that has evolved over the years, connecting experts, researchers, and enthusiasts in the field of wood science and technology.

This year marks a significant juncture for ICWST, as we explore the endless possibilities within wood-based materials. Building upon the success of previous conferences, ICWST 2023 is set to be a catalyst for innovative discussions, collaborations, and breakthroughs in the ever-expanding realm of wood science.

Our conference is honoured to be hosted by esteemed institutions such as the Faculty of Forestry, University of Zagreb; Biotechnical Faculty, University of Ljubljana; Faculty of Forest Industry, University of Forestry - Sofia, and InnovaWood. This collaborative effort reflects the commitment of diverse scientific communities to the advancement of wood science and its applications.

In the spirit of tradition and progress, ICWST 2023 seeks to create a multidisciplinary platform where the exchange of ideas transcends borders. We anticipate the convergence of scientists and researchers from a variety of backgrounds, fostering an environment conducive to scientific novelty, industrial applicability, and comprehensive syntheses of high-impact subjects.

As we reflect on the achievements of the past, present, and future, ICWST 2023 is proud to unveil a program that encapsulates the essence of wood science. Distinguished speakers will explore a wide range of topics. We are honoured to host renowned experts who will share their insights, contributing to the rich tapestry of wood science discourse.

In conclusion, ICWST 2023 extends its gratitude to the institutions and companies whose financial support has made this conference possible. This year's conference aims to go beyond the realms of wood science and technology, touching upon interconnected topics such as materials, technologies, design, and more. We aspire to raise awareness about the vital role of wood as a natural resource in the bioeconomy, advocating for its use as a green building material in the fight against climate change.

We look forward to a conference filled with intellectual exchange, collaboration, and the exploration of the untapped potential within wood-based materials. May ICWST 2023 be a stepping stone towards a future where the sustainable utilization of wood contributes to the betterment of our world.

Editors

CONTENTS

Evaluation of the Irregularities of the Milled Surface of Beech, Maple and Birch Wood using Areal Surface Texture Parameters

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ABSTRACT

Milling of natural wood on a 5-axis CNC machine tool is a common part of the production sphere today. In practice, however, it is problematic to appropriately set the individual machining parameters, which have a fundamental effect on the irregularities of the created surface. The aim of the article is to analyse and quantify the irregularities created after milling with a spiral router cutter. The effects of three different values of the thickness of the removed layer and the feed speed on maple, beech and birch wood will be investigated. Surface irregularities will be quantified through a digital microscope and expressed by areal surface texture parameters measured in accordance with the EN ISO 25178. The measurements showed combinations of feed speed and thickness of the removed layer, which create the highest quality and lowest quality surface for each wood. The objectives of the present paper will help to choose the correct technological parameters of milling regarding the quality of the created surface.

Key words: areal surface texture parameters, CNC milling, diffuse porous wood, surface irregularities, surface quality

1. INTRODUCTION

Milling is a type of chip woodworking, which, like sanding, contributes to the formation of the final surface quality. In addition to classic lower spindle moulders, milling on CNC machine tools has also come to the fore in the last decade (Davim *et al.,* 2009; Lungu *et al.,* 2023; Piernik *et al.,* 2023). Their versatility predisposes them to the use of a large number of cutting tools operating at different machining parameters (i.e., cutting speed, feed speed, thickness of the removed layer) (İşleyen and Karamanoğlu, 2019; Pelit *et al.,* 2021). With their correct alignment, two types of milling can be performed on CNC machines: roughing and finishing. In both mentioned cases, it is necessary to adjust the parameters regarding the quality of the created surface, which can be defined through various properties. The most common is the evaluation of the surface through irregularities, namely the roughness of wood (Gurau *et al.,* 2007; Henke *et al.,* 2022), waviness (Gurau *et al.,* 2019) or primary profile. However, to determine the average value of surface roughness or waviness, it is necessary to take several profile traces that represent surface irregularities in more detail. When measuring wood surface irregularity, it is advisable to repeat this procedure both in the direction perpendicular to the grains (where greater surface irregularities are assumed) and parallel to the grain. This can be very time-consuming and the resulting values of measured parameters from profile traces may not correspond to the actual condition of the created surface. The solution is to measure the areal surface texture parameters, which has become widely used especially in recent years. This surface assessment represents a very fast method of measurement, which contains many points in the evaluated area, from which the areal surface texture parameters are determined. The evaluation area is carried out in accordance with the EN ISO 25178 series of standards. In this paper, surface irregularities will be measured using areal surface texture parameters Sa, Sz, Sv, Sp, Ssk, Sku. These parameters are equivalent to Ra, Rz, Rv, Rp, Rsk and Rku, but the profile extracted from the S-L or S-F surface is not mathematically the same as in profile surface texture parameters.

The aim of the paper is to analyze and quantify surface irregularities after milling at a CNC 5-axis machining center. The impact of the thickness of the removed layer and feed speed on the quality of the created surface of beech, birch and maple wood will be evaluated. These types of wood were selected as representatives of diffuse-porous wood species of higher and lower density. All three are often used both in furniture production and in increasingly used thermal or hydrothermal treatment processes, where research requires mutual comparison of surface quality after milling native and modified wood. The paper thus contributes to the issue of surface irregularities after milling, which, however, it defines by areal surface texture parameters. These, despite their advantages, are not so extensively researched at present. Objective of the paper will be also identification of a combination of machining parameters where surface irregularities are lowest by means of 3D plot graphs. The objective will help to better understand the setting of values of the milling input parameters with respect to the quality of the created surface.

2. MATERIALS AND METHODS

2.1. Sample preparation for milling

27 samples with dimensions 5 × 30 × 600 mm (thickness × width × length) were made of beech (*Fagus sylvatic*a L.), birch (*Betula pendula*) and maple (*Acer platanoides*) wood with radial surface texture. The samples were dried to an equilibrium wood content of 8 to 10 %. Before milling on the 5-axis CNC machining center SCM Tech Z5 (Scm Group, Rimini, Italy), wood blanks were sawn on a circular saw, which were then milled on a jointer and peripheral milling machine to a final dimension of 30 × 100 × 600 mm (thickness × width × length).

2.2 Milling process

The used tool was a negative LEUCO VFW 178354 spiral finishing cutter with a diameter of 20 mm, with a cutting-edge length of 55 mm. The parameters of milling process were: spindle speed n = 20,000 min^{-1} and the varying thickness of the removed layer ae = 1, 3 and 5 mm and the varying feed rate vf = 2, 4 and 6 $m \cdot min^{-1}$. After milling, a sample was cut from the blank to measure surface irregularities with final dimensions of 5 × 30 × 600 mm (thickness × width × length).

2.3. Measurement of surface unevenness

The measurement of surface irregularity parameters was carried out using the Keyence VHX-7000 digital microscope (Osaka, Japan). The digital microscope performs measurements of areal surface texture parameters using the implemented VHX-H5M software. Before the measurement, it was necessary to perform image stitching to the final size of 13 × 13 mm so that the measurement complies with the EN ISO 25178 series of technical standards.

A total of 6 evaluation areas were scanned from each sample evenly along the entire length of the milled surface. Depending on EN ISO 25178-3 ("EN ISO 25178-3. Geometrical product specifications (GPS) Surface texture: Areal Part 3: Specification operators," 2012), the evaluated area was the S-L surface, i.e., a square measuring 12.5 × 12.5 mm. The chosen values of the S-filter were 25 μm and 2.5 mm, respectively. The evaluated areal surface texture parameters were Sa (Arithmetic mean height), Sz (Maximum height), Ssk (Skewness), Sku (Kurtosis), Sp (Maximum peak height) and Sv (Maximum pit depth).

3. RESULTS AND DISCUSSION

Before statistical evaluation in the program STATISTICA 12 (Statsoft CR s.r.o., Czech Republic) outliers were removed for individual combinations of machining parameters from the data set of parameters Sa, Sz, Sv, Sp, Ssk and Sku. In the first step, the modified input data matrix was evaluated using descriptive statistics methods, the results of which were summarized in a bar chart (*Figure 1*). While higher values of measured parameters can be considered as lower surface quality, the worst quality was measured for beech wood. On the contrary, the best surface quality was measured for maple wood. The expected influence in this case is the density, which for maple wood reaches a value of 600.1 ± 50.1 $kg{\cdot}m^{-3}$ (Dudiak, 2021), for birch wood 649,4 ± 26,9 $kg{\cdot}m^{-3}$ and for beech wood 683,5 ± 65,1 $kg{\cdot}m^{-3}$ (Dzurenda and Dudiak, 2020). (*Figure 1*) also shows that while the values of Sa and Sv for beech wood are approximately the same as for other types of wood, a jump increase can be observed for Sp (and therefore Sz) and Sku. Measurements show that beech wood irregularities were significantly pointy and with a large hill (and peaks) on the surface. This kind of irregularity is often caused by the fuzzy surface, i.e., protruding fibers. The parameter Ssk is also proof that the surface of beech wood after milling was mainly made up of hills of the surface.

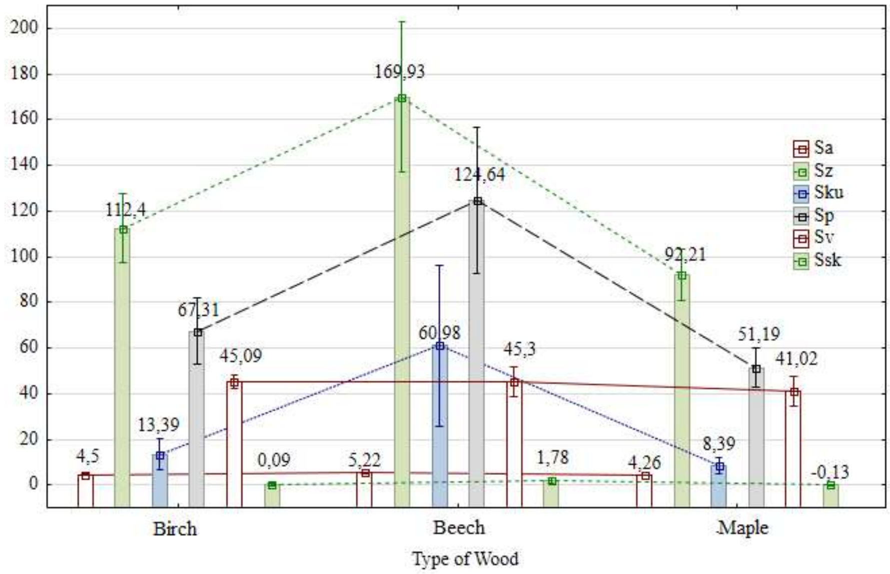

Figure 1. Measured values of area parameters for individual tree species (vertical columns indicate diameter ± 0.95 Confidence interval).

Maple wood *(Figure 2)* had the lowest surface quality with a thickness of the removed layer of 3 mm and a feed speed of 2 $m{\cdot}min^{-1}$. This results from the maximum height (Sz). For the surface parameter Sz, most of the height irregularity is the surface peaks, probably caused by the fuzzy wood after milling. Proof of this statement is the development of the surface parameter Sp, which is highest in this area. The claim is also supported by the surface parameter Ssk, which is greater than 1 μm in this area, indicating a predominant peaks surface. At the same time, from the Sku values, it can be argued that the surface is defined by pointed unevenness, probably due to protruding fibers. The combination of a thickness of the removed layer of 3 mm and a feed speed of 6 m·min-1 creates critical surface irregularities. With this combination the surface is defined predominantly by pits (Sv), probably caused by torn fibers. Evidence of valleys is also the parameter Ssk, which in this area is less than -0.8 μm. Although it is not possible to compare the values of areal surface texture parameters with profile parameters at the same time, it is possible to compare the resulting surface quality in other experiments. Best surface quality (*Figure 2*) was achieved with a thickness of the removed layer of 1 mm and a feed speed of 6 m·min^{-1}. In this case, the parameters Sa, Sp, Sz and Sv reach the lowest values, the parameter Ssk define distribution of peaks and valleys, and Sku is evidence of an even distribution of pointiness.

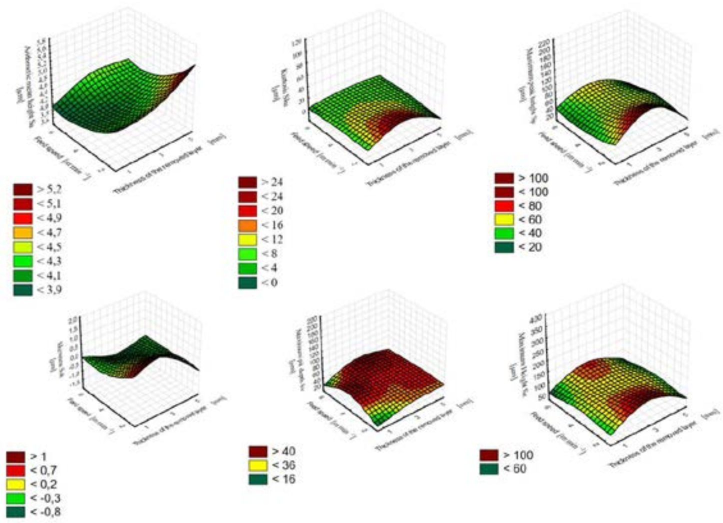

Figure 2. Influence of feed speed and thickness of the removed layer on evaluated areal surface texture parameters of maple wood.

Birch wood (*Figure 3*) had the worst surface quality achieved in a thickness of the removed layer of 3 mm and a feed speed of 6 m·min^{-1}. The graphs show that with this combination of values of the milling parameter, significantly protruding fibers (fuzziness of the surface) have formed on the surface. Proof of this claim is the high value of the parameter Sp as well as a sharp increase in Ssk, which reaches values higher than 2 μm (predominant peaks). There is also an evident deterioration of surface quality with increasing feed rate when milling birch wood (Pinkowski *et al.,* 2012). The highest quality after milling was achieved with a combination of thickness of the removed layer of 3 mm and a feed speed of 4 m·min^{-1}. The surface in this case has evenly distributed hills, and the valleys of the profile and irregularities have the smallest height.

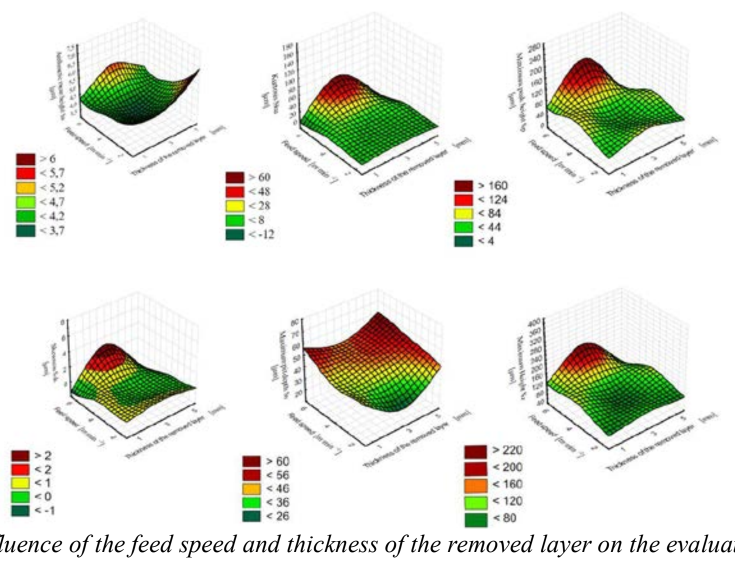

Figure 3. The influence of the feed speed and thickness of the removed layer on the evaluated areal surface texture parameters of birch wood

The unevenness of beech wood can be considered difficult to assess (*Figure 4*). From the parameter Sa it is possible to see a different development of irregularity than in the case of other parameters, which cannot be explained without additional microscopic analysis. The most critical surface quality was measured when combined thickness of the removed layer of 3 mm and feed speed 2 m·min^{-1}. Highest irregularities at feed speed 2 m·min^{-1} when milling beech wood also follow from the work of Pinkowski et al. (2012). The authors claim that with the increase in feed speed, there is an improvement in surface quality. This was partially measured in this experiment. When combining these values of milling parameters, the surface showed a sharp increase in the height of the irregularities. Those are mainly formed by protruding fibers, which is also evidenced by the Sp parameter. This statement also follows from the increase in skewness values (Ssk). At the same time, Sku shows that irregularities in this area are more pointed, with significant extremes. On the contrary, the highest surface quality after milling was achieved at approximately thickness of the removed layer of 3 mm and a feed speed of 4 m·min^{-1}. During this combination there was a leap decrease in the height of irregularities. The protruding fibers were milled, and there was no significant formation of torn fibers.

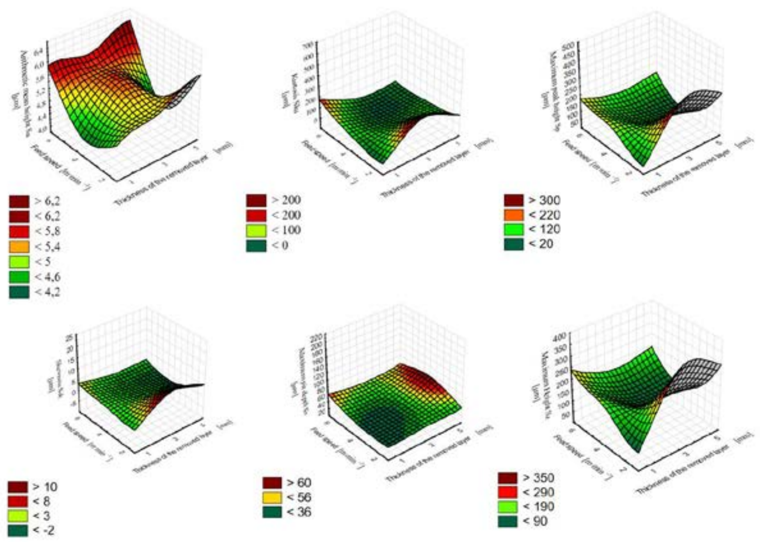

Figure 4. Influence of feed speed and thickness of the removed layer on the evaluated area parameters of beech wood unevenness

4. CONCLUSIONS

In the presented results, the effects of two milling parameters – feed speed and thickness of the removed layer on the areal surface texture parameters of maple, beech and birch wood were examined. The analysis of variances showed that all three monitored factors have a statistically significant effect on parameters in interaction with each other. This was expressed through 3D plot graphs, where a combination of the thickness of the removed layer and the feed speed was identified, forming the highest quality and lowest quality wood surface. The measurements in the experiment resulted in similar conclusions as in the works of other authors. The identified combinations of the thickness of the removed layer and the feed speed for each type of wood were:

Maple wood:
3 mm and 2 m·min^{-1} (the lowest quality surface)
1 mm and 6 m·min^{-1} (the highest quality surface)

Birch wood:
- 3 mm and 6 $m \cdot min^{-1}$ (the lowest quality surface)
- 3 mm and 4 $m \cdot min^{-1}$ (the highest quality surface)

Beech wood:
- 3 mm and 2 $m \cdot min^{-1}$ (the lowest quality surface)
- 3 mm and 4 $m \cdot min^{-1}$ (the highest quality surface)

This knowledge contributes to knowing the correct setting of the combination of milling parameters with respect to the quality of the created surface. The measured data show that for birch and beech wood, the highest quality was achieved with a thickness of the removed layer of 3 mm and not 1 mm as indicated by theory of machining.

Acknowledgements: *This experimental research was prepared within the grant project APVV-21-0051 "Research of false heartwood and sapwood of Fagus sylvatica L. wood in order to eliminate color differences by the process of thermal treatment with saturated water steam" as the result of the work of the author and the considerable assistance of the APVV agency and within the projects by the Slovak Research and Development Agency under contracts VEGA 1/0324/21 "Analysis of the risks of changes in the material composition and technological background on the quality of the working environment in small and medium-sized wood processing companies". The contribution was also prepared within the project agency IPA TUZVO, which contributed significantly to the creation of this contribution through the project: IPA TUZVO 9/2023.*

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ABSTRACT

This study series shows activities in wood science at the University of Sopron, Hungary. In this article, we review some of our test results concerning different nanomaterials, the compression of wood along the grain, the properties of different poplar clones and the nail and screw withdrawal resistance of poplar. Several nanoparticles were proved to be suitable for improving wood properties. The metal nanoparticles offer an excellent opportunity to increase biological durability and outdoor colour fastness. Improving fire resistance is possible with clay mineral-based particles or metal oxide nanoparticles. For hydrophobization, silicon-based nanoparticles seem to be the best solution. The compression of wood along the grain changes the whole structure of the wood. At the submicroscopic level, microfibrils are crinkled with a wavelike shape, like the cell walls at the microscopic level. The modulus of elasticity decreases highly, ensuring a high pliability for the treated wood.

Key words: wood modification, nanomaterials, wood compression, poplar wood

1. INTRODUCTION

The University of Sopron, Hungary deals extensively with the proper management of trees and wood from both scientific and practical perspectives. The Faculty of Forestry is the only place in Hungary to train, among others, forest engineers and nature conservation engineers, while the Faculty of Wood Engineering and Creative Industries trains, among others, engineers for the wood industry, specialists in the creative industry, and product designers. The former Institute of Wood Science, now part of the Institute of Basic Sciences, deals with wood's properties and modification possibilities. Good examples are the following scientific publications: (Komán and Fehér, 2020; Kern *et al.*, 2022; Komán and Varga, 2020; Horváth and Fehér, 2023; Komán, 2022; Fehér *et al.*, 2014; Komán and Ábrahám, 2021). This study aims to present the activities and significant results we have carried out in recent years to present research regarding the wood industry. We believe that the work we do is globally significant. In this article, we would like to give a short review of the treatment of different wood species with different nanomaterials in our Institute and a short review of the wood compression along the grain, aka pleating.

1.1. Improving wood properties using nanomaterials

Wood is one of the most important renewable raw materials today, with the added benefit of being recyclable and CO_2-neutral. It is a highly versatile material used for various purposes for thousands of years. The demand for wood is constantly growing. Wood science is constantly detecting these growing demands, but much research and development will be needed to overcome the problems in the future. Modification of wood is a general term that describes the use of chemical, physical, or biological methods to purposefully alter the properties of a material (Hill, 2006). The demand for modified timber is increasing worldwide due to the emergence of various industrial timber modification processes in recent decades. The goal is to increase the performance of the wood by improving dimensional stability, fungal resistance, weather resistance, etc. Reducing moisture adsorption can be a key factor in improving biological durability or solving the dimensional stability problem (Turgut Sahin and Mantanis, 2011).

Nanomaterials could be used to enhance existing wood-based products in terms of its functionality. For example, the use of nanomaterial in a wood coating such as nano zinc oxide or nano titanium oxide can enhance the functionality of the wood in terms of its durability, fire resistance and UV absorption as well as decrease water absorption (Cristea *et al*., 2010; De Filpo *et al*., 2013; Francés Bueno *et al*., 2014). On the other hand, the application of nanoencapsulation in wood preservatives (Liu *et al*., 2002) could improve the impregnation of wood with pesticides by ensuring that chemicals can penetrate deeper into the wood, thus reducing the issue of excessive leaching. This improves the durability of treated wood against biodegradation agents.

A new way to reduce water adsorption is to produce hydrophobic surfaces. One-step methods such as laser/plasma/chemical etching or lithography have been developed to produce low surface energy materials (Han and Steckl, 2009; Kang *et al*., 2010). The hydrophobic surface can also be prepared by two-step methods, where the first step is to produce a coarse coating on the support and then a modification step to achieve hydrophobicity (Saleema *et al*., 2011). SiO_2 is often used to produce nano-level roughness on surfaces as inorganic nanoparticles due to its low cost and environmentally inert nature. This effect can be enhanced when modified to achieve excellent water repellency (Athauda *et al*., 2012; Xu and He, 2012). Nowadays, superhydrophobic surfaces are popular in various fields due to their excellent properties such as hydrophobic and/or oleophobic or self-cleaning nature (Chang *et al*., 2008; Sarkar and Saleema, 2010).

In recent years, several opportunities have been explored at the former Institute of Wood Science to increase the biological durability and outdoor colour fastness of wood, as well as to increase dimensional stability and fire resistance. During this work, several nanoparticles were proved suitable for improving individual wood properties and how they should be used. Different metal nanoparticles offer a good opportunity to increase biological durability and outdoor colour fastness. Improving fire resistance is possible mainly with clay mineral-based particles, but good results can also be obtained with metal oxide nanoparticles. In the field of hydrophobization, various silicon-based nanoparticles have given satisfactory results.

The most important results of the research conducted at the former Institute of Wood Science during the last years on this topic were the following:

- The applicability of zinc oxide and zinc borate nanoparticles to increase the biological durability of wood at low concentrations was explored (Lykidis *et al*., 2016; Németh *et al*., n.d.).
- The dimensional stabilizing effect of using hydrophobic titanate nanotubes and hydrophobic titanate nanofibers in wood materials was proved (Bak *et al*., 2017).
- The use of metal nanoparticles has led to significant improvements in the biological durability of wood materials. The minimum concentrations required for efficiency for each nanoparticle were revealed. The efficiency of fixation in the wood and the effect of leaching on the wood protection efficiency were tested. It was found that besides high efficiency, leaching resistance is low, except in zinc-oxide nanoparticles (Bak and Németh, 2018).
- The dimensional stabilizing effect of hydrophobized silica nanoparticles on wood was revealed. The stable fixation of the nanoparticles on the surface of the cell wall of the wood was solved, and the hydrophobic nature was strengthened (Bak *et al*., 2019).
- The basic wood-water relations of microporous silica aerogel-modified wood were cleared. It was found that water uptake is decreased, resulting in dimensional stabilization of wood (Bak *et al*., 2022).
- Fluorinated silica nanoparticles have been proven to be effective in improving the dimensional stability of wood. A simple, one-step method was used to achieve a long-

lasting hydrophobization effect, showing near-superhydrophobic (water contact angle of around 130-140°) properties (*Figure 1*; (Bak *et al*., 2023)).

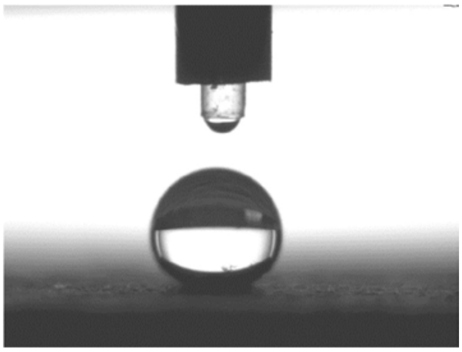

Figure 1. Water droplet on a fluorinated silica nanoparticle-modified wood surface.

1.2. Wood compression along the grain (aka. pleating)

Natural wood has several beneficial properties that have made it suitable since historical times to serve as the raw material for our objects, furniture, buildings, etc. In the wide range of wood modification processes, compression in the fibre direction (a.k.a. pleating) is a relatively new process still undergoing industrial development. Expanding the range of (mostly bent) products that can be produced and improving their properties requires research based on materials science, which has to fill the gap in the present knowledge. My research aims to understand better the changes in this bendable modified wood from the molecular and submicroscopic level, to explore the possibilities and limits of modification, and to determine technological parameters that are also useful for industry.

Beech and oak wood specimens were compressed after steaming using unique equipment developed for laboratory purposes. We used specimens with moisture content above their fibre saturation point, with minimal grain slope, free of knots and other defects. The relative rate of compression was 20-25 %/min and the compression ratio was 20 % compared to the original length of the specimens (20 × 20 × 200 or 2 × 30 × 200 mm). We used two main procedures: either, when the compression finished, the modification completed and the specimens were ready for further use. In the other method, fixated specimens were formed by constantly holding the specimen at the applied compression level for a predetermined time. The tests on the finished specimens were preferably performed according to the relevant standards.

Fixation strengthens the changes induced by pleating; a good example is the modulus of elasticity, which decreases to 40 % due to compression. Fixation for at least 3 hours after compression results in a decrease of modulus of elasticity to 25 % of the initial value, and the pliability of the wood will show a further significant improvement (*Figure 2*). Distortions occur in the cellular structure, the cell walls of vessels and fibres buckling mainly on their weakly supported sections. Examining pleated wood at the submicroscopic level, the indentation modulus and hardness of the S2 cell wall layer decrease. Moreover, the dimensional stability in the direction parallel to the grain deteriorates significantly. This is explained by the atomic force microscopy images, where it is seen that the microfibrils are crinkled with a wavelike shape. Thus, their significant transverse dimensional change due to moisture change acts partly parallel to the longitudinal axis of the cell. Infrared spectroscopic studies have shown that steaming, compression and fixation all cause changes in hydroxyl groups and in additional C-O and C-H functional groups. This affects the sorption behavior of pleated wood, which responds more slowly to changed climatic conditions. The fibre saturation point decreases. As a result of pleating, a 1 % change in moisture content changes the modulus of elasticity by 5.0 %, the modulus of rupture by 4.2 %, and the highest available deformation by 7.6 %. The shrinkage and swelling in the direction parallel to the grain is up to ten times compared to untreated wood, mainly due to cell structure changes. Lactic acid impregnation has greatly improved dimensional stability problems while preserving the environmental friendliness of pleated wood. For more information on this topic, please read the review article of Báder and Németh (Báder and Németh, 2023).

Figure 2. Typical bending test specimens in the material testing machine at the moment of failure: untreated (a), compressed along the grain and fixated for 1 minute (b), and compressed and fixated for a long time, which did not break during the bending test (c).

2. CONCLUSIONS

We presented in this article several studies on the treatment of wood with different nanomaterials, on the compression of wood along the grain, on some properties of different poplar clones and on the nail and screw withdrawal resistance of poplar.

The metal nanoparticles such as zinc oxide and zinc borate offer a good opportunity to increase biological durability and outdoor color fastness even at low concentrations. Clay mineral-based particles and metal oxide nanoparticles improved fire resistance. For hydrophobization, the titanate nanotubes and hydrophobic titanate nanofibers were good solutions, and silicon-based nanoparticles seem to be the best solutions. The fixation of the nanoparticles on the cell wall surfaces was solved, strengthening the hydrophobic property. Microporous silica aerogel decreased the water uptake, resulting in dimensional stabilization. Fluorinated silica nanoparticles improved the dimensional stability of wood, too, and had a long-lasting near-superhydrophobic effect.

The compression of wood along the grain causes changes in all structural levels of wood. Of course, its properties change as well. For example, the modulus of elasticity decreases to 40 % as a result of compression and fixation for at least 3 hours after compression, resulting in a further decrease to 25% of the initial value. These decreases ensure high pliability for wood. At the submicroscopic level, it can be seen that the microfibrils are crinkled with a wavelike shape, similar to the cell walls at the microscopic level.

***Acknowledgements**: This article was made in the frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.*

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The Influence of Structural Elements on the Measurement of Thermal Conductivity Using the Hot Disc Method of Wood-based panels

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ABSTRACT

Thermal conductivity is one of three ways of heat transfer in materials. In aim of reducing heat loss through materials knowledge of thermal conductivity plays important role in energy savings. Aim of this paper was to examine statistical differences in thermal conductivity of wood-based low environmental impact panels made with oak wood, glue, mineral fibre panel, cardboard, paper and cork. Samples were divided in 3 groups. First group were samples prepared with oak veneer made by cutting and glued with polyurethane glue (PU) with different veneer thickness. Second group were the same as first, except samples were glued with polyvinyl acetate glue (PVAC). Third group were samples with oak peeling veneer and different sandwich elements. Statistical analysis was made within the groups according to veneer thickness, glues and sandwich elements. In results, glue type was shown to have statistical influence, as well as veneer thickness, where panel made with thicker veneer showed higher conductivity even due opposite expectation. More experiments must be done to determine every possible influence on thermal conductivity of these wood-based panels.

Key words: Thermal conductivity, hot disk method, wood-based panel, statistical analysis

1. INTRODUCTION

Wood is well known to have good insulation properties. Hard density woods have higher thermal conductivity, so low density wood is more appropriate for use as a thermal insulation building (Kang *et al.*, 2015). However, oak wood is very appreciated and used from prehistoric times. It is long known because of heartwood durability, mechanical properties (Haneca *et al.*, 2009) and texture, and it is the most important wood in European culture heritage (Cufar *et al.*, 2014). In aim to increase quantitative volume of oak, veneer rests were used. Combination of oak and other sustainable, renewable, biodegradable and low-cost material can reduce energy consumption. An example of such material is mineral wool, which is produced as half of production of all insulating materials (López-García *et al.*, 2022; Alpackiy, 2023). Some other materials are also used as insulation materials for building: cork (Gil, 2011), recycled paper (Jensen and Alfieri, 2021) and recycled cardboard (Mathews *et al.*, 2023).

2. MATERIALS AND METHOD

Materials

Rest from oak (*Quercus robur* and *Quercus sessiliflora*) veneer was used as first and last layer in panels. Samples were cut on CNC machine in 30 mm and 100 mm diameter. Structure of veneer was mostly tangential and included sapwood and hardwood. Both sides of all samples were made of oak veneer cut or peeled and 15 mm thick mineral fibre was used as middle layer. First group were samples prepared with oak veneer cut in different thickness: 2.3 mm, 2.9 mm, and 3.5 mm, then glued with PU glue on 15 mm thick mineral board. Second group were the same as first except samples were glued with PVAC glue. Third group were samples with oak peeling veneer 0.6 mm thick or glued as 3 x 0.6 mm veneer and then made with different sandwich elements: cardboard, paper, cork and 15 mm thick mineral fibre panel. Total of 10 subgroups were examined. Details can be found in (*Table 1*).

Table 1. This table presents 3 groups of samples with 3 subgroups of first and second groups and 4 subgroups of third group.

Group	Description	Sample mark
First group of samples	Sawn veneer 2.3 mm + PU glue + Armstrong board 15 mm + PU glue + sawn veneer 2.3 mm	2.3OAK,PU,ARM
	Sawn veneer 2.9 mm + PU glue + Armstrong board 15 mm + PU glue + sawn veneer 2.9 mm	2.9OAK,PU,ARM
	Sawn veneer 3.5 mm + PU glue + Armstrong board 15 mm + PU glue + sawn veneer 3.5 mm	3.5OAK-PU,ARM
Second group of samples	Sawn veneer 2.3 mm + PVAC glue + Armstrong board 15 mm + PVAC glue + sawn veneer 2.3 mm	2.3OAK,PVAC,ARM
	Sawn veneer 2.9 mm + PVAC glue + Armstrong board 15 mm + PVAC glue + sawn veneer 2.9 mm	2.9OAK,PVAC,ARM
	Sawn veneer 3.5 mm + PVAC glue + Armstrong board 15 mm + PVAC glue + sawn veneer 3.5 mm	3.5OAK-PVAC,ARM
Third group of samples	cut veneer 0.6 mm + PVAC glue + cork 2 mm + PVAC glue + Armstrong board 15 mm + PVAC glue cork 2 mm + PVAC glue + cut veneer 0.6 mm	0.6OAK,PVAC,CORK,ARM
	Cut veneer 0.6 mm + PVAC glue + cardboard 2 mm + PVAC glue + felt + Armstrong board 15 mm + PVAC glue + felt + cardboard 2 mm + PVAC glue + cut veneer 0.6 mm	0.6OAK,PVAC,CARDB,ARM
	Cut veneer 0.6 mm + PVAC glue + 2 layers of recycled paper + PVAC glue + Armstrong board 15 mm + PVAC glue + 2 layers of recycled paper + PVAC glue + cut veneer 0.6 mm	0.6OAK,PVAC,PAPER,ARM
	Three-layer cut veneer 1.8 mm + PVAC glue + Armstrong board 15 mm + PVAC glue + three-layer cut veneer 1.8 mm	1.8OAK,PVAC,ARM

Methods

Measurements were performed with modified transient plane source technique (MTPS) with guard ring produced by C- Therm acc. to ASTM D7984. All measurements were performed in ambient temperature and humidity (23 ± 2°C and 55 ± 10 %). This method provides simple preparation and fast results (Colinart *et al*., 2021) with small variations in the same measurement. Samples were centered on a measurment ring and a 500 g weigh was put on top to make good contact between ring and sample. Before measurments, calibartion for insulation material was made and softweare measuremnts were selected for insulation materials. Each sample was measured 5 times. Measurements can be seen in (*Figure 2*).

Figure 2. Measurement preformed with C-Therm, hot disk method. In background, samples of 30 and 100 mm diameter can be seen with hardwood and sapwood on surfaces

3. RESULTS

From (*Table 2*) can be seen that the samples in group 1, which were glued with PU glue, had the lowest values of TC, then the second group with PVAC and the third group with more complex sandwich structure and more PVAC glues layers. That would suggest that PVAC glue has impact on TC. The lowest values in all groups had samples with thicker veneer in first second and third group. These data are not expected due to higher TC of oak wood in comparison to mineral panel.

Table 2. Table presents average values, standard deviation and number of measurements of all samples

	Sample	Average thermal conuctivity (W/mK)	Standard deviation	Number of measurements
First group of samples	2.3OAK,PU,ARM	0.0672	0.0025	15
	2.9OAK,PU,ARM	0.0675	0.0161	25
	3.5OAK-PU,ARM	0.0607	0.0105	25
Second group of samples	2.3OAK,PVAC,ARM	0.0757	0.0056	25
	2.9OAK,PVAC,ARM	0.0726	0.0079	25
	3.5OAK-PVAC,ARM	0.0666	0.0153	25
Third group of samples	0.6OAK,PVAC,CORK,ARM	0.0951	0.0226	30
	0.6OAK,PVAC,CARDB,ARM	0.1055	0.0050	30
	0.6OAK,PVAC,PAPER,ARM	0.0994	0.0145	30
	1.8OAK,PVAC,ARM	0.0925	0.0064	30

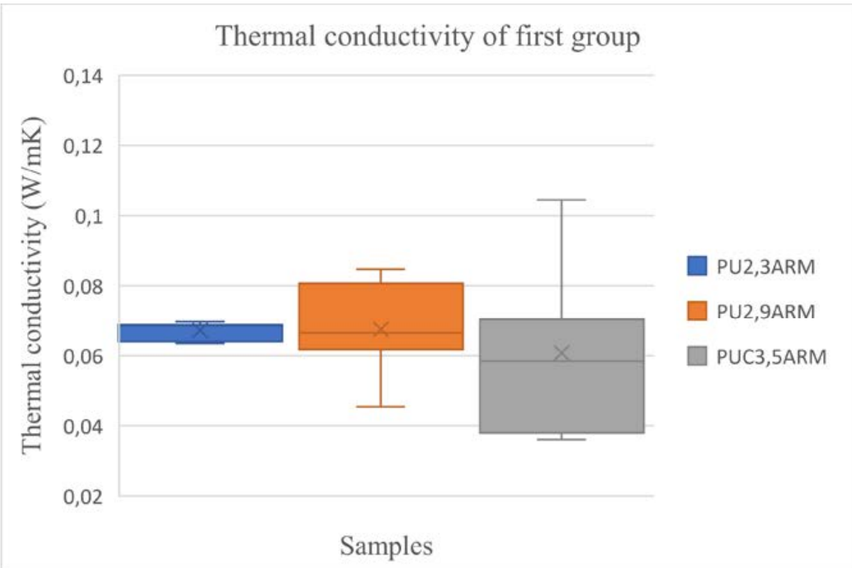

Figure 3. Subgroups of first group of samples

In (*Figure 3*) TC of first group is shown. Three subgroups of first group are presented as different veneer thickness. Lowest average value has PU3.5ARM but with most variation, then PU2.3ARM with lowest variation and similar average had PU2.9ARM. In (*Table 3*) statistical analysis anova was preformed and thickness of veneer had no statistical impact with *p* value of 0,05.

Table 3. Statistical analysis of first group of samples

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
PU2.3ARM	15	1.0078	0.067187	6.14E-06
PU2.9ARM	25	1.6875	0.0675	0.000194
PUC3.5ARM	25	1.5184	0.060736	0.000599

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000681	2	0.00034	1.103604	0.3381	3.145258
Within Groups	0.019117	62	0.000308			
Total	0.019797	64				

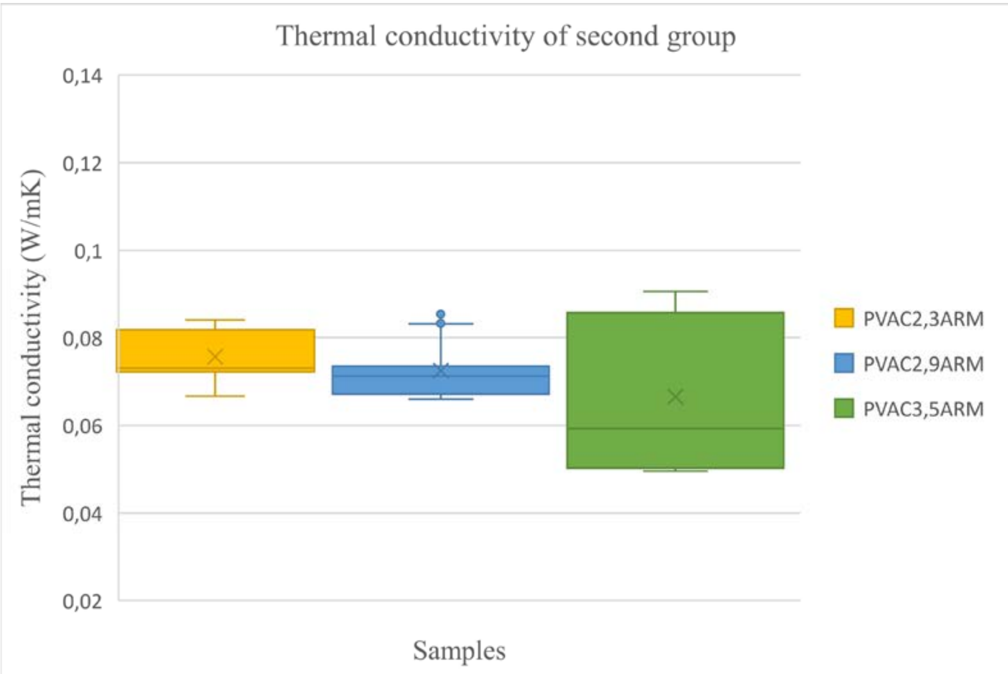

Figure 4.Subgroups of second group of samples

Three subgroups of second group are presented as different veneer thickness (*Figure 4)*. Lowest average value has PVAC3.5ARM but with most variation, then PVAC2.3ARM with lowest variation and similar average as PVAC2.9ARM. Statistical analysis anova was preformed and thickness of veneer had statistical impact with p value of 0.05. After anova, post hoc test was preformed to determine what subgroup had impact and from (*Table 4)* it can be found that there is statistical difference in veneer thickness between 2.3 and 3.5 mm.

Table 4. Statistical analysis of second group of samples with Bonferroni post hoc test

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
PVAC2.3ARM	25	1.89157	0.075663	3.46E-05
PVAC2.9ARM	25	1.81397	0.072559	4.21E-05
PVAC3.5ARM	25	1.6642	0.066568	0.000297

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001069	2	0.000534	4.292246	0.017335	3.123907
Within Groups	0.008963	72	0.000124			
Total	0.010032	74				

post hoc - Bonferroni

Groups	significant
PVAS2.3ARM vs PVAC2.9ARM	No
PVAC2.3ARM vs PVAC3.5ARM	Yes
PVAC3.5ARM vs PVAC2.9ARM	No

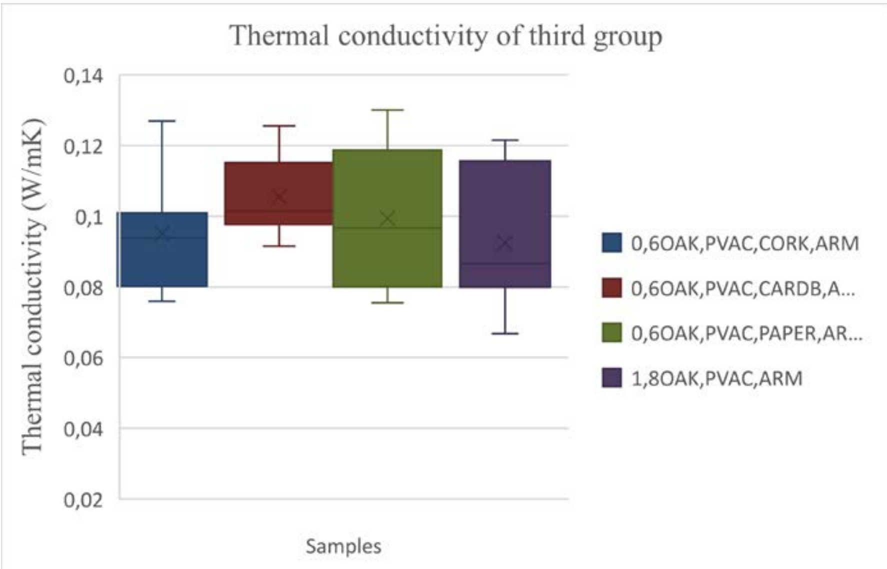

Figure 5. Subgroups of third group of samples

Subgroups of third group are presented as different sandwich elements, (*Figure 5*). Lowest average value has 1.8OAK,PVAC,ARM, then 0.6OAK,PVAC,CORK,ARM and after that samples with layers of paper and cardboard. Statistical analysis anova was preformed (*Table 5*) and there was statistical impact with p value of 0.05. After anova, post hoc test was preformed and there was statistical difference between first and second subgroups and between second and fourth subgroups.

Table 5. Statistical analysis of third group of samples with Bonferroni post hoc test

SUMMARY

Groups	Count	Sum	Average	Variance
0.6OAK,PVAC,CORK,ARM	30	2.8535	0.095117	0.000259
0.6OAK,PVAC,CARDB,ARM	30	3.1649	0.105497	0.000129
0.6OAK,PVAC,PAPER,ARM	30	2.9828	0.099427	0.000372
1.8OAK,PVAC,ARM	30	2.77607	0.092536	0.000354

ANOVA

SourceofVariation	SS	df	MS	F	P-value	F crit
BetweenGroups	0.00289	3	0.000963	3.460175	0.018699	2.682809
WithinGroups	0.032292	116	0.000278			
Total	0.035182	119				

post hoc - bonferroni	significant
0.6OAK,PVAC,CORK,ARM vs 0.6OAK,PVAC,CARDB,ARM	Yes
0.6OAK,PVAC,CORK,ARM vs 0.6OAK,PVAC,CARDB,ARM	No
0.6OAK,PVAC,CORK,ARM vs 1.8OAK,PVAC,ARM	No
0.6OAK,PVAC,CARDB,ARM vs 0.6OAK,PVAC,PAPER,ARM	No
0.6OAK,PVAC,CARDB,ARM vs 1.8OAK,PVAC,ARM	Yes
0.6OAK,PVAC,PAPER,ARM vs 1.8OAK,PVAC,ARM	No

4. CONCLUSIONS

Three groups of samples were divided into additional subgroups (total of 3 for the first and second group and total of 4 for the third group). Analisys was made according to thicknesses, glues and different sandwich structures. The lowest values had samples from the first group glued with PU glue, which would mean that PU has the lowest impact on TC. Second and third group was glued with PVAC glue. Another conclusion that can be made is that more layers increase TC. For the first group there were no statistical differences that would suggest that veneer thickness had impact. In the second group, there were differences between thinner and thicker veneer (2.3 and 3.5 mm). These indicate that oak has lower TC values than PVAC glue, especially that TC decreases as veneer thicknesses increases.

The lowest values in the third group had samples with thicker veneer followed by samples with cork and than with paper and cardboard. More layer increases TC but it is not implemented because of layers or glue applied between layers.

There are also other influences of TC in wood that had been investigated, but were not used as referent in this paper, such as: heardwood and sapwood (Haman, 2015; MacLean, 1941), extractives (Vasubabu et al., 2016) and presence of defects (Chen, 1997).

Acknowledgements: *This paper was made due to project: "Research and development of innovative wooden wall coverings, partitions and load-bearing walls for sustainable construction".*

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Modified PUR Adhesive and its Effect on Longitudinal Tensile Strength Under Tensile Stress

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ABSTRACT

The study focuses on using a modified polyurethane (PUR) adhesive with a thermosetting polymer for bonding laminated timber from deciduous species. Three types of gluing combinations have been tested: simple adhesive bond, deep penetration adhesive bond with deep penetration (Methyl ester of acrylic acid) and deep penetration adhesive bond combined with a thermosetting polymer. This included adding 10 % thermoset (Epoxy phenol resin) to the PUR adhesive. Surface treatments were sanding and planing applied to enhance the bonding process. Samples glued with each type of adhesive system were tested for longitudinal tensile strength at 12 % moisture content and elevated moisture content after 4 hours of soaking in water. The wood species used for the samples were beech (*Fagus sylvatica,* L.), oak (*Quercus petraea,* (Matt.) Liebl.), and black locust (*Robinia pseudoacacia,* L.). Surface roughness and surface energy were measured to assess the quality of the surface. The study concludes that the most effective approach for glued laminated timber in structural applications involves a combination of surface treatment through sanding and the use of a modified adhesive with a thermosetting polymer, along with deep penetration. The PUR adhesive application could be used for structures exposed to higher moisture content regularly or occasionally.

Key words: longitudinal tensile strength under tensile stress, modified polyurethane, surface treatment, thermosetting polymer

1. INTRODUCTION

For higher-quality glued units, splitting the wood and selecting better quality is used for gluing load-bearing units. Therefore, a sufficient gluing process must be done properly to use those quality timber selected in the first place. For glued-laminated units, mostly softwood species were and still are used. Nowadays, there is a tendency to use hardwood as well. As a result of climate change, there might be a change in the layout of wood species in Europe. Thus, this paper focuses on how hardwood could be glued for load-bearing units; specifically, it is concerned with oak, beech, and black locust.

A great number of studies have been carried out about the utilization of hardwood in load-bearing units (Uzelac Glavinic *et al.,* 2023; Šuhajdová *et al.,* 2023; Uzelac Glavinic *et al.,* 2020; Brunetti *et al.,* 2019). It is known that softwood gluing was mostly used in load-bearing units. In this academic paper, the heartwood gluing process for glued laminated timber is carried out. For these units, the PUR adhesive system has qualities for a sufficient gluing process. Some studies also considered PUR adhesive for load-bearing units (Sanni and Ekundayo, 2022; Arum *et al.,* 2021). Gluing hardwood could be problematic due to its high density, smooth surface, and potentially high abundance of extractives (Novosel *et al.,* 2022).

Penetration of adhesive into the hardwood is much more challenging than into the softwood species. Factors that affect this are wood specie, anatomical orientation, surface roughness, adhesive viscosity, applied pressure and temperature. The study (Hass *et al.,* 2012) describes PUR adhesive penetration of cell walls through scanning-thermal microscopy (SThM) on spruce and beech wood. For softwood is far simpler; adhesive is in tracheids and forms interconnected zones. The adhesive in hardwood fills vessels differently; hence, it is further from the bond line.

For the above-mentioned, it seems important to be more concerned about surface pretreatment before gluing process and then even modify a sufficiently adhesive system to meet quality properties for glued laminated timber made of hardwood species.

2. MATERIALS AND METHODS

2.1. Material

The wood used to manufacture the samples was standard commercially bought oak, beech, and black locust. Lamellas had dimensions of 1000x55x5 mm, and they were manufactured using standard machining methods. Surface treatment of those lamellas was 2 types: sanded and planed surface. The sanding surface was done with an SCM Sandya 300 wide belt sander (SCM Group SA, Italy) with a belt roughness of P60, a sliding speed of 4 m/min, and a griding accuracy of 0,01 mm. The planed surface was done with SCM s630 class (SCM Group S.P.A., Italy) with a 7 m/min feed rate, grinding precision of 0,1 mm and planning head with four knives.

For the adjustment of the moisture content of the wood to 12 % (±1 %), conditioning was used. Air conditioning conditions were 65 % relative humidity and a temperature of 20 °C.

The gluing process was carried out by 3 types of gluing. The first was simple gluing with clean adhesive as a reference to the two other systems; this type was marked as an (A) – polyurethane adhesive. The second type of gluing was polyurethane adhesive with deep penetration of the surface marked as (PA). The third type was gluing with polyurethane modified with thermosetting polymer and surface treatment with deep penetration marked as (PTA). The quantity of adhesive system was from 280 to 290 g/m^2 and deep penetration for surface treatment was from 30 to 40 g/m^2. The ratio of thermosetting polymer to adhesive was 1:10 by weight. After the gluing process, samples were put into the heating chamber for thermosetting polymer and adhesive crosslinking; conditions were 120 °C of temperature for 30 mins.

Then samples were tested according to the norm EN 302-1 for the lap joint shear strength (2013).

2.2. Method

2.2.1. Measuring the surface quality

The standard contact method was done with Talysurf 50 (Taylor Hobson, England) that measured roughness parameters, such as Ra, Rz and Rsm, with a measured length of 12,5 mm and base length of 2,5 mm. A Drop Shape Analyzer measured contact angle; polar liquids such as water and non-polar liquids such as diiodomethane were used. Also, those results could be used to measure surface tension. The contact angle was carried out from the edge of the surface to a tangentially approximated circle circumscribed by the drop. Time was measured after the drop reached the surface, after 5 seconds from the contact of the wetted surface. After this, the OWRK method (Owen-Wend-Rabel-Kaeble) calculated the glued surface's total surface tension, and also it could separate disperse and polar parts as well.

2.2.3. Lap joint shear strength

As mentioned above, this standard method was carried out according to the standard EN 302-1. (2013) This method was done by machine TIRA test 2850 (TIRA GmbH, Germany); the test speed was set to 50 mm/min according to the standard EN 302-1 (2013). Samples were either conditioned or soaked in water. Conditioning was at conditioning chamber Memmert

HPP 750 with 65 % relative humidity and temperature at 20 °C. The second batch of samples was soaked in water at room temperature for 4 hours. Samples were put into the machine and ensured in claws so the test could be carried out correctly without slipping. The length of samples that were set in claws was approximately 45 mm, so about 900 mm^2 of the sample was in a claw on the side of the sample. After the force damaged the sample irreversibly, the force was calculated by datalogger ALMENO 2690-8 (Ahlborn GmbH, Germany). Data were then calculated according to standard EN 15425 (2023).

2.2.3. Evaluation and Calculation

Parameters of surface roughness were determined as follows:
Parameter Ra gives the mean arithmetic deviation; it is the arithmetic mean of the absolute values of the ordinated Z(x) in the range of the base length. This parameter is supposed to be followed by other surface parameters cause two surfaces with different properties can have the same Ra value (Hron, 2017; Gajdošík, 2013).

$$Ra = \frac{1}{l}\int_0^1 |Z(x)| dx \tag{1}$$

Parameter Rz is described as the roughness height characteristic. It is given by the sum of the highest peak and the lowest groove in the range of the base length measurement. This parameter serves as an additional parameter to assess the surface roughness (Hron, 2017).

$$Rz = maxZpi + maxSvi \tag{2}$$

Parameter Rsm is the arithmetic average of the widths of the elements in the range of the basic measurement length, which always starts and ends by crossing the centre line of the X-axis. Rsm defines the spacing of the surface roughness used for the length rating of the surface roughness (Hron, 2017; Gajdošík, 2013).

$$Rsm = \frac{1}{m}\sum_{i=1}^{m} Xs_i \tag{3}$$

In terms of the OWRK (Owens-Wendt-Rabel-Kaeble) method, surface free energy was calculated.

$$\sigma_{sl} = \sigma_s + \sigma_l - 2(\sqrt{\sigma_s^D * \sigma_l^D} + \sqrt{\sigma_s^P * \sigma_l^P}) \tag{4}$$

In this equation, σ_s and σ_l are two surface tensions, σ^D and σ^P are geometric means of dispersive and polar part of surface free energy.

The lap joint shear strength was calculated according to the standard mentioned before, EN 302-1. (2013).

$$\tau = \frac{F_{max}}{l_2 * b} \tag{5}$$

For this equation, τ is lap joint shear strength with units MPa, then F_{max} is the maximum loading force at the breaking point with units N, l_2 is the length of the glued area, and b is the width of the glued area, both with mm. So, the force is divided by square mm, which implies MPa.

3. RESULTS AND DISCUSSION

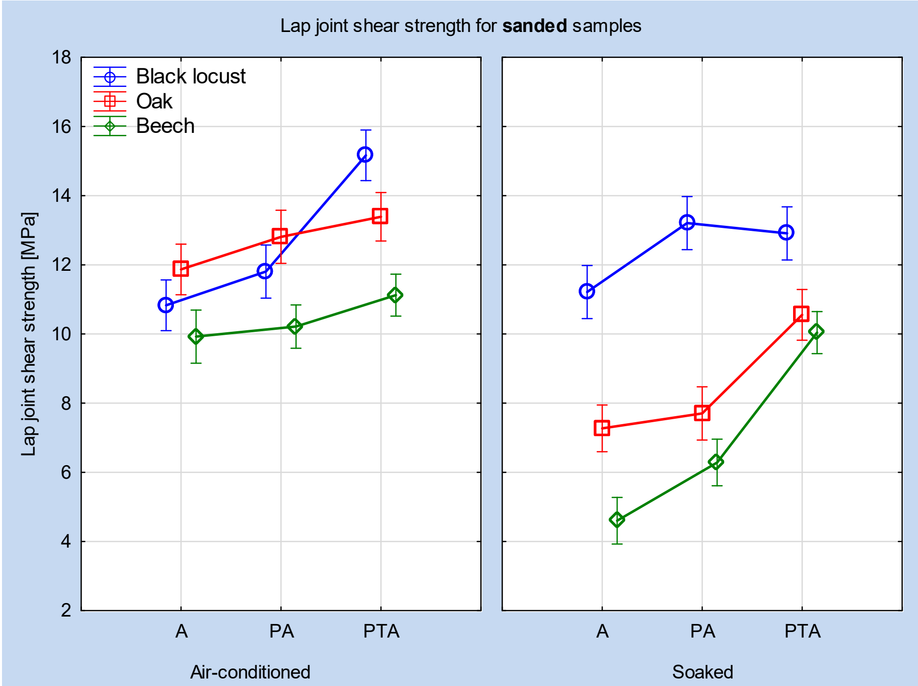

Figure 1. Comparison of lap joint shear strength between air-conditioned and soak for sanded samples.

Figure 1 shows the results of sanded samples in comparison between air-conditioned and soaked samples. For black locust, the increase of the strength for air-conditioned between samples glued with pure adhesive (A) to samples glued with adhesive modified with thermosetting polymer with deep penetration of surface (PTA) is from 10,83 MPa to 15,17 MPa (40,1 %) and for soaked samples increased lower, from 11,21 MPa to 12,91 MPa (15,2 %).

More sufficient results were found for oak and beech samples. For air-conditioned samples of oak glued with pure adhesive (A) to samples glued with adhesive modified with thermosetting polymer with deep penetration of surface (PTA), the increase was from 11,87 MPa to 13,39 MPa (12,8 %), but for oak soaked samples, the increase was from 7,27 MPa to 10,55 MPa (45,1 %).

The same comparison for beech, between samples glued with pure adhesive (A) to samples glued with adhesive modified with thermosetting polymer with deep penetration of surface (PTA), an increase of strength for air-conditioned samples was from 9,92 MPa to 11,12 MPa (12,1 %) and for soaked samples, an increase was from 4,60 MPa to 10,04 (118,3 %).

An increase was significant for black locust, but just for air-conditioned samples between pure gluing with clean adhesive (A) and gluing with adhesive modified with thermosetting polymer with deep surface penetration (PTA). For this figure, an important fact is that for oak and beech samples, an increase was high for soaked samples, 45,1 % for oak and 118,3 % for beech samples. This tendency could be in terms of thermosetting polymer crosslinking with a polyurethane adhesive system. It seems that this adhesive system is sufficient for samples that are exposed to higher moisture content and could be used in situations where higher moisture content is expected.

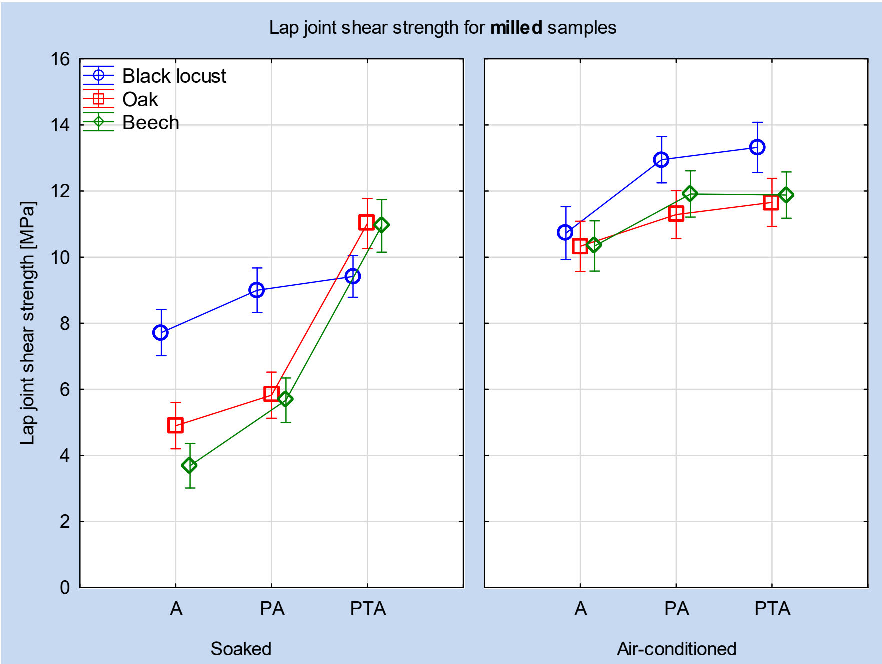

Figure 2. Comparison of lap joint shear strength between air-conditioned and soak for planed samples.

Figure 2 describes the results for planed samples in comparison between air-conditioned and soaked samples. Black locust samples resulted in an increase of strength for samples glued with pure adhesive (A) to samples glued with adhesive modified with thermosetting polymer with deep penetration of surface (PTA) for air-conditioned samples from 10,73 MPa to 13,32 MPa (24,1 %) and for soaked samples was increase from 7,72 MPa to 9,42 MPa (22 %).

A similar trend was for oak and beech samples. Oak samples glued with pure adhesive (A) to samples glued with adhesive modified with thermosetting polymer with deep penetration of surface (PTA) had an increase of strength for air-conditioned samples from 10,33 MPa to 11,66 MPa (12,9 %). The soaked samples had strength from 4,9 MPa to 11,02 MPa (124,9 %).

For beech samples glued with pure adhesive (A) to samples glued with adhesive modified with thermosetting polymer with deep penetration of surface (PTA) for air-conditioned samples was increased from 10,34 MPa to 11,66 MpP (12,8 %). Soaked samples had strength from 3,69 MPa to 10,95 MPa (196,7 %).

Table 1. Surface parameters of planed samples

Planed	Ra (µm)	Rz (µm)	RSm (µm)	Contact angle water (°)	Contact angle diiodo-methane (°)	Surface free energy (mN/m)
Black locust						
Natural surface	6.10 (0.18)	46.69 (0.12)	1153.67 (0.23)	64.27 (0.12)	47.23 (0.14)	48.21 (0.04)
Surface with deep penetration	5.79 (0.29)	43.16 (0.27)	530.43 (0.00)	70.57 (0.12)	66.90 (0.12)	37.64 (0.09)
Surface with deep penetration and thermosetting polymers	7.14 (0.30)	58.29 (0.22)	855.19 (0.6)	70.67 (0.08)	61.66 (0.13)	38.44 (0.07)
Beech						
Natural surface	4.59 (0.08)	30.65 (0.12)	681.00 (0.34)	61.08 (0.07)	35,68 (0,15)	52,82 (0,03)
Surface with deep penetration	5.00 (0.24)	31.49 (0.2)	528.21 (0.21)	87.67 (0.05)	63,45 (0,12)	30,13 (0,09)
Surface with deep penetration and thermosetting polymers	4.39 (0.25)	29.44 (0.23)	594.1 (0.18)	93.55 (0.18)	71.71 (0.05)	25.20 (0.06)
Oak						
Natural surface	11.08 (0.34)	79.24 (0.27)	1994.12 (0.47)	69.42 (0.09)	39.61 (0.19)	47.62 (0.02)
Surface with deep penetration	9.20 (0.19)	68.09 (0.16)	1546.56 (0.43)	41.49 (0.23)	62.90 (0.10)	58.23 (0.04)
Surface with deep penetration and thermosetting polymers	13.04 (0.35)	102.51 (0.32)	1620.32 (0.27)	70.03 (0.15)	69.02 (0.14)	37.39 (0.15)

*Values in parenthesis represent the coefficient of variability

Table 1 shows the average values of surface parameters of all planed samples of black locust, beech and oak. Namely, parameters Ra, Rz and Rsm for surface roughness, contact angles for water and diiodomethane and then surface free energy.

Table 2. Surface parameters of sanded samples

Sanded	Ra (μm)	Rz (μm)	RSm (μm)	Contact angle water (°)	Contact angle diiodo-methane (°)	Surface free energy (mN/m)
Black locust						
Natural surface	6.21 (0.16)	41.20 (0.16)	510.39 (0.27)	40.59 (0.30)	34.80 (0.29)	64.17 (0.12)
Surface with deep penetration	6.03 (0.12)	40.29 (0.18)	530.43 (0.00)	73.40 (0.08)	65.47 (0.11)	35.73 (0.03)
Surface with deep penetration and thermosetting polymers	12.10 (0.32)	80.18 (0.23)	530.43 (0.00)	80.37 (0.07)	75.12 (0.17)	28.91 (0.03)
Beech						
Natural surface	4.75 (0.11)	33.28 (0.15)	489.55 (0.20)	43.16 (0.20)	26.02 (0.34)	64.72 (0.04)
Surface with deep penetration	7.16 (0.14)	41.87 (0.17)	530.43 (0.00)	85.17 (0.07)	60.42 (0.10)	32.94 (0.07)
Surface with deep penetration and thermosetting polymers	11.36 (0.26)	72.87 (0.23)	680.47 (0.44)	72.79 (0.10)	52.97 (0.12)	40.80 (0.06)
Oak						
Natural surface	12.43 (0.13)	80.94 (0.15)	720.10 (0.35)	60.27 (0.11)	28.89 (0.33)	54.94 (0.03)
Surface with deep penetration	13.76 (0.14)	82.66 (0.16)	667.34 (0.17)	36.84 (0.32)	61.48 (0.16)	61.23 (0.06)
Surface with deep penetration and thermosetting polymers	17.93 (0.12)	113.13 (0.12)	843.58 (0.24)	78.71 (0.14)	75.25 (0.09)	29.58 (0.15)

*Values in parenthesis represent the coefficient of variability

Table 2 shows the same average values of surface parameters, contact angles for water and diiodomethane and surface free energy, but for sanded samples.

For roughness parameters, most of them are higher for sanded samples than for planed samples. Those results are how it was expected to happen in terms of surface treatment. Planing, especially with dull knives, could sometimes press wood layers, and therefore, the roughness was not so high. Even with sharp knives, planed samples have lower roughness parameters than sanded samples. This conclusion confirms several studies (Kúdela *et al.,* 2018; Kilic *et al.,* 2006). Contact angles are lower for sanded samples, which implies that wetting is sufficient for those surfaces that have been sanded. Lower contact angles and rather higher surface free energy are observed on those sanded samples that have been sanded with higher grain size sanding paper, which caused roughness parameters to be higher (Ugulino and Hernández 2018).

4. CONCLUSIONS

1. For black locust glued laminated systems, sanding seems to be a sufficient surface treatment with a combination of gluing with deep surface penetration and adhesive with thermosetting polymer. Sanded samples had overall better results for both air-conditioned and soaked samples.
2. For the oak and beech laminated system, slightly better results for soaked samples were after planing a surface in comparison to a sanded surface. Still, there was a higher increase of strength for planed samples between the pure adhesive system and adhesive system with deep penetration of surface and adhesive with thermosetting polymer.

3. Modifying PUR adhesive with thermosetting polymer seems like a good combination for samples exposed to higher moisture content. Therefore, this adhesive system, in combination with deep penetration of the surface with chemicals, manifests as a hydrophobic adhesive system.
4. For further utilization, surface treatment should be considered as it has a big impact on the final results and quality of the adhesive system. Then, deep chemical penetration should be used in terms of better adhesive gluing processes. PUR adhesive seems to be a perspective adhesive for gluing laminated timber from hardwood species; also, this adhesive could be modified with a thermosetting polymer. Lastly, those combinations could be suggested for further investigation on more wood species with different deep penetrations and types of thermosetting polymers.

Acknowledgements: *Authors are grateful for the support of "Advanced research supporting the forestry and wood-processing sectors´ adaptation to global change and the 4th industrial revolution", No. CZ.02.1.01/0.0/ 0.0/16_019/0000803 financed by OP RDE ".*

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Basic Physical and Mechanical Properties of Driftwood Used for Art Installations

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ABSTRACT

This paper investigated the basic technical properties of driftwood collected from the marine coast in Dubrovnik, Croatia. The driftwood was used to create art installations at the Department of Art and Restoration of the University of Dubrovnik as part of the project promoting recyclable materials' utilization. Two different driftwood samples were identified as poplar and sycamore wood. The third sample was softwood species. The discoloration, partial rot, or the effects of wood-boring insects were observed in all wood samples. Density for various wood moisture contents and compressive strength parallel to the grain were investigated for all driftwood samples. The bending strength and modulus of elasticity of poplar wood were determined. The poplar driftwood density is approximately the same as the literature value or slightly reduced for samples with insect damage. The shape of the sycamore samples and the density indicate that the driftwood was part of the tree root system. The softwood sample density was reduced due to burning. The results of compressive strength and bending strength tests showed that the mechanical properties of driftwood have decreased or have changed in the zones exposed to external influence, and, therefore, driftwood has a remarkably reduced quality for construction.

Key words: driftwood, physical and mechanical properties, recyclable materials, wood identification

1. INTRODUCTION

Driftwood is defined as remains of trees that have been generated from natural occurrences such as flooding, storms and winds or as a side effect of logging. These trees can often be found along marine shores as a result of the action of wind, tide, wave or man (Chuchala *et al*., 2021; Tsai *et al*., 2011). Coastal driftwood accumulation is a significant issue for the economy and environmental aesthetics. In countries with developed tourism, driftwood deposited along the coasts is an unpleasant sight and unwelcoming to tourists, which can result in lost tourism revenue. Driftwood is usually removed from the beaches and generally disposed of in garbage sites, which is a huge cost for local authorities (Cotana *et al*., 2016). Cortana *et al.* (2016) investigated the chemical properties of marine driftwood and discovered high chlorine content in the material, which would be of great environmental concern if burnt without reducing the toxic content. They concluded that washing driftwood during a rainfall simulation for one month reduced the chlorine content by 80 % - 90 %.

Driftwood has been used for various purposes for centuries, especially in places that have been relatively poor in terms of native timber resources. In subarctic Norway and the North Atlantic islands from the Viking Age onwards, driftwood was used for construction, boatbuilding, and artefact production (Mooney *et al*., 2023). The inhabitants on the North Pacific coast relied on driftwood mainly as an energy source (Lepofsky *et al*., 2003). But only after World War II the artistic beauty of driftwood was recognized. At first, it metaphorically symbolized the wreckage that the world survived, as the „uprooted, bleached and dried driftwood testified to the largely destructive effects of unleashed natural forces" (Bourdon, 1965 pp. 27). During the late 'forties and early 'fifties of the 20th century, Abstract Expressionism largely embraced an "organic chaos," an "open-mindedness" of design, and balanced asymmetries of driftwood pieces as opposed to the classical preference for symmetry and proportions. What can be recognized as the unique artistic quality of driftwood is that it is the handiwork of nature, not men, and no two pieces are ever alike (Bourdon, 1965).

Because of the increasing environmental problems, designers are more interested in using ecological materials for furniture and art design (Yuksel and Kilic, 2015). Therefore, the use of wood as a raw material is increasing (Bego, 2022). Besides raw and natural materials, recycled materials are often used in ecological design. Recycling can be defined as "the process of collecting and processing materials that would otherwise be thrown away as trash and turning them into new products" (Alqandi and Yousef, 2018). By using driftwood waste in furniture design, the cost of raw material components is significantly reduced, as well as the need to log natural forests (Alqandi and Yousef, 2018; Gunawan *et al.,* 2023). This way, eco-friendly products are created using waste and preserving the environment (Gunawan *et al*., 2023). In countries where driftwood is used for various purposes, collected material is first scanned, and the high-value tree species are used for furniture making, decorative woodwork, and sculptures, while the low-value pieces are used as organic fertilizer or as an energy source (Tsai *et al*., 2011).

Driftwood is naturally modified wood, generally of diverse types and shapes (*Chuchala et al.,* 2021; Qatarneh *et al.,* 2021). This natural modification affects the physical and mechanical properties of wood (Chuchala *et al*., 2021), but in the literature, little information can be found on the properties of coastal driftwood (Cotana *et al*., 2016), which is highly important if considering the use of driftwood in construction, or for furniture making (Chuchala *et al*., 2021).

This paper investigated the basic physical properties and mechanical properties of driftwood that were randomly collected on the marine coast. The objectives were to identify the wood of driftwood samples and to determine the difference between the basic properties of driftwood and natural wood. The study aimed to explore the "quality" of driftwood and the capabilities and limitations of the use of driftwood for wooden constructions, i.e., outdoor furniture, exteriors, or elements of children's playgrounds.

2. MATERIALS AND METHODS

The driftwood was collected on the island of Jakljan in Dubrovnik-Neretva County, Croatia in August 2023, during the 20th anniversary of the Šipan Film Summer School, *Figure 1* (left). The collected driftwood was used to create art installations in an ecological workshop of the Department of Art and Restoration, University of Dubrovnik, Croatia, *Figure 1* (right).


Figure 1. Collected driftwood (left), art installation (right).

The sampling of driftwood was conducted at the Department of Art and Restoration, University of Dubrovnik. Three groups of driftwood samples were selected for properties testing: log of small diameter and without bark, part of the root system, and burnt wood. The discoloration, partial rot, and the effects of wood-boring insects were observed in the wood of all three groups of samples. The wood defects were visually noted but were not subject to analysis and evaluation in this paper.

The test specimens were made and the basic physical and mechanical properties of driftwood were tested at the Department of Wood Technology, University of Sarajevo, Mechanical Engineering Faculty, Bosnia and Herzegovina, *Figure 2*.

Figure 2. Cutting three different driftwood samples.

The type of performed mechanical properties tests and the number of standard specimens were dependent on the dimensions, shapes, and wood defects of the driftwood samples*, Figure 3*.

Figure 3. The shapes and wood defects of the driftwood cut samples.

The nonpermanent slides of cross-section, radial, and tangential sections for microscopic wood identification were made from driftwood samples. Macroscopic and microscopic wood identification was performed by a light microscope Motic B1 with Moticam 2.0 digital camera and Motic Image Plus 3.0 software, as well as by USB hand microscope Bresser. The observed features in sections were compared with reference data in the IAWA list, InsideWood database, and Wood anatomy of central European Species (Schoch *et al*., 2004).

Determination of moisture content and density of the driftwood were carried out in accordance with standards ISO13061-1 (2014) and ISO13061-2 (2014). Prismatic specimens (25×20×20 mm) were used to determine the moisture content and density of the driftwood under ambient conditions at the time of the specimen's processing. After that, the specimens were stored for seven days in the climate chamber (Binder - model KMF 240) at T=20 °C (air temperature) and RH=65 % (relative air humidity), and for those laboratory conditions, the moisture content and density of wood were calculated. Oven-dry wood was obtained after the specimens were stored in a drying chamber (Memmert UF110m) for 48 hours at T= 103±2 °C. Driftwood porosity is calculated based on the expression cap P equals open paren one minus 0,667 bullet rho sub 0 close paren bullet 100 % where rho sub 0–density of absolutely dry wood (Kollmann and Cote, 1968).

The compressive strength parallel to the grain, the driftwood's bending strength, and the modulus of elasticity were determined per the procedures described in ISO 13061-17 (2017), ISO 13061-3 (2014), and ISO 13061-4 (2017), respectively. The tests were carried out on a universal testing machine Zwick 1282, *Figure 4*. The displacement velocity during tests was maintained at 10.0 mm/min in all cases. The compressive strength parallel to the grain was determined for all three groups of samples. The dimensions of the specimens were 40×20×20 mm. In contrast, the bending strength was tested only on specimens cut from small-diameter logs. Dimensions of the specimen cross-section were 20×20 mm and the distance between supports (span) was 280 mm.

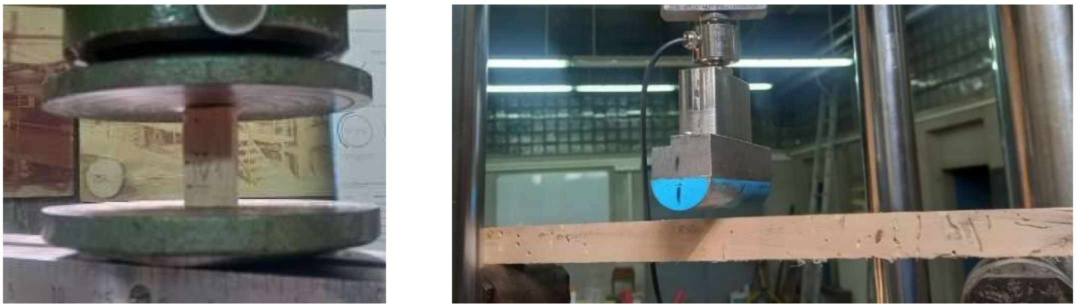

Figure 4. Testing of mechanical properties of driftwood: compressive strength parallel to the grain (left), bending strength (right)

The main statistical features of the test results were determined by descriptive statistics methods. The average values are shown only for the results obtained by testing a small number of specimens.

3. RESULTS AND DISCUSSION

The wood type of small-diameter driftwood logs and driftwood roots were identified to the genus and species level, respectively. The precise scientific identification of the burnt driftwood was not possible, and it was defined as softwood.

Based on the macrostructure and microstructure of the wood cross-section, the wood type of driftwood logs was identified as poplar wood (*Populus spp*.), *Figure 5.* The wood has a creamy and grayish-white color with no gloss and it is diffuse-porous with distinct growth ring boundaries. The pores are small, numerous, solitary, or in radial multiples, and the rays are indistinct.

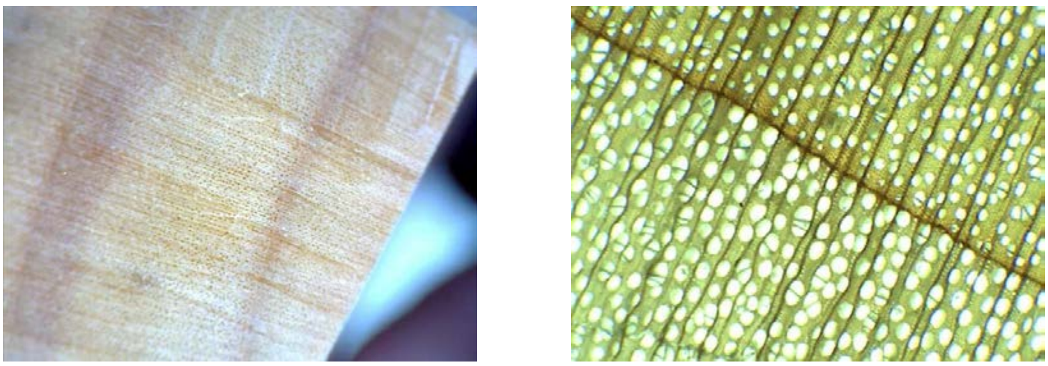

Figure 5. Cross-section of wood from small-diameter logs – poplar (Populus spp.): macroscopic view (left), microscopic view (right).

Based on the macrostructure and microstructure of the wood cross-section, the wood type of driftwood root was identified as sycamore (*Platanus orientalis* L.; *Platanus occidentalis* L.),

Figure 6. The wood has a medium brown color and it is diffuse-porous with distinct and uniformly distributed pores and uniformly large and evenly spaced rays are visible to the naked eye.

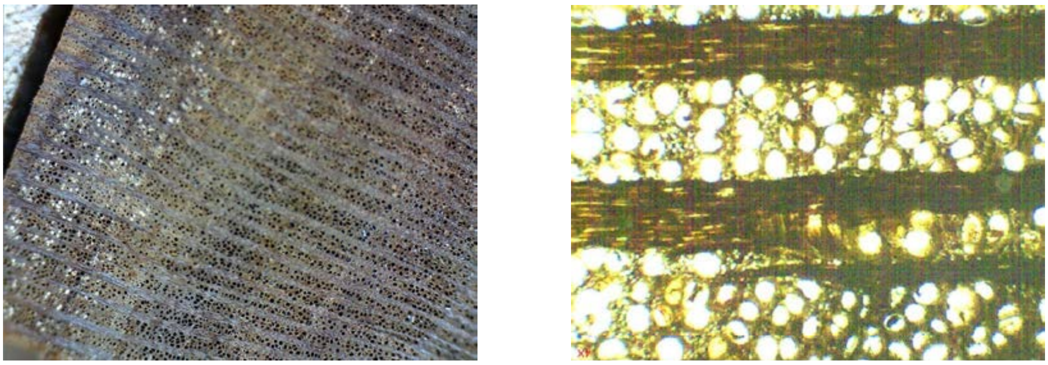

Figure 6. Cross-section of wood from part of the root system – sycamore (Platanus orientalis L.; Platanus occidentalis L.): macroscopic view (left), microscopic view (right).

The results of moisture content and density of poplar wood are given in *Table 1*. The test samples were divided into the group of the poplar clear wood specimens (nine specimens) and the group of poplar wood with defects specimens that were visible on the wood surfaces (fourteen specimens). The average values of moisture content of the two specimen groups in the storage ambient conditions were about 10,0 % and the equilibrium moisture contents for laboratory conditions were about 13.5 %. The average density of the clear wood specimens of poplar was higher than those of the poplar specimens with wood defects for all three moisture contents. The oven-dry wood density of 0.43 g/cm^3 and the average porosity value of 71.3 % for the clear wood specimens show that poplar is extremely light wood and that the results correspond to literature data (Karahasanović, 1992; Forest Products Laboratory 2021).

Table 1. Moisture content and density of poplar driftwood

Physical properties		Storage ambient conditions	Laboratory conditions, T=20°C, RH=65 %	Ovendry wood, W=0 %
Clear wood specimens				
Moisture content, %	Mean	9.86	13.41	-
	Stan. dev.	0.62	0.77	-
	Range	1.57	2.06	-
Density, g/cm^3	Mean	0.45	0.46	0.43
	Stan. dev.	0.03	0.03	0.03
	Range	0.08	0.09	0.08
Specimens with wood defects				
Moisture content, %	Mean	10.17	13.77	-
	Stan. dev.	0.45	0.47	-
	Range	1.39	1.49	-
Density, g/cm^3	Mean	0.43	0.44	0.42
	Stan. dev.	0.01	0.01	0.01
	Range	0.06	0.07	0.06

The average values of moisture content, density and porosity of sycamore wood and burt softwood specimens are given in *Table 2*. The average density of the sycamore wood specimens was lower than the literature density values of 0.55 g/cm^3 for a moisture content of 12 % (Wood database, Forest Products Laboratory 2021), and the porosity was higher. The average values of density for all values of the moisture content correspond to the literature values of some low-density softwood species (Karahasanović, 1992; Forest Products Laboratory, 2021).

Table 2. Moisture content and density of sycamore and burnt softwood sample of driftwood

Physical Properties – mean value	Storage ambient conditions	Laboratory conditions, T=20°C, RH=65 %	Ovendry wood, W=0 %
Sycamore specimens			
Moisture content, %	12.21	14.65	-
Density, g/cm^3	0.42	0.42	0.37
Porosity, %	-	-	75.02
Burnt softwood specimens			
Moisture content, %	9.09	13.15	-
Density, g/cm^3	0.33	0.34	0.32
Porosity, %	-	-	78.98

The results of compressive strength of all driftwood samples are given in *Table 3*. The test poplar sample was divided into clear wood specimens (six specimens) and specimens of wood with defects (six specimens). Mean values indicated that compressive strength parallel to the grain of poplar clear wood specimens is 39.1 % higher than the same strength of poplar wood with defects. The high standard deviation for specimens of poplar wood with defects indicates that the values are spread out over a wider range. Also, the value of the range of poplar wood with defects indicates a higher interval of statistical dispersion. The experimental results of compressive strength parallel to the grain of poplar clear wood specimens agree with the literature data of 38 MPa (Forest Products Laboratory 2021). The compressive strength of the sycamore wood specimens (four specimens) and the burnt softwood specimens (four specimens) is very low compared to any literature data (37,1 MPa for sycamore wood). One of the causes is that the longitudinal geometric axis of some of the samples was not parallel to the grain.

Table 3. Compressive strength poplar, sycamore and burnt softwood driftwood samples (Laboratory conditions: T=20°C, RH=65 %)

Compressive strength, MPa	Clear wood specimens of poplar (W=13.41%)	Specimens of poplar with wood defects (W=13.77 %)	Sycamore specimens (W=14.65 %)	Burnt softwood specimens (W=13.15 %)
Mean	41.86	30.08	12.44	4.81
Stan. dev.	1.70	8.64	-	-
Range	4.51	20.95	-	-

The fractures of the specimens after testing the compressive strength parallel to the grain are shown in *Figure 7*. The fracture patterns were affected by wood defects or the deviation of wood grain direction.

Figure 7. Wood specimen failures of compressive strength parallel to grain testing: poplar with wood defects (left), sycamore wood (right).

The results of the bending strength and the modulus of elasticity of the twelve poplar driftwood samples are given in *Table 4*. The test poplar sample was not divided into clear wood and defective wood specimens. The mean value of bending strength is 45.10 MPa, and it is lower than the literature value of bending strength of 70 MPa (Forest Products Laboratory

2021). *Figure 8.* shows the curves of force-displacement diagrams of the bending strength of the poplar wood specimens. Two different groups of curves are noticeable, which indicates a significant variation in the modulus of elasticity of poplar wood samples. The mean value of the modulus of elasticity of poplar wood samples is 6.07 MPa, and it is lower than the literature value of 10.90 MPa (Forest Products Laboratory 2021). The test results have shown that the maximal value of the modulus of elasticity of 10.47 GPa corresponds to the literature data of the modulus of elasticity for poplar wood.

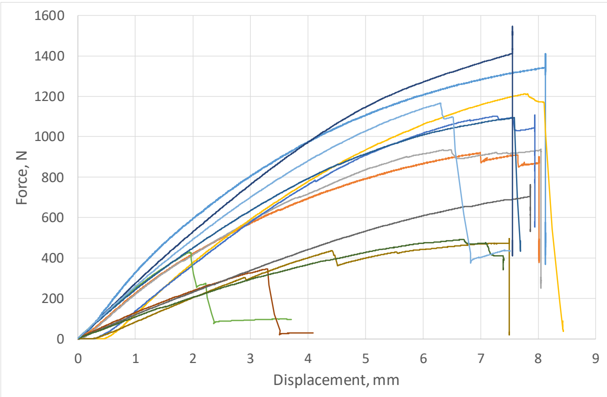

Figure 8. Testing of bending strength: force-displacement curves.

Table 4. Bending strength and modulus of elasticity of the poplar driftwood samples (Laboratory conditions: T=20°C, RH=65 %)

Wood specimens of poplar	Bending strength, MPa	E modulus, MPa
Mean	45.10	6.07
Stan. dev.	18.53	2.50
Range	57.73	8.22

The high standard deviation and the range of the bending strength and modulus of elasticity for specimens of poplar wood indicate a high dispersion of the test results and the effect of wood defects on the analyzed mechanical properties of wood.

4. CONCLUSION

In this paper, the basic physical and mechanical properties of randomly collected driftwood were investigated. The type of wood of driftwood samples was identified from three groups of driftwood samples: logs of small diameter and without bark, part of the root system, and burnt wood. Based on the macrostructure and microstructure of the wood cross-section, the wood type of driftwood logs was identified as poplar wood (*Populus spp*.), the wood type of driftwood root was identified as sycamore (*Platanus orientalis* L.; *Platanus occidentalis* L.), and because the precise, science identification for the burnt driftwood was not possible, it was defined as softwood. The results of the physical properties analysis show that the poplar driftwood density of clear wood specimens is approximately the same as the literature value and it is slightly reduced for specimens with wood defects. The average density values of the sycamore wood specimens and burnt softwood samples are much lower than the literature density values. The compressive strength parallel to the grain of clear poplar wood specimens is approximately the same as the literature value, and it is reduced for specimens with wood defect, while the compressive strength of the sycamore and the burnt softwood specimens is very low compared to any literature data. The bending strength and modulus of elasticity were determined for the poplar driftwood only and for this test, wood samples were not divided into clear wood and defective wood specimens. The mean value of bending strength and modulus of elasticity are lower than the literature values. The high standard deviations of bending strength and modulus of elasticity show a strong effect of wood defects on the mechanical properties of wood. From the analysis of the physical and mechanical properties of various driftwood samples, it can be concluded that properties of naturally modified wood vary and are dependent on wood defects as a result of exposure to external influences. For clear poplar wood logs, the results show that they can be used for wooden constructions of wooden furniture, sculptures, or elements of children's playgrounds, but low-quality wood can only be used for energy generation. Therefore, it is necessary to first scan and sort collected driftwood material, based on its quality, before deciding for what purpose it can be used.

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Wood Research at the University of Sopron – Modifications pt. 1

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ABSTRACT

This study series presents activities in wood science of the University of Sopron, Hungary. In this article, we show some of our fungal decay and durability test results. The acetylated hornbeam (*Carpinus betulus* L.) was almost perfectly resistant to 3 major fungi species despite that the hyphae appeared in the wood. London plane (*Platanus acerifolia*) suffered serious colour change after thermal treatment at 180 and 200 °C, but sapwood and heartwood to a different degree. Its soil durability tests are in progress. According to the Hungarian building regulations, the low-durability wood species used for construction must be treated with chemical wood preservative before installation. We examined impregnability properties of glued-laminated spruce (*Picea abies*) and Pannonia poplar (*Populus* × *euramericana* cv. Pannonia) specimens and found that poplar can be impregnated 2-3 times more easily and thus, can be classified in a higher durability class after impregnation.

Key words: acetylated hornbeam, colour measurement, durability test, fungal decay, glued-laminated Pannonia poplar and spruce, heat treated London plane, impregnation

1. INTRODUCTION

The University of Sopron, in Hungary deals extensively with the proper management of trees and wood from both scientific and practical perspectives. The Faculty of Forestry is the only place in Hungary to train, among others, forest engineers and nature conservation engineers, while the Faculty of Wood Engineering and Creative Industries trains, among others, engineers for the wood industry, specialists in the creative industry, and product designers. The former Institute of Wood Science, now part of the Institute of Basic Sciences, deals with the properties and modification possibilities of wood. The following scientific publications are some good examples: (Fehér *et al.*, 2014; Ghavidel *et al.*, 2023, 2021; Horváth and Fehér, 2023; Kern *et al.*, 2022; Komán, 2022; Komán and Ábrahám, 2021; Komán and Fehér, 2020; Komán and Varga, 2020; Lykidis *et al.*, 2023). Our aim with this study is to present the activities and some of our important results we have carried out in the recent years, in order to present research regarding the wood industry. We believe that the work we do is globally important. In this article, we present some of our research and results on the microscopic and fungal decay properties of modified woods.

In the first part of this article, the microscopic studies of acetylated hornbeam (*Carpinus betulus* L.) were elaborated to give a broader picture of the changes on microscopic level and to demonstrate whether fungi is able to colonize acetylated hornbeam or not. After acetylation, wood becomes more hydrophobic which increases its weathering durability and soil durability through its resistance to fungal decay. The microscopic studies were carried out on specimens exposed to fungi, as well as on specimens exposed to a soil durability test.

The next parts of the study deal with the heat treatment of London plane (*Platanus acerifolia*), as well as with the impregnation tests of spruce (*Picea abies*) and Pannonia poplar (*Populus* × *euramericana* cv. Pannonia) glued-laminated timber. Pressure impregnation processes are undoubtedly the most important and successful industrial methods for applying wood preservatives (Wilkinson, 1979). These autoclave processes, which provide preventive chemical protection, offer the potential for the preservative treatment of larger cross-sectional timbers, including railway sleepers, telecommunication and electric distribution columns, palisades, garden poles, stakes and rods for supporting grapevines, garden furniture, mine timbers, structural and cabinetmaking products, shingles and other assortments manufactured in greater series (Bálint, 1967; Reinprecht, 2013). The use of the impregnated wood, the preservative and the amount applied determine the treatment schedule chosen (Müller, 2005). The aim of impregnation procedures is to introduce as much preservative as possible into the wood in a short time and to recover as much preservative as possible at the end of the procedure so that only the prescribed amount remains in the treated selection (Gyarmati *et al*. 1964). In the vacuum pressure impregnation of air-dried wood, vacuum pressure technologies for chemical protection are different in the degree of vacuum (V), atmospheric pressure (A) and positive pressure (P) control. By properly controlling these stages, the necessary penetration and retention of the solvent and active ingredient(s) in the wood is ensured. Several well-known vacuum pressure technologies are mentioned in the literature, of which PPV and VPV schedules are particularly used in practice. PPV schedules include the Lowry, also known as PV (positive pressure on liquid-vacuum) and the Rüping, also known as PPV (positive pressure on wood-positive pressure on liquid-vacuum) processes. The pre-vacuum, VPV processes under investigation include the VAV (vacuum-atmospheric pressure on liquid-vacuum) and Bethell, or VPV (vacuum-positive pressure on liquid-vacuum) processes. Combined technologies exist with variations of these main processes, such as the double-Rüping process (Reinprecht, 2013). In line with the environmental concerns of our time, the question arises whether adequate protective efficacy can be achieved with modified treatment schedules and applying less biocide.

Imported spruce is a common structural timber used in the Hungarian construction industry. Pannonia poplar is abundant in the country. The two species have almost identical physical-mechanical properties (Molnár, 2004). According to the Hungarian building regulations, both the low-durability Pannonia poplar and the pine species used in the construction industry until now have to undergo additional chemical wood preservative treatment before installation. Our research involved a comparative study of the impregnability and the protective agent absorption properties of glued-laminated spruce and Pannonia poplar specimens.

2. MATERIALS AND METHODS

2.1. Acetylation and different tests on hornbeam

Half of the edged and air-dried (15.2 ± 0.6 %) hornbeam boards remained untreated, and the other half was acetylated under industrial conditions. The WPG ranged between 13.6 % and 16.5%, having an average of 15.3%. The average acetyl content was 21.9 ± 0.7 %. The average moisture content decreased to 3.3 ± 0.1 %.

Microscopic studies were carried out with Leica DM 2000 (Leica Microsystems CMS GmbH, Germany) optical microscope, Tescan Vega 4 scanning electron microscope (Tescan Orsay Holding, a. s., Czech Republic) and Hitachi S-3400N PC-Based Variable Pressure Scanning Electron Microscope (Hitachi, Tokyo, Japan). For microscopic studies, cutting of smooth, undamaged sections of acetylated hornbeam was only possible after swelling and softening in acetone (Inoue et al., 2008a; Obataya and Shibutani, 2005a). It swells and softens less in water, which makes it much more difficult to cut without cracking or damaging it. After producing sections, they were stained to allow chemical changes and fungal degradation to be seen. Safranin was used to indicate lignin, and astra blue to indicate polysaccharides. The same staining method was used as described by Mohebby (Mohebby, 2003). Further results are available in related research papers (Fodor *et al*., 2022; Rousek *et al.*, 2023).

The signs of decay were evaluated on samples which have been exposed to fungi according to EN 113 (2021). The mass loss of the untreated hornbeam samples was 47.6 %, 21.7 %, and 35.6 % for *Coniophora puteana*, *Rhodonia (Poria) placenta,* and *Trametes (Coriolus) versicolor*, respectively. On the other hand, only minor mass loss was observed in acetylated hornbeam samples: 1.1 %, 0.5 %, and 1.0 %, respectively.

Samples were also exposed to soil in a 7-year-long durability test according to EN 252 (2015). 12 pieces of 20 × 50 × 300 mm^3 (t × w × l) sized stakes were buried in the outdoor exposure testing field at the University of Sopron (47°40′41.4″ N 16°34′32.6″ E) in April 2016. Untreated hornbeam stakes lasted for a maximum of 3.5 years while most of the acetylated hornbeam stakes are still in the soil. There was one acetylated stake which had local signs of decay after 18 months of exposure. This stake was taken out for examination after 5.5 years of exposure. Hornbeam lost about one-third of its mass while this acetylated stake lost only 6 %.

2.2. Heat treatment of London plane

In the second part of this article, some of the properties of untreated and thermally modified London plane timber were compared. The thermal modifications were carried out at 180 °C and 200 °C reaction temperatures. The timber was kept at the reaction temperature for 5 hours in both cases. We used the fungal test method described in EN 113 (2021). Experiments were carried out using white-rot fungus, *Coriolus versicolor* and brown-rot fungus, *Coniophora puteana*. Three specimens were placed into each Kolle-flask: an untreated one, a treated one at 180 °C and a treated one at 200 °C. The three specimens were selected uniformly from the heartwood (*Figure 1a*) or from the sapwood (*Figure 1b*) region of the wood.

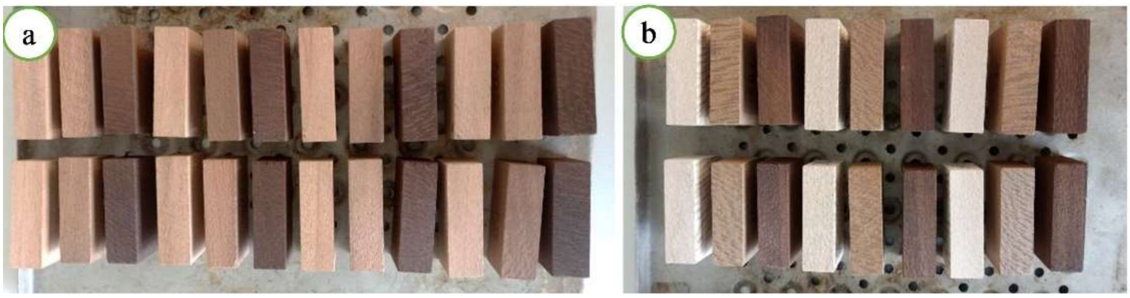

Figure 1. Heartwood (a) and sapwood (b) samples.

Colour measurements of the heat-treated London plane heartwood and sapwood were carried out using the CIE Lab colour measurement system. The colour difference due to the treatments can be determined by the total colour difference (Δ*E*). When assessing the overall colour difference of the samples, the results are classified into five categories based on Δ*E*: between 0 and 1, there is no colour shift; between 1 and 2, it is slight shift; between 2 and 4, it is significant; between 4 and 5, it is strong and above 5, it is very strong (Horváth, 2008). The study was carried out on specimens conditioned in a normal climate (20 °C / 65 % RH).

The natural weathering test of the untreated and heat-treated London plane specimens was carried out under conditions corresponding to the IV. hazard class (EN 350:2016). The aim of the test was to compare the outdoor durability of untreated and at thermally modified heartwood and sapwood samples at 180 ℃ (*Figure 2a*). The test specimens have been buried in soil since the summer of 2019 (*Figure 2b*). The test will continue until the last specimen is ruined.

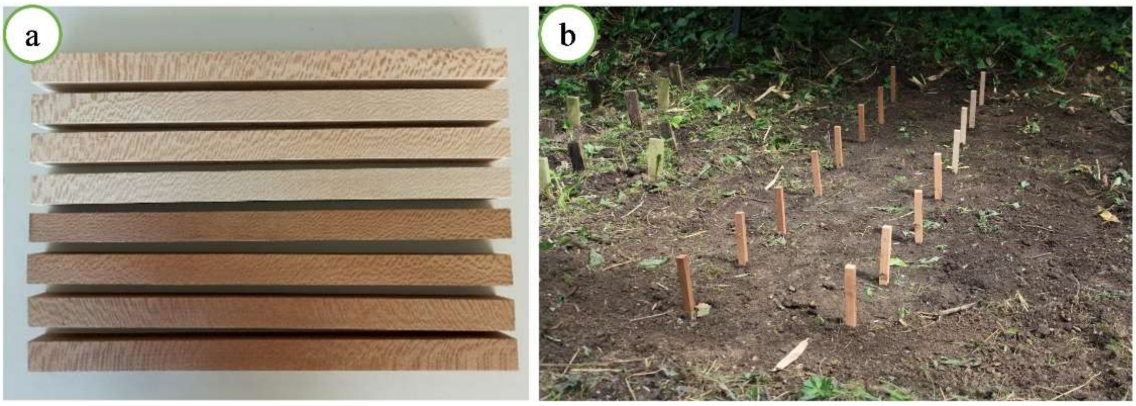

Figure 2. Untreated (top) and at 180°C heat treated (bottom) London plane sapwood test specimens (a) and the buried specimens (b).

2.3. Impregnation tests of spruce and poplar glued-laminated timber

All the specimens were bonded with Jowat686.60 PUR adhesive according to the technical data sheet, using 3 pieces of 7 mm thick lamellae. The specimens were cut along the grain. The final size of the specimens was 21×55×55 mm. To avoid the penetration of the protective agent in the direction of the end grain, the end grain of the specimens was sealed with polyurethane sealant type APP-PU 50. Impregnation was done in a MEMMERT vacuum drying oven VO400-230V (Memmert GmbH + Co. KG). Two different impregnation schedules were used on the bonded test specimens. During the first impregnation the specimens were held under vacuum at 10 mbar for 45 minutes immersed in a 5 % copper sulphate distilled water solution, and then held at atmospheric pressure for 120 minutes. A weakened schedule was used in the second impregnation experiment according to Csizmadia (Csizmadia, 2020). The test parameters were 550 mbar vacuum for 45 minutes and atmospheric pressure for 120 minutes. The mass of the specimens was measured before (m_b) and after (m_a) the treatment. The mass of the copper sulphate solution taken up (Δm) was calculated from the difference between their weights (Eq. 1).

$$\Delta m = m_a - m_b \tag{1}$$

Δm – the mass of the copper sulphate solution taken up (g)
m_a – the measured mass after the treatment (g)
m_b – the measured mass before the treatment (g)

$$m_{CuSO_4} = \Delta m \cdot 0{,}05 \tag{2}$$

m_{CuSO_4} – the calculated mass of copper-sulphate (g)

After the weight measurements, the specimens were placed in a drying oven and then the dried specimens have been cut up with a circular saw. Finally, the cut cross-sections were sprayed with a reagent to visually assess the presence of copper sulphate.

3. RESULTS AND DISCUSSION

3.1. Acetylation

Although the mass loss of acetylated hornbeam was very low, microscopic images show that fungi were able to colonize the cell wall, which also means that acetylated wood is durable and not toxic to fungi. Safranin-stained untreated hornbeam, but not acetylated hornbeam (*Figure 3*), which indicates successful acetylation. After staining, polysaccharide degradation and lignin were observed in acetylated sections (*Figure 3*). After acetylation, there were no cracks nor fractures observed due to the process. Bright-field microscopy revealed significant new deposits in acetylated hornbeam, which were not apparent in untreated wood. These were located mainly in the parenchyma cells in rays, and also in axial parenchyma.

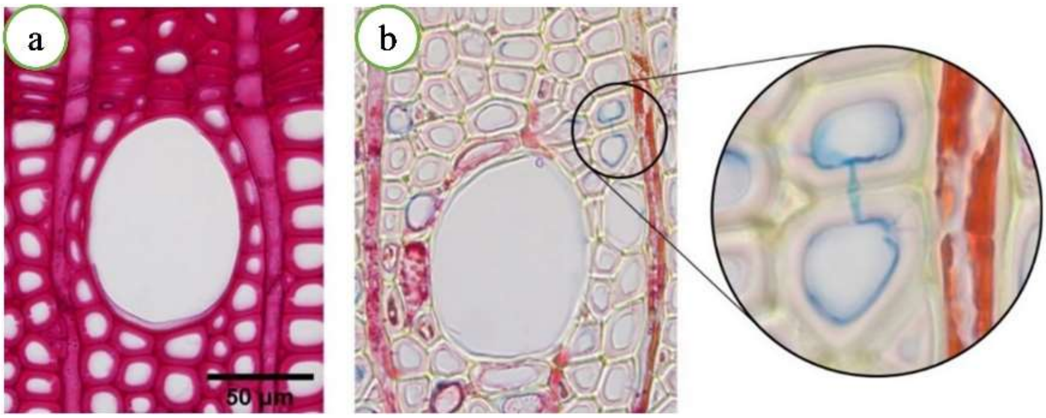

Figure 3. Bright-field microscopy of a cross section of untreated hornbeam (a) and acetylated hornbeam (b) after the durability test. Brown deposits in cell lumina are stained red with safranin; hyphae of brown rot Coniophora puteana are stained with astra blue.

Although acetylated hornbeam had no sign of fungal decay and had less than 1 % mass loss, some hyphae were observed in the microscopic sections. The hyphae, which were stained blue, grew through lumina and pits. They were observed in the cross section (Figure 3) and also in the radial section. In acetylated hornbeam, few hyphae and no signs of decay were found in specimens treated with any of the three fungi *Coniophora puteana*, *Rhodonia (Poria) placenta*, or *Trametes (Coriolus) versicolor*.

An analysis of cell-wall thickness proved that acetylation increased the thickness by 7.0 % and the difference was statistically significant. The average thickness (and standard deviation) of two cell walls of two big adjacent fiber cells and the middle lamella between them was 6.28 ± 0.95 µm in untreated hornbeam and 6.72 ± 0.98 µm in acetylated hornbeam. Scanning electron microscopy revealed fine details of hyphae in untreated hornbeam. Significant fungal growth and wood decay was observed. Hyphae were found very rarely in acetylated wood and no decay of the wood structure was observed; on the other hand, hyphae were able to colonize the cell lumina and penetrate pits without decaying the wood. This phenomenon was also observed by other researchers (Mohebby, 2003; Mohebby and Militz, 2010; Rowell and Bongers, 2015).

White rot fungi degrade hornbeam and acetylated hornbeam more readily than brown rot fungi. The scarce and apparently random presence of fungal hyphae can be explained if the cell walls in wood are not uniformly acetylated during the acetylation process, and there are regions in the cell walls where the acetyl content is low enough for the fungi to colonize. The local decayed part of the specimen may have been a "wet pocket" in the untreated wood, which was less acetylated due to its higher moisture content. When wood is acetylated with higher moisture content, there is a loss of the reagent as acetic acid is formed, and the WPG decreases with increasing moisture content (Hill, 2006).

3.2. Colour change of London plane by heat treatment

The average *ΔE* values of the heat-treated heartwood and sapwood specimens compared to the untreated specimens are summarised in Table 1. Specimens treated at 200 °C showed a greater total colour difference than specimens treated at 180 °C. The total colour difference after treatment at 200 °C for heartwood samples was very strong. From both treatments, sapwoods underwent a greater colour change than the heartwood samples. The greater colour change of the sapwood may be explained by the different amount of by-products (Molnár, 2004).

Table 1. Total colour difference results. Abbreviations: ΔL - difference in lightness; Δa* - red colour difference; Δb* - yellow colour difference; ΔE - total colour difference*

	180°C heartwood	200°C heartwood	180°C sapwood	200°C sapwood
*ΔL**	-21.82	-41.00	-24.91	-51.66
*Δa**	-1.42	-0.38	3.91	5.13
*Δb**	1.13	-0.13	7.88	7.40
ΔE	21.90	41.00	26.42	52.44

3.3. Impregnation test results of glued-laminated spruce and poplar

In the first treatment, the Pannonia poplar sample took up an average of 42.415 g of solution, and the spruce sample 20.969 g. In the weakened second treatment, the Pannonia poplar sample took up 19.403 g and the spruce sample 6.933 g. In the first treatment, the poplar sample took up twice as much solution as the spruce sample. In the second treatment, poplar took up almost three times more of the solution than the spruce sample.

Some of the Pannonia Poplar specimens resulted in complete cross-section impregnation due to occasional inadequate end-grain sealing. The difference between the two species is striking. Spruce specimens showed less impregnation with the copper sulphate solution in both treatments (*Figure 4*). The spruce specimens can not be treated as efficiently due to their anatomical characteristics. Considering the almost identical durability classification (EN 350:2016) of the two species and the wood preservation and application aspects, Pannonia poplar was found to be the better choice for the smaller specimens tested. Pannonia Poplar can be classified in a higher durability class due to its easier impregnation.

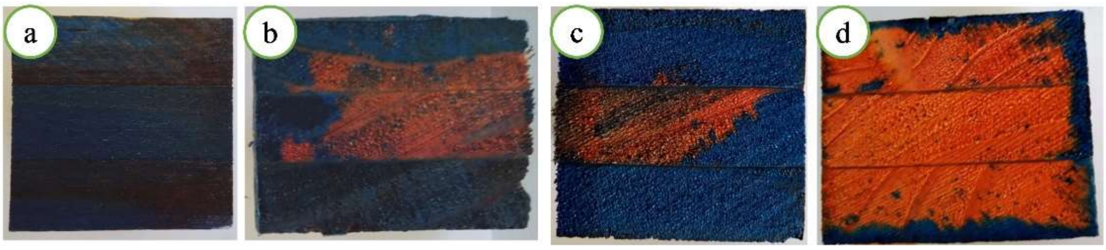

Figure 4. Cross sections of specimens treated with reagent: Pannonia poplar (a) and spruce (b) impregnated with the standard treatment, Pannonia poplar (c) and spruce (d) impregnated with weakened treatment.

4. CONCLUSIONS

Several studies on acetylated hornbeam, heat-treated London plane and impregnated spruce and Pannonia poplar were presented with main focus on their durability against fungi in laboratory conditions and in soil.

The results of these studies show that although the mass loss in acetylated wood was negligible, below 1 %, fungal hyphae still appeared in small quantities after the fungal decay tests. Cell wall regions were found where the acetyl content is low enough for the fungi to colonize.

London plane underwent a great total colour change after thermal treatment at 180 °C and 200 °C. The total colour change (ΔE) was between 21.90 and 52.44, depending on the treatment temperature and if sapwood or heartwood was the treated part.

For impregnation with a chemical wood preservative, Pannonia poplar turned out to be much better compared to spruce. Poplar can take up two to three times more preservative, which gives this species higher durability against biological deterioration.

Acknowledgements: *This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme. The authors are thankful for the microscopic investigations of Radim Rousek and Miklós Bak on hornbeam wood. The acetylation process and professional follow-up of Ferry Bongers from Accsys Technologies is also greatly appreciated.*

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Design Requirements of Upholstered Furniture for Seating and Rest for Smaller Living Spaces Based on the User's Needs

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ABSTRACT

Contemporary trends and the availability of real estate determine the life of an average young family in smaller living spaces. The adequate floor plan organization of all elements in the space, presents the most important activity in order to maximize the space usage. Such a procedure requires the design of furniture of small dimensions. The survey questionnaire was used to investigate trends, user needs and living habits in smaller living spaces. The results provided preliminary guidelines for requirements on the future development of the concept of upholstered furniture for sitting and resting in smaller living spaces.

Key words: upholstered furniture, sitting and resting, design guidelines, multi-functionality, user needs, trends

1. INTRODUCTION

Contemporary trends and the availability of real estate in cities determine the life of the average young family in smaller apartments. In order to make optimal use of small living spaces and to achieve maximally comfortable and functional living in them, appropriate furniture design and proper functional organization of all elements in the space are important.

Modern furniture, in addition to the basic one, tries to provide an additional new function that would further adapt to the habits and needs of the user, whereby one of the main values of furniture becomes multifunctionality (Domljan *et al*., 2006). The development of technologies conditions human dependence on material and technological achievements in smart houses and apartments, which affects the development of certain types of residential furniture (Domljan and Grbac, 2007; Šlegl, 2022; Vlaović *et al*., 2023).

Each person experiences the world in a different way, and reality for an individual is only what is perceived to exist or what appears. The experience is based on personal needs, desires, values and experiences. The latest products show how functional furniture can be comfortable, individual and aesthetically pleasing (IMM Cologne Press, 2021).

In a survey conducted in the U.S.A., Ponder (2013) found that, in general, living with a spouse influences respondents' decision to purchase a certain type of furniture. At the same time, he found that many consumers see their home and furniture as an embodiment of themselves, therefore buying furniture can be considered an emotional purchase. Knoškova and Garasova (2021) conclude that the most influential factors when buying are: product appearance, material, place of production and price.

The disease COVID-19, in addition to changing people's daily lives, also changed the attitude towards the living space (Pirc Barčić *et al*., 2021; Šlegl, 2022). In times of uncertainty, the comfort of home provided people with security. Living spaces had to be adapted to new requirements. The home has become a multipurpose space for a human being (IMM Cologne press, 2020). Compact and multifunctional furniture solutions that can save the interior space are becoming particularly popular. People want to combine private life and work during the day and then separate them again in the evening. Small, urban apartments often lack space for dedicated functional spaces such as an home office, living room or dining room. Intelligent multipurpose solutions are needed that can be integrated as subtly as possible into individual interiors (Šlegl, 2022).

The concept of a large or small apartment depends on the community, environment, opportunities, culture and habits of the environment. Neufert (2002) recommends that apartment sizes, depending on the number of people, should be within the limits of 45 m^2 (one-room apartment) to approximately 107 m^2 and more (five-room apartment), where it is optimal for the living room to occupy about 20 m^2. Regardless of the size of the apartment, in every living space it is important to determine which room has the function of a space for daily rest. Trends in room furnishing play a big role in understanding not only the function of the space, but also the appearance of the room and its atmosphere. The atmosphere of the space is defined by design elements, i.e., colours, materials, light, textures, volumes and other elements of architectural expression, while the brand plays a major role in defining the style that varies according to user preferences: minimalist, bohemian, industrial, traditional, modern, rustic, maximalist and other (Lamot, 2023).

Trends are a good orientation if the manufacturer adheres to them. This increases the possibility of sales. However, equally, trends change relatively quickly, which puts additional pressure on the manufacturer, because the development of the prototype and the adaptation of production to the product must take place as quickly as possible.

Kaputa et al. (2016) indicate that respondents' preferences differ depending on the climate and country where they live. At the same time, they state that in Croatia the brand does not play a big role in the purchase of furniture (only about 33.4 %). Statistics reveal that as many as 60 % of Croatian consumers care and are interested in warranty conditions and their rights regarding the quality of furniture. The brand represents a company whose customers are satisfied because they are already familiar with a reliable way of buying and the product itself. In most cases, it is experienced through a logo or a trademarked name assigned by manufacturers to a specific product or company (Jelić, 2021). Such elements are used so that consumers associate certain values with the brand. This can be product quality, services, business method, delivery speed, product origin, availability, consulting or others.

In living room spaces, where the average family spends most of their time, special requirements are placed on the design of multi-purpose cushioned furniture for sitting and resting that is smaller in size to fit into the living space.The most important factor to be guided by, is the need of the user, which will stimulate a new idea for the development of the product even before the conceptual solution is reached. After reviewing the current needs, requirements and wishes of the user, then with an unconventional view of the product, a new addition can be discovered that will functionally improve the product.

Methods often turn out to be extremely useful because they broaden the horizons in solving problems (Lapaine, 1993). The basic need and function of a upholstered sofa is sitting, lying down, resting, communication with others and more. Depending on the users, a certain group of people needs an additional bed that can be contained by the sofa.

The aim of this work is to present the preliminary results of the analysis of the preferences of potential buyers when purchasing new sofas, which will help in defining the requirements for the design of upholstered furniture for sitting and resting that will meet the needs of users' lives in smaller apartments.

2. MATERIALS AND METHODS

2.1. Polygon and subjects

A well-known furniture salon in Zagreb (Croatia) was chosen as the research polygon, which has a large selection of upholstered furniture for sitting and resting (about 40 different models, nine of which are modular).

Participants in this research were potential buyers of living room sofas. During the research, all potential customers between the ages of 18 and 65, regardless of gender, were considered as respondents.

2.2. Methods

An anonymous online questionnaire was used for feedback from consumers and potential buyers.

The respondent downloaded the link with a smartphone and filled out the questionnaire in the salon or later at home.

The structure of the questionnaire can be seen in Table 1. The survey questionnaire is divided into two parts. The first part refers to basic information about the respondents, while the second part refers to their preferences, with a score of 1 meaning the least and 5 meaning the most preferred choice. The survey was conducted from May 10th to August 30th, 2023.

Table 1. Questions in the questionnaire

	QUESTIONS	ANSWERS				
1	Gender	Male		Female		
2	Age range	18 - 25	26 - 34	35 - 49	50 - 99	
3	Education degree	Elementary	Highschool	University		
1	What type of material do you prefer the most?	Smooth-finish leather	Artificial leather	Brushed-finish leather	Fabric	Plush
2	How important is the comfort of the sofa?	1	2	3	4	5
3	How important is an additional bed in sofa?	1	2	3	4	5
4	How important is it that the sofa takes up less space?	1	2	3	4	5
5	How important is the storage option in the sofa ?	1	2	3	4	5
6	How important is the height of the sofa from the floor?	1	2	3	4	5

3. RESULTS AND DISCUSSION

Total of 64 subjects participated in the research (55.7 % male and 44.3 % female).

The age range in the survey was classified into four groups (*Figure 1*).

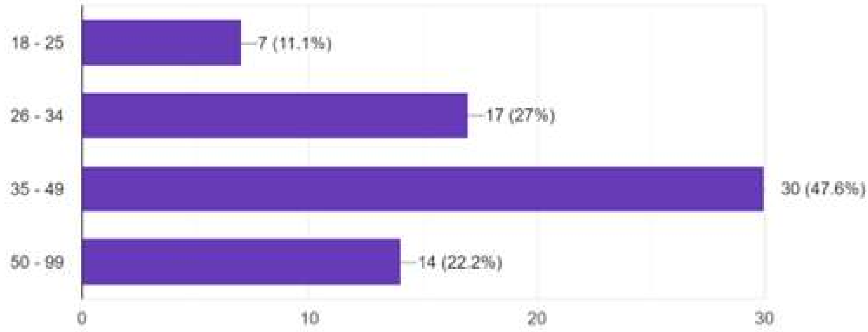

Figure 1. Structure of subjects according to age groups (n=64).

The level of education of the respondents is shown in *Figure 2*.

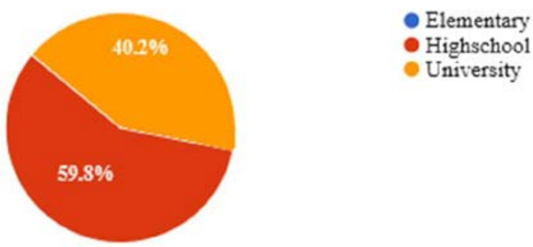

Figure 2. Completed level of education of the subjects (n=64).

When asked which type of material they prefer the most, the respondents mostly opted for fabric as the type of sofa cover (53.1 %). After which they chose brushed leather (20.3 %), plush (12.5 %) and smooth leather (10.9 %), while the smallest percentage (3.1 %) chose artificial leather (*Figure 3*).

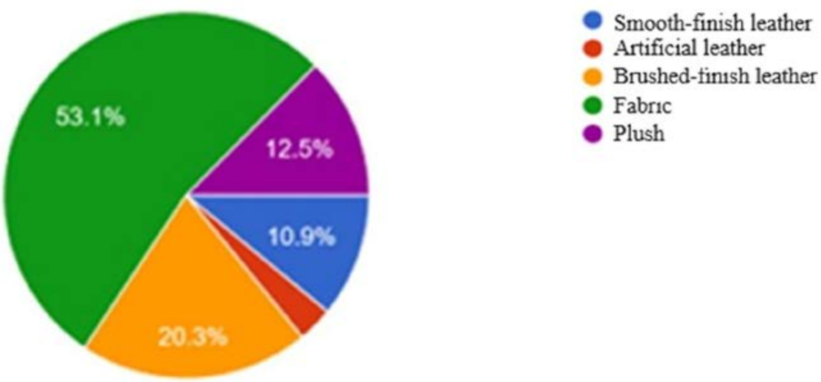

Figure 3. Subjects' answers about material preferences (n=64).

The comfort of the sofa (*Figure 4*) is considered by respondents to be a very important factor when choosing a particular model (81.3 %).

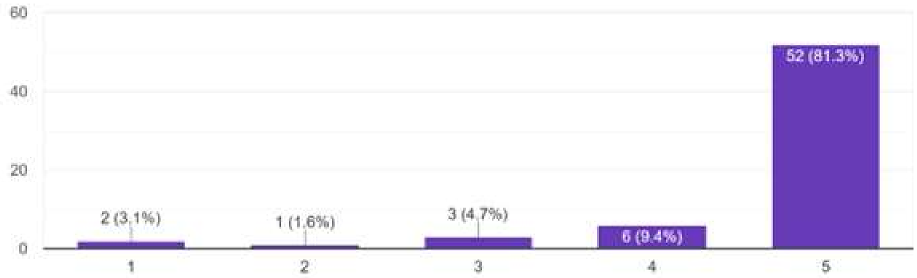

Figure 4. Share of answers about the comfort of the sofa (n=64).

An additional bed is a requested function among sofas, which is confirmed by the result that almost 90 % of respondents show an interest in an additional bed (*Figure 5*). 29.7 % of the respondents are looking for an additional bed as something without which they do not want to buy a new sofa, while the rest of the respondents, 31.3 % of them, consider it desirable, but not necessary. 28.15 % of respondents declare that an additional bed is welcome, but not necessary. Fewer respondents (11 %) do not need such a function.

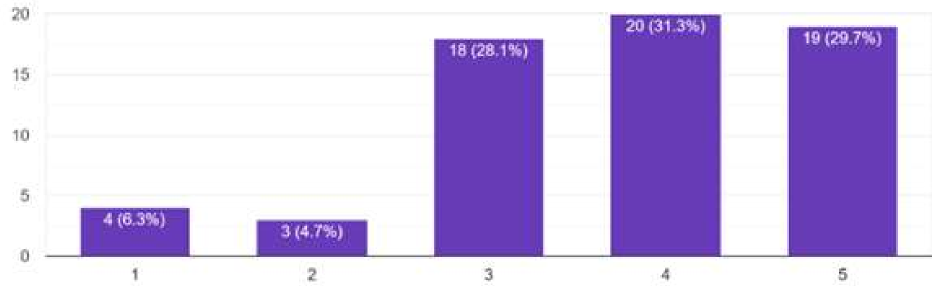

Figure 5. Share of responses regarding the importance of an additional bed (n=64).

A small percentage of respondents (7.8 %) has no limit for the size of the sofa, because they have a large enough living space (*Figure 6*). A slightly higher percentage (12.5 %) of customers think that they should pay attention to their dimensions in the space, while the largest share (40.6 %) of respondents have a problem with the dimensions of the corner sofa in their space, but manage to find what they want. For 29.7 % of those surveyed, the limiting dimensions of the space determine the importance of the size of the furniture and is an important factor in the selection. The rest of the 9.4 % of buyers own smaller apartments that are completely limited and whose main factor that is difficult to fulfill is precisely the size.

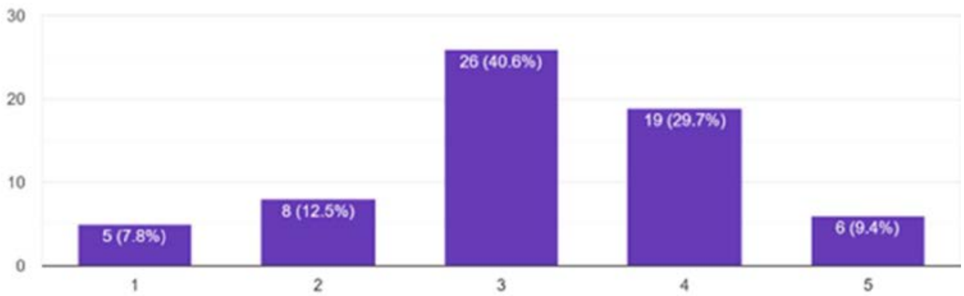

Figure 6. Share of answers about the importance of the size of the sofa (n=64).

Interesting answers were given to the question of how important the storage space inside the sofa is. 17.2 % of respondents think that storage is very important and is a decisive factor when buying, while 26.6 % of people think that this function is very useful and necessary in their space, the same percentage considers it desirable (26.6 %). It can be concluded that the majority of respondents still consider the storage component to be quite significant. 12.5 % believe that an additional storage space is not a necessary function, however, it is not bad to have this possibility, while 17.2 % believe that there is no need for it or they do not need it at all (*Figure 7*).

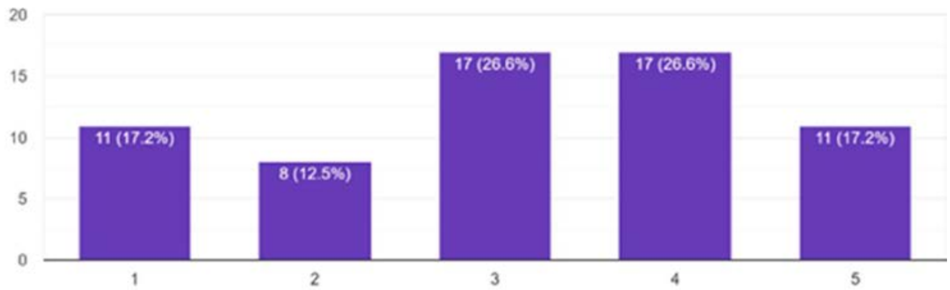

Figure 7. Share of answers about the importance of having storage space in the sofa (n=64).

The analyzed answers from the survey represent only the first and tentative instructions for defining the requirements for product design in more detail, which resulted from research into the preferences of potential buyers of seating furniture related to functionality and comfort.

The guidelines that are highlighted for further work on the development of this type of product for the purpose of defining the requirements should, in addition to the mentioned functional preferences of the respondents regarding the desirability of an additional bed and storage space and types of materials, be connected with the knowledge of the literature, and refer to the analyzed dimensions of living spaces (Neufert, 2002), recommended product dimensions in relation to user anthropometry (Panero and Zelnik, 1979); sociological guidelines in living trends and ecological trends (IMM Köln, 2023), technological capabilities of the company, price categories of products, and other preferences (Oblak et al., 2017).

It is important to distinguish requirements from desires, since requirements should be seen as required and necessary product characteristics that should be used or respected (because they are expected by most customers when they buy a product), while desire is a subjective category, supplementing the product with certain characteristics (e.g. accessories) that would enrich, improve or advance the product, but it does not have to be fulfilled for every individual customer.

4. CONCLUSION

Apartments in cities are even smaller and smaller, so furniture design requirements play a big role in order to ultimately equip the space with appropriate furniture that meets the user's needs.

The results provided guidelines for setting requirements for the future development of the concept of upholstered furniture for seating and resting intended for furnishing smaller living spaces and will be supplemented by future research. It is necessary to carry out more extensive research with a larger number of subjects and test sites in order to make the development of this type of product as successful and profitable as possible.

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Increasing the Durability of the Exterior Coating System by Surface Sealing

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ABSTRACT

This study focused on assessing how treating oak wood by the technology of sealing surface pores with epoxy resin affects the performance of transparent coating systems when exposed to outdoor conditions. Over the exposure period, various parameters, including color, gloss, surface wetting, and both macroscopic and microscopic surface features, were consistently monitored. The samples were divided into two sets: one underwent pre-treatment and the second did not. Subsequently, four different coating systems were applied to the samples, consisting of two solvent-based coatings and two water-based coatings. The experiment lasted for two years and relied on natural weathering methods within the grounds of the Czech University of Life Sciences in Prague. The epoxy resin pre-treatment exhibited improved resistance across all coating systems. Analysis showed a significant divergence in gloss and color after 12 months of exposure to weathering, with little impact on surface wetting and sealing. However, after 24 months of weathering, no substantial differences were observed between sealed and unsealed surfaces. The most effective pre-treatment was rated in properties was seen in the water-based coatings.

Key words: weathering, pretreatments, coatings, exterior, durability.

1. INTRODUCTION

The use of wood products in exterior applications is gaining popularity, but they require protection from factors like weathering (Požgaj *et al.,* 1993). Transparent coatings are often preferred for wood with distinctive patterns, leading to increased research in this area (Čabalová *et al.,* 2022). However, these coatings can face durability issues and require frequent maintenance, particularly on wood species with unique anatomical structures and high extractive content (Nutsch, 2006). English oak, chosen for its durability and aesthetic appeal, poses challenges for coating systems due to its extractive content (Rowell, 2013; Tomak and Gonultas, 2018). Several factors, including wood species, moisture content, coating type, surface adhesion, and susceptibility to cracking and warping when exposed to moisture and UV radiation, can affect the durability of transparent coating systems (Dawson *et al.* 2008; Pánek *et al*., 2018). English oak's high extractive content, while providing natural resistance to pests, complicates protection through coating systems (Wagenführ, 2007). These extractives affect wood color and resistance, negatively impacting surface treatments (Pánek *et al.,* 2019). They are also sensitive to UV radiation, leading to color changes, and can hinder surface wetting and the curing time of the coating layer (Tondi *et al.* 2013; Evans *et al.* 2015).

The cross-section of oak wood is large vessels in the springwood and smaller vessels in the summerwood (Wagenführ, 2007). The diameter of spring vessels in oak ranges from 150 to 350 μm, occasionally reaching sizes up to 1 mm, while summer vessels typically have diameters ranging from 30 to 140 μm (Požgaj, 1993). Additionally, the length of oak wood fibers is generally up to 1.74 mm (Kubovský *et al.,* 2018). Achieving adhesion of paint materials to oak wood can be problematic due to the presence of these large pores (de Meijer, 2001; Nikafshar *et al.,* 2021), which allow water-soluble extractives, such as tannins, to migrate to the surface to a significant extent. Subsequently, these extractives can react with the coating system, resulting in color changes (Bockel *et al.,* 2019). Tondi *et al*. (2013) noted that tannins exhibited similar UV-radiation vulnerability to lignin. Although tannins can temporarily protect wood by absorbing UV light, they eventually degrade (Sivrikaya *et al.,* 2019).

The coating system protects the wood against the penetration of moisture, thereby reducing the migration and subsequent leaching of extractive substances and potential cracking risk (Kropat *et al.,* 2020). Cracks are created due to uneven tension between the inner and outer layers, which allows deeper water penetration and provides an entryway for biotic pests (Tomak and Gonultas, 2018). Therefore, appropriate surface preparation, for example using pore fillers, can improve coating system quality and level surface acidity and limit the negative effects of pore size (Sjökvist, 2019). Numerous scientific studies have been conducted to investigate the impact of various coating systems or the effects of pretreatment on the properties of oak wood, but so far with unsatisfactory results (Sandberg, 2016; Kržišnik *et al.,* 2018; Rao *et al*., 2019; Reinprecht *et al.,* 2020; Hýsek *et al.,* 2022).

2. MATERIALS AND METHODS

2.1 Wood Samples, Treatment, and Exposure

Heartwood samples from English oak (*Quercus robur* L.) with dimensions 378 × 78 × 20 mm (L × T × R) were prepared according to EN 927-3 (2019) from wood harvested in the Czech Republic, distributed by WoodStore©, Czech Republic, Prague. Clear samples were conditioned for a relative humidity (ϕ) = 65 ± 5 % and temperature (t) = 20 ± 2 °C to achieve an equilibrium moisture content (EMC) of 12 %. The surfaces of the conditioned samples were sanded (120-grit) before treatment. The average density of the oak wood was 795 $kg \cdot m^{-3}$.

Two main sets of samples were used. The first set did not undergo pore filling treatment, and the second set underwent epoxy resin pore filling treatment. For the pore filling treatment, a colorless two-component epoxy resin (EPINAL UR 36.14), and hardener (EPINAL UH 36.14) from Acolor© (Acolor, Benesov, Czech Republic) were applied. The back and side surfaces of both sets of samples were treated with an auxiliary transparent coating, while the front surfaces were sealed with silicone glue to reduce wetting from sides other than those being tested. Each main set of test samples was further divided into four subsets according to the resulting surface treatment and are shown in *Table 1*.

Table 1. Overview of sample preparation.

Wood	Code	Modification	Code	First Layer	Second Layer	Coating System Number	Number of Sample
Oak	D	Sealed pores	T	Rhenodecor Trans TIX	Protector−Plus	1	1, 2 ,3
				Rhenocryl FK 47 High Solid	Protector–Plus	2	1, 2, 3
				Aquawood Ligno + Base	Aquawood Ligno + Top	3	1, 2, 3
				Lignofix	Lignofix	4	1, 2, 3
Oak	D	Unsealed pores	B	Rhenodecor Trans TIX	Protector–Plus	1	1, 2, 3
				Rhenocryl FK 47 High Solid	Protector–Plus	2	1, 2, 3
				Aquawood Ligno + Base	Aquawood Ligno + Top	3	1, 2, 3
				Lignofix	Lignofix	4	1, 2, 3
Oak	D	Reference	REF	Natural wood without coating			1, 2

2.2. Changes in colour determination

The colour parameters CIE L*a*b* (Tolvaj and Faix, 1995) of the test specimens were measured after 0, 3, 6, 12, and 24 months of natural weathering using a CM-600d spectrophotometer (Konica Minolta, Osaka, Japan). Eight measurements were carried out for each sample at each weathering time point. Colour change evaluations were done in the CIE L*a*b* colour space, where L^* is lightness from 0 (black) to 100 (white), a^* is chromaticity coordinate + 60 (red) or – 60 (green), and b^* is the chromaticity coordinate + 60 (yellow) or – 60 (blue). The total colour difference ΔE* was subsequently calculated based on the relative changes in colour (ΔL*, Δa*, and Δb*) using Equation (1). The colour changes were further compared to the values described in the EN 927—3 standard (2019).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (1)$$

2.3. Changes in hydrophobicity determination

The contact angle of distilled water on the tangential surfaces of tested samples was measured using a goniometer (Krüss DSA 30E, Krüss, Hamburg, Germany). Ten random positions on each sample were selected to measure the contact angle. The sessile drop method was used, with 10 measurements conducted per sample before and after 3, 6, 12 and 24 months. Distilled water drops with a dosing volume of 5 μL were used for the measurement, and the contact angle was determined after 5 s. The contact angle measurement helps determine the wettability of a surface.

2.4. Visual evaluation and microscopic analyses

Visual changes were monitored by scanning on a desktop scanner at a resolution of 300 DPI (Canon 2520 MFP, Canon, Tokyo, Japan) before, during and after weathering. A confocal scanning laser microscope (Lext Ols 4100, Olympus, Tokyo, Japan) was used for microscopic analysis.

3. RESULTS AND DISCUSSION

A visual comparison of the color change of each sample was regularly recorded and scanned. The progression of visible degradation over time is presented in Table 2. Visible color changes were noticed in all samples. The initial treatment by pore filling showed smaller color changes. However, after 24 months of aging, significant color changes were observed in all samples.

Table 2. *Macroscopic scans of samples.*

	Time of Weathering (Months)				
	0	3	6	12	24
B-1					
T-1					
B-2					
T-2					
B-3					
T-3					
B-4					
T-4					

Microscopic images of the surfaces shown in *Table 3* demonstrate the infestation of the wood samples by mould spores and the presence of surface fouling caused by fumes and dust particles, leading to damage to the coating system and also contributing to the greying of the wood surface. The most significant difference between the filled-pore and non-filled-pore surfaces was revealed in the 12th month. The filled-pore samples showed better coating stability and better maintenance of the original colour of the oak, although some initial defects were observed due to the presence of fungal spores. This damage serves as one of the first indicators of incipient surface degradation. After 24 months of weathering exposure, the surfaces of both filled-pore, and non-filled-pore surfaces appeared relatively similar. In *Table 3* are moulds shown by the blue arrow and surface roughness shown by the red line.

Table 3. *Microscopic scan of sample surfaces (scale of bar is 6:100)*

Natural Oak—Reference	12 Months		24 Months	
	Unmodified	Modified	Unmodified	Modified
				

The positive effect of pore filling in oak wood was manifested during the first 12 months of the experiment. During this period, the filled-pore samples showed minor colour changes (*Figure 1*). The reduced colour changes in the filled-pore samples were attributed to the decreased leaching of extractives, as sealing the pores limited their diffusion. The degree of colour change varied depending on the type of covering paint system used, which could be attributed to differences in surface tension. Varying surface tension values can negatively affect the wetting of the surface by the paint, resulting in uneven paint layers and increased susceptibility to colour changes. The positive trend of surface smoothing was observed only up to the 12th month. After 12 months of weathering exposure, noticeable degradation was observed, even in the filled-pore samples, which eventually reached comparable values after 24 months.

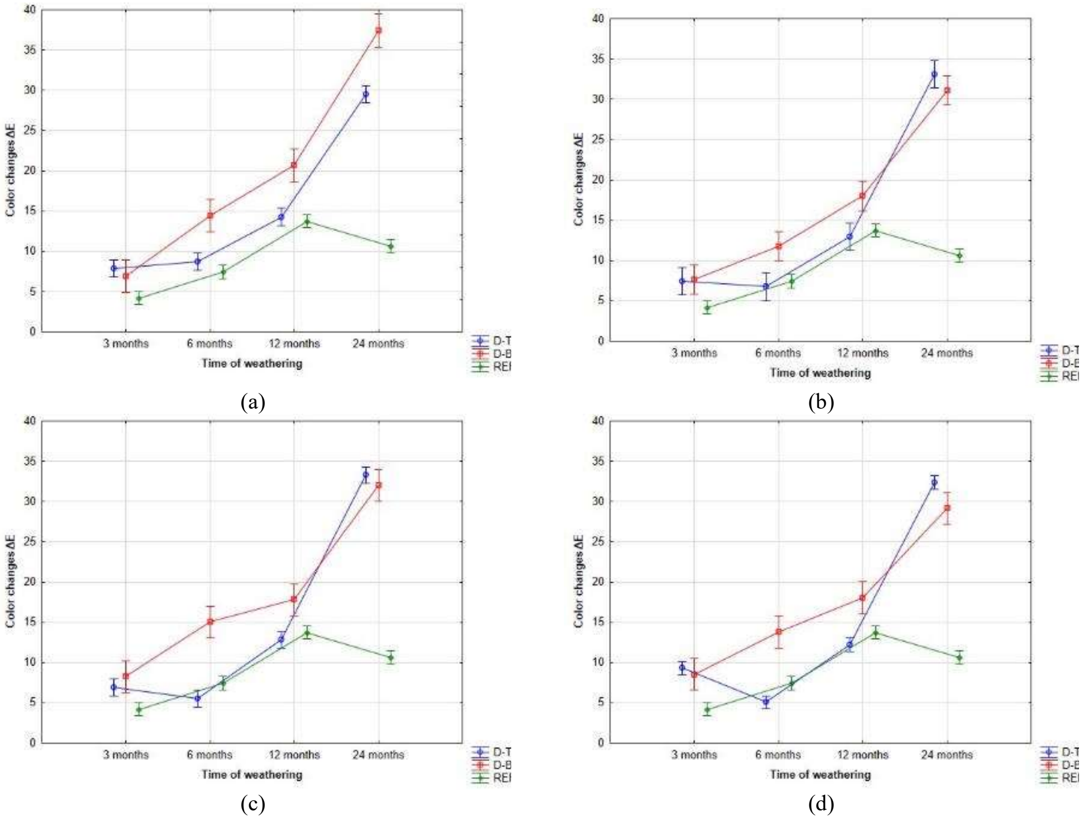

Figure 1. Colour changes. (The evolution of the total colour changes: (a) coating system 1; (b) coating system 2; (c) coating system 3; and (d) coating system 4.).

The results show that the wettability of the surface was not significantly affected by the modification. This finding was consistent across all coating systems tested (*Figure 2*). There were minimal differences in surface wettability observed between the different coating systems. However, it should be noted that the contact angles of all coatings decreased after 24 months of weathering exposure, indicating a loss of hydrophobic properties and an increase in the wettability of the wood surface.

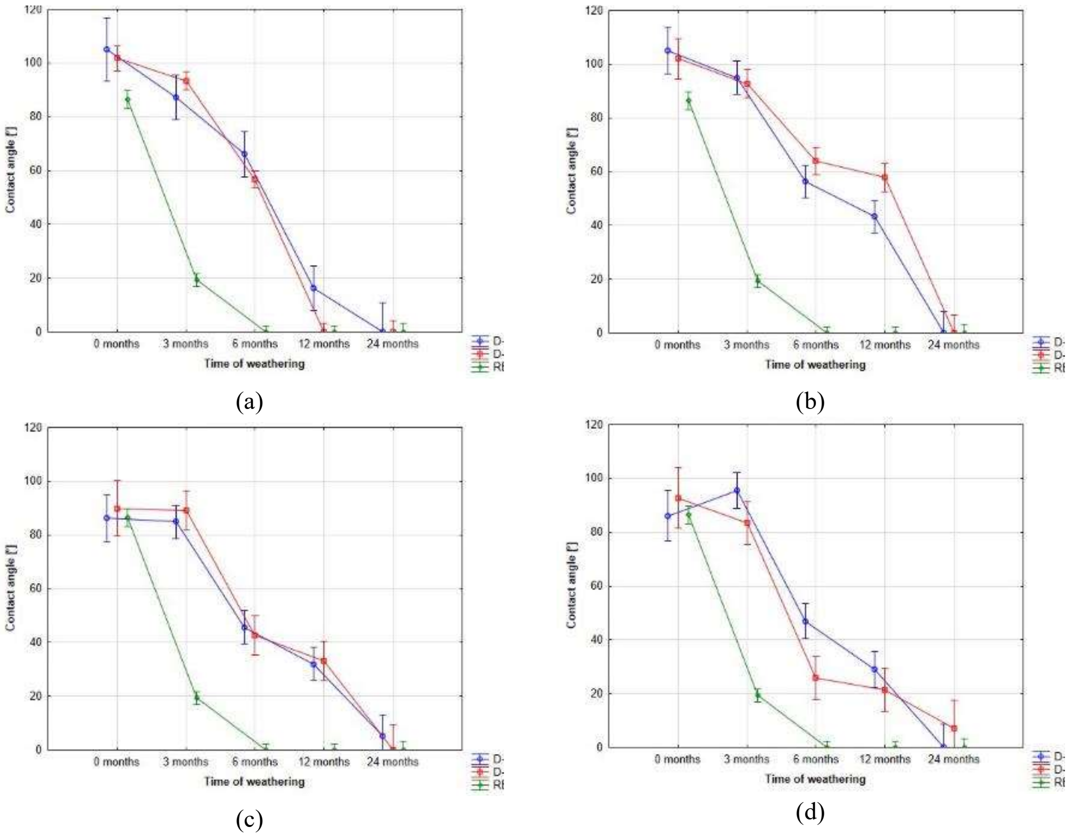

Figure 2. Contact angle changes (The evolution of the contact angle: (a) coating system 1; (b) coating system 2; (c) coating system 3; (d) coating system 4.).

Previous research has suggested that filling the surface pores of wood can lead to a smoother and more suitable surface for coating, resulting in more even application of paint layers (Pánek *et al.,* 2019; Hanifah *et al*., 2022; Dvorak *et al.,* 2023). The use of primer resins, such as epoxy resin, was found to be effective in filling the pores, limiting the sorption of water vapor, and preventing associated degradation effects (Žigon *et al.,* 2020). Wang *et al*. (2019) compared different types of fillers, including alkyd, one-component polyurethane, and two-component polyurethane. Alkyd filler was found to have the highest adhesive strength for oak, while one-component polyurethane filler has the lowest. Pavlič *et al*. (2021) compared one- and two-component polyurethane and acrylic resins and concluded that the two-component polyurethane with a higher solid content had a better filling capability, similar to the results of Oberhofnerová *et al*. (2019) or Li *et al*. (2018). Jankowska *et al*. (2018) confirms the positive effect of surface preparation, which is evidenced by the improvement of surface wettability characteristics.

4. CONCLUSIONS

The research suggests that filling the pores of wood surfaces, especially oak, can enhance their properties when applying paint layers. Oak wood can be chemically treated to protect against mould, rot, insects, and weathering. Using a base sealer like epoxy resin can effectively fill the pores, preventing water absorption and degradation. Sealing initially didn't affect surface wetting, but it showed some differences in contact angles with different coatings. Sealing affected the wood's colour, darkening the L* coordinate and changing the a* and b* coordinates.

It also helped prevent lignin degradation and leaching, with significant colour changes observed between 3 and 6 months of exposure. Certain sealants had better colourfastness, and visually, filled-pore coatings had less colour change compared to non-filled-pore samples, noticeable after 12 months of weathering exposure.

***Acknowledgements**: Acknowledgements to the Internal Grant Agency of the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences in Prague for founding from program: "Optimization of core wood surface adhesion to increase the strength of the glued joint ", reg. č. A_04_22.*

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Energy Efficiency and Machined Surface Roughness in Machining Solid Oak Wood (*Quercus robur* L.) on the High Performance Two-Side Thicknessing Planer

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ABSTRACT

The article presents an analysis of the energy efficiency and machined surface roughness obtained in industrial conditions on the high performance two-side thicknessing planer for surfacing and thicknessing in one operation. Measurements were carried out in representative industrial conditions, during the testing phase of the production with the new line for secondary processing of solid oak wood *(Quercus robur* L.). The main task for this machine was surface preparation of the boards for subsequent in-line machine vision scanning. For scanning to work according to specification, the machined surface had to be prepared accordingly, and it also had to have required capacity. Feed speed of 60 m/min was used, which resulted in the effective feed per knife (f_{zeff}) of 10.6 mm. This value is much higher than usual recommendations. Accordingly, measured roughness parameters were on the average R_a = 8.2 µm, R_q = 10.6 µm and R_z = 47.8 µm and waviness parameter W_z = 27.4 µm. To determine the energy efficiency of the machine, electrical power during machining was measured. From the measured values it was determined that the average specific cutting energy was 0.0036 kWh/dm^3 of removed wood, specific cutting pressure 13 N/mm^2 and on the average, electrical energy of 0.8 kWh was required for planing 1 m^3 of input lumber. It was also determined that the machine, on the average, utilised only about 26 % of the main motor rated nominal power.

Key words: hardwood machining, two-side thicknessing planer, energy efficiency, surface roughness

1. INTRODUCTION

Two-side thicknessing planers for surfacing and thicknessing in one operation are rarely used for wood machining in woodworking industry. For this type of operation, four-sided planers are usually used and requirements for the quality of machined surface are usually high, which means that fine quality of machined surface is usually required. In our case, high performance two-side thicknessing planer was used as part of production line where its main purpose was to process the material to a given thickness and to provide good enough surfaces for optical scanners to obtaine the images that were used for on-line optimization of the arrangement of circular saw positions in the multi-blade circular saw for edging and ripping.

As is often the case in practice, selection of the machines and the choice of operating parameters is not based on detailed analysis and this can result in suboptimal results. Energy efficiency of machining process and machined surface roughness can be used as parameters to determine how well the processing parameters and the machine itself are selected.

Energy efficiency and machined surface roughness, among other variables such as cutting force, temperature in the zone of the machining and chip characteristics, are one of the main factors in the assessment of the machinability of workpiece material (Šavar, 1990). In machining of wood, usuallymachined surface roughness and the average power required for machining, due to the relative ease of measurement, is measured (Aguilera, 2011; Ispas *et al*., 2016; Kubš and Kminiak, 2017; Nasir and Cool, 2019; Yu *et al*., 2023).

There is a difference between what is generally meant by efficiency and the efficiency of wood machining expressed through machinability. According to Astakhov (2014) this "old notion" of machinability can mean "all things to all men", so the new concept of machinability was proposed. The machinability of work material is directly correlated to process machinability. On the other hand, process machinability depends on a lot of variables (cutting speed, feed speed, tool geometry, tool material, workpiece material and characteristics etc.) and can be used as a measure of machining economy, so the specific cutting energy (E_n) is suggested as a quantity that can be used to represent the correlation between work material and process machinability, e.g. as a quantity that represents process machinability. Specific cutting energy represents the average energy consumed for cutting in relation to unit production (Goglia, 1994) and in general case can be calculated as:

$$E_n = \frac{P_c}{V_h} \quad (1)$$

P_c – average cutting power
V_h – material removal rate

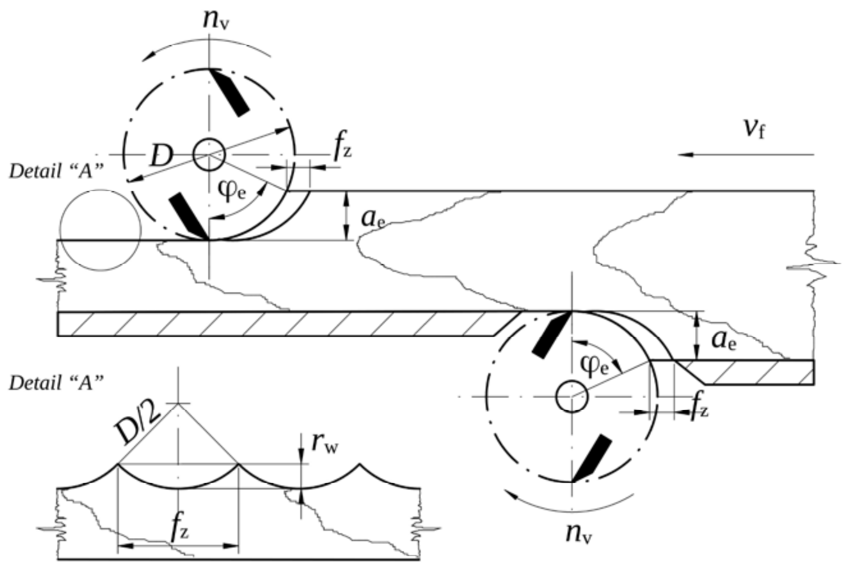

Figure 1. Simplified representation of machining on the two-side thicknessing planer for surfacing and thicknessing in one operation (a_e – cutting depth, n_v – cutter head rotational direction and frequency, v_f – feed speed, f_z – feed per knife, D – diameter of the circle described by the knives, r_w – theoretical height of the knife marks left on the machined surface).

From *Figure 1* it can be seen, that for peripheral up milling, material removal rate (for each cutter head) can be calculated from equation

$$V_h = v_f \cdot a_e \cdot a_p \quad (2)$$

v_f – feed speed
a_e – cutting depth
a_p – cutting width

The average cutting power can be calculated from equation (Goglia, 1994)

$$P_c = k_c \cdot V_h = k_c \cdot v_f \cdot a_e \cdot a_p \quad (3)$$

k_c – specific cutting pressure.

If we combine *Equation (2)* and *Equation (3)*, according to *Equation (1)*, specific cutting energy can be expressed as:

$$E_n = \frac{P_c}{V_h} = \frac{k_c \cdot v_f \cdot a_e \cdot a_p}{v_f \cdot a_e \cdot a_p} = k_c. \quad (4)$$

It can easily be seen that average energy required for removal of given volume of workpiece material is equal to the specific cutting pressure. Experimentally determined values of specific cutting pressure in given cutting conditions and for different woodworking machines, as well as the influence of different machining parameters (cutting direction, workpiece material, chip thickness, cutting tool angles etc.), are available for long time now (Afanasjev, 1962) and the influence of different machining parameters on the specific cutting energy can be easily determined.

In order to determine energy efficiency of the whole machine, the total energy required for machining of given unit production (E_b) can be used. In accordance with *Equation (1)* it can be calculated as:

$$E_b = \frac{P_{tot}}{V_h} \quad (5)$$

P_{tot} – average total power required for machining (usually average electrical power needed by the machine) of a given unit production.

Total energy required for machining of given unit production is used by some authors (Wittstock and Paetzold, 2013) as a parameter for energy efficiency classification of machine tools in accordance with the ISO 14955.

In theory, machined surface roughness obtained after milling is represented by the height of knife marks left on the machined surface (r_w), as can be seen in *Figure 1* (Detail "A") and it can be expressed using equation (Ettelt and Gittel, 2004):

$$r_w = \frac{1}{2} \cdot \left(D - \sqrt{D^2 - f_z^2}\right)$$
$$r_w \cong \frac{f_z^2}{4 \cdot D} \quad (6)$$

D – diameter of the circle described by the knives
f_z – feed per knife

The quality of the machined surface roughness after peripheral milling can be grouped in three categories, given r_w values (Ettelt and Gittel, 2004). This categories are:

- fine quality – r_w = (0.03 - 0.3) µm,
- medium quality – r_w = (0.3 - 1.2) µm and
- coarse quality – r_w = (1.2 - 10) µm.

In industrial practice expressing quality of machined surface by the value of r_w is not so practical, instead the value of effective feed per knife is used ($f_{z\ eff}$) and according to those recommendations machined surface roughness after milling can be grouped in the next three categories (Leitz, 2011):

- fine quality – $f_{z\ eff}$ = (1.3 - 1.7) mm,
- medium quality – $f_{z\ eff}$ = (1.7 - 2.5) mm and
- coarse quality – $f_{z\ eff}$ = (2.5 - 5.0) mm.

The value of $f_{z\ eff}$ is used instead of f_z, because most of standard planers in woodworking industry can't achieve that all knives describe the same diameter *D,* which results in so-called one-knife finish. Effective feed per knife ($f_{z\ eff}$) in that case can be calculated as

$$f_{z\,eff} = \frac{v_f}{n_v} \tag{7}$$

n_v – rotational frequency of a cutter-head.

Only in the case where all of the knives in the cutter-head describe the same diameter *D* (planers with hydro clamping of cutter-head and subsequent jointing of knives on the machine) effective feed per knife can be calculated as

$$f_{z\,eff} = \frac{v_f}{n_v \cdot z} \tag{8}$$

z – number of knives in the cutter-head.

In order to investigate the energy efficiency and machined surface roughness after peripheral milling (climb cutting) of solid oak wood (*Quercus robur* L.) on the high performance two-side thicknessing planer, the measurements and analysis of electrical power required for cutting in industrial conditions were carried out and machined surface roughness was later measured and analysed in a laboratory.

2. MATERIALS AND METHODS

Measurements were carried out during representative working conditions on the high performance two-side thicknessing planer for surfacing and thicknessing in one operation REX, Type: BM2/63-K, Ser.No.: 23.031. Schematic representation of cutting on the two-side thicknessing planer can be seen in *Figure 1*. Cutter-heads that were used on the machine (*Figure 2*) had a diameter of the circle described by the knives (*D*) of 200 mm, six knives made of high-speed steel (HS) with rake angle (γ) of 30 ° and clearance angle (α) of 17 ° were in each cutter-head, cutter-head width was 625 mm and maximum allowable rotational frequency was 6000 min^{-1}. Each cutter-head was driven by the three-phase induction motor with rated mechanical power (P_{em}) of 55 kW and nominal voltage U = 400 V, current I = 96 A, power factor cos φ = 0.88 and nominal efficiency 94.3 % in delta connection. During experiment, rotational frequency of each cutter-head (n_v) was 5750 min^{-1}, so cutting speed (v_c) was 60 m/s, which is in the range of recommended values for this type of operation (Leitz, 2011). Feed speed (v_f) was 60 m/min and according to Equation (8) feed per knife (f_z) should than be equal to 1.7 mm. According to practical recommendations (Leitz, 2011), resulting machined surface quality should be somwhere between fine and medium. Cutting depth (a_{e1}) in a surfacing operation (first cutter-head) was 2.2 mm and in thicknessing (a_{e2}) it was 0.9 mm on the average.

Workpiece material were common oak (*Quercus robur* L.) boards, with average length of 3 m, average width (equal to average cutting width - a_p) 37 cm and average thickness 27,7 mm, with radial/tangential texture. Average moisture content of workpiece material was (9.0 $\pm$ 0.7) %. Moisture content was determined afterwords by the oven dry method (HRN EN 13183-1:2008) on the representative sample of 10 elements.

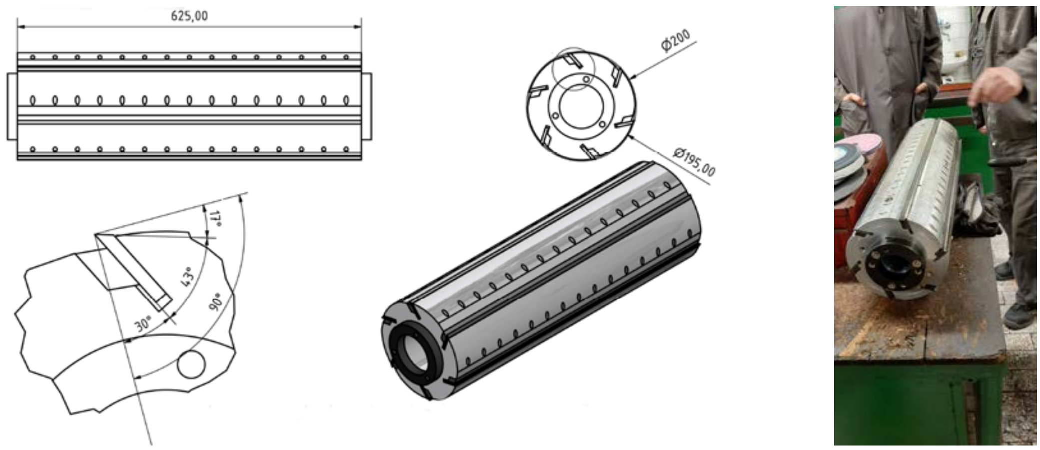

Figure 2. *Geometry of the cutter-heads that were used on the two-side thicknessing planer during experiments (D = 200 mm, z = 6, γ = 30°, β = 43°, α = 17°).*

Machining tests in controled setting were conducted on sample of 15 boards. For each board, electrical power required during machining was measured with Fluke 435-II Three Phase Power Quality and Energy Analyzers. The measurements were made simultaneously on each cutter-head drive motor. Average required cutting power (P_c) was calculated as

$$P_c = P_{tc} - P_0 \tag{9}$$

P_{tc} – average total mechanical power during cutting
P_0 – average mechanical power during no-load operation of the machine.

P_{tc} and P_0 can be determined by the means of circular diagram from the measured electrical powers on the three phase induction motor (Skalicki, 1976), but we used simplifed method described by Hamm (1970), which has the maximum relative error of 2 % with respect to a circular diagram method and it was used in similar type of measurements (Goglia, 1992; Beljo and Malek, 1995). According to a method described by Hamm (1970), mechanical power at the output shaft of the each cutter-head drive motor was calculated from measured electrical power, by the equation

$$P_{mech} = 0.969 \cdot P_{el} - 1709.868 \tag{10}$$

P_{mech} – average mechanical power at the output shaft of the cutter-head drive motor
P_{el} – average measured electrical power at the input of the cutter-head drive motor.

From the calculated values of P_c for each sample board and for each cutter-head, the values of specific cutting energy and specific cutting pressure were calculated *(Equations (1)* and *(3)*). Total average electrical power (P_{tot}), measured at the input of the machine, required during machine operation in longer time frame (several hours) was also measured. This measurements were used to estimate the average electrical energy required for processing the given volume of input material in one work shift.

From the planed boards, representative sample of elements was taken for measurements of machined surface roughness. Surface roughness was measured in the Laboratory of Mechanical Wood Processing at the Faculty of Forestry and Wood Technology in Zagreb, with surface roughness tester Mitutoyo SurfTest SJ-500 (Ser. No. B0007 1808) with an amplitude measurement range of 2 mm. The measurements were done following ISO 4287 (1997) and the R and W profile were measured. The stylus tip radius was 10 μm and following recommendations in ISO 3274 (1996) the λ_s profile filter cut-off was 25 μm and the λ_c profile filter cut-off was 8 mm. A Gaussian filter was used, although its limitations in measurement of surface profiles on materials with large pores, such as oak wood, are known, it is still most widely used filter. Evaluation length was 40 mm. Recommendations from ISO 4288 (1996) and Leach (2001) and also, the recommendations specific to wood surface roughness evaluation, given by Gurau *et al*. (2006) and Gurau and Irle (2017), were taken into account. During measurements the stylus tip traversed the machined surface in the direction that corresponded to the direction of the feed movement vector (v_f). Values of R_a, R_q and R_z parameters were automatically calculated for 60 surface roughness profiles on the machined surfaces of test samples taken from processed boards. This parameters were used, because they are the most widely used in the characterization of wood surface roughness, but *W* profile was also used for the assesment of the machined surface quality.

3. RESULTS AND DISCUSSION

From the measured values of the electrical power required during no-load and during machining of the sample boards, the average cutting power for each cutter-head was calculated according to *Equations (9)* and *(10)*. From the obtained cutting power values, specific cutting energy for each cutter-head was calculated according to *Equations (1)* and *(2)* and resulting specific cutting pressure was calculated according to *Equation (4)*. The results can be seen in the *Table 1*.

Table 1. *Results of the measured average required electrical power on the surfacing and thicknessing cutter-head in the two-side thicknessing planer and calculated values of average cutting power, specific cutting energy and specific cutting pressure during machining in the given machining conditions*

Cutter-head	*Measured and calculated quantities*				
	P_{0el}, kW	P_{el}, kW	P_c, kW	E_n, kWh/dm^3	k_c, N/mm^2
Surfacing	7.0	(16.9 ± 3.4)	(9.5 ± 3.3)	(0.0036 ± 0.0011)	(13 ± 4)
Thicknessing	6.8	(13.2 ± 1.5)	(5.6 ± 1.4)	(0.0036 ± 0.0014)	(13 ± 5)

If the results of specific cutting pressure are compared to values that can be found in the literature (Afanasjev, 1962) it can be conclude that the values are in line with values reported in literature. From the exemination of data from literature, it can be seen that one of the main factors affecting the value of specific cutting pressure is feed per knive, actually the value of mean chip thickness, on which it has direct influence. According to *Equation (4)*, it can be seen that the value of specific cutting energy should be also favorable and it can be stated that machining on this machine with given machining parameters is energy efficient. But, we can also see that on the average, total electrical power required for machining is 30.1 kW and according to main motor drives data, their combined nominal electrical power is 117 kW, which results in only 26 % utilization of total motor power, which indicates that the main drive motors are oversized. From measured data it can be easily calculated that on the average, electrical energy required for planing of 1 m^3 of input lumber was 0.8 kWh/m^3.

Results of the measured roughness parameters can be seen in *Table 2*.

Table 2. *Results of the measured roughness parameters obatined from surface profiles of machined surfaces after machining on the two-side thicknessing planer*

Cutter-head	*Measured roughness parameters*		
	R_a, μm	R_q, μm	R_z, μm
Surfacing	(7.60 ± 0.73)	(9.43 ± 0.87)	(43.69 ± 3.72)
Thicknessing	(8.87 ± 1.41)	(11.79 ± 1.96)	(51.83 ± 7.88)

In the ideal situation, theoretical roughness of machined surface after peripheral milling, represented by the height of knife marks left on the machined surface (r_w), should be equal to the value of R_z parameter. Due to different influences it can have much higher values. If we compare the obtained average values of R_z parameter with sample roughness profile in *Figure 3*, it can easily be seen that the height of the waves is around 25 µm. This value is much lower than obtained values of R_z parameter, due to influence of wood anatomical roughness and other surface defects, like chipped grain, which was present on the machined surfaces.

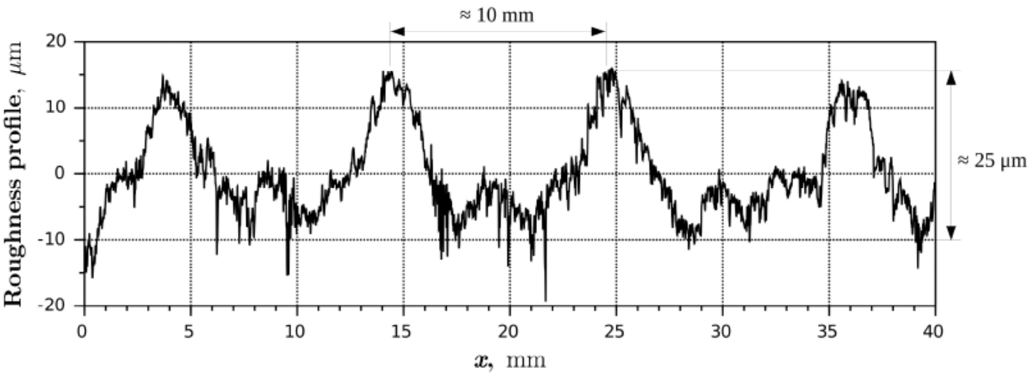

Figure 3. *Representative sample of the measured roughness profile on the machined surface of solid oak wood after machining on the two-side thicknessing planer for surfacing and thicknessing in one operation, in the observed machining conditions.*

Waviness parameters were also measured and the average value of the W_z parameter for surface obtained after surfacing was (25.23 $\pm$ 3.04) µm and for surface obtained after thicknessing it was (29.60 $\pm$ 5.48) µm. From *Figure 3* it can easily be seen that the values of W_z parameters are in good agreement with visually determined height of profile waves on the machined surface. It can be concluded that a good choice of parameter, or parameters, is essential for good quantitative description of surface quality.

From *Figure 3* it can also be seen that distance between two consecutive peaks of surface profile is around 10 mm, which is a lot more than our calculated value of 1.7 mm for feed per knife. If f_{zeff} is calculated according to *Equation (7)*, the value of 10.6 mm is obtained, which is in agreement with our measured value. From this result, it can be stated that we have one knife finish in this case and there is no need for more than two or four knives in the cutter-head, because only one knife defines the quality of machined surface. Accordingly, the feed speed should be lowered to more appropriate levels, in line with practical recommendations (Leitz, 2011). If the results are compared with recommended values (Ettelt and Gittel, 2004; Leitz, 2011) it can easily be seen that the resulting quality of the machined surface is much worse than what is recommended even for coarse quality. In order to obtain better surface quality with higher feed speeds, that this machine is capable of, jointing operation should definitely be used. It can also be seen that if the theoretical height of knife marks left on the machined surface (r_w) is calculated according to *Equation (6)* with our input parameters, it differs significantly from calculated values, so it can't be concluded that it can't be used for reliable prediction in such cases.

4. CONCLUSIONS

From the performed analysis of the energy efficiency and machined surface roughness in machining of solid oak wood (*Quercus robur* L.) on the high performance two-side thicknessing planer in industrial settings, it can be concluded that:

- relatively small amount of energy is required for the removal of the unit volume of the workpiece material and in our case specific cutting energy was equal to 0.0036 kWh/dm^3,
- because of the direct relationship between specific cutting presure and specific cutting energy, previous knowledge of the influencing factors on specific cutting pressure can be used in the analysis,
- on the avreage specific cutting pressure was 13 N/mm^2 which is in line with data available in the literature and it indicated that chosen machining parameters resulted in the energy efficient cutting process,
- on the other hand it was concluded that only 26 % of the rated motor power was used on the average, which indicated that the machine was oversized for its current use,
- due to inadequate preparation of the tool, surface quality was dictated by the so called one knife finish and the quality of the resulting machined surface was coarse, with effective feed per knife around 10 mm, which is much higher than what is usually recommended,
- for this type of operation, if larger waves due to kinematic traces of knives on the machined surface are present, waviness parameter W_z is better choice for surface quality assement than roughness parameters obtained from *R* profile and
- it seems that prediction of the theoretical height of knife marks left on the machined surface based on the known equations is not effective way to predict the surface quality with standard input parameters in situations where one knife finish is present.

Acknowledgements: *The authors would like to thank company Bjelin Spačva d.o.o. for making the measurements on their production lines possible and to acknowledge the support of the European Structural and Investment Funds through financing the IRI project "Research in the company Spačva d.d. for the purpose of developing innovative massive doors made of Slavonian oak" - KK.01.2.1.01.0117.*

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Real Parameters of a Focused CO_2 Laser Beam and its Determination when Using Lenses with Different Focal Lengths

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ABSTRACT

This paper proposes a method for practical calculating of the real parameters of a focused laser beam – focal spot diameter and depth of focus. These parameters are of great importance for describing the interactions processes (cutting/engraving) between the CO_2 laser beam and the wood material. These processes are analysed with mathematical models, where the laser beam is assumed to be a perfect Gaussian beam (TEM_{00}). The calculated real values of these parameters will give greater credibility to the results of these models and their analysis.
For this research ZnSe lenses were used with focal lengths: F = 38.1 mm, F = 50.8 mm, F = 63.5 mm and F = 76.2 mm. They are part of the equipment of a laser machine, model AEON MIRA 9 for cutting and engraving of wood and wood-based materials (WBM).

Key words: CO_2 laser beam, focal spot diameter, depth of focus, real parameters, wood and wood-based materials

1. INTRODUCTION

Lasers and laser technologies are now integral part of modern industry and society, including woodworking and furniture production.

One of the main factors that determines the CO_2 laser (wavelength λ = 10.6 μm) applicability for wood and WBM processing is the absorption capacity of the material, which for most wood species is of the order of 88 % (Gochev, 1996).

In addition to being a cutting tool, the laser beam, can also be used as a means of surface treatment – engraving, marking and creating complicated decorative images on wood and WBM.

Numerous experimental studies show that laser power and cutting/engraving speed are the dominant factors influencing the quality in the laser process (Pagano *et al.* 2009; Hernández-Castañeda *et al.* 2011; Petutschnigg *et al.* 2013; Eltawahni *et al.* 2013; Martinez-Conde *et al.* 2017; Gurau *et al.* 2017; Vidholdová *et al.* 2017; Sikora *et al.* 2018; Jurek *et al.* 2021). In addition, the spatial distribution of the laser beam power density in the focusing spot, the type of focusing lens, the focusing conditions, etc., also have an influence (Gochev *et al.* 1994; Gochev 1996; Gochev and Dinkov, 1996; Dinkov *et al.,* 1996; Eltawahni *et al.,* 2011; Ion 2005; Kubovský *et al.,* 2020).

In cases where the laser is used for cutting/engraving wood and WBM, it is necessary to transport the beam coming out of the resonator to the place of processing using a system of reflective mirrors and focusing optics. The path of the laser beam exiting the resonator (tube) and directed to mirror № 1 must be parallel to the laser beam that passes from mirror № 2 to mirror № 3 and perpendicular to that between reflecting mirror № 2 and № 3 (*Figure 1*).

In the process of processing wood or WBM, the focal plane occupies one of the three positions shown in *Figure 2*; above the surface (*Figure 2A*), on the surface (*Figure 2B*), and inside (under the surface) of the material (*Figure 2C*). In the first case, depending on the distance ΔF, the possibility of defocusing the light energy increases proportionally. As ΔF

grows, the radius of the light spot on the surface of the material increases, and therefore the flux density decreases. This case applies when surface machining or cutting to a certain depth in the material is required.

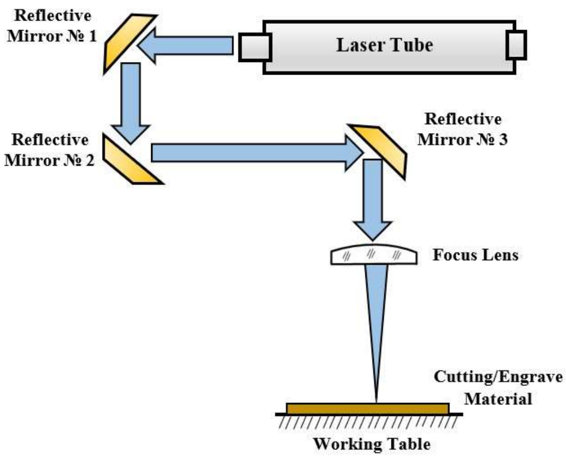


Figure 1. Scheme of the external optical path of the laser beam.

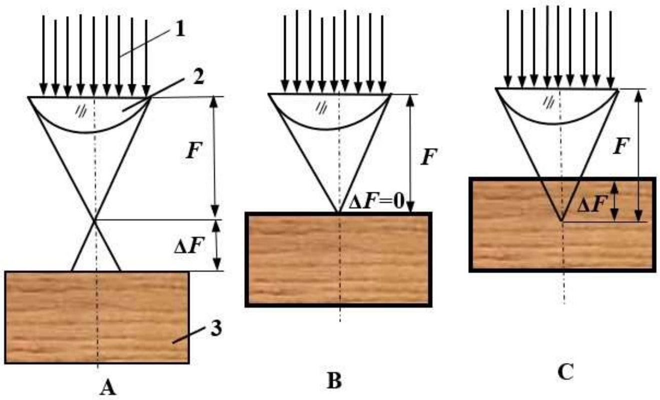


Figure 2. Position of the focal plane of the focusing lens relative to the surface of the material: 1 - laser beam; 2 - focusing lens; 3 - processing material.

A laser beam is an electromagnetic wave consistent with the wave optics (the physical optics), it cannot be focussed to a sharp point. As a consequence, the focus diameter is not zero.

The focus diameters of the lenses are much larger than the values calculated as a Gaussian beam in the fundamental TEM mode.

2. OPTICAL PARAMETERS OF A GAUSSIAN LASER BEAM

The intensity of the laser beam changes along the length of the optical axis, increasing in the area of convergence and decreasing in the area of convergence. The beam dissipation (ψ) can be roughly estimated from the diameter D of the laser beam measured at the exit of the resonator (Duley, 1983):

$$\psi = \frac{4\lambda}{\pi . D} \quad (1)$$

λ – wavelength for CO_2 lasers (10.6 μm)

Since the wavelength λ is much smaller than the beam radius ωo, the angle ψ is very small, on the order of a few mrad. Because of its coherence and monochromaticity, it is possible to focus the laser beam at a single point. The diameter of the spot is of the order of the wavelength. The heating zone is therefore highly localized. The slot width is very narrow and material loss is minimal.

The simplest calculation of the intensity distribution in the focus area is possible for an ideal Gaussian beam, i.e., for a TEM_{00} fundamental mode beam and aberration-free optics. In such a case, the radius of the focal spot is (Duley, 1983; Subhasisa, 2020):

$$\omega_o = \frac{2F\lambda}{\pi . D} \tag{2}$$

F – focal length of the lens (mm)

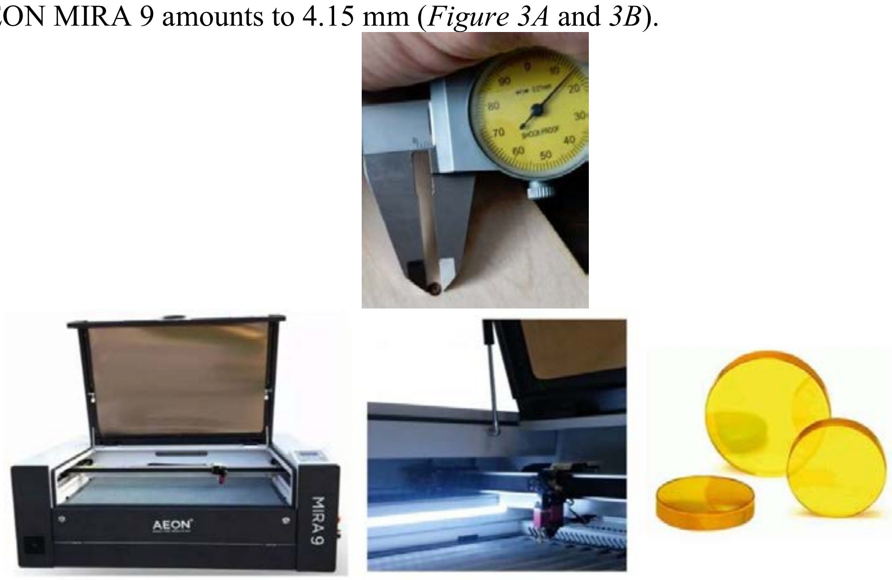
A commonly used definition of the beam diameter is the width at which the beam intensity has fallen to $1/e^2$ (13.5 %) of its peak value. This applies to the Gaussian beam in the fundamental TEM_{00} mode (ISO 11146-1:2021-07; Menga *et al.,* 2019).

The following important characteristic of a focused laser beam is the depth of focus *z*. The depth of focus is a measure of the change in the waist of the beam on either side of the focal plane.

It is assumed that with a 5 % increase in the focal spot along its axis, i.e., $\omega_{(z)} = 1.5\omega_o$ the power density does not change significantly. Depth of focus can be represented as (Duley, 1983; Makherjee *et al.,* 1994; Subhasisa, 2020):

$$z = \frac{0.64\pi . \omega_o^2}{\lambda} \tag{3}$$

The experimentally determined beam diameter at the exit of the laser machine resonator, model AEON MIRA 9 amounts to 4.15 mm (*Figure 3A* and *3B*).



A **B** **C**

Figure 3. A – beam diameter at the resonator exit; B – laser machine, model AEON MIRA 9; C – ZeSe focusing lenses.

Table 1 shows the values calculated, based on equations (2) and (3), for the radius of the Gaussian laser beam in the focal plane (ω_o) and the depth of focus (z) for ZnSe lenses (*Figure 3C*) with focal lengths: *F* = 78 mm; *F* = 38.1 mm; *F* = 50.8 mm; *F* = 63.5 mm и *F* = 76.2 mm.

Table 1. Dimensions of the Gaussian laser beam radius in the focal plane ω_o and its depth z for lenses with different focal lengths

F (mm)	ω_o (µm)	z (µm)
38.1	62	728.8
50.8	82.6	1293.5
63.5	103.3	2023.0
76.2	124	2915.1

3. DETERMINATION OF THE ACTUAL PARAMETERS OF THE FOCUSED LASER BEAM

The radius of the laser beam at a distance z from the focal plane in the direction of propagation of the beam is (Duley, 1983; Ion, 2005):

$$\omega = \omega_0 \left[1 + \left(\frac{\lambda . z}{\pi . \omega_0^2}\right)^2\right]^{0.5} \quad (4)$$

In real operating laser systems, the minimum radius is larger than the above diffraction-limited radius ω_o, mainly due to spherical aberration. Therefore, it can be assumed that the actual diameter of the laser beam is approximately:

$$d = \delta d_0 + 2\omega_0 \left[1 + \left(\frac{\lambda . z}{\pi . \omega_0^2}\right)^2\right]^{0.5} \quad (5)$$

Were, $\delta d_0 = d_0 + 2\omega_0$;

d_o – real focal spot diameter;
δ – coefficient accounting for the difference between the actual and the Gaussian diameter of the focal spot.

If we increase the laser beam trace in the area of the focal plane, it will have approximately the form shown in *Figure 4*.

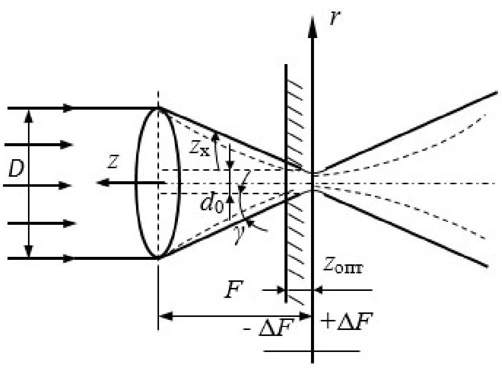


Figure 4. Area of the focal plane.

It can be seen from the figure that when focusing the laser beam with an optical system, near the focal plane, there is an area of caustic (from Greek *καύστικος* - a bundle of rays that do not converge at one point), determined by the axial distance (for example, $2z_{opt}$). In this region, in an arbitrary diametrical section, the radiation power density is sufficient to vaporize the material. When placing the processed surface lower than the focal plane but not more than a

z_{opt}, it is useful to use (from the point of view of dimensional destruction of the material) only part of the specified area. If the focal plane is located in the depth of the material (with displacement $\Delta F = z_{opt}$), then the entire caustic area is included in the processing process.

As a result of the aberrations inherent in each optical system, an increase in the size of the focal spot occurs. It has not only an increased diameter, but is also drawn along the axis of the optical system and is characterized by the parameter mentioned above-, depth of focus *z.* Depth of focus estimation is useful for valuing the area of interaction of the laser beam with the material. The definition of depth of focus is that it is variable and depends on its application.

According to (Duley, 1983) the depth of focus is defined as the value of *z* where $\mathrm{d}\frac{d}{d_o} = 1.5$, so:

$$|z_o| = \frac{\pi.\omega_o^2}{\lambda}\left[(0.5k_1 + 1)^2 - 1\right]^{0.5} \tag{6}$$

Were, $k_1 = \frac{d_o}{2\omega_0}$.

The above formula is suitable because, when the beam diameter increases to $11.5d_o$ ie. at a distance z_o (*Figure 5*), the power density will decrease to 1/2.25 of that in the focal plane, and such power can only slightly heat the wood.

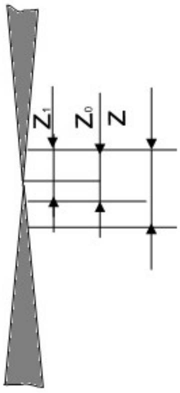


Figure 5. Effective beam penetration depth.

The effective penetration depth of the beam is $z = z_o + z_1$, where z_1 is the distance from the focal plane below the workpiece surface ($0 < z_1 < z_o$). The maximum effective beam penetration depth is $z_{max} = 2z_o$, when $z_1 = z_o$.

If we consider the the spot size in the focal plane, i.e., at $= 0$, then the depth of focus $|z_o|$ will be equal to 0. Equality (6) can be written as:

$$0 = \left|\frac{\pi.\omega_o^2}{\lambda}\left[\left(\frac{0.5d_0}{2\omega_o} + 1\right)^2 - 1\right]^{0.5}\right| \tag{7}$$

Squaring and doing the transformations gives:

$$d_0 = |8\omega_o| \tag{8}$$

Because $\delta = 1 - \frac{2\omega_o}{d_o}$, for lenses with different focal lengths, the coefficient accounting for the difference between the actual and Gaussian size of the spot will be $\delta = 0.75$.

4. CALCULATION OF THE EFFECTIVE DIAMETER AND DEPTH OF FOCUS OF A LASER BEAM FOR LENSES WITH DIFFERENT FOCAL LENGTHS

Based on the conducted theoretical studies and derived dependencies, the actual diameter of the laser beam in the focal plane was calculated (d_o) and the depth of focus $|z_o|$ for ZnSe lenses with focal lengths: F = 38.1 mm; F = 50.8 mm; F = 63.5 mm и F = 76.2 mm.

These lenses are often used when working with a laser machine model AEON MIRA 9 in the „Laser Technologies" laboratory at the University of Forestry - Sofia. The results are presented in *Table 2*.

Table 2. Dimensions of the actual diameter of the focus d_o and its depth $|z_o|$ for lenses with different focal lengths

F (mm)	d_o (μm)	$|z_o|$ (μm)
38.1	496.0	3220.7
50.8	660.8	5716.5
63.5	826.4	8940.7
76.2	992.0	12882.9

At distance $|z_o|$ from the focal plane, the actual diameter d for these types of lenses will be respectively: $d_{38.1}$ = 744 μm; $d_{50.8}$ = 991.2 μm; $d_{63.5}$ = 1239.6 μm и $d_{76.2}$ = 1239.6 μm. The maximum effective beam penetration depth (*Figure 6*) is: $z_{38.1_{max}} = 6441.4\ \mu m$; $z_{50.8_{max}} = 11433\ \mu m$; $z_{63.5_{max}} = 17881.4\ \mu m$ и $z_{76.2_{max}} = 25765{,}8\ \mu m$.

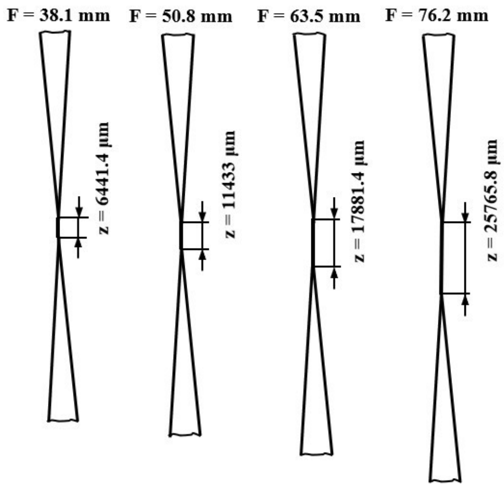


Figure 6. Actual view of the laser beam for lenses with different focal lengths.

5. CONCLUSIONS

From the analysis and mathematical calculations for the parameters of the focused laser beam, the following conclusions can be drawn:

Based on the theoretical studies in the literature on the focused laser beam parameters, the coefficient accounting for the difference between the actual and the Gaussian size of the spot is derived. Its value is $\delta = 0.75$. It can be used to calculate focus diameter d_o and its depth $|z_o|$ for lenses with different focal lengths.

The actual focus diameter d_o and its depth $|z_o|$ are calculated for lenses with different focal lengths most commonly used in the "Laser Technologies" laboratory (F = 38.1 mm; F = 50.8 mm; F = 63.5 mm и F = 76.2 mm).

he maximum effective depth penetration of the beam into the material was determined. For the different focusing lenses, it is: $z_{38.1_{max}} = 6441.4\ \mu m$; $z_{50.8_{max}} = 11433\ \mu m$; $z_{63.5_{max}} = 17881.4\ \mu m$ и $z_{76.2_{max}} = 25765{,}8\ \mu m$. The parameters of the focused laser beam very well match the actual appearance of the laser beam for lenses with different focal lengths.

Optics with a large focal length have a bigger focal spot diameter and focus depth, but have a smaller power density. An optic with a short focal length produces a smaller focal spot diameter and focus depth, but samore significant r power density.

The maximal thickness of materials which can be cut efficiently is limited by the optimum focal length and the focus position relative to the surface of the material. When cutting thin materials, it is advisable to use lenses with short focal lengths and a position of focus on the material surface e. Cutting thicker materials requires lenses with a greater depth of focus, respectively with a greater focal length and position of the focus below the material surface.

The parameters determined by the focused laser beam make it possible to use them in mathematical models describing the interaction of the laser beam with wood and WBM, in which the parameters of an ideal Gaussian beam are used. Through them, the credibility of the described processes will be maximally accurate.

Acknowledgements: *We would like to thank the Research Sector of the University of Forestry, Sofia, Bulgaria, with whose support, through Contract No. NIS-B-1284/19.10.2023, this research was carried out.*

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Acoustic Parameters of Birch Wood Compared to Maple Wood and Medium Density Fibreboard

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ABSTRACT

This work deals with the analysis of acoustic properties of chosen wood species and wood-based materials, like maple, birch, and medium-density fibreboard. Acoustic properties that are analysed in this article are acoustic radiation and acoustic wave impedance. For that measurements were used ultrasound and resonance methods. Both of the used methods show that birch could be a good alternative for use in musical instruments instead of maple. Emphasis was also placed on the use of selected materials for the production of speaker enclosures. If maple was considered as the default, birch showed acoustic radiation values 20 % higher than maple and medium-density fibreboard 57 % lower. In the case of acoustic wave impedance, the average value of birch was 30 % higher, and for medium-density fibreboard the value was 35 % lower than that of maple. Based on the measured values, recommendations are derived for the use of selected woods and materials for the music industry and audio engineering.

Key words: sound, acoustic radiation, acoustic wave impedance, wood-based materials

1. INTRODUCTION

In our daily lives, sound is everywhere, often experienced through speaker systems. For some, sound isn't just routine; it's a profession, a way of life, or a passionate pursuit. This connection with sound extends beyond electronics to musical instruments, where wood plays a crucial role, much like it does in speaker enclosures (Toumpanaki 2021). This paper delves into the acoustic qualities of specific wood types used in these interconnected realms.

We begin with Medium Density Fiberboard (MDF), a key material in crafting speaker enclosures. MDF shapes sound quality, enhancing the auditory experience (Toman, 2010). In the world of musical instruments, we turn to Maple, a revered wood used in violins and stringed instrument necks. Its unique acoustic traits influence the timbre and resonance, defining musicians' artistic expression (Zhou *et al.*, 2017; Bucur, 2023). Birch, a versatile wood, is also explored. It holds potential in both sound reproduction for speakers and the craftsmanship and tonal range of musical instruments.

This paper explores the intersection of science and art, investigating the acoustic intricacies of these woods and their impact on sound quality and artistic expression in audio technology and music (Kozel, 2021).

2. MATERIALS AND METHODS

This methodics aims to elucidate critical acoustic parameters through the evaluation of pertinent test samples. The parameters of interest encompass the acoustic constant, which delineates the fundamental acoustic behavior and acoustic wave resistance, characterizing the medium's response to sound transmission. This meticulous examination and measurement process serves as a foundation for unraveling the intricate acoustic properties and fundamental principles governing sound propagation and resonance (Nasir *et al*., 2019).

2.1. Measurement of physical and mechanical properties of wood

The primary objective in the examination of these materials is to determine the aforementioned acoustic parameters. Simultaneously, the density of the samples will be established, as well as the speed of sound propagation, dynamic modulus of elasticity, and, for comparative purposes, the static modulus of elasticity. This comprehensive analysis encompasses the critical acoustic attributes and material characteristics, enabling a holistic understanding of the acoustic behavior and structural properties within the tested materials.

2.1.1. Determination of density

Determining the density is essential for further calculations. The measurement takes place on already air-conditioned bodies. First, the transverse dimensions will be measured with an electronic caliper with an accuracy of 0.01 mm and distinguishing the radial and tangential directions, for the following tests. Next, the length of the samples is measured using a fixed gauge with an accuracy of 1 mm. The volume will be calculated from these dimensions. Then the bodies are weighed on a laboratory weighing-machine with an accuracy of 0.01 g. The measured and calculated values will be entered into the formula (1); according with ČSN 490108:

$$\rho_w = \frac{m_w}{V_w} \tag{1}$$

m_w – weight at humidity w (kg)
V_w – volume of wood at the same humidity (m^3)

2.1.2. Measuring of resonance frequency

The principle is based on determining the frequency of oscillations that pass through the body per unit of time. For this experiment, were used bodies with a length of 600 mm, which fulfills the requirements for their minimum length of 0.5 m or at least five times the width. The length l in meters is used to calculate the expected frequency f (Hz) according to formula (2):

$$f = \frac{2500}{l} \tag{2}$$

Each test object is placed on damping pads during measurement so that the signal is not affected in any way. The distance of the pad from the fronts of the sample is 132 mm, as it must meet the prescribed value of 0.22 l. The recording apparatus consists of a microphone (Behringer ECM 8000) connected to an amplifier (Steinberg UR22 MK2), which is further connected to a laptop with the necessary software (Fast Fourier Vibration analyzer), see *Figure 1*. We use a steel hammer as an impact object, which initiates the formation of waves. The weight of the hammer must correspond to a value of 0.5-5 % of the weight of the tested sample. Before striking, the pickup microphone is placed close to (but not touching) one face of the sample and the other face is struck. For solid wood, the frequency value should be within 20 % of the value obtained from the previous formula. This value is displayed in the software on the laptop, but it is only displayed until another signal is captured, which can be very weak. Therefore, as a rule, the body is struck several times to make it clear which value is correct (Fakopp Enterprise Bt.).

From the measured values, it is possible to calculate the propagation speed of the acoustic wave *c* (m/s) in the wood in the longitudinal direction according to the formula (3):

$$c = 2 \cdot l \cdot f \tag{3}$$

l – body length (m)
f – resonant frequency (Hz)

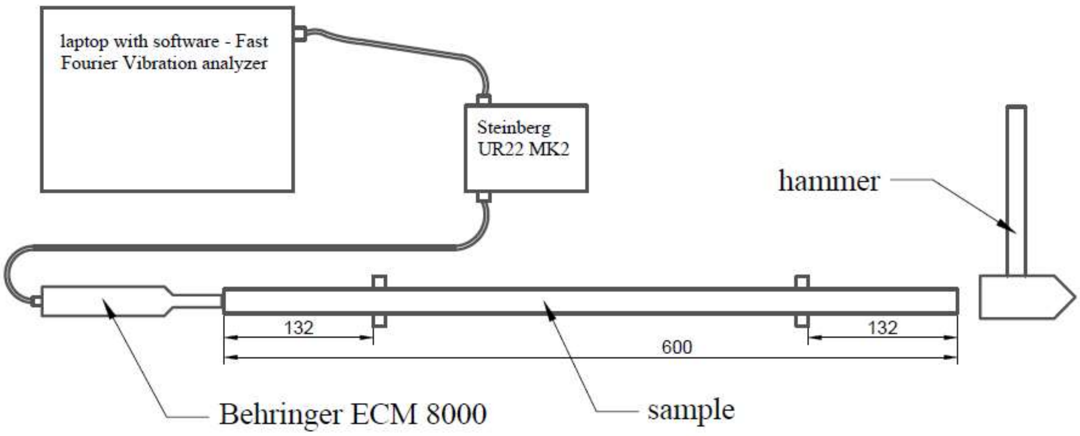

Figure 1. Measuring apparatus of the resonance method.

2.1.3. Measuring the time of passage of an ultrasonic wave

The testing is conducted on specimens measuring 20 x 20 x 300 *mm* (height x width x length). The measurement system employed is the FAKOPP Ultrasonic Timer, comprising two piezoelectric probes along with the device itself, as illustrated in Figure 2. Operators manually position the probes on the surface of the specimen, initiating an ultrasonic pulse to start the timing process. The ultrasonic wave must traverse the material until it reaches the second probe, at which point the time measurement concludes.

Multiple measurement distances are considered, specifically 60, 100, 140, 180, and 220 *mm*. To ensure precise probe placement, markers are applied at these designated positions on each specimen. However, the distance of 140 *mm* is specifically used to calculate the speed of wave propagation within the wood. The remaining distances are employed to determine the correction required for the probe's zero-distance.

The value of the speed of sound wave passage through wood is crucial information that can be utilized to determine many wood properties (Roohnia, 2016). However, this parameter can be influenced by several factors, as described by various authors. Gerhards (1982) summarized that wave speed changes with fiber deviation, moisture, temperature, wave frequency, and amplitude. It has also been demonstrated that speed correlates with elasticity moduli and density. These relationships form the foundation for determining strength characteristics and receive significant attention (Bucur, 2006). The speed of ultrasonic wave passage c (m/s) can be calculated using formula (4):

$$c = \frac{l}{t-k} \tag{4}$$

l – probe distance (m)
t – time of wave passage (s)
k – correction required for the probe's zero-distance (s)

These parameters collectively contribute to the calculation of the dynamic modulus of elasticity E (MPa) using formula (5).

$$E = c^2 \cdot \rho \tag{5}$$

Of course, the dynamic modulus can also be determined for the resonance method according to identical formulas (Tippner *et al.*, 2023).

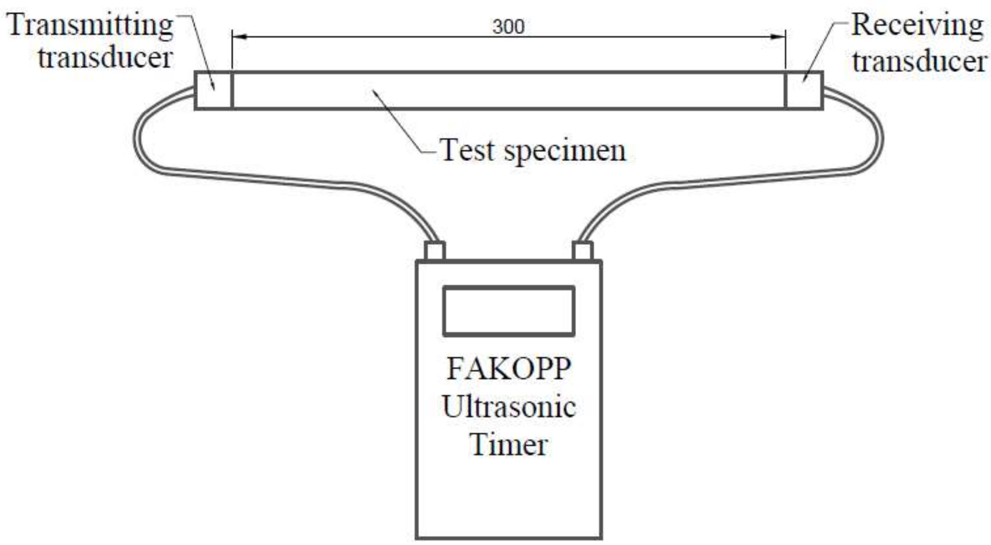

Figure 6 Measuring apparatus of the ultrasonic method

2.1.3. Determination of acoustic constant and acoustic wave resistance

The resistance of the medium to a planar sound wave is referred to as acoustic wave resistance. It involves internal friction induced by the material, which is greater in wood than in metals. This parameter is primarily influenced by the density and speed of sound propagation (Horáček, 2008).

Since the value of the dynamic modulus of elasticity is already known, it is possible to determine the value of the acoustic constant K_A (m^4/kg·s), which can be expressed by formula (6):

$$K_A = \sqrt{\frac{E}{\rho^3}} \tag{6}$$

E – dynamic modulus of elasticity (Pa)
ρ – density of the material (kg/m^3).

Since we know all the necessary variables, we can determine the value of the acoustic wave resistance using the formula (7):

$$Z = \rho \cdot c = \rho \cdot \sqrt{\frac{E}{\rho}} \; [kg \cdot m^{-2} \cdot s^{-1}] \tag{7}$$

3. RESULTS AND DISCUSSION

3.1. Acoustic wave resistance

From *Figure 4*, it is evident that birch wood exhibits the highest acoustic wave resistance, as observed through both methods used to determine this parameter. In the ultrasonic method, birch wood had an average acoustic resistance value of $33.3 \cdot 10^{-5}$ kg/m^2·s, and in the resonance method, it was $32.6 \cdot 10^{-5}$ kg/m^2·s. From *Figure 5* and *Tables 1 and 2*, it is apparent that differences in the mean values of acoustic wave resistance determined by both methods are negligible for individual materials, but not among different materials. For maple wood, the mean values of acoustic resistance in both cases were lower, measuring $25.9 \cdot 10^{-5}$ kg/m^2·s for the ultrasonic method and $24.9 \cdot 10^{-5}$ kg/m^2·s for the resonance method. The lowest values were observed in MDF (12.6 and $16.2 \cdot 10^{-5}$ kg/m^2·s).

Birch wood exhibited the highest degree of variability (8.8 %), while MDF showed the least (1.9 %). The determined values of acoustic wave resistance are closest to those available in the literature in the case of maple, although for this comparison, only a similar wood species in structure (hardwood with a ring-porous structure), namely beech, is cited by Požgaj *et al.* (1993) with an acoustic wave resistance value of $22 \cdot 10^{-5}$ kg/m^2·s.

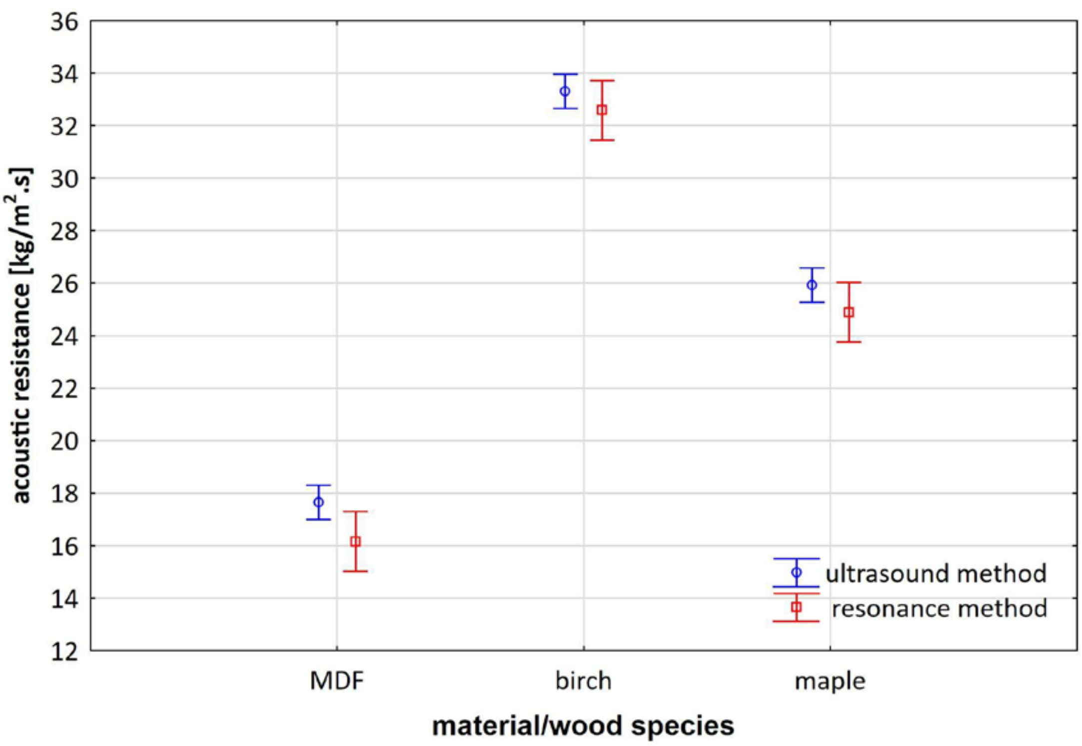

Figure 4. Acoustic wave resistance of tested materials.

Table 1. Acoustic wave resistance – ultrasound method

Acoustic wave resistance - ultrasound method [kg/m^2·s]·10^{-5}						
Material/ wood species	N	Average value	Min.	Max.	Standard deviation	Coefficient of variation [%]
MDF	32	17.6	16.9	18.5	0.3	1.9
Birch	32	33.3	26.7	39.3	2.9	8.8
Maple	32	25.9	22.1	27.6	1.2	4.8

Table 2. Acoustic wave resistance – resonance method

Acoustic wave resistance - resonance method [kg/m2.s]·10-5						
Material/ wood species	N	Average value	Min.	Max.	Standard deviation	Coefficient of variation [%]
MDF	32	16.2	15.8	16.5	0.2	1.4
Birch	32	32.6	16.0	36.7	5.1	15.6
Maple	32	24.9	21.0	35.7	2.4	9.5

3.2. Acoustic constant (radiation constant)

From *Figure 5*, it is apparent that birch wood achieved the highest mean values of the acoustic constant in both measurements, reaching 8.5 m^4/kg·s in the ultrasonic method (*Table 3*) and 8.1 m^4/kg·s in the resonance method (*Table* 4). Both methods also showed the highest degree of variability. Požgaj *et al*. (1993) reported slightly lower values for this wood species, at 7.5 m^4/kg·s. For maple, values of 7.1 and 6.8 m^4/kg·s were observed, which are higher than those reported by Požgaj *et al*. (1993) in their work on maple wood, where a value of 5.8 m^4/kg·s was cited. The lowest mean values with the least variability were recorded for MDF, at 3.1 *m^4/kg·s* for the ultrasonic method and 2.9 m^4/kg·s for the resonance method.

Although solid wood achieves higher values than MDF, MDF is the preferred material for speaker enclosures. The reason lies in its lower sound radiation, which could affect the output frequency response of the speaker system. The extent to which this difference affects the frequency response remains to be observed.

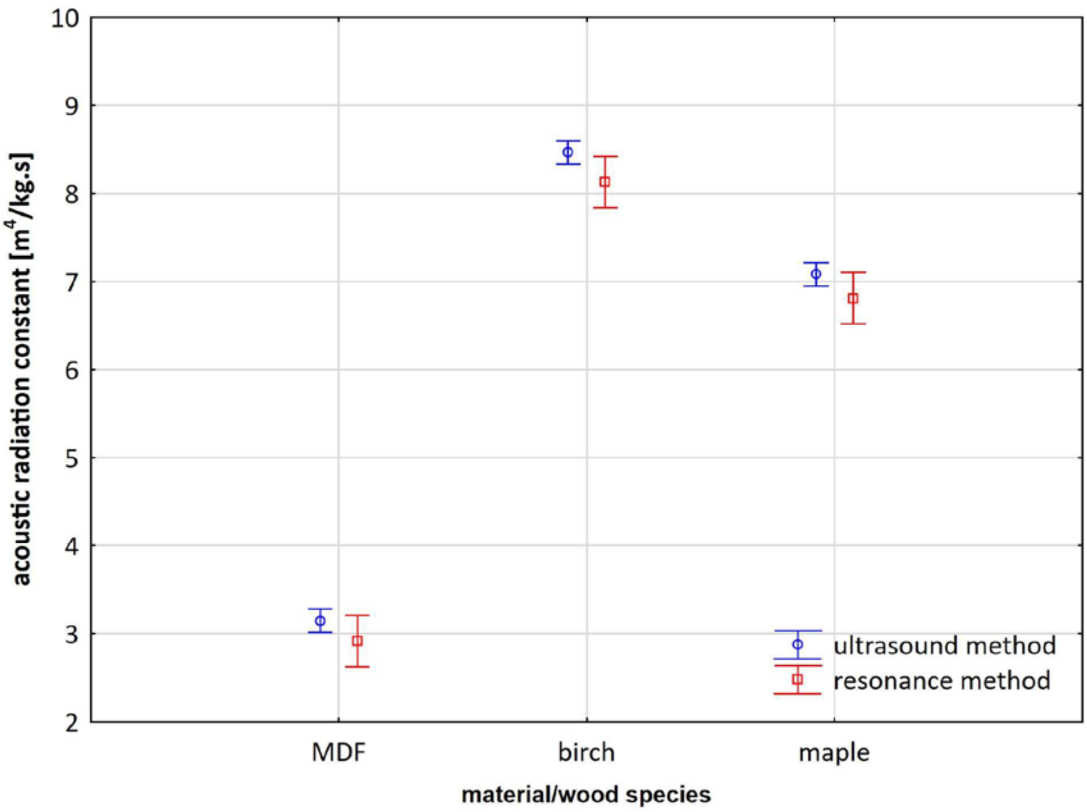

Figure 5. Acoustic constant of tested materials.

Table 3. Acoustic constant – ultrasound method

Acoustic constant - ultrasound method [$m^4/kg{\cdot}s$]						
Material/ wood species	N	Average value	Min.	Max.	Standard deviation	Coefficient of variation [%]
MDF	32	3.1	3.0	3.3	0.1	1.7
Birch	32	8.5	7.6	9.8	0.5	6.5
Maple	32	7.1	6.0	7.8	0.4	5.1

Table 4. Acoustic constant – resonanace method

Acoustic constant - resonance method [$m^4/kg{\cdot}s$]						
Material/ wood species	N	Average value	Min.	Max.	Standard deviation	Coefficient of variation [%]
MDF	32	2.9	2.9	3.0	0.0	0.9
Birch	32	8.1	2.9	8.9	1.4	17.2
Maple	32	6.8	6.1	8.4	0.3	5.1

4. CONCLUSIONS

The results of comparing the acoustic properties of the materials used indicate that the acoustic constant is the lowest for MDF board, with its value nearly half of that for solid wood. Birch achieved higher values than maple, following a similar trend in acoustic wave resistance. The dynamic modulus of elasticity showed a same distribution, with birch wood having the highest value, followed by maple, and the lowest values observed for MDF. All these results are consistent with existing literature.

Birch appears to be a promising alternative to maple, not only for musical instruments but also as a suitable material for constructing speaker enclosures. The choice of enclosure shape, eventualy complemented by acoustic filling to mitigate diffraction effects, plays a significant role in this context (Newell *et al.*, 2007; Hardwood *et al.*, 1977). The potential of Birch and other pioneer woods opens avenues for further research, not only in the realm of acoustics but also from broader perspectives.

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Mycelium-Based Biocomposites from Recycled Wood: Influence of Fungal Species on Properties of Biocomposites

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ABSTRACT

Mycelium-based bio-composites (MBB) are composite materials that are produced by the growth of fungal mycelia on the substrate from lignocellulosic (LC) materials such as straw, husks or wood particles. Adhesives are not used in this technology to produce composites, because the LC particles are bonded by mycelium. MBB can be used for packaging, decorative design objects or for furniture. In the presented research particles from recycled wood were used to produce not-pressed MBB. *Ganoderma lucidum, Ganoderma lingzhi* and *Pleurotus ostreatus* were selected to grow the MBB from recycled wood. Tensile strength perpendicular to the plane of the board (internal bonding) and moisture uptake of the produced variants of MBB as well as fungi growth rate were evaluated. It was observed that all used fungal species were able to fully colonise the substrate from recycled wood and that the contaminants present in the recycled wood did not negatively affect the ability of fungi to colonise the substrate. Produced MBB reached promising properties that offer the possibility of using the developed material for thermal insulation purposes.

Key words: bio-composite, cellulose, heat insulation, mycelium, recycled wood

1. INTRODUCTION

The need to reduce production from traditional materials based on non-renewable resources goes hand in hand with the demand for circular production. Two types of materials, plastics and wood-based composites, have become the most used in furniture production in recent decades. However, the current production and disposal of plastics pose a social threat. In producing particleboards and MDF boards, synthetic resins are used as binders. These resins often contain formaldehyde, a volatile organic compound (VOC). Although both materials can be recycled to some extent, the presence of synthetic resins makes the recycling process more difficult and limited. Mycelium-based biocomposites (MBB) are considered promising ecologically sustainable alternative synthetic materials. They use waste from organic farming and woodworking. The key advantages of the resulting MBB are the low cost of raw materials, rapid biodegradability, recycling and a minimal carbon footprint (Dias *et al*., 2021).

MBBs are created on the principle of the growth of a saprophyte fungus. The mycelium connects the particles of the nutrient substrate through a 3D network of hyphae. As a substrate, various secondary agricultural and forestry wastes rich in cellulose, hemicelluloses and lignin are used (Butu *et al*., 2020). MBB is grown on lignocellulosic substrates without the addition of adhesives or harmful waste generation (Elsacker *et al*., 2019; Yang *et al*., 2021). MBBs offer a range of uses that depend on the properties given by the main factors, i.e., by the choice of fungi and lignocellulosic substrate, their interaction, growth conditions and processing techniques (Sydor *et al*., 2021).

The binder of MBB is the mycelium of wood-decaying fungi, in which structurally chitin predominates, complemented by β-glucans and glycoproteins (Shen *et al*., 2023). The mycelium grows into a three-dimensional network of filamentous long hyphae approximately 2 to 20 µm in diameter that form the vegetative part of the fungi (Fricker *et al*., 2007). Hyphae attach lignocellulosic particles to each other by breaking down polymers of cellulose, hemicelluloses, lignin and other sugars from their substrate into smaller molecules by secreting enzymes. The mycelium on the surface forms a compact layer, referred to as fungal skin (Yang *et al*., 2021; Aiduang *et al*., 2022a).

Studies indicate the choice of fungus as an essential factor for future material properties (Appels *et al*., 2019). The required criteria for the selection of mycelium are the growth rate, resistance to contamination, undemanding to growth conditions, especially temperature and humidity, the hyphal system and the type fungus. Based on studies with the published name of the fungal species, the most suitable in terms of MBB formation is the *Pleurotus* genus with 25.0 %, followed by *Ganoderma* (22.2 %), *Trametes* (18.1 %), *Pycnoporus* (4.2 %), *Polyporus* (2.8 %), *Agaricus* (2.8 %), *Coriolus* (2.8 %) and *Lentinula* (2.8 %) (Aiduang *et al*., 2022a; Cerimi *et al*., 2019).

In summary, lignocellulosic residues from agricultural and woodworking production are used for the production of MBB (Javadian *et al*., 2020). The substrate can be sawdust, shavings, chips, shavings, straw and other waste materials such as cardboard, coffee waste, oat bran, hemp fibres, cotton, coconut fibres, rapeseed straw fibres, reed fibres, raw cellulose (from sewage treatment), flax fibres, wood chips, sorghum, husks, elephant grass, Miscanthus (Dias *et al*., 2021). Shavings and sawdust from beech wood, together with cardboard and wood chips, appear to be a potential material for the formation of MBB (Vašatko *et al*., 2022). An ideal substrate for fungal growth should provide nutrients such as carbon, nitrogen, minerals and water (Beck *et al*., 2018). The composition, character and properties of the substrate affect the ability of fungi to grow and are a key factor in the resulting physical and mechanical properties of MBB (Jones *et al*., 2020). Cellulose and lignin are essential for mycelial growth, they are the components that give MBB stiffness and strength (Yang *et al*., 2021). Cellulose is used by the mycelium for its growth, cellulose molecules are in the mycelium assembled into long bundles of microfibrils. In many studies, the substrate was supplemented with a substance containing simple sugars and minerals, to provide energy for mycelial growth. Rice bran, wheat flour (Vidholdova *et al*., 2019), calcium carbonate, calcium or sodium sulphate (Aiduang *et al*., 2022a), potato starch (Dias *et al*., 2021), cellulose (Vašatko *et al*., 2022), coffee grounds (Soh and Le Ferrand, 2022), wheat grains, millet, gypsum and others (Shen *et al*., 2023). The resulting MBB properties also depend on the properties of the substrate and the size of the particles used. Particles of approximately 5-30 mm in size have been reported in studies (Aiduang *et al*., 2022b; Elsacker *et al*., 2019; Vašatko *et al*., 2022). A larger fraction of the substrate leads to stronger MBB but at the same time, too large particles cause slow growth of the fungus. Fine sawdust and dust lead to clumping of parts and impair oxygen distribution (Elsacker *et al*., 2019).

The presented study aims to produce MBBs from recycled wood (RW) avoiding using valuable agricultural rests and to determine the effect of fungal species on the properties of MBB from RW.

2. MATERIALS AND METHODS

2.1. Materials

Three fungi species were used to produce composites from recycled wood (RW), namely *Ganoderma lucidum* (VURV-F 5275, Crop Research Institute, Czech Republic), *Ganoderma lingzhi* (M9724, Mycelia, Belgium) and *Pleurotus ostreatus* (Ivory, Sylvan, USA). Grain spawn was used as inoculum. Wheat grains with the addition of gypsum were hydrated (47±2 % moisture content), sterilised and inoculated by fungi species. The inoculum was 10 days incubated in glass bottles at a temperature of 24 °C.

2.2. MBB production

Composites were produced by mycelia growth on substrate from recycled wood. Recycled wood was obtained from Kronospan CR company, and particles initially intended to be used in the middle layer of particleboards were used. The substrates were hydrated to reach the absolute moisture of 60 % and were inoculated with prepared inoculum. The inoculation rate was 10 % (wet weight/wet weight). Inoculated substrates were climatised at a temperature of 24 °C and relative humidity (RH) 95 %. After 14 days the substrates were fully colonised by fungi, were manually shredded, and filled into cube forms with a side dimension of 50 mm. For heat insulation properties measurement, cylindrical samples with a diameter of 100 mm and height of 70 mm were produced. The composites grew in forms for eight days at a temperature of 24 °C and RH 95 %. After this period, samples (examples are depicted in *Figure 1*) were removed from forms, and the fungi growth was ended by composite drying at a temperature of 103 °C for 5 hours.

To quantify the growth rate of individual fungi species on RW, a growth rate test was performed. Hydrated and sterilised RW substrate at an amount of 75 g was filled into glass test tubes with dimensions of 40 mm in diameter and 240 mm in length. The test tubes filled with substrates were inoculated by laying 4 g of inoculum on the top, the test was conducted vertically. Four test tubes were prepared from each variant, and growth increments were marked every three days.

Figure 1. Produced specimens of MBB, from the left P. ostreatus, G. lingzhi and G. lucidum

2.3. MBB properties estimation

The growth rate test was evaluated by measuring increments of mycelium on RW, every tube was measured in three places. The daily increments were presented graphically, and the growth rate was calculated as follows:

$$GR = \frac{l}{t} \quad (1)$$

GR – Growth rate (mm/day)
l – total length of colonised substrate (mm)
t – total time of substrate colonisation (days)

Tensile strength perpendicular to the plane of the board (internal bonding) was measured using a TIRAtest 2850 universal testing machine. The method was adopted from EN 319:1993.

A total of 10 samples from each variant were measured, and internal bonding was calculated as follows:

$$IB = \frac{F_{max}}{a*b} \quad (2)$$

IB – internal bonding (N/mm^2)
F_{max} – maximal force applied to the sample (N)
a, b – area dimensions of the test specimen (mm)

Water uptake was measured based on EN 1609:2013. Shortly, after weighing the oven-dried samples, the samples were placed in a test tank on a grid that allowed water to pass through. After 24 h submersion in water, the samples were removed from the tank and for 10 minutes placed on a grid that was at an inclination angle of 35° – 40°, and after that, the samples were weighted. Water uptake per dry mass of board was calculated as follows:

$$W = \frac{m_{24} - m_0}{m_0} \cdot 100 \quad (3)$$

W – water uptake per dry mass of board (%)
m_{24} – weight of the sample after 24 h water submersion (kg)
m_0 – weight of the oven-dried sample (kg)

The analysis of variance was employed to determine whether any of the pairwise differences of the measured properties were statistically significant, and software Statistica12 was used. The Tukey posthoc test was performed to determine significant differences between group means.

3. RESULTS AND DISCUSSION

The results clearly show that all three used fungal species are able to colonize substrate from RW particles, the results of the growth test are depicted in *Figure 2* and the calculated values of growth rate are presented in *Table 1*. The highest growth rate was reached by *G. lingzhi* was 4.9 mm/day, *P. ostreatus* reached 4.8 mm/day, the difference between the means is not statistically significant. *G. lucidum* reached the lowest growth rate, however the lower growth rate did not negatively affect the properties of produced MBB.

Table 1. Growth rate results

Fungus	Growth rate (mm/day)	Standard deviation (mm/day)
G. lucidum	1.9	0.4
G. lingzhi	4.9	0.1
P. ostreatus	4.8	0.3

Table 2. Density of produced MBB

Fungus	Density (kg/m^3)	Standard deviation (kg/m^3)
G. lucidum	155.9	5.7
G. lingzhi	154.1	2.9
P. ostreatus	144.6	6.8

Note: Density of oven dry MBB

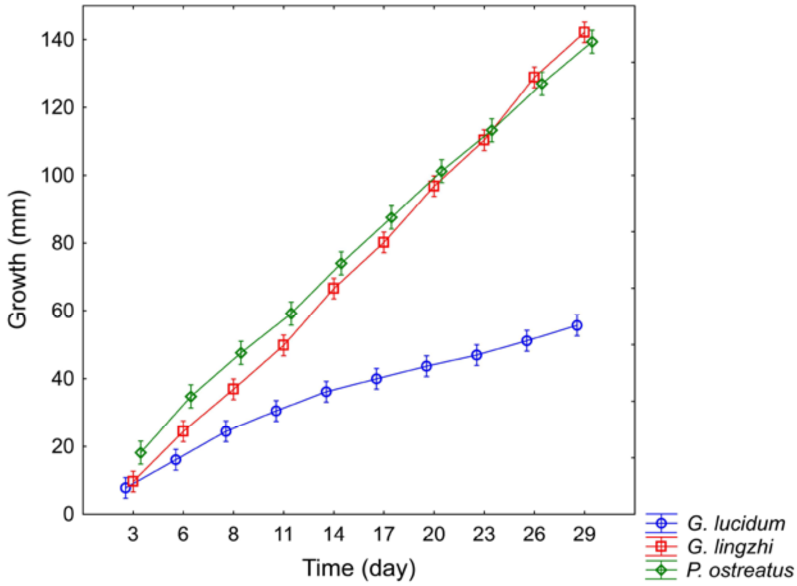

Figure 2. Influence of fungus on growth rate.

Density significantly affects the properties of wood-based materials and therefore density of produced MBB was monitored. The density of produced MBB is listed in *Table 2*, the target density was 150 kg/m^3, however, due to manual production, small variations occurred. MBB produced using *P. ostreatus* reached a lower density than the other two MBB variants which is caused mainly due to falling out of particles from the *P. ostreatus* MBB variant during MBB removal from forms. This phenomenon of missing particles in the surface layer of MBB can be seen in *Figure 1*.

All produced MBB reached low internal bonding. The overall low internal bonding values are caused by the short time of the growing phase during MBB production process. It was already reported that a longer time of MBB growing phase significantly improves mechanical properties of the final MBB (Elsacker *et al*., 2019; Sydor *et al*., 2021). MBB produced using *G. lingzhi* reached the highest internal bonding, the difference between *G. lingzhi* and *G. lucidum* is statistically significant at the significance level of 0.05. Except for time of growth, internal bonding can be further improved by different substrate composition, substrate moisture and fungal species used (Aiduang *et al*., 2022b; Elsacker *et al*., 2019; Vašatko *et al*., 2022).

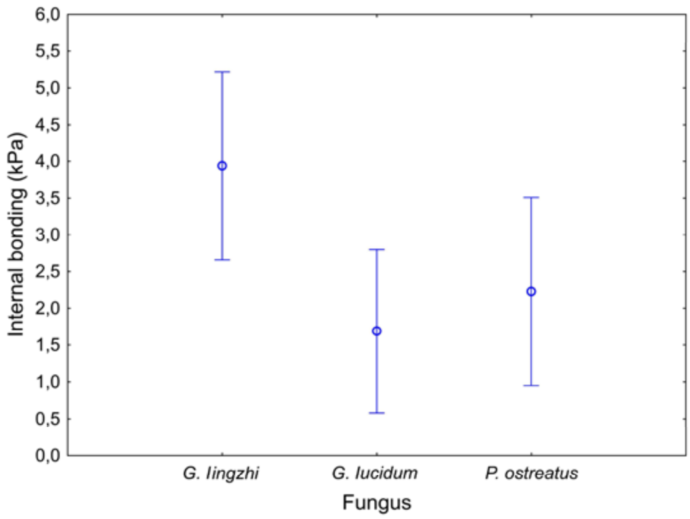

Figure 3. Influence of fungus on internal bonding of MBB

The developed MBB exhibited 24 h water uptake in the range from 85 % to 163 %. MBB produced using *G. lingzhi* and *G. lucidum* exhibited lower water uptake which was caused by fungal skin grown on the surface of MBB. *P. ostreatus* did not form fungal skin on the surface of the samples and therefore water was allowed to fully penetrate the samples. The results of 24 h water uptake can be seen on the *Figure 4*. Greater thickness of fungal skin could even further decrease the 24 h water uptake. The higher thickness of fungal skin can be achieved by an additional MBB growing phase after MBB removal from the forms (Elsacker *et al*., 2019).

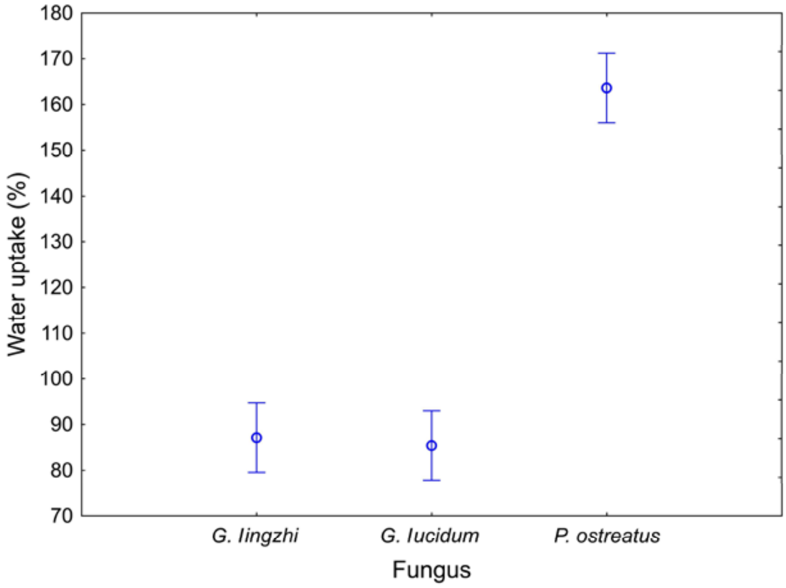

Figure 4. Influence of fungus on water uptake of MBB

4. CONCLUSIONS

The presented paper presents a development of MBB from recycled wood produced using three different fungal species, namely *G. lingzhi, G. lucidum* and *P. ostreatus*. The results clearly show that all three used fungal species are able to colonize substrate from RW particles. Produced MBB showed low internal bonding which was caused by a short growing phase during the MBB production. It was observed that *G. lingzhi* and *G. lucidum* were able to form a fungal skin on the surface of samples which enhanced the water uptake. *G. lucidum* exhibited a lower growth rate which negatively influenced the internal bonding of produced MBB but did not negatively influence 24 h water uptake.

Thanks to the low density and internal bonding of MBB, the results indicated that the produced MBB can be considered only for utilisation for heat insulation properties. However, the methodology of MBB production will be further optimised and it is expected that both the physical and mechanical properties of MBB from RW particles can be substantially improved.

Acknowledgements: *This research was supported by HORIZON-MSCA-2022-PF-01-01, project number: 101105443, project acronym: LignoMBB.*

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The Effect of Wooden Material Type and Additional Adhesive Fortification on the Withdrawal Capacity of the Double-thread Nuts

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ABSTRACT

The construction of furniture is often carried out by assembling double-thread nuts. During exploitation, furniture is exposed to various forces that cause it to pull out double thred nuts and damage the strength of the structure. This study aimed to investigate the effect of wooden material type and adhesive type on the withdrawal capacity of double-thread nuts. For this purpose, an experimental setup consists of one type of double-thread nuts with a diameter of seven mm and a length of thirteen mm, three types of wooden materials (beech, medium-density fibreboard, and particleboard), and four adhesives. An analysis of variance (ANOVA) was performed to evaluate the impact of wood materials and the effect of using different adhesives. The results showed that the best withdrawal capacity is obtained for samples with beech wood glued with Silan terminated polymers. The lowest results were obtained for the samples in particleboard glued with polyvinyl acetate mounting D2 glue.

Key words: double-thread nuts, withdrawal capacity, wooden materials, adhesives

1. INTRODUCTION

Constructive interconnections in furniture are realized through different types of fittings. One of the basic aims in the construction of furniture is the use of connection elements that will enable disassembly construction to reduce the costs of assembly and transportation, and increase the competitiveness of the product. One of the ways to connect furniture elements is to use a connection with double-threaded nuts and thread bolts. This method of connecting furniture is very cheap from the point of production technology because it does not require the production of complicated connection elements, but only the drilling of holes is required for this connection. This method of connection is quite common in the production of tables, where the connection between the leg and the top board is achieved by this type of connection.

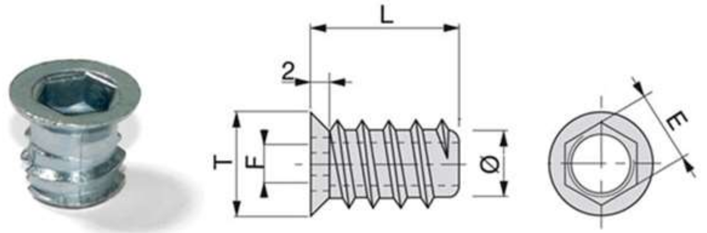
In addition, the use of double-threaded nuts enables connection with metal angles, which results in a high-quality interconnection that do not impose great requirements during assembly (Mihulja *et al*., 2012). On the other hand, during exploitation, the furniture is exposed to different forces that cause tension or pressure in the joints, which in combination with long exposure time leads to the weakening of the structures. The necessary connections between structural parts are generally the critical point of wooden structures (Ribeiro, 2018). The structural connections or connections with double-threaded nuts exposed to withdrawal forces tend to extract from the material that considerably impairs the strength and stiffness of the structure. In the production process it has been noticed that during the bed structure assembly, the double thread nuts fixed in the wood tend to loosen up (Mihulja *et al*., 2008). This problem of extracting double-threaded nuts was researched by Mihulja *et al*., (2012). They established that the diameter of the hole has a large effect on the extraction of nuts. The basic requirement for fixing such nuts is a properly drilled hole in wood. If the hole is too small, screwing will be hindered and the outer thread will destroy the part of the surface close to the hole and thereby impair the system's carrying capacity. On the other hand, understandably, an excessively large outer thread will not hold wood material firmly enough and the system's carrying capacity will be weakened.

Given the differences in the properties of the material used, it is understandable to expect that the mentioned properly drilled hole or its "proper dimensions" will not have the same effect on the strength of the joint. Therefore, it is logical to apply an additional strengthening factor that will neutralize this factor and subsequently increase the strength of the joint without corrections to the diameters of the drill bits for processing the wooden elements of the product. The adhesive is imposed here as the only possible solution as bonding is one of the ways to strengthen all constructive interconnections. The strength of the connection depends on several factors, such as the type of adhesive, the type of material, the thickness of adhesive line, etc. (Dzincic and Zivanic, 2014). Standard polyvinyl acetate adhesive (PVAC), the most often used in the production of furniture, has proven to be a better alternative compared to polyurethane adhesive (PUR) when gluing dowels (Acar *et al*., 2022) and other wood connections (finger joint) (Ibrišević *et al*., 2021). The bonding mechanisms of adhesives are manifested differently on wood and metal surfaces (Patel *et al*., 2009). Because of this, adhesives that have shown good properties when bonding wood in combination with metal have a different strength of the bonded joint, and therefore it is necessary to investigate which is the optimal combination of material and adhesive to maximize the withdrawal forces of double-threaded nuts.

This paper aims to determine how different types of adhesives affect the withdrawal force of double-threaded nuts on different types of wooden materials.

2. MATERIALS AND METHODS

Three types of wooden materials were used to test the withdrawal capacity of double-threaded nuts. Three-layer particleboards, medium-density fibreboard (MDF), and beech wood (*Fagus sylvatica* L.*)* were used in the experimental investigation. Particleboard and MDF were chosen as materials that are dominant in the production of corpus furniture, and beech was chosen as wood species that was dominant in the production of furniture in Bosnia and Herzegovina. The producer of MDF and particleboard was Castamonu, Romania. The thickness of the samples was 18 mm. Random material samples were taken from the furniture production factory, and they did not have any visible defects. The material **s**amples were cut on dimensions 380 x 50 x 18 mm. The material sample dimensions were chosen because of the better positioning of the workpiece in the drilling process. A double-threaded nut like in *Figure 1* was used for the experiment.



L	13 mm
F	M6
T	11 mm
E	6 mm
Ø	7 mm

Figure 1. Double-thread nut.

Six holes, with a distance of 64 mm between them, were drilled on samples, and the diameter of the holes was 8 mm. According to research conducted by Mihulja *et al*., (2012), the best withdrawal capacity of double-threaded nuts obtaining for the diameter of the hole 1-1.5 mm wider than the extended diameter of the nut. In this case, the diameter of drilled hole was 8 mm, and the hole depth was 14 mm. The drilling was performed on drilling machine SCM STARTECH 21. During drilling, the samples are fixed with two pneumatic presses to reduce vibrations. Double-thread nuts were screwed into the specimens with an electric screwdriver, in the same way as what is practiced in production. The samples were divided into five groups according to the types of adhesives and for each type of wood material. Before screwing the double-thread nuts, the glue was put in the holes to further strengthen the double-thread nuts. For each group of materials, five different adhesives were used. The samples are marked as the letter indicates the type of material (M-MDF, P-particleboard, B-beech), and the number indicates the types of used adhesive (i.e., B4-beech with STP adhesive). Characteristics of used adhesive are shown in *Table 1*.

Table 1 . Characteristics of used adhesive

Group	Producer	Type	Base	Label	Bond quality
1.	without adhesive			NO adhesive	
2.	KLEIBERIT	300.0	Polyvinyl acetate	PVAC-D3	D3
3.	KLEIBERIT	305.0	Polyvinyl acetate	PVAC-D2	D2
4.	KLEIBERIT	605.1	Silan terminated polymers	STP	D4
5.	KLEIBERIT	501	Polyurethane	PUR	D4

The samples were conditioned for 24 hours in laboratory conditions with a relative air humidity of 60±5 % and a temperature of 20±2 °C. The last phase of the preparation included cutting the samples into the final dimensions of 50 x 50 x 18 (*Figure 2*). In this way, 15 groups were formed (5 types of adhesive x 3 types of materials) with 15 samples each (225 in total).

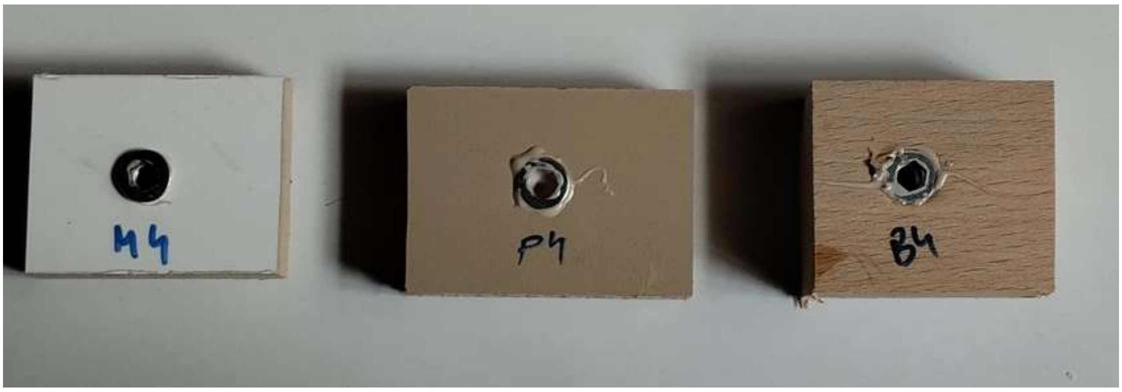


Figure 2. Final samples with screwed and glued double-thread nuts.

The samples were tested in the laboratory for composite materials at the Faculty of Mechanical Engineering in Sarajevo. The "ZWICK" machine was used for testing. The method of fixing the samples on the machine is shown in *Figure 3.* The withdrawal force of the double-threaded nuts is read on the force indicator.

Figure 3. ZWICK testing machine, and testing procedure.

Descriptive statistics were performed for the obtained data. Statistical processing of the measurement results was performed using the method of one-factor analysis of variance (ANOVA), and the Tukey Pairwise Comparisons test with a 95 % confidence level was additionally performed. All analyzes were performed in JASP statistical data processing software.

3. RESULTS AND DISCUSION

The results, shown in *Table 2*, were obtained by testing the withdrawal force of double-threaded nuts. The results show that the withdrawal force values of screwing the double-threaded nuts are higher if the adhesive was used.

Table 2. Descriptive statistics of the withdrawal force of double-thread nuts results

	Beech			MDF			Particleboard		
	Means	Std.Dev.	Coef.of.var.	Means	Std.Dev.	Coef.of.var.	Means	Std.Dev.	Coef.of.var.
NO adhesive	2820.2	384.8	0.1	1296.2	182.3	0.1	977	188.7	0.2
PVAC-D3	3148.5	420.1	0.1	1711	172.6	0.1	1232.6	176.9	0.1
PVAC-D2	3202	182.7	0.1	1569.3	122.9	0.1	1062.3	97.3	0.1
STP	3684	399.5	0.1	1881	194	0.1	1337.3	140.8	0.1
PUR	3722	283.9	0.1	2047.3	128.5	0.1	1329.5	128.9	0.1

By looking at *Figure 4*, it can be seen that the highest withdrawal forces are obtained with beech wood. As expected, the smallest withdrawal forces were obtained with particleboard, while slightly higher forces were obtained with MDF. Typical failure mode of some MDF and beech speciments are shown in *Figure 5*.

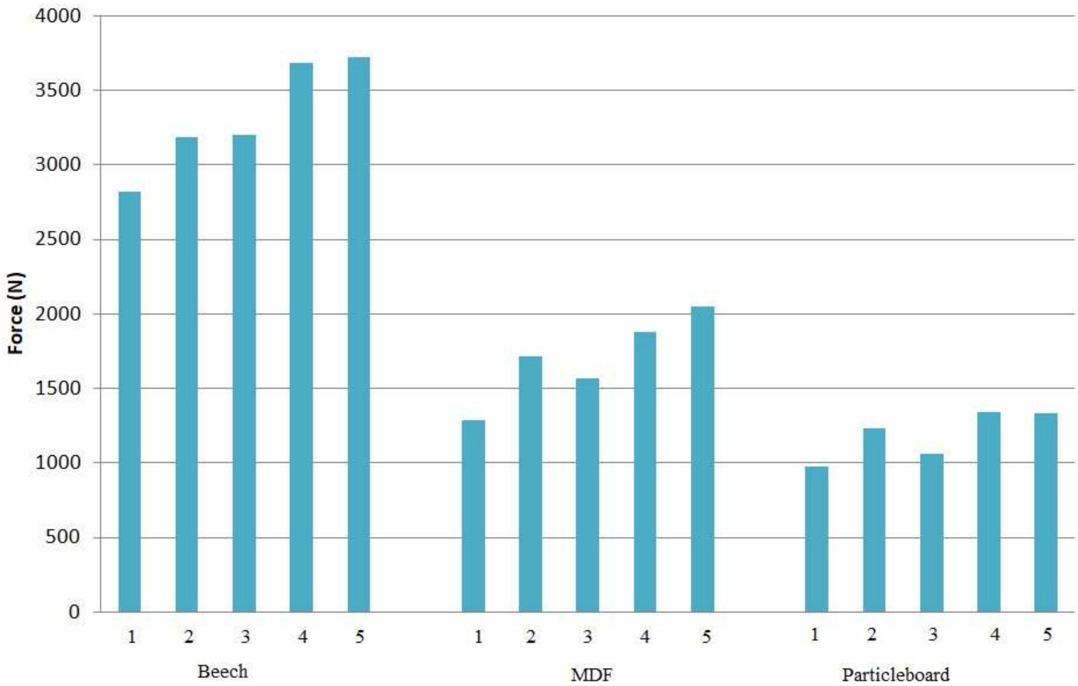


Figure 4. Withdrawal force for different wooden materials (1-NO adhesive; 2-PVAC-D3, 3-Assembly Glue PVAC-D2, 4-STP, 5-PUR).

Figure 5. Typical failure mode of MDF and beech specimens.

Research by Mihulja *et al*., (2012) showed that a more uniform structure ensures better contact with the thread of the nut, and thus greater friction. Particleboard is a porous material, so the friction between the thread of the nut and the material is reduced, and thus less force is obtained to withdrawal the double-thread nuts. The mechanical properties of the material also affect the withdrawal forces of the double-thread nuts. Materials with lower mechanical properties have lower double-thread nut withdrawal force values (Mihulja *et al*., 2012). Of the observed materials, particleboard has the lowest values of mechanical properties (Wood Handbook, 2010), and the lowest withdrawal forces were obtained. The density of beech is the largest of all three observed materials, while the density of particleboard is the smallest (Wood Handbook, 2010). It can be concluded that the density plays a significant role in the withdrawal capacity of double-thread nuts

The influence of the used adhesive on the withdrawal strength of the double-thread nuts was second factor observed in this investigation. The obtained results show that the use of adhesive results in an increase in withdrawal capacity of double-thread nuts, thus the lowest results were achived for nuts screw-in material without adhesive.

From *Figure 4*, it can be seen that application of all adhesive type results with an increase of withdrawal force of the double-thread nuts, although some of them have poor adhesion to metal. The use of PVAC assembly glue (type 3, *Table 1)* results in smallest increase in withdrawal force in all tested combinations. In samples that use this adhesive, the withdrawal forces of the double-thread nut increase in beech by 10.5 %, MDF by 17.5 %, and particleboard by 8 % compared to tests without adhesives. In samples with the standard PVAC-D3 adhesive (type 2, *Table 1*), the withdrawal forces increase by 12 % for beech, 24 % for MDF, and 11 % for particleboard. Although the mean values of withdrawal forces in the samples bonded with PVAC-D3 adhesive are slightly higher than the samples bonded with PVAC-D2 adhesive, analysis of variance (ANOVA) and Tukey test showed that there is no statistically significant difference between these two types of samples (*Figure 6*, *Table 3* and *Table 4*).

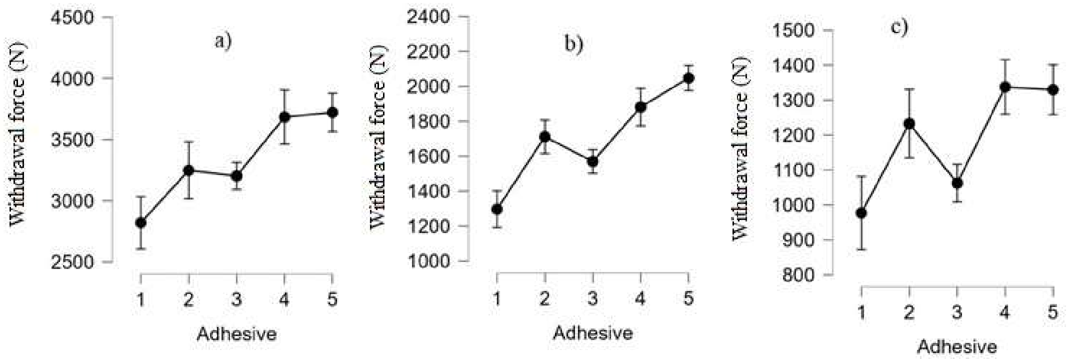


Figure 6. Statistical analyzes of results of withdrawal forces of double-thread nuts from: a) beech wood; b) MDF; c) particleboard; (1-NO adhesive, 2-PVAC-D3, 3-Assembly Glue PVAC-D2, 4-STP, 5-PUR).

Table 3. Differences of withdrawal force from beech-wood specimens

Tukey test: Beech (Withdrawal force)
Marked differences are significant at $p < 0.05$

Adhesive	NO Adhesive	PVAC-D3	PVAC -D2	STP	PU
NO Adhesive		0.011	0.040	< 0.001	< 0.001
PVAC-D3	0.011		0.997	0.009	0.004
PVAC -D2	0.040	0.997		0.005	0.002
STP	< 0.001	0.009	0.005		0.998
PUR	< 0.001	0.004	0.002	0.998	

For samples made of particleboard, ANOVA showed a statistically significant difference between these two groups of samples (*Table 5* and *Figure 6*). The STP adhesive use (type 4, *Table 1*) leads to increased withdrawal forces for beech by 23.5 %, MDF by 31 %, and particleboard by 27 %. The highest withdrawal force values are obtained for specimens with PUR adhesive (type 5, *Table 1*). For the specimens that use this type of adhesive, the withdrawal forces increase for beech by 24.5 %, MDF by 37 %, and particleboard by 26.5 %. Statistical analysis shows that it does no statistically significant difference between samples bonded with STP and PUR glue for beech and particleboard specimens.

Based on the results, the highest percentage of increase in the withdrawal force was for MDF and the smallest for beech.

It can be concluded that there are two key factors within this research. The first refers to the properties of the adhesive, i.e., that an adhesive with better properties achieves the expected better result of withdrawal force. At the same time, some adhesives have better properties in applications with a thicker layer of adhesive due to filling the space between the nut body and the material into which it is screwed. Other adhesives give better results in the creation of composites, due to which the destruction within the material caused by nut screwing will be better strengthened, and consequently, in some materials, this can be caused solely by a better or easier penetration of the adhesive into the material, increasing its strength. The second factor refers to the properties of the material into which the double-threaded nut is screwed. The type of the wood-based materials has significant influence on the specificwithdrawal capacity of the screws (Jivkov *et al.*, 2017). In the case of materials with the worst properties, the pulling force can be expected to be increased the most. Research conducted by Sydor *et al.*, (2023) show that materials with lower mechanical properties have lower withdrawal screws resistance. This may refer to damage caused by drilling and/or nut screwing, especially in materials with a more brittle surface layer and/or weaker delamination properties within its cross-section, such as porous chipboard. The other property of a material that can be severely upgraded by the adhesive impact is the fortification of deformed material around drilled holes caused by high screwing forces. Material like MDF develops great resistance to screwing due to friction between nut threads and densely distributed fibers. At the same time, beech has better elastic properties at the wood cell level than MDF, as well as better plastic properties compared to particleboard connected with brittle, usually KF adhesives that in total result with generally best results without adhesive application, i.e., the smallest increase in withdrawal forces due to adhesive applications.

Table 4. Differences of withdrawal force for MDF specimens

Tukey test: MDF (Withdrawal force)

Marked differences are significant at $p < 0.05$

Adhesive	NO Adhesive	PVAC-D3	PVAC -D2	STP	PU
NO Adhesive		< 0.001	< 0.001	< 0.001	< 0.001
PVAC-D3	< 0.001		0.132	0.042	< 0.001
PVAC -D2	< 0.001	0.132		< 0.001	< 0.001
STP	< 0.001	0.042	< 0.001		0.050
PUR	< 0.001	< 0.001	< 0.001	0.050	

Table 5. Differences of withdrawal forces for particleboard specimens

Tukey test: Particleboard (Withdrawal force)

Marked differences are significant at $p < 0.05$

Adhesive	NO Adhesive	PVAC-D3	PVAC -D2	STP	PU
NO Adhesive		< 0.001	0.530	< 0.001	< 0.001
PVAC-D3	< 0.001		0.022	0.322	0.401
PVAC -D2	0.530	0.022		< 0.001	< 0.001
STP	< 0.001	0.322	< 0.001		1.000
PUR	< 0.001	0.401	< 0.001	1.000	

4. CONCLUSION

Based on the results presented in this paper, increasing the strength of the material leads to an increase in the withdrawal forces of the nuts, which is the result of an increase in the friction between the nut and the material. The highest nut withdrawal forces were obtained with beech and the lowest with particleboard.

Using different adhesives can significantly prevent the extraction of double-threaded nuts. Classic PVAC-D3 adhesives, which are most often used in the production of furniture, increase the extraction strength of nuts by 10-25 %. Higher withdrawal forces for double-threaded nuts can be obtained by using special adhesives, namely STP and PUR adhesives. Using these adhesives, the withdrawal force of the nuts increases by 25-40 % compared to nuts screwed without the use of adhesives. The highest nut withdrawal forces are obtained by using PUR and STP adhesive. According to this, same withdrawal capacity of double-thread nuts can be achieve using cheeper adhesive. Due to the property of PUR adhesive that it expands when it hardens, the inner metric thread of the nut gets dirty, and it needs to be cleaned, which is a problem. Due to all of the above, the best results in terms of strength and technology of use are obtained by using STP glue.

Acknowledgements: *This paper was supported by the Ministry of Science, Higher Education and Youth of Canton Sarajevo, Bosnia and Herzegovina in the framework of research project no. 27-02-35-37082-44/23.*

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Water Resistance of Fiberglass Reinforced Plywood during Prolonged Water Exposure

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ABSTRACT

The aim of this research is to study the water absorption and thickness swelling of plywood reinforced with fiberglass fabrics pre-impregnated with alcohol-soluble phenol-formaldehyde resin during prolonged water exposure. Four experimental reinforced plywood models were made from peeled beech veneers with thickness of 1.5 mm and 1.85 mm bonded with the same resin used for fabric pre-impregnation. In each model, sheets of pre-impregnated fabric (prepreg) were incorporated in different adhesive layers of the plywood structure. One additional model was made without reinforcements as comparing plywood model. On the basis of the obtained data for the changes of water absorption and thickness swelling of reinforced plywood after immersion in water continuously for a period of 192 days, water resistance of experimental plywood was evaluated. The research results showed that the application of fiberglass prepreg as reinforcement in plywood structure significantly decreases the values of water absorption and thickness swelling. After full water treatment plywood models have good dimensional stability and do not show deformations.

Key words: Fiberglass, plywood, prepreg, reinforcement, water exposure, water resistance

1. INTRODUCTION

Typically, plywood is made of wood veneers with cross-laminated layup. It has high strength to weight ratio, good dimensional stability, decreased anisotropy compares to solid wood, as well as possibility to receive and distribute loads. Because of its characteristics plywood is considereted as constructional material with highest performance, so its application as structural or non-structural materials in construction is on a significant level. Plywood is used in many applications in construction, such as flooring, roofing, shear walls, production of engineered wood products, as well as for formwork.

High dimensional stability and consistency with low dimensional changes and low water absorption of plywood during water exposure are required when it is used in high humidity conditions.

Plywood properties can be improved through reinforcement in their structure, which are related to the application of non-wood materials, that will transfer their properties to the end product, thereby enabling higher physical and mechanical properties to be achieved (Davalos *et al*., 2000; Jakimovska Popovska and Iliev, 2019; Jakimovska Popovska and Iliev, 2021).

Fiber-reinforced polymers can be used for enhancement of plywood properties including better durability and water resistance (Hardeo and Karunasena, 2002; Choi *et al*., 2011; Zīke and Kalniņš, 2011).

Different fibers and resins were used in many studies for reinforcement of plywood with fiber-reinforced polymers (Xu *et al*., 1996; Xu *et al*., 1998; Brezović *et al*., 2002; Brezović *et al*., 2003; Brezović *et al*., 2010; Biblis and Carino, 2000; Hrázský and Král, 2007; Maniņš and Zīke, 2011). Research was also done on plywood reinforcement with prepregs and technical fabrics (Rowlands *et al*., 1986; Kohl *et al*., 2013).

The characteristics of fiber-reinforced polymer composites and their advantages are a motive to explore the possibilities for producing plywood reinforced with polymer composites such as fiberglass prepregs.

The aim of this research is to study the water absorption and thickness swelling of plywood reinforced with fiberglass fabrics pre-impregnated with alcohol-soluble phenol-formaldehyde resin during prolonged water exposure.

2. MATERIALS AND METHODS

For the purpose of this research four experimental models of reinforced plywood were made from beech veneers with thickness of 1.5 and 1.85 mm, with cross-laminated layup of veneers. Plywood reinforcement was made by inserting sheets of fiberglass prepreg (fiberglass fabric pre-impregnated with resin) into the adhesive layers in plywood structure. Each reinforced plywood model has different position of the reinforcements in plywood composition (*Figure 1*).

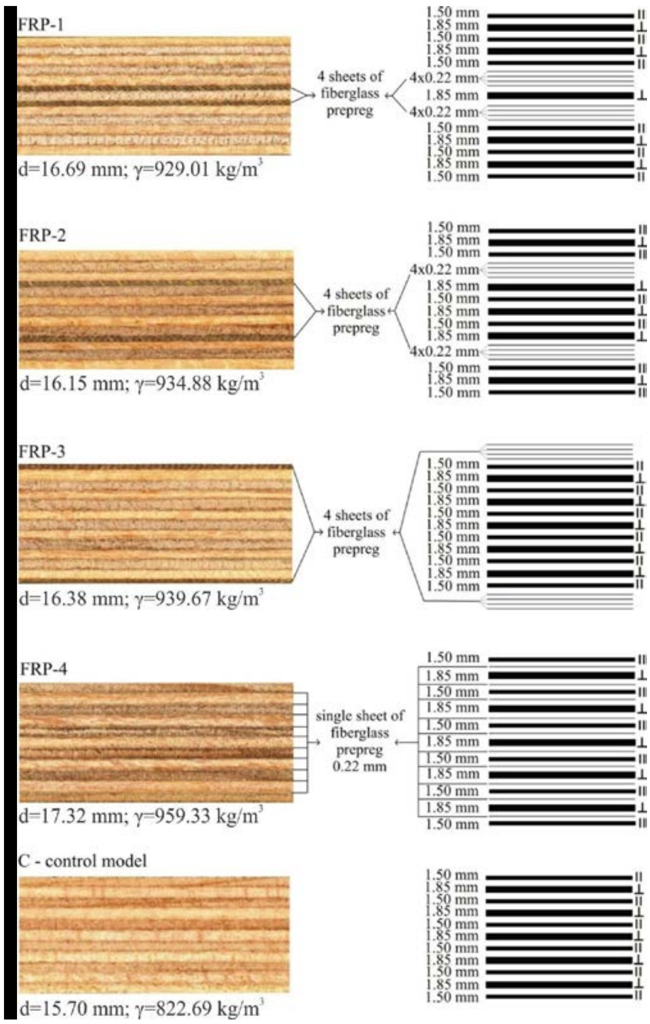


Figure 1. Cross-section and composition of plywood models (Jakimovska and Iliev, 2019).

In three models of reinforced plywood, each reinforcement layer is consisted of four sheets of fiberglass prepreg placed one above the other and inserted into the panel structure symmetrically on both sides with respect to its axis of symmetry. In the structure of the first model (FRP-1), the reinforcements are positioned next to the central veneer sheet, respectively in the fifth and sixth adhesive layer, while in the structure of the second model (FRP-2) they are inserted into the third and eighth adhesive layer. In the third model (FRP-3), the reinforcements represent the surface layers of the panel (*Figure 1*). The fourth experimental model of reinforced plywood (FRP-4) was made by inserting single sheets of fiberglass prepreg in each adhesive layer of the panel.

One control model of plywood was made without reinforcements for comparison of the results.

The fiberglass prepreg was made form fiberglass fabric made of E-glass fibers with simple "plain" weaving, which was pre-impregnated with methyl alcohol soluble phenol-formaldehyde resin in quantity of 140 g/m^2. Resin with 51 % dry matters content was used. The same resin was used for veneer bonding, applied on the veneers in quantity of 180 g/m^2. The threads that make up the wrap and fill of the fabric are identical. The wrap of the fabric was parallel to the grain direction of the surface veneers.

The thickness of non-impregnated fiberglass fabric was 0.173 mm. After impregnation, the thickness of the prepreg was 0.22 mm.

The technical characteristics of the fiberglass fabric, the characteristics of the resin and the impregnation process are described in another research (Jakimovska and Iliev, 2019).

Assembled plywood compositions were pressed in a hot press under specific pressure of 18 kg/cm^2 at temperature of 155ºC for 30 min.

The water resistance of plywood models was evaluated after conducted tests for water absorption (WA) and thickness swelling (TS) during immersion in water continuously for a period of 192 days. During the immersion test, control measuring of the dimensions and mass of the test specimens was done in intervals of: 1 day, 2, 3, 4, 6, 8, 12, 16, 24, 32, 42, 52, 72, 92, 112, 152 and 192 days.

The tests for these properties were done according to standard MKC D.C8.104 on test specimens with dimensions of 100×100 mm.

Statistical software SPSS Statistic was used for statistical analysis of the obtained data. One way ANOVA was used for determination of the significance of the effect of fiberglass prepreg reinforcements on plywood tested properties. Tukey's test was applied to evaluate the statistical significance between the mean values of the properties of different plywood models. The tests were conducted at 0.05 probability level.

3. RESULTS AND DISCUSSION

The results for the water absorption and thickness swelling of plywood models are shown in *Table 1, Table 2* and on *Figures 2, 3, 4* and *5*.

The analysis of the obtained results of water absorption and thickness swelling showed that all reinforced plywood models have lower values of these properties during the whole water treatment compared to the control model of unreinforced plywood.

The lowest value of water absorption during the whole period of water treatment is achieved in model FRP-3 in which the reinforcement layers are positioned as surface layers of plywood. Compare to the control model C, reinforcement of plywood with fiberglass prepreg positioned as surface layers of the panel decreases the water absorption after 24 h immersion in water for 68.4 %. At the end of the water treatment, after 192 days of immersion in water, the reinforced model FRP-3 has lower value compared to the control model C for 40.4 %.

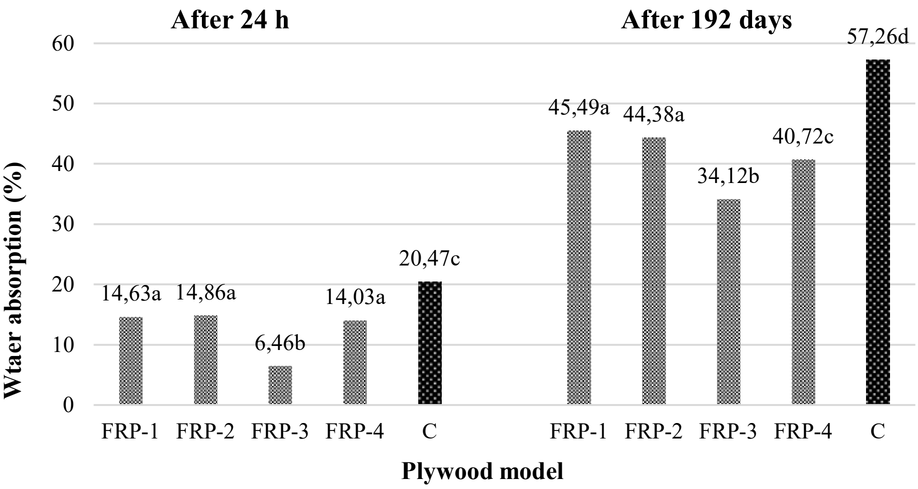
The analysis of variance of the obtained data for water absorption after 24 hours immersion in water (ANOVA: $F(4, 20) = 132.775$; $p << 0.001$) and at the end of the water treatment after 192 days of immersion (ANOVA: $F(4, 20) = 186.296$; $p << 0.001$) and conducted post-hoc Tukey's test for multiple comparison between models showed that there is statistically significant difference in the mean value of the control model compared to all reinforced plywood models. Within the reinforced models, the differences in the mean values of WA after 24 hours immersion in water in models FRP-1, FRP-2 and FRP-4 are very small and they are not statistically significant. The mean value of WA after 24 hours and after 192 days immersion in water in model FRP-3 statistically differs from other three reinforced models.

Table 1. Mean values for water absorption (WA) and thickness swelling (TS) of plywood models

Immersion in water (days)	WA (%)					TS (%)				
	FRP-1	FRP-2	FRP-3	FRP-4	C	FRP-1	FRP-2	FRP-3	FRP-4	C
1	14.63	14.86	6.46	14.03	20.47	4.59	6.19	2.82	4.57	7.18
2	19.56	19.48	10.02	18.62	26.73	5.68	7.41	4.62	5.62	8.31
3	22.95	22.56	12.62	21.52	30.84	6.25	8.01	5.83	6.14	8.83
4	25.30	24.52	14.63	23.75	33.64	6.61	8.35	6.50	6.62	9.29
6	27.98	27.17	17.40	26.42	37.01	6.99	8.84	7.32	7.12	9.81
8	29.57	28.45	19.33	28.03	38.88	7.14	9.05	7.84	7.43	10.07
12	31.43	30.84	21.74	29.74	40.51	7.40	9.32	8.32	7.67	10.21
16	33.05	32.25	23.74	31.04	42.02	7.55	9.47	8.77	7.79	10.37
24	34.25	33.21	25.27	31.91	43.24	7.68	9.65	9.29	7.94	10.51
32	35.84	34.65	26.85	33.07	45.29	7.78	9.75	9.56	8.03	10.59
42	37.23	36.48	28.16	34.31	47.14	7.84	9.84	9.67	8.10	10.67
52	38.47	38.23	29.13	35.25	48.70	7.90	9.87	9.72	8.13	10.70
72	40.36	39.56	30.58	36.69	51.09	7.96	9.94	9.80	8.17	10.77
92	41.84	40.95	31.60	37.77	52.79	7.98	9.96	9.83	8.19	10.82
112	42.83	41.95	32.26	38.50	54.04	7.98	9.96	9.85	8.20	10.83
152	44.38	43.42	33.28	39.74	55.93	7.99	9.98	9.87	8.21	10.84
192	45.49	44.38	34.12	40.72	57.26	7.99	9.98	9.87	8.21	10.84

The lowest value of thickness swelling in the period of 24 hours immersion in water up to 4 days of immersion is achieved in reinforced model FRP-3. From the sixth day of immersion up to the end of the water treatment, the lowest value of thickness swelling is achieved in model FRP-4 which is reinforced with single sheets of prepreg in each adhesive layer. The mean value of model FRP-3 after 24 hours immersion in water is lower for 60.7 % compared to the control model C. Reinforced models FRP-1, FRP-2 and FRP-4 have higher values of TS after 24 hours compared to the model FRP-3 for 62.8 %, 119.5 % and 62.1 %, respectively.

After full treatment of 192 days of immersion in water the lowest achieved value of TS in model FRP-4 is lower compared to the control model for 24.3 %.

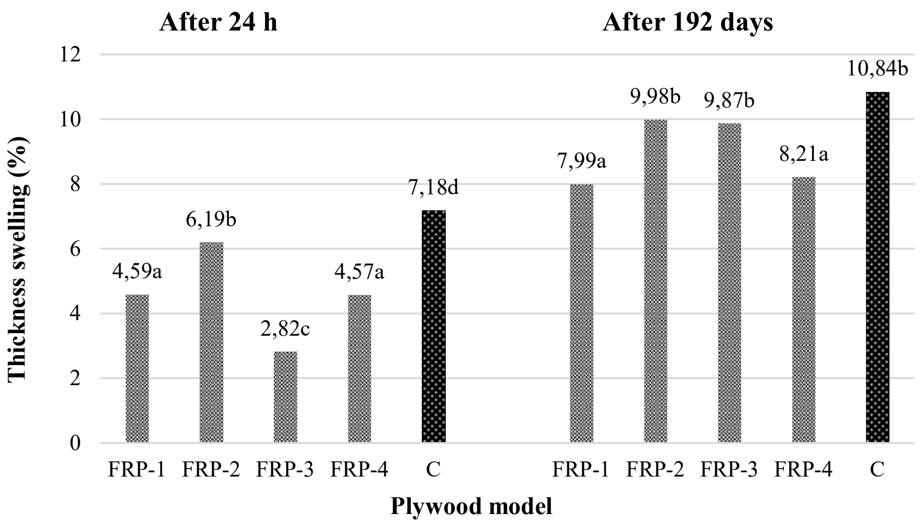


**The mean values with the same letters are not significantly different at 0.05 probability level*
Figure 2. Water absorption of plywood models after 24 hour and 192 days of immersion in water

The analysis of variance of the obtained data for thickness swelling after 24 hours immersion in water (ANOVA: F (4, 20) = 206.275; p << 0.001) and conducted post-hoc Tukey's test for multiple comparison between models showed that there is statistically significant difference in the mean value of the control model compared to all reinforced plywood models. Within the reinforced models, the values of models FRP-1 and FRP-4 are similar and are not significantly different.

At the end of the water treatment after 192 days of immersion in water the analysis of the variance (ANOVA: F (4, 20) = 22.096; p << 0.001) and the post-hoc Tukey's test showed that the differences in the values in models FRP-2, FRP-3 and control model C are not statistically significant, as well as the differences in the values between models FRP-1 and FRP-4.

The results for the thickness swelling showed that after 192 days of immersion in water, all experimental plywood models do not exceed 12 % which is defined as a maximal value for thickness swelling after 24 hours immersion in water by the national standard MKS D.C5.032. The obtained values for TS, which are below 12 % during the full water treatment, showed that the plywood models can be used in high humidity conditions and it will be stable under prolonged water impact.



**The mean values with the same letters are not significantly different at 0.05 probability level*
Figure 3. Thickness swelling of plywood models after 24 hour and 192 days of immersion in water

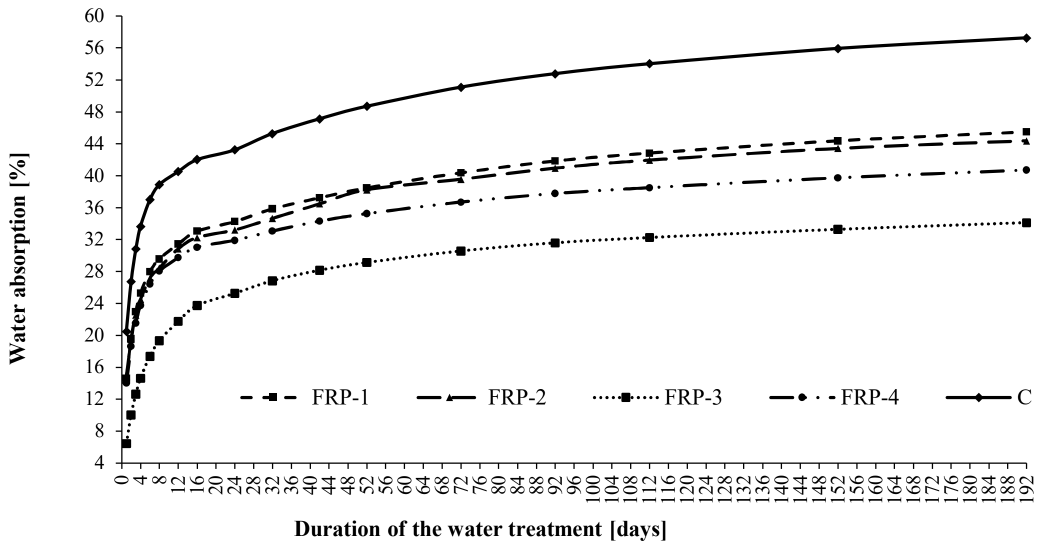


Figure 4. Tendency of increasing of WA during 192 days of immersion in water

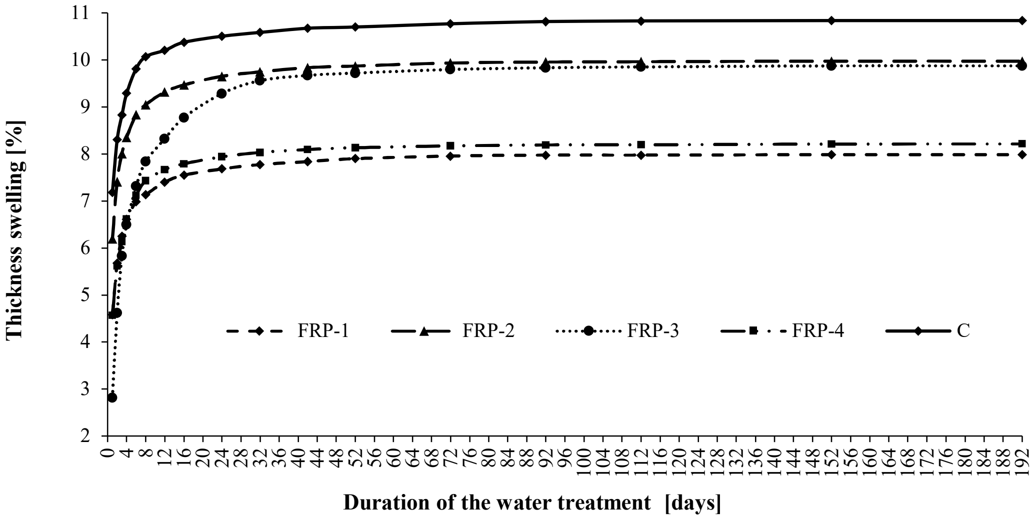


Figure 5. Tendency of increasing of TS during 192 days of immersion in water

The increment of the mean value of WA and TS between two successive measuring can be seen from the data given in *Table 2*.

*Table 2. Increment of the mean value of water absorption (ΔWA) and thickness swelling (ΔTS) between two successive measuring**

Period for which the increment is calculated	ΔWA (%)					ΔTS (%)				
	FRP-1	FRP-2	FRP-3	FRP-4	C	FRP-1	FRP-2	FRP-3	FRP-4	C
1→2d	33.71	31.10	55.01	32.68	30.57	23.85	19.66	63.91	22.97	15.67
2→3d	17.33	15.78	25.92	15.58	15.39	10.06	8.05	26.29	9.23	6.33
3→4d	10.25	8.69	15.98	10.35	9.08	5.73	4.29	11.52	7.81	5.20
4→6d	10.57	10.82	18.91	11.27	10.01	5.78	5.79	12.48	7.66	5.60
6→8d	5.70	4.69	11.07	6.09	5.06	2.07	2.44	7.12	4.32	2.63
8→12d	6.29	8.42	12.47	6.08	4.18	3.72	2.95	6.22	3.20	1.35
12→16d	5.13	4.55	9.21	4.39	3.72	2.02	1.62	5.36	1.60	1.66
16→24d	3.64	3.00	6.44	2.79	2.91	1.76	1.94	5.86	1.91	1.26
24→32d	4.64	4.32	6.26	3.62	4.74	1.20	0.98	2.96	1.17	0.78
32→42d	3.87	5.28	4.88	3.77	4.08	0.82	0.92	1.17	0.78	0.82
42→52d	3.34	4.81	3.44	2.72	3.30	0.79	0.36	0.52	0.46	0.24
52→72d	4.91	3.47	4.97	4.11	4.92	0.72	0.65	0.77	0.49	0.67
72→92d	3.65	3.52	3.34	2.92	3.32	0.24	0.20	0.38	0.26	0.40
92→112d	2.37	2.44	2.08	1.95	2.38	0.00	0.07	0.18	0.03	0.14
112→152d	3.61	3.49	3.18	3.20	3.50	0.12	0.13	0.23	0.20	0.07
152→192d	2.50	2.22	2.52	2.46	2.37	0.00	0.00	0.00	0.03	0.00

**d-days*

The results from the conducted tests for the water absorption and thickness swelling showed that the values of these properties are increasing by prolongation of the immersion in water, whereupon the maximal values after 192 days of immersion. The most intense increasing of WA and TS occurs in the initial period of immersion in water, after which the increasing of the values is with lower intensity (*Table 2, Figures 4 and 5*).

In the initial period from 24 hours to 48 hours of immersion, the intensity of increasing of WA and TS of reinforced models is highest (increment of WA from 31.1 % in FRP-2 up to 55.01 % in FRP-3; increment of TS from 19.66 % in FRP-2 up to 60.02 % in FRP-3). In the next period, from 48 to 72 hours, the increasing of WA and TS is with lower intensity and the increment of the value of WA and TS is about twice as low as the increment in the previous period (*Table 4*). In the period from the fourth day to the sixth day of immersion, the intensity of increasing of WA and TS is higher compared to the previous period, from the third to the fourth day of immersion.

By prolongation of the water treatment, the increment of the mean value of WA and TS between two successive measurements is lower. In the last period of the treatment the increment of WA does not exceed 2.22 % and there is no increment at all of TS (with exception in model FRP-4 in which the increment is only 0.03 %), which shows that low increment of WA at the end of water treatment cannot cause changes in TS of plywood.

The visual analysis of plywood test specimens after completed full treatment of immersion in water for 192 days showed that there were no deformations, delaminating and warping of the plywood test specimens (*Figure 5*). The stability of the form after prolonged water exposure show that high-quality plywood is made durable for application in high humidity conditions.

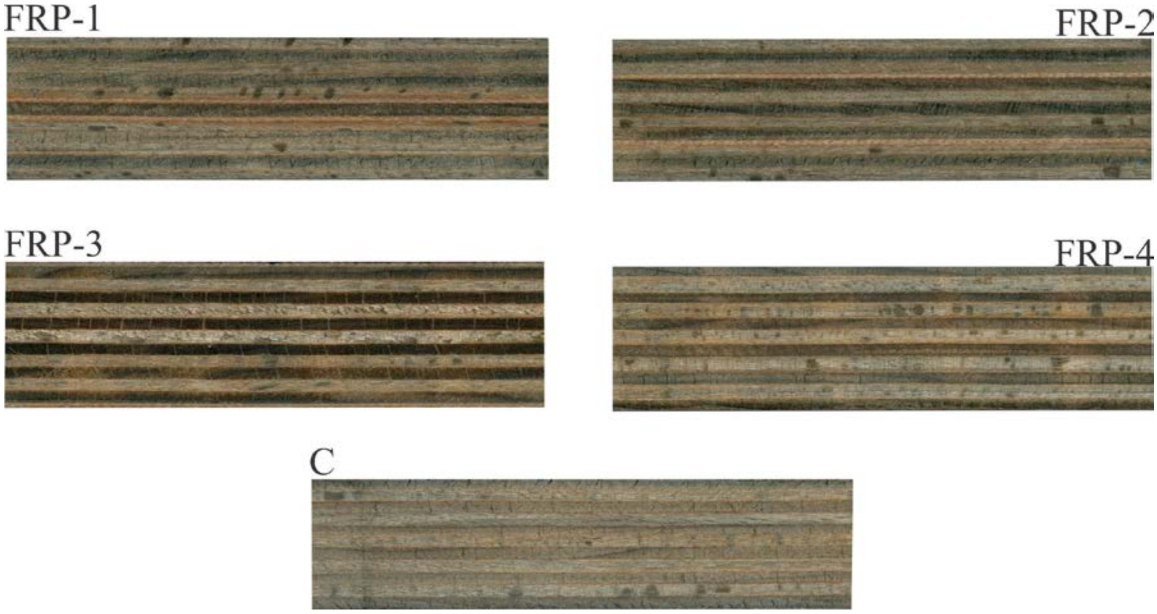


Figure 6. Cross-section of test specimens of plywood models after 192 days immersion in water

4. CONCLUSIONS

The application of fiberglass prerpegs as reinforcements of plywood significantly decreases the water absorption and thickness swelling of plywood and gives the opportunity for production of panels with high dimensional stability during prolonged water exposure. After full water treatment of 192 days immersion in water plywood models do not exceed the limitation value of 12 % for thickness swelling after 24 hours defined by the standard.

The position of the reinforcements in the plywood structure influences the values of water absorption and thickness swelling of plywood. By applying the fiberglass prepreg sheets as surface layers of plywood the water absorption and thickness swelling after 24 hours immersion in water are decreased by 68 % and 60 %, respectively, compared to the control model of the unreinforced plywood.

This kind of research presented in the paper can help in material selection and defining the technological parameters for production of dimensionally stable water-resistant plywood durable for application in high humidity conditions.

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Influence of the Inappropriate School Furniture on the Bodies of Children in Development

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ABSTRACT

Range of activities performed in a sitting position are requiring a particular sitting angle, meaning many different positions of the body are considered as 'sitting". A wrongly chosen position for a particular activity may affect the curvature of the spine, can cause fatigue of the muscles on the back, on the abdomen, in the pelvis and in the femur bone, can affect the circulation in the lower extremities, and can increase pressure on the nerves affecting temperature exchange of the body. With the increase of the time spent in a sitting position and the consequences that can be brought by an incorrect sitting position, it is necessary to pay more attention when designing the chairs. The influence of the sitting position is especially expressed in the groups of users who are spending most of the time in this position while performing their daily activities. This group of users also includes children of school age spending the school day in a sitting position. If it is not carefully dimensioned and designed, the long-term use of furniture for sitting and working in educational institutions can cause harm to the health of the users. The purpose of this research is to provide data on the effect of a wrongly dimensioned chair on different height users of school furniture.

Key words: anthropometry of children, physical development, school chairs, school desk, school furniture.

1. INTRODUCTION

The design of furniture for the educational institutions requires greater dedication and attention in terms of the anthropometric measurements. Having in mind that the category that uses this type of furniture is especially vulnerable in the sense of deformities, it is necessary for the final design of the chairs and desks for the educational institutions to be properly checked and controlled.

Educational institutions are facilities where each person spends many years of their life. Chairs used in these institutions are designed with specific features of shape, material and size. Long-term use of chairs in educational institutions may be the cause of damage to the health of users if they are not carefully designed and dimensioned.

The height of the shin is significant in terms of the height of the seat, since if it is too high, it makes greater pressure on the blood vessels on the lower part of the thigh and it decreases the circulation of blood and causes stiffness on the student's legs. A lower chair causes flattening of the lumbar part of the pelvis and by doing so it increases the load on the lumbar disk on the pelvis (Mehanović, 2017).

The users of the chairs and desks in the educational institutions have big differences in height. These are the primal reasons for having the divisions in the standard. The division of the chairs and desks in the educational institutions in "EN 1729-1:2015 Furniture - Chairs and tables for educational institutions – Part 1: Functional dimensions" standard is made into 8 groups depending on the height of the end users. The height of the end users is given within a certain span. In *Table 1* it is shown to which group the users belong to according to their height. Despite the number of the group, the standard also divides them in colors as well. Before any kind of measurement of a chair or a desk, one needs to determine the group of users they are meant for in order to be able to compare the taken measures with those required, meaning the allowed measures of the standard of that same group.

Table 1. Height groups of chairs and desks for educational institutions

Number and color of the group	0	1	2	3	4	5	6	7
User's height	800-950 mm	930-1160 mm	1080-1210 mm	1190-1420 mm	1330-1590 mm	1460-1765 mm	1590-1880 mm	1740-2070 mm

After determining the height group for which the chairs and desks in the educational institutions are meant, one conducts the measurement on certain dimensions and the same are compared to the required, i.e., the permitted dimensions in the standard. Those dimensions are: height of the seat, the effective depth of the seat, the width of the seat, the distance between the lumbar point and the back edge of the seat, the height of the seat back, width of the seat back, horizontal radius of the seat back, the angle of the seating surface, the angle between the seat and the seat back. If the model of the chair is with armrest, in that case the armrests need to be measured and compared with the functional dimensions for armrests: height of armrests, distance from seat back to the frontal edge of the armrests, width of the armrests and length of the armrests. The statistical and dynamical anthropometrical characteristics of the average size of the students at a certain age while sitting are of importance when determining the optimal dimension of a school chair and school desk. (Panero and Zelnik, 1990). This paper aims to demonstrate what happens when school chairs are inappropriately sized for their users, and how a certain inappropriate chair size could have a negative impact on the user's body.

2. GOALS AND TASKS OF THE RESEARCH

The aim of this research is to show how much and in what way the inappropriate school chair has a negative impact on the users. Chairs that were found as real samples in the primary schools are of inappropriate dimensions, meaning dimensions that do not meet the requirements of the standard "EN 1729-1:2015 Furniture - Chairs and tables for educational institutions – Part 1: Functional dimensions" will be used by different height groups of users and will show` the absence of comfortable seating.

3. HYPOTHESIS

It is assumed that if school chairs with inappropriate dimensions are used, they can negatively affect the health of the user who uses them for a prolonged period of time. Any prescribed measure in the standard "EN 1729-1:2015 Furniture - Chairs and tables for educational institutions – Part 1: Functional dimensions" that would not be respected during the design and construction of seating furniture in educational institutions would negatively affect a different part of the user's body, as well as the general comfort of sitting as well as the correct posture.

4. RESULTS

Whether and to what extent the set measures of the standard are important to be respected, we will also consider them through an analysis of their impact on different age groups of real users. The analysis was done through six participants belonging to different height groups according to the standard "EN 1729-1:2015 Furniture - Chairs and tables for educational institutions – Part 1: Functional dimensions".

4.1. Measurement of respondents

The height of all the participants was measured and compared to the standard and accordingly they were assigned to appropriate height group.

Respondent no. 1
Height 950 mm
0 (white)
1(orange)

Respondent no. 2
Height 1210 mm
2 (violet)
3(yellow)

Respondent no. 3
Height 1260 mm
3(yellow)

Respondent no. 4
Height 1330 mm
3(yellow)
4(red)

Respondent no. 5
Height 1400 mm
4(red)

Respondent no. 6
Height 1650 mm
5 (green)
6 (blue)

Figure 1. Measurement of respondents.

4.2. Impact of incorrect measurements of school chairs on the user's body

The height of all the participants was measured and according the standard, they were assigned appropriate height group.

4.2.1. Height of seat

The height of the chairs is actually a measure that classifies it in a certain height group. Failure to use a chair with the appropriate height significantly affects the comfort of sitting and, depending on whether it is smaller or larger, it strains the muscles or the nerves and affects the circulation in the legs.

A B

Figure 2. Examples of respondents from different groups.

In example "A" of *Figure 2*, the subject who belongs to group 3 yellow group is sitting on a chair whose height corresponds to group 4 red group. In the example "B" of *Figure 2*, there is a subject who is belonging to a red group 4 chair, but it is sitting on a blue chair group 6. In both examples, it can be seen that the height of the chair is bigger than the one required for the subjects. Sitting is certainly possible, but the user's legs hang down. The feet do not touch the ground, resulting in pressure on the nerves and blood vessels behind the knee. Prolonged use of the chair in this position leads to disruption of the circulation in the user's legs and to a feeling of heaviness and pain in the legs. For these reasons, the respondents need to move constantly.

Figure 3. Using chairs with a lower height.

In the example of *Figure 3*, the subject who belongs to the 6 blue group is sitting on a chair that belongs to the 4 red group. From the example, it can be seen that the knees are excessively bent and thus unnecessarily burden the muscles and ligaments of the legs. The legs are in a position of fatigue, even though the feet are able to touch the surface, the subject constantly moves from a position of high raised knees, which further presses the stomach and internal organs, leading to bending of the legs to the side of the chair in order to release the stomach.

4.2.2. Effective depth of seat

Effective seating depth is related to femur length. The deviation of this measure from that required according to the height group is manifested by not using the backrest at all or to an increased distance from the working and writing surface. In both cases, long-term use causes back and abdominal muscle fatigue.

Figure 4. Using chairs with less effective seating depth.

In the example of Figure 4, the subject who belongs to group 6 blue group is sitting on a chair that belongs to 4 red group. It can be seen from the example that a large part of the femur has no support. The body curves laterally to bring the writing pad closer. Fatigue is increased on the back and on the legs while the organs in the stomach are pressed.

Figure 5. Using chairs with greater effective seating depth.

In the example of *Figure 5*, the subject who belongs to group 0 white and 1 orange group is sitting on a chair that belongs to 2 purple group. It can be seen from the example that when the body tends to get closer to the backrest, the front edge of the seat hits the back of the calf and constantly puts pressure on it. This disrupts the circulation and causes legs stiffness.

4.2.3. Seat width

The width of the seat depends on the width of the user's hips, and if it is larger, it has no effect. But if a chair with a smaller seat width is used, the comfort of sitting is impaired because if the chair has armrests, sitting would not be possible at all, and if the chair is without armrests, the edges will make a longitudinal cut on the buttocks, which will further burden the muscles and disrupt the circulation, and the user will have the feeling of hanging on the chair.

4.2.4. Depth of seat

Seat depth as a measure is related to effective seating depth. This measure is often mistaken. The depth of the seat should be 20-30 mm smaller than the effective seating depth according the height group. In almost all examined samples, the difference is significantly greater, so that users either have their buttocks hanging between the saddle and the backrest, or the back support has a large gap in the lumbar part, the part that should have the greatest support by the backrest (*Figure 6)*.

Figure 6. Using chairs with greater seating depth.

4.2.5. Lumbar point height

The lumbar point is the closest (innermost) point of the backrest. The height at which this point is placed is of great importance for supporting the back and providing lumbar support. As the height groups increase, so should the height of the lumbar point. If the lumbar point is set lower or higher, it will only make harm to the lower back or to the shoulders and the backrest will not help the back muscles and the spine to rest but will fatigue them instead.

4.2.6. Backrest height

The height of the backrest is the same in all groups and it only has a minimum value of 100mm. The height of the backrest is a measurement from the lumbar point to the upper edge of the backrest. The minimum value of 100 mm is set in order that anything less would put pressure on only one vertebra and would make the back not comfortable at all for the user. In all examined samples, this measure is satisfied.

4.2.7. Width of the backrest

As subjects grow in height, so do their bodies grow in width, including the torso. The width of the backrest does not affect significantly if it is larger. For these reasons, the standard specifies only a minimum width for each height group. The problem arises if a backrest is used that is of a smaller width. In that case, the end edges of the backrest exert pressure and strain on the shoulders, which disrupts the full support of the back.

4.2.8. Horizontal radius of the backrest

As with the width of the backrest, the standard also specifies the minimum value for the radius, which in this case is the same for all height groups and is set to a minimum of 300 mm. All tested samples were within the limits for this measure

4.2.9. Inclination of the backrest

The backrest angle for all height groups should range from 95° to 110°. This measure gives the actual position of sitting and working (writing, drawing). Anything smaller than the 95° angle would not perform the role of supporting the back, but instead would push the back forward. Conversely, anything greater than 110° would put the body in a semi-recumbent position, which is not suitable at all for writing or drawing. Contrary to the negative examples, if a sample that fulfills all the measures required by the standard is analyzed and if that sample is used by an appropriate user, seating would be comfortable with proper horizontal and vertical body support.

5. DISCUSSION AND CONCLUSION

Using an inappropriate school chair has a great impact on the body of the user who spends prolonged periods of time in a sitting position during the school day. Each wrong dimension of the stool affects a different part of the body and gradually hurts it with long use. Incorrectly designed measures of the school chair have a negative impact on the spine, blood flow, muscles, nerves (*Table 2*). Depending on whether the measure exceeds the size or is smaller than prescribed, it negatively affects the body of the user in a different way.

Table 2. Impact of inappropriate measures on the human body

Incorrectly designed dimension of a school chair	Negative impact on certain parts of the user's body
Height of seat	Higher - hanging of the legs, interruption of circulation, pinching of nerves Lower – unnecessary bending of the spine, unnecessary bending of the legs and muscle strain
Effective depth of seat	Fatigue of back and abdominal muscles, abnormal curvature of the spine
Seat width	Muscle strain, circulation disorder
Depth of seat	Abnormal curvature of the spine
Lumbar point height	Fatigue of back and abdominal muscles
Backrest height	Back muscle fatigue
Width of the backrest	Back muscle fatigue
Horizontal radius of the backrest	Back muscle fatigue
Inclination of the backrest	Fatigue of back and abdominal muscles, abnormal curvature of the spine

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The Influence of Drying and Initial Moisture Content of Milled and Solid Oak Wood (*Quercus robur* L.) Samples on its Solubility in Cold Water

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ABSTRACT

In this research paper, the cold water extraction (*Method A*) according to the procedure described in the ASTM D1110-21 standard was conducted to determine solubility of milled and solid oak wood *(Quercus robur* L.) samples. *Method A* provides a measure of the tannins, gums, sugars, and colouring matter in the wood, respectively extractives. In addition to the basic building components (cellulose, hemicellulose and lignin), extractives are also found in the wood and can be extracted from the wood with water or other solvents. Although they occupy a small percentage of the total composition of wood, extractives can affect the quality of the implementation of hydrothermal procedures, in particular, they can affect the colour of the wood and its change. The oak wood (*Quercus robur* L.) was used in this research because it is technically the most valuable wood specie in the Republic of Croatia.

Key words: cold water, extraction, extractives, milled, oak wood, solid, *Quercus robur* L.

1. INTRODUCTION

Hydrothermal treatments of wood in the industry often results in changes in the colour of the treated wood. This change is influenced, among other factors, by the chemical composition of the wood itself. When these colour changes are unwanted or uneven, it becomes a production problem that leads to financial losses. The chemical composition of wood consists of primary and secondary constituents that form the cell walls of wood. The composition of primary constituents varies from one wood species to another. Cellulose, the most abundant component, typically accounts for 46-56 %, followed by hemicelluloses at 23-35 %, and lignin ranging from 15-35 % (Babiak, 2007).

Furthermore, wood contains secondary constituents known as extractives, albeit in very small quantities. These extractives can either fully or partially infiltrate the cell wall of wood, and their presence is not crucial for the structural organization of wood. Despite constituting a small proportion of wood's chemical composition, their presence can influence various wood characteristics, including resistance to biological decay and pests, wood colour and odour. Moreover, their presence is associated with wood permeability and physical properties. Extractives include a wide range of components such as waxes, fats, fatty acids, alcohols, steroids, higher hydrocarbons, and resin mixtures (*eg*. terpenes, lignans, stilbenes, flavonoids and other arenes) (Boddy, 1992; Fengel and Wegener, 1989). As previously mentioned, these substances contribute to many wood properties that can either positively or negatively impact subsequent wood hydrothermal processing (drying, steaming, boiling), influencing factors like process speed and colour, among others. Additionally, the chemical changes in wood that cause colour changes primarily occur in the presence of water. Hence, it is interesting to assess the ammount of extractives obtained, considering the initial water content of the samples.

Therefore, the objective of this study is to explore the extraction of oak wood (*Quercus robur* L.) samples using cold water (*Method A*), following the standard procedure outlined in

ASTM D 1110-21 standard. This research aims to determine the quantity of extractive material that can be obtained, taking into account the initial moisture content of the milled and solid oak wood samples.

2. MATERIAL AND METHODS

2.1. Material

In this research, oak wood (*Quercus robur* L.) was used for both milled and solid wood samples. Additionally, ASTM type II deionized water was used as the solvent for cold-water extraction to determine solubility.

Oak wood lamellas, measuring 1000 mm × 130 mm × 7 mm (length × width × thickness) were cut using Einhell TC-SB 200/1 band saw into smaller sections. The cutting process involved the removal of excess material by trimming 70 mm from each front side and 30 mm along each side of the lamella. Samples were then taken from the central part of the lamella. The central section of the lamella was further cut lengthwise and crosswise to obtain smaller samples, approximately measuring 31 x 18 mm, suitable for further milling. For solid wood testing, samples were cut to approximate dimensions of 20 x 15 mm, with the aim of achieving an approximate weight of 2 grams.

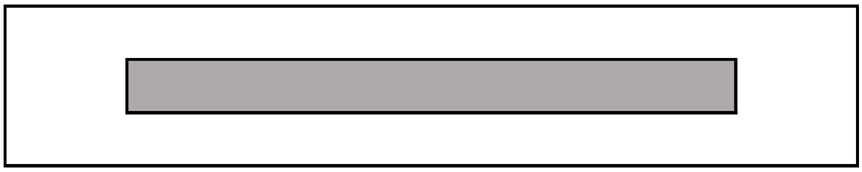

Figure 1. Sampling for milled wood (grey area.)

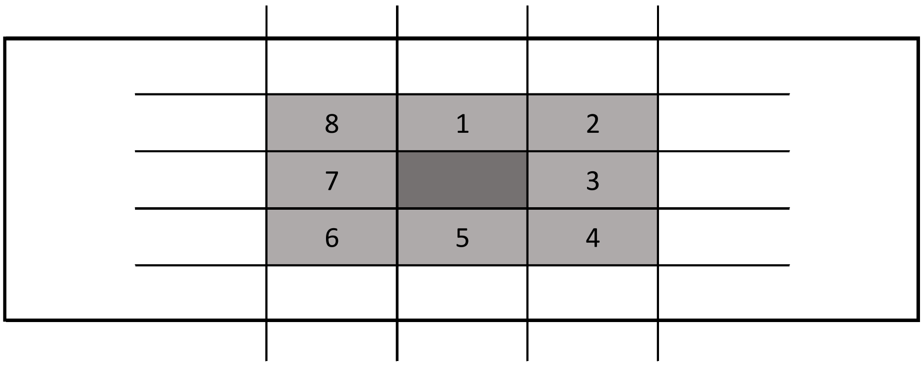

Figure 2. Sampling for solid wood (grey area), with darker areas designated for initial gravimetric moisture content determination.

Slightly air-dried wood samples were initially milled at the Retsch SM400 mill with a 4 mm mesh sieve. Subsequently, the Retsch SR300 mill was utilized for finer milling with 1 mm and then 0.5 mm mesh sieves. Following the milling process, the milled wood samples underwent sieving using laboratory sieves with mesh sizes of 425 μm and 250 μm. The portion of the sample retained on the 250 μm sieve was used in the experiment, while the coarser and finer wood shavings were excluded from further experiments. Both milled and solid samples were air-dried before extraction.

Figure 3. Retsch SM400 mill.

Figure4. Retsch SR300 mill.

2.2. Methods

2.2.1. Gravimetric determination of moisture content

The initial moisture content of both milled and solid wood samples was determined gravimetrically using a drying oven (Memmert UF 110 plus) and a laboratory scale (Sartorius CPA225D). Approximately 1 gram of the milled and sieved wood was weighed and placed in weighing bottles, which were then placed in the drying oven at a temperature of 103±2 °C until a constant mass was achieved. After drying, the samples were transferred to a desiccator to cool to room temperature and were subsequently re-weighed.

Moisture content was calculated using the following formula:

$$\omega = [(W_1 - W_0) / W_0] \times 100 \quad (1)$$

ω –moisture content (%)
W_1 – mass of the sample in its raw state (g)
W_0 – mass of the sample in an absolutely dry state (g)

2.2.2. Extraction and filtration

Four different sets of samples were extracted, and each set had 6 replicates:

1. milled samples with a certain moisture content,
2. milled samples in an absolutely dry state,
3. solid wood samples with a certain moisture content,
4. solid wood samples in an absolutely dry state.

To determine the solubility in cold water, approximately 2 grams of each sample set were weighed into a 300 mL Erlenmeyer flask. After weighing, 300 mL of distilled water was added to each flask. The prepared solution was placed on an electromagnetic stirrer for extraction. A small magnetic stir bar was placed in the flask to ensure constant mixing of the solution. The electromagnetic stirrer was set to 700 revolutions per minute, and extraction occurred for 48 hours with continuous stirring at a room temperature of 23±2 °C.

Figure 7 Extraction of milled sample.

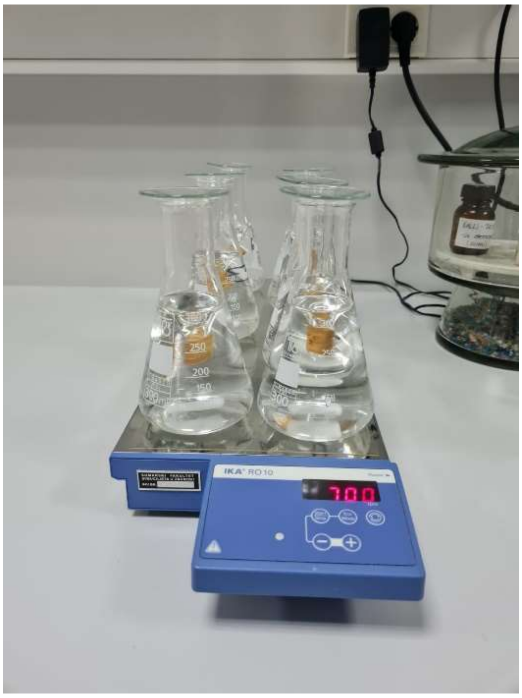

Figure 8 Extraction of solid sample.

After 48 hours, the samples were filtered using vacuum filtration. The filtration apparatus consisted of a vacuum pump, a vacuum flask, and filter crucibles with porous bottoms. Following filtration, the content retained on the crucible was dried at a temperature of 103±2 °C until a constant mass was achieved, using a Memmert UF 110 plus drying oven. Upon completion of drying the crucibles with the samples were placed in a desiccator, cooled to room temperature, and then the sample mass was determined.

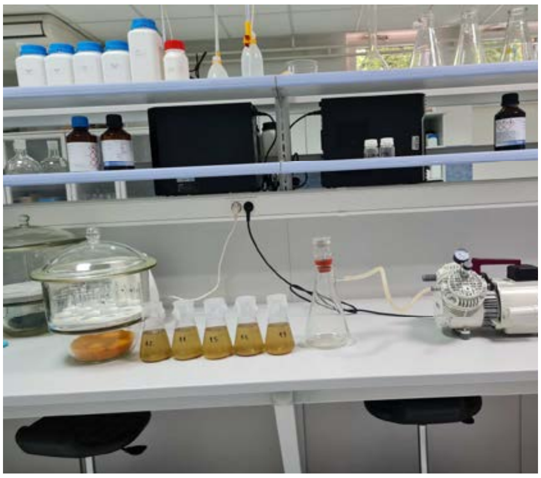

Figure 7. Filtration apparatus (before).

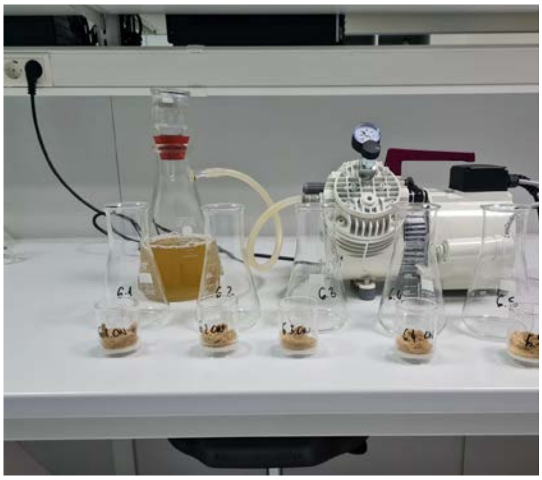

Figure 8. Filtration apparatus (after).

3. RESULTS AND DISCUSION

After the experiment was prepared and conducted, the data were processed, and the descriptive statistics are shown in *Table 1* below.

Table 1. Descriptive Statistics for Solubility in Cold Water [%]

	MW9.19	MW0	SS11.40	SS0
Number of observations	6	6	6	6
Minimum	8.005	7.408	14.605	2.692
Maximum	9.735	10.252	20.095	3.154
1st Quartile	8.764	8.055	15.505	2.824
Median	9.219	8.308	16.963	2.865
3rd Quartile	9.393	9.743	17.507	2.899
Mean	9.041	8.745	16.889	2.883
Variance (n-1)	0.389	1.421	3.863	0.023
Standard deviation (n-1)	0.624	1.192	1.965	0.153

Legend: MW9.19: Milled sample with 9.19 % water content; MW0: Milled sample that is absolutely dry; SS11.40: Solid sample with 11.40 % water content; SS0: Solid sample that is absolutely dry.

The moisture content appears to play a significant role in the solubility of the materials in cold water, with dry samples exhibiting a distinct behaviour compared to those containing water. The physical state of the sample, whether milled or solid, also influences its interaction with cold water, as evidenced by the differences in mean solubility and variability. Solid samples with moisture content have the higher solubility in cold water, suggesting that, for these samples, water facilitates interaction with the solvent. In contrast, when solid samples are absolutely dry, they become less soluble. These observations are crucial for understanding the material's behaviour in different conditions and can have practical implications in processing or using these materials where solubility in cold water is a factor.

Milled samples with a certain water content show a slightly higher mean solubility than absolutely dry milled samples. This might suggest that a small amount of water may enhance solubility in milled samples. The modest difference is somewhat surprising and is probably due to the fact that the extractives on smaller wood particles were more exposed to air and heat, leading to easier degradation, regardless of the investigated moisture content. It is highly probable that there would be a greater difference in solubility between the absolutely dry samples and the moist samples, if the moist samples were significantly higher in moisture content or in a green state.

Solid samples with water content show a significantly higher mean solubility than absolutely dry solid samples. This indicates that water content may be crucial in the dissolution or interaction of solid samples in cold water.

Solid samples with water content have a significantly higher mean solubility than milled samples with comparable water content. In contrast, the absolutely dry solid sample has a much lower mean solubility than all other samples, which suggests that the solid form without any water content is least affected by cold water.

The dry milled sample shows greater variability in solubility compared to when it has water content. This suggests that the drying process or absolute dry state results in a less consistent solubility profile. Similarly, solid samples show a decrease in variability when dry compared to when they have water content, indicating that water might contribute to a more varied interaction with cold water across different parts of the sample.

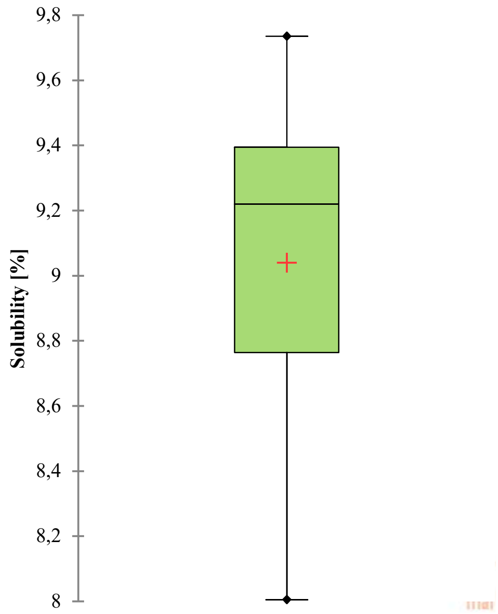

Figure 9. Milled sample with 9.19 moisture content.

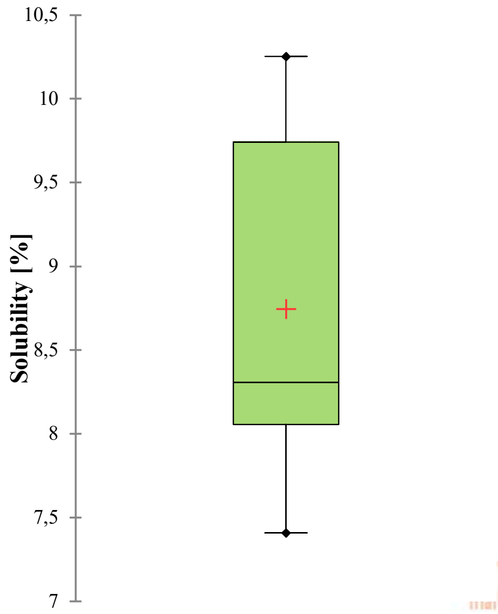

Figure 10. Milled sample absolutely dry.

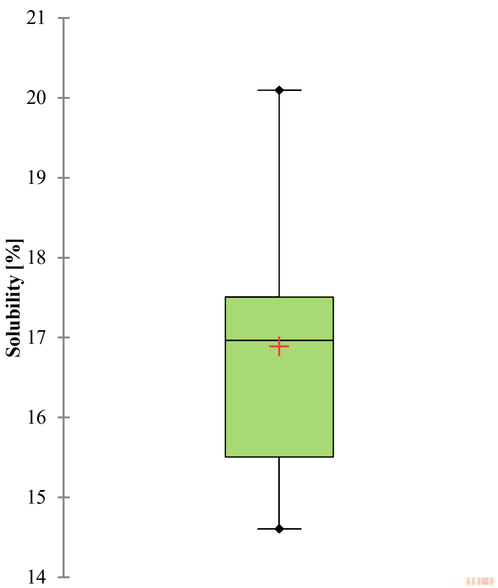

Figure 11. Solid sample with 1.,40 moisture content.

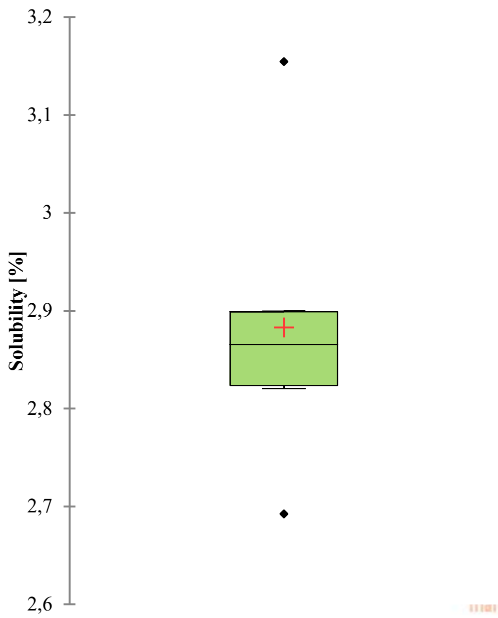

Figure 12. Solid sample absolutely dry.

The box plots provide a comparative visualization of solubility in cold water of different material samples sets. The milled material sample with 9.19 % moisture content exhibits a tight interquartile range, suggesting a consistent solubility across the samples. Conversely, the absolutely dry milled material indicates more variability in solubility, as seen by the broader range, yet the data is relatively symmetric around the median. For the solid material with 11.40 % moisture content, a significantly wider distribution is observed, including a higher median which points to a greater spread in solubility. In contrast, the absolutely dry solid material maintains a narrow range, signalling less variability, though there are some extreme values marked as outliers. Overall, the milled materials demonstrate less variability in solubility than the solid samples, with the solid materials showing greater variance when moisture is present but similar consistency to milled materials when dry.

In comparison of samples a nonparametric test, the Wilcoxon signed-rank test was chosen for analysis due to the non-normal distribution of the data and the small sample size. The Wilcoxon test provides additional sensitivity by ranking the magnitudes of the differences. This test is employed to determine whether two related samples are from the same distribution without the need for normality.

Table 2. Wilcoxon signed-rank test / Two-tailed test

	MW9.19-SS11.40	MW0-SS0	MW9.19-MW0	SS11.40-SS0
V	0	21	13	21
Expected value	10.500	10.500	10.500	10.500
Variance (V)	22.750	22.750	22.750	22.750
p-value (Two-tailed)	0.031	0.031	0.688	0.031
alpha	0.05	0.05	0.05	0.05

Legend: MW9.19: Milled sample with 9.19 % water content; MW0: Milled sample that is absolutely dry; SS11.40: Solid sample with 11.40 % water content; SS0: Solid sample that is absolutely dry.

The Wilcoxon signed-rank test considers the magnitude of differences and ranks them. A low *V* value suggests that most differences are on one side of the median, indicating a difference between the two samples. In the Wilcoxon signed-rank test, significant differences were found between the milled samples with 9.19 % moisture content (MW9.19) and the solid samples with 11.40 % moisture content (SS11.40), as well as between the absolutely dry milled samples (MW0) and the absolutely dry solid samples (SS0), with *p*-values of 0.031, indicating statistically significant differences at the 5 % significance level. In contrast, the comparison between the milled sample with 9.19 % moisture content (MW9.19) and the absolutely dry milled sample (MW0) did not show a statistically significant difference (*p*-value 0.688). Additionally, a significant difference was observed when comparing the solid samples with 11.40 % moisture content (SS11.40) with the absolutely dry solid samples (SS0) with a *p*-value of 0.031. The variance remained unchanged across the tested pairs, suggesting consistency in the variability of the measurements. The results suggest that the presence of water in both milled and solid samples have a statistically significant effect compared to their absolutely dry states.

4. CONCLUSIONS

This research focused on the solubility of oak wood (*Quercus robur* L.) through cold water extraction, highlighting the significance of extractives within the wood's chemical composition. Although present in minor quantities, these extractives, which include tannins, gums, sugars, and colouring matter, have a profound influence on the wood's characteristics, particularly its colour and hydrothermal processing attributes. The study utilized the ASTM D1110-21 standard method to meticulously evaluate the extractive content in both milled and solid wood samples under varying moisture conditions. Results indicated that moisture content plays a pivotal role in the solubility of extractives; solid wood samples with inherent moisture exhibited greater solubility, suggesting that the water within the wood facilitated better interaction with the extracting solvent. Furthermore, the study observed that milled wood samples, despite their increased surface area, did not significantly differ in extractive solubility compared to solid wood samples when both were in an absolutely dry state. This finding could reshape current perceptions regarding the impact of physical state and moisture content on the extraction efficiency of wood. The application of the cold water extraction method proved effective in quantifying the extractive content, which is essential for industries where wood colour consistency and hydrothermal treatment quality are of utmost importance. The results of this research offer valuable insights that can be applied to improve industrial processes, such as drying, steaming, and boiling of oak wood, ensuring better product quality and reducing financial losses due to colour imperfections. This study not only contributes to the fundamental understanding of oak wood's chemical behaviour in the presence of cold water but also provides practical guidance for enhancing the hydrothermal treatment of wood. The findings underline the critical need to consider the unique properties of wood extractives in industrial applications, paving the way for more efficient and cost-effective wood processing techniques

Acknowledgements: *This research paper is a part of Bachelor thesis of student Borno Matišev.*

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The Effect of Thermal Modification on the Quality of the Milled Surface of Beech and Pine Wood

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ABSTRACT

The article deals with the effect of thermal modification on the quality of the created surface during milling on CNC milling cutters. The quality of the created surface is evaluated based on surface roughness, specifically its roughness parameter Ra. The observed surface is created by a shank cutter with a diameter of 20 mm and three cutting edges in a spiral at a standard speed of 18,000. min^{-1}. The article compares thermally modified pine wood and beech wood of at temperatures of 160, 180, 200 and 220 °C with a reference sample of kiln dried wood of the given wood species. The article also monitors the variability of the quality of the created surface due to the change in the feed speed of 2, 4 and 6 $m \cdot min^{-1}$ and the thickness of removal of 1, 3 and 5 mm within the given degree of thermal modification. The article points to the fact that the average value of the arithmetic mean height (Ra) is below 10 μm for both types of wood, regardless of the degree of thermal modification. This meets the general requirements for the surface quality of furniture blanks. The mutual comparison of wood species showed that beech wood forms an average of 1.5 μm higher quality surface than wood pine. Thermal modification within both studied wood species improves the quality indicators of the created surface. In terms of the effect of specific temperatures, the highest quality of the created surface is at 180 °C and deteriorates in the range of 180, 200, 160, 220 °C. From the point of view of the influence of the investigated technological factors, no statistically significant influence of either the feed speed or the thickness of removed layer was demonstrated.

Key words: beech wood, pine wood, thermally modified wood, temperature of thermal modification, quality of the created surface, technological parameters of the process

1. INTRODUCTION

The current trend is to reduce the environmental footprint of the production process. One of the aspects is the minimization of the consumption of chemical substances in the production process, especially in the case of products for children. One of the potential ways is to change the color and increase the resistance of the surfaces due to the thermal treatment of the wood.

In general, thermal treatment can be defined as a process in which high temperatures in the range of 150 to 260 °C are applied to wood in an environment with different types of media (steam, nitrogen, oil, etc.) without chemicals (Sandberg and Kutnar, 2016). As noted by Budakci *et al.* (2013), the effect of these modifications depends on the medium used and its temperature. In Europe, the most commercially used technologies include ThermoWood in Finland, Plato Wood in the Netherlands, oil-heat treatment (OHT) in Germany and Les Bois Perdure and the rectification process (Retiwood) in France (Esteves and Pereira, 2011; Reinprecht and Vidholdova, 2008).

The production process of thermally modified wood is associated with several chemical changes in the structure of the material, in simplified terms it is a change in the proportion of lignin and the degradation of higher cellulose to lower cellulose, and these changes subsequently affect its physical and mechanical properties (Reinprecht and Vidholdová, 2008; Kačíková and Kačík, 2011; ThermoWood Handbook, 2003; Čabalová *et al*., 2016).

The intensity of the change in physical and mechanical properties consequently limits the use of thermally modified material. For this reason, this article was also created, the aim of which is to assess the effect of thermal modification on the quality of the machined surface. At the same time, the article aims to carry out the given assessment not with the help of classic technologies, as is customary, but with the use of CNC technology.

2. MATERIAL AND METHODS

Experimental samples: In the experiment, native and heat-treated blanks of Scots pine (*Pinus sylvestris*) and European Beech (*Fagus sylvatica* L.) with dimensions of 30 × 55 × 500 mm and moisture content 8 ± 1 % were used.

Heat treatment of wood: Samples for the experiment were heat treated with ThermoWood technology at the FLD Arboretum area (ČZU Prague) in Kostelec nad Černými lesy. Thermal treatment was carried out using the chamber S400/03 (LAC Ltd., Czech Republic). The course of the process was controlled by temperature and humidity sensors directly on the processed samples. The course of thermal modification itself was controlled via a computer, using a program from the company Katres spol. Ltd. The treatment process for individual thermal treatments is shown in *Figure 1*.

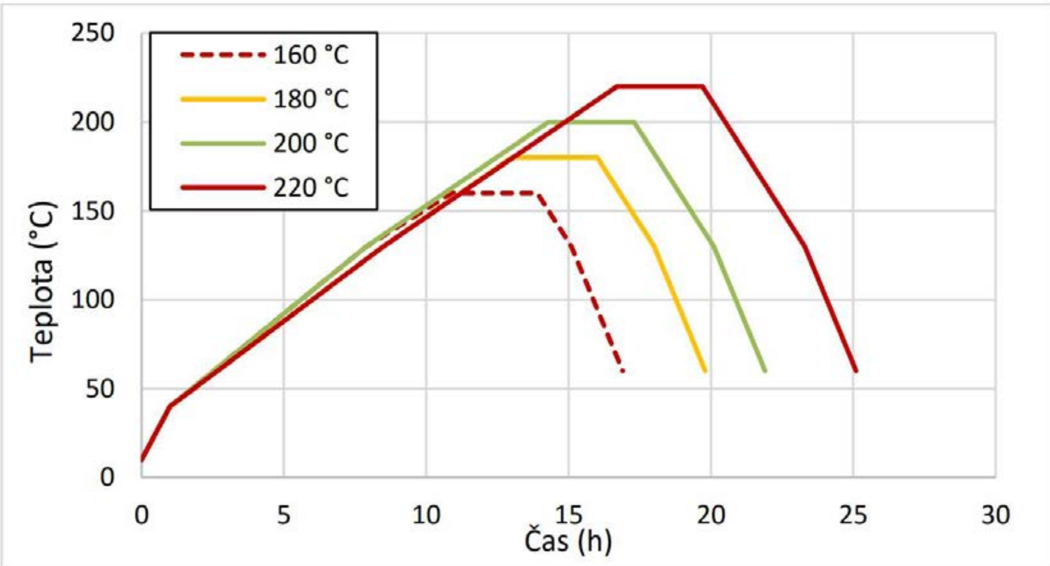

Figure 1. Graphic representation of temperature and time dependence for individual stages of thermal treatment of samples (Korčok et al., 2018).

Machine and tooling: The blanks were milled on a 5-axis CNC machining center SCM Tech Z5 (*Figure 2*) supplied by SCM–group, Rimini, Italy. The basic technical and technological parameters indicated by the manufacturer are listed in *Table 1*. LEUCO VFW 178354 finishers (*Figure 3*) from LEUCO (Beinheim, France) were used for milling. The basic technical and technological parameters indicated by the manufacturer are listed in the *Table. 2*

Figure 2. CNC machining center SCM Tech Z5 (https://www.scmgroup.com/en).

Table 1. Technical and technological parameters of the CNC machining center SCM Tech Z5. (https://www.scmgroup.com/en)

Technical parameters of CNC machining center SCM Tech Z5	
Useful desktop	x = 3,050mm , y = 1,300mm, z =300mm
Speed X axis	0 ÷ 70 $m.min^{-1}$
Speed Y axis	0 ÷ 40 $m.min^{-1}$
Speed Z axis	0 ÷ 15 $m.min^{-1}$
Vector rate	0 ÷ 83 $m.min^{-1}$

Technical parameters of the main spindle - electric spindle with HSK F63	
Rotation axis C	640°
Rotation axis B	320°
Revolutions	600 ÷ 24,000 $ot.min^{-1}$
Power	11 kW
Maximum tool diameter	D = 160 mm L = 180 mm

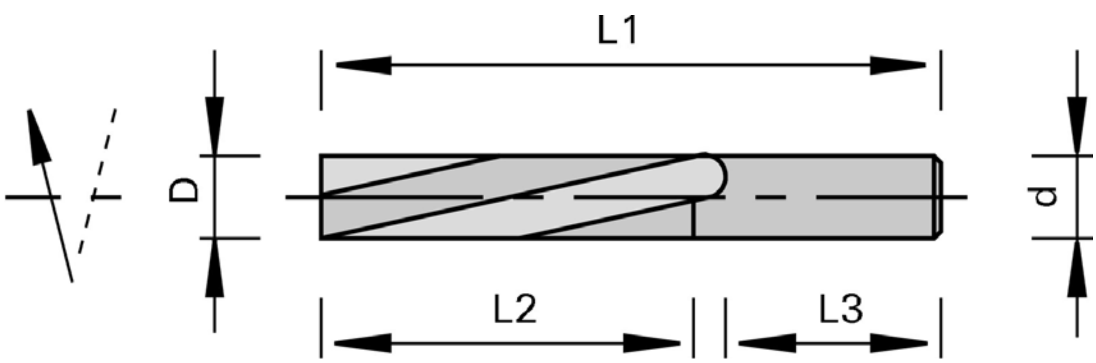

Figure 3. A Finishing cutter LEUCO VFW 178354. (https://www.leuco.com/EN/US/web/home).

Table 2. Technical and technological parameters of finishing cutters LEUCO VFW 178354 (https://www.leuco.com/EN/US/web/home)

Feature	Value
Ø D = Cutting circle diameter	20 [mm]
L2 = Cutting width	55 [mm]
Ø d = Shank diameter	20 [mm]
L3 = Shank length	50 [mm]
L1 = Total length	115 [mm]
Z = No. of teeth	3
Helical direction = Helical direction	negative
n_{max} = maximum RPM	30,000 [min^{-1}]
L/R = cutting direction	R

Milling process: A LEUCO VFW 178354 milling cutter was fitted to a SOBO 302680291 GM 300 HSK 63F hydraulic chuck from Gühring KG Albstadt. The blanks were placed in the CNC machining center so that the longer side was in the X axis and the shorter side was in the Y axis. clamped with mechanical clamps VCMC-S4 145x145x50 12-80 from J. Schmalz GmbH, Glatten, Germany. The milling process took place at a constant milling speed n = 20,000 min-1 and varying thickness of the removal layer a_e = 1, 3 and 5 mm and varying feed speed z vf = 2, 4 and 6 m.min^{-1}.

Determination of surface roughness: The surface roughness of the samples was measured with a laser profilometer LPM-4 (*Figure 4*) from the manufacturer Kvant s.r.o. Slovak Republic. The profilometer uses the triangulation principle of laser profilometry. The image of the laser line is captured at an angle by a digital camera. The cross-sectional profile of the object is then evaluated from the scanned image. The obtained data are mathematically filtered and individual indicators of the primary profile, waviness profile and roughness profile are set (Kminiak and Gaff, 2015)

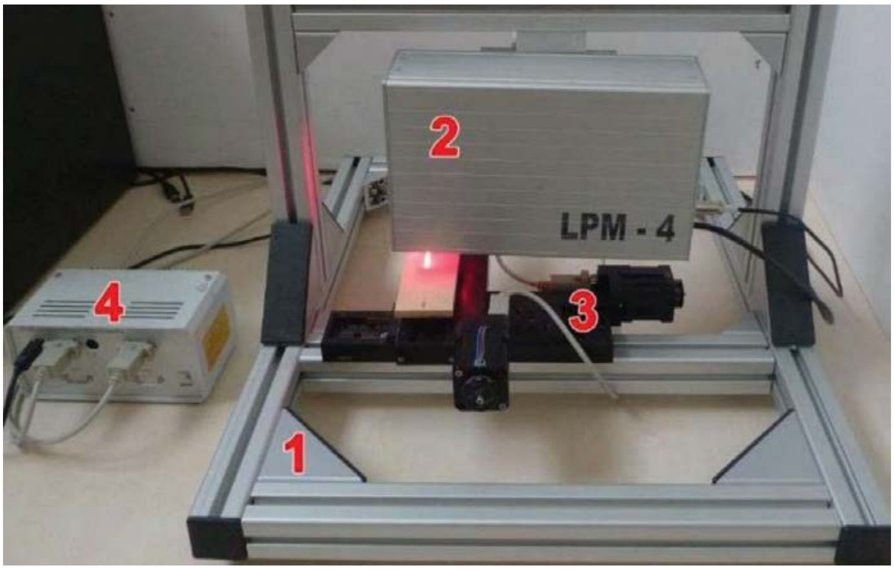

Figure 4. Laser Profilometer LPM - 4 (1 - supporting structure allowing manual setting of working distance and fitting of profilometric head and trolley system, 2 - profilometric head, 3 - feed system of the XZ axis, 4 - control system of working desk shifts) (Kminiak and Gaff 2015).

The methodology of Siklenka and Adamcova (2012) was used to measure the surface roughness, which meets the EN ISO 4287 standard. Within each sample, measurements were made in three traces, located in the center of the sample, evenly distributed over the entire surface of the sample. sample width (5/10/15 mm from the edge of the sample), the traverse length was 60 mm, and the trace was oriented in the direction of spindle displacement in the milling process. The surface roughness was evaluated using the parameter of the arithmetic mean of the deviation of the roughness profile Ra.

3. RESULTS AND DISCUSSION

Background: Changing the quality of the created surface as a result of the thermal modification of wood is not the goal of the thermal modification, but its side effect. The aim of this article is to assess the risks of thermal modification on quality indicators of the surface, whether it is necessary to choose different technical-technological parameters of the process when processing thermally modified wood than when processing wood without thermal modification.

As an objective criterion for assessing the effect of thermal modification on the quality of the created surface, the roughness of the created surface was chosen, specifically its parameter, the „Ra" mean arithmetic deviation of the roughness profile. The reason for choosing the roughness parameter as the most representative quality parameter is the premise, surface roughness and waviness are interconnected parameters, surface waviness is primarily dependent on machining kinematics, and surface roughness primarily depends on the tool-workpiece interaction. Based on the following premise, roughness reacts more sensitively to material changes, which was also confirmed in the given experiment.

Analysis of the obtained data: The measured data were subjected to analyses in the statistic software STATISTICA 12.

- the effect of the type of wood, the degree of thermal modification and the thickness of the removal layer was shown to be statistically significant, on the other hand, the effect of the feed speed was shown to be statistically insignificant,
- the order of statistical significance of the factors decreases in the order of type of wood, degree of thermal modification and the thickness of the removal layer, all three investigated factors proved to be highly statistically significant
- the roughness of the surface of beech wood ranges from 4.6 μm to 8.2 μm, the roughness of the surface of pine wood ranges from 5.2 to 9.7 μm, the surface of pine wood is 1.4 μm rougher on average like the surface of beech wood (see *Figure 5*).

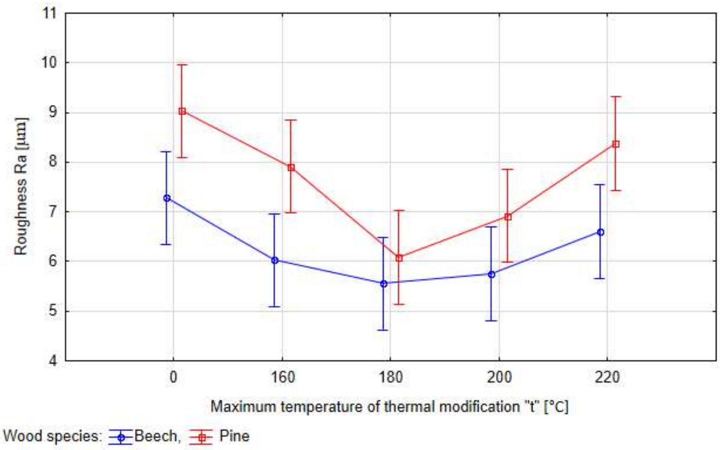

Figure 5. The effect of thermal modification on the quality of the created surface (vertical bars denote 95 % confidence interval for the mean.).

The roughness of the surface of thermally treated beech and pine wood is lower than that of wood without thermal modification, in terms of the influence of specific temperatures, the lowest roughness of the created surface is at 180 °C (on average beech wood 5.6 μm / pine wood 6.1 μm) and deteriorates in the order 180 °C, 200°C (on average beech wood 5.7 μm/ pine wood 6.9 μm), 160 °C (on average beech wood 6.0 μm/ pine wood 7.9 μm), 220 °C (on average beech wood 6.6 μm/ pine wood 8.4 μm) and the reference sample (on average beech wood 7.2 μm/ pine wood 9.0 μm), due to thermal modification there is a decrease in roughness depending on the temperature modifies in the range of 0.7-1.5 μm for beech wood and 0.7-3.0 μm for pine wood.

The statistical significance of the effect of the thickness of the removal layer on the roughness of the created surface was confirmed only within pine wood, in the case of beech wood the given effect is statistically insignificant, in the case of pine wood, as a result of increasing the removal from 1 mm to 3 mm, the roughness of the created surface worsens on average by 1.1 μm, and in the case of an increase in removal from 3 to 5 mm, the roughness will deteriorate by an average of 1.3 μm (see *Figure 6/a)*.

The expected influence of the feed speed on the roughness of the created surface was not confirmed, surface roughness differences due to a change in the feed speed by 2 $m.min^{-1}$, the surface roughness changes on average by 0.3 μm for beech and by 0.7 μm in the case of pine. It is not possible to observe an unequivocal trend of increase or decrease in roughness due to changes in the feed rate (see *Figure 6/b*).

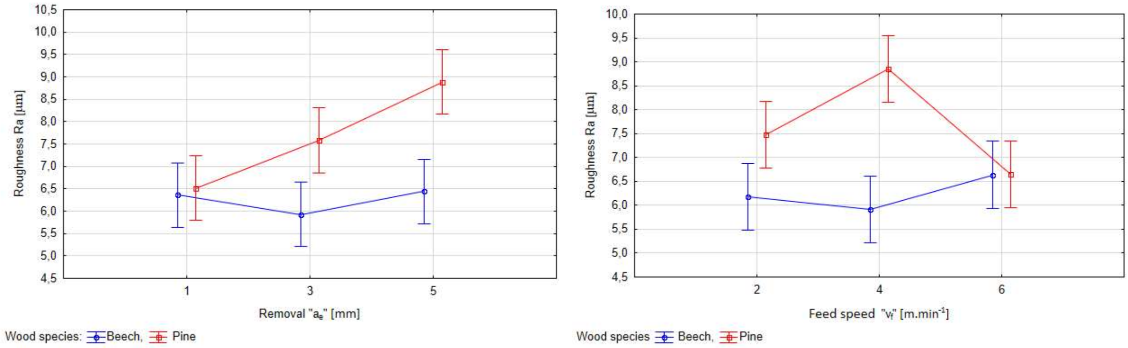

Figure 6. a) The effect of the amount of removal on the quality of the created surface b) the effect of the size of the feed speed on the quality of the created surface (vertical bars denote 95 % confidence interval for the mean.)

Scientific interpretation of the obtained data: For the sake of objectivity, it is necessary to emphasize at the outset the fact that most authors dealing with the given issue use the milling process on the bottom single-spindle cutter and a cutter with a diameter of 120 to 140 mm for surface creation. The experiment carried out by us is carried out on a CNC milling machine with a tool diameter of 20 mm. From a macro point of view, we remove identical layers of material, but from a micro point of view, the chip formation mechanism is not identical. We will use the example of the contact angle, for a tool with a diameter of 120 and a clearance of 1 mm, the contact angle is 10°, and for a tool of 20 mm and a clearance of 1 mm, the contact angle is up to 25°. At the same time, a specific feature of tools for CNC milling machines is the development of the cutting edge into a screw. Both facts significantly influence the vectorization of forces during the creation of new surfaces.

As stated by Škaljič *et al*., (2009), the physical and mechanical properties and anatomical structure of the wood affect the roughness of the surface. The resistance to blade penetration into wood depends on the size and shape of the cells, as well as the thickness and strength of the cell walls. This creates the hypothesis that the denser and more homogeneous the wood, the better the surface it creates. This statement corresponds to our conclusions as well as the conclusions of Malkoçoðlu and Özdemir (2006) and Malkoçoðlu (2007) showed in their research that with the same processing parameters, the surface of conifers is of lower quality than the surface of hardwoods.

The results obtained by us confirm the conclusions of Vančo *et al.*, (2017) that the quality of thermally treated wood is higher than the quality of native wood, at the same time we agree with the trend that when the temperature increases to about 200 °C, the quality improves and above this limit it gradually deteriorates. Thermal modification of wood is a process that changes its chemical structure, making the wood more fragile and easier to protect. As stated by (Ispas *et al.*, 2016), the brittleness of wood is a consequence of the loss of amorphous polysaccharides.

An explanation of the break and the reverse increase in roughness at a temperature of 200-220 °C is offered by Čabalová *et al.*, (2016). A noticeable mass loss (ML) at temperatures above 220 °C suggested there was intensive decomposition of the wood matter. The ML of wood is one of the most important features in heat treatment, and it is commonly referred to as an indicator of quality (Esteves and Pereira, 2009).

Technological interpretation of the results: From a technological point of view, it is necessary to interpret the obtained data regarding the limit value of the surface roughness. Based on our own experience, a milled surface can be considered high-quality if the surface roughness does not exceed the value of Ra = 20 μm. Within the setting of technological parameters, thermal modification will not cause changes in material properties that would relate to quality indicators and limit values. From this point of view, there is no need for a differentiated approach when processing thermally modified wood, and it is possible to use the same technical-technological settings of the machining process. From the point of view of the specific values of the technical-technological parameters, it is appropriate to increase them, this is not prevented by other limiting factors (cutting forces Fc, the ability to evacuate classes S_{zm},...).

4. CONCLUSIONS

Thermal modification, in addition to the targeted change for which it is carried out – a change in color, also brings a change in physical-mechanical properties, which subsequently affect the machinability of the material. From the point of view of the quality of the created surface, specifically the surface roughness parameters, it is possible to state that, under the conditions of machining by means of CNC technology, thermally modified wood shows a higher quality of the created surface than natural wood. As the temperature of the thermal modification increases, the quality of the created surface increases approximately up to a temperature of 200 °C, and above this limit the reverse phenomenon occurs, namely that the quality of the surface decreases with further temperature increases. In absolute terms, the values of the surface roughness in the range of recommended values of the technical-technological parameters usual for the given type of CNC machining are below the limit values, and therefore the quality of the surface created in this way can be considered acceptable.

Acknowledgements: *This experimental research was prepared within the grant project: APVV- SK-PL-21-0059 "Effect of the application of machining fluids in minimum quantity lubrication (MQL) system on the milling process results of heat-treated wood" and VEGA 1/0324/21 "Analysis of the risks of changes in the material composition and technological background on the quality of the working environment in small and medium-sized wood processing companies"*

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Rationalization of Furniture Constructions in the Design Phase Using the CAD Program Inventor

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ABSTRACT

The research focuses on the challenges brought by the adaptation of furniture production to the market demands of small-scale and unique production of variable designs. The emphasis of the work is on determining the optimal dimensions of the elements within the assembly of the chair and conducting product quality testing in the early stages of design. The goal of the research was to investigate the possibilities of applying rationalization at the earliest possible stage of the production process, which leads to cost reduction. In performing the rationalization, the Finite Element Method (FAM) was used with the support of the Nastran and Inventor CAD programs. On the example of a chair with a metal frame construction, a simulation was performed according to the current standard HRN EN 1728 (2012) for testing chairs. Simulation with the application of different materials and dimensions resulted in an optimal solution and prevented the creation of a prototype that would not satisfy the physical model test, which significantly reduced the production time of a high-quality product in the early design phase.

Key words: finite element method, furniture design, Inventor, quality, rationalization, three-dimensional modeling

1. INTRODUCTION

Observing furniture production throughout history, it can be concluded that mass production is a thing of the past, and looking to the future, production capacities must be ensured and directed towards the known customer. In such a market situation, it is necessary to further strengthen the production preparation system, which certainly includes the product development and innovation phase. Within such dynamic and flexible production, market competitiveness must also ensure the rationalization of the construction of the produced furniture, which is often overlooked.

Rationalizing the construction based on personal experiential judgment can be a rather risky endeavour in ensuring the quality of the final product. Such a practice is outdated and is no longer applicable, especially because more and more new materials are being introduced into today's products. One of the possibilities to overcome this problem is to use the Finite Element Method (FEM) in the early design phase. Some studies have highlighted the increasing prevalence of FEM in the structural analysis of furniture systems. For instance, Tankut *et al.* (2014) conducted a bibliographical review that focuses on FEM's utilization in the analysis of wooden furniture products. Additionally, another study underscores the potential for significant variations in chair design when straightforward calculations are employed. Furthermore, it was emphasized in this research that there is a growing need to shift the focus of wood analysis from the scale of "building size" to "furniture size" (Gustafsson, 1995).

Moreover, it's worth noting that Mackerle (2005), conducted an extensive review of more than 300 articles published between 1995 and 2004, specifically related to the application of FEM in wood products and construction. The findings from this review underscored the paramount importance of understanding the mechanical properties of wood in the context of FEM application within wood products.

However, when considering the use of wood, it's important to acknowledge the complexity of analyzing wood's mechanical properties using FEM due to its anisotropic nature. To facilitate computational modeling, wood is typically treated as an orthotropic material. In this case, wood's mechanical properties can be determined in the longitudinal, radial, and tangential directions using appropriate wood samples (Hu *et al*. 2020).

Furthermore, it's crucial to mention that the application of FEM methods for structural analysis provides reasonable estimations of the overall strength of these structures, consistently aligning with actual performance testing outcomes. This conclusion holds true for various structural materials, emphasizing the significance of accurate structural analysis and mechanical property understanding (Ceylan *et al*. 2021).

Joints are a crucial component in most structures, and their substantial impact on the structure's behaviour cannot be disregarded in the analysis. Numerical stiffness analysis and the optimization of existing structures can be performed under various and complex loading conditions. The results obtained through the direct stiffness method affirm its suitability for analyzing structural behaviour in the early design phase (Hajdarević and Busuladžić, 2014).

2. METHODOLOGY OF WORK

The fundamental starting point in the application of the finite element method of furniture within its normal functional use and expected unusual use was the standard for testing furniture. These standards vary depending on the product being tested. For the purposes of applying the finite element method in furniture testing, in this paper, an example of a chair with a metal frame is used. According to the requirements, the chair is subject to testing according to the standard HRN EN 1728 (2012). Within the standard, mechanical requirements are specified that the chair must meet in terms of external forces and deformability. In practice, this standard entails various mechanical tests conducted in a laboratory setting. However, this study primarily focuses on the static testing of the seat and backrest.

2.1. Creation of a three-dimensional virtual chair model

To create a curved base, a 2D sketch is used in the Inventor Professional software. The basis for creating a three-dimensional body consists of a two-dimensional sketch on which various geometric shapes are operated to create a three-dimensional body (Prekrat and Čavlović, 2022). The base is drawn using the "line" command, dimensions are determined, and symmetry is achieved. The edges of the chair are rounded, and then the process transitions to 3D modeling and setting the path for forming the chair. On an additional work plane, the pipe's diameter and wall thickness are defined. By using the "sweep" command, a section, plane, and path for the section's movement are selected. Finally, the other half of the base is created using the central plane and the "mirror" command.

To create the seat, a 2D sketch is used in the XZ plane. In this sketch, the geometry of the seat surface is formed, including dimensions and curved seat angles. Subsequently, the process transitions to 3D modeling to define the thickness of the seat using the "extrude" command. Furthermore, markings are added to the one of the surfaces for future drilling of holes through which rivets will be fastened. Hole drilling specifications, including direction, diameter, and depth, are configured using the "hole" command.

2.2. Setting the conditions for the test simulation

In this phase of testing, the standard entails subjecting the chair to a force of F_1 = 1300 N on the seat area and a force of F_2 = 450 N acting on the backrest *(Figure 1*) according to standard HRN EN 1728 (2012).

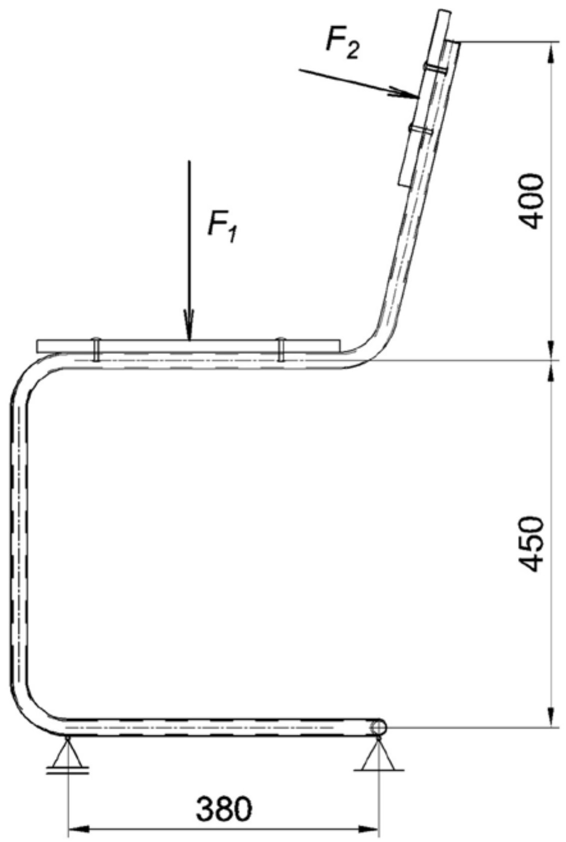

Figure 1. A sample figure

Using Autodesk's CAD program Inventor Professional 2023, which enables 2D or 3D sketching and 3D modeling, along with its addition Inventor Nastran, the finite element method was implemented through the so-called "FEM analytic" option. This option provides the possibility of performing simulation testing directly on the virtual model.

2.3. Material selection and structural sizing

In this study, a chair with a metal frame was selected, which incorporates variable factors related to material selection and dimensional characteristics. Through testing, various types of steel *(Table 1)* and different diameters of chair frame tubing were considered. This simulates real-world scenarios for the selection of materials and construction parameters in relation to mechanical requirements. Within this study, it provides assistance in determining the product's compliance with the established standards. For the seat and backrest, an oak *(Quercus alba L.)* veneered panel has been selected.

Table 1. Metal specification

	Stainless steel	Stainless Steel, 440C	Stainless steel, Austenitic	Steel	Steel, High Strength, Low Alloy	Titanium
Young's modulus (GPa)	192.98	206.70	190.30	210.01	200.02	102.80
Poisson's ration	0.30	0.27	0.30	0.30	0.29	0.36
Shear modulus (GPa)	85.98	83.91	85.98	110.32	128.73	44.00
Density (kg/m^3)	7999.49	7750.37	7999.49	7861.09	7861.09	4511.82
Yield Strength (MPa)	250.00	688.99	228.01	206.98	275.79	275.58
Tensile Strength (MPa)	540.00	861.16	540.0	345.01	448.02	344.53

In addition to the use of various types of metals, the research also varied the diameters of the pipes from which the frame of the chair was made. The range includes diameters of 20 mm, 25 mm, 30 mm and 35 mm, all with a constant wall thickness of 2 mm. This makes it possible to observe the variation in stress and strain related to the choice of material and the size of the chair frame.

3. RESULTS

Considering all the mentioned values, material proportions, and structural dimensions that have been input into the FEM analysis process, in relation to the regulatory framework stated previously, we obtain the following results *(Table 2; Figure 2)*.

Table 2. The relationship between metal selection, diameter and deformation

(mm)	*20*	25	30	35
Stainless steel	112.221	58.2078	35.4878	24.0729
Stainless Steel, 440C	104.906	54.3936	33.2215	22.5891
Stainless steel, Austenitic	113.75	58.989	35.9786	24.3976
Steel	81.8261	53.4698	42.8733	22.1155
Steel, High Strength, Low Alloy	84.2028	56.1946	44.6506	23.2725
Titanium	209.961	108.434	58.0278	44.6659

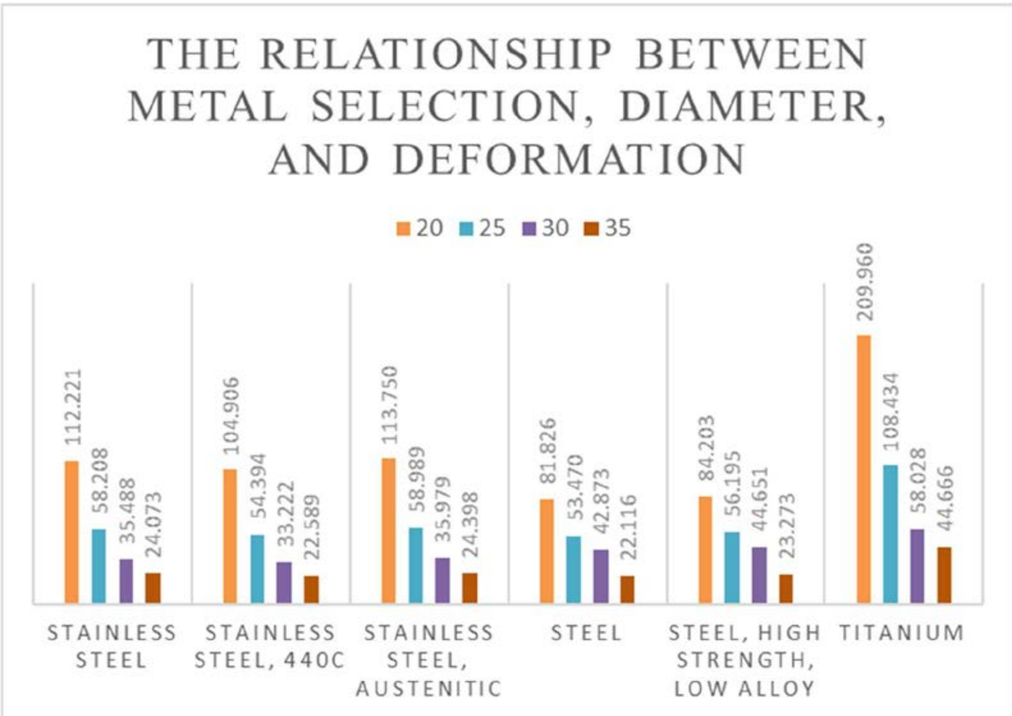

Figure 2. The relationship between metal selection, diameter and deformation.

Using the finite element method within the mentioned software system, it is also possible to accurately predict the weight of the chair, as well as its center of gravity in relation to the geometric center. This directly affects stability and allows the prediction of numerous other characteristics that influence the production process, transportation, or the functionality itself.

The center of gravity of the chair in relation to the geometric center is x = 0 mm, y = 71.0883 mm, and z = -43.8338 mm, and it is not dependent on the testing variables.

Based on the obtained parameters of the model and testing standards, it is necessary to determine the range within which the deformation of the backrest in relation to the seat can occur without the chair tipping backward. To obtain the desired range, the values specified in the standard were used, specifically the part dealing with tipping risk assessment. Although this goes beyond the domain of static testing of the seat and backrest, these parameters are undoubtedly interconnected. The stresses that will be generated and result in deformation are a matter of material selection, while this topic is more related to the functionality and stability of the chair. The applied force, regardless of the type of chair, in this section of the standard, is 600 N acting on the seat. The force on the backrest is calculated based on the input parameters of the model.

If the chair is lower than 720 mm, it is subjected to a force according to the formula:

$F_1 = 0{,}2857 \times (100 - H)$
F_1 – force acting on the backrest of the chair (N)
H – height of the chair expressed (mm)

For the load on the backrest, the obtained value is $F_1 = 99.995$ N. By including these forces in the model and starting the FEM system, the deformable behaviour of the chair under these loads is obtained. When the angle between the seat and the backrest is at its maximum, the center of gravity of the load could not be positioned behind the tipping point of the chair, which is the point at which the rear leg makes contact with the floor. The position of the center of gravity of the load can be determined using a graphical method (Langová *et al*. 2019).

After that, the deflection angle that the backrest has made in relation to the seat in its original form is measured. The angle between the seat and the backrest was initially 103° in the model, and after the force was applied, it deforms to 111°, which is a difference of 8°. Through subsequent calculations and a graphical model, it can be concluded that the length that closes the 8° angle is approximately 50 mm (*Figure 3).* Although the obtained deformation in the direction of the force on the backrest is significantly larger, to ensure the stability and safety of the product, it is necessary to perform such a calculation of the limit angle, and subsequently, the limit deformation, from which the condition is derived:

$u_d \leq 50 \text{ mm} = u_{max}$
u_d – allowable deformation

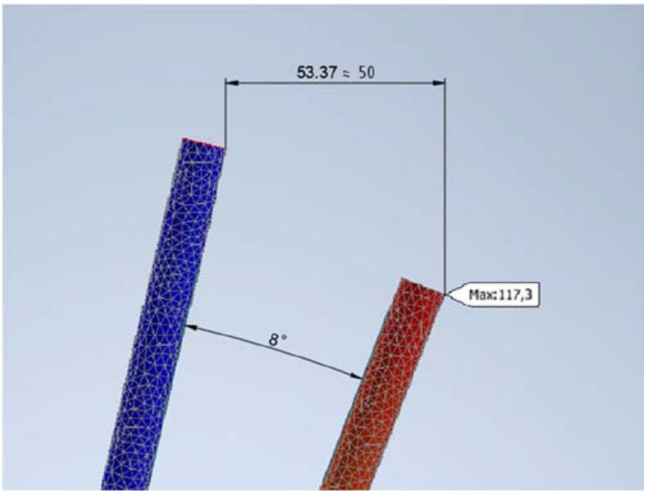

Figure 3. Defining maximum deflection.

With the application of the obtained deformation parameters as the maximum permissible deformation to the deformation parameters obtained with regard to the material and dimensions tested by FEM, all values below the "50" line meet the necessary standards in terms of defining dimensions and selecting materials (*Figure 4*).

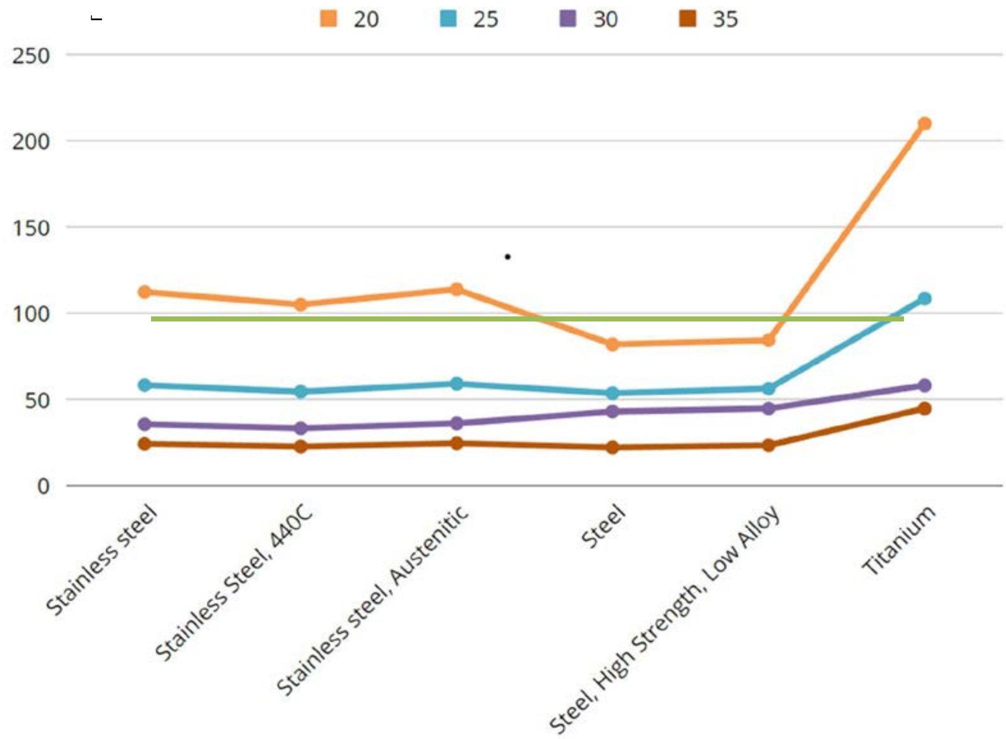

Figure 4. Review of the structure concerning the maximum allowable deformation (mm).

This research is grounded in normative requirements, and from it, we have derived data that are reliable and demonstrate that deformations within allowable limits were achieved with diameters of 30 mm and 35 mm, except for titanium. Titanium displayed suboptimal performance under this type of loading concerning dimensional constraints and met the required parameters only at a 35 mm diameter. It's worth noting that dimensional parameters can still be further adjusted to achieve the desired appearance. The testing employed a constant wall thickness of 2 mm.

4. CONCLUSIONS

Load simulation performed on a virtual three-dimensional model using the Nastran program within Inventor can be a useful tool in deciding on dimensioning and material selection in furniture design.

In addition to essential mechanical properties, other useful parameters such as mass and center of gravity were obtained. These parameters can be further utilized for early error prediction in construction and design.

The use of simulations in the early design phase reduces the possibility of large errors, and the optimal selection of materials reduces the costs of further production.

Well-trained engineers speed up the production process with the approach of performing simulations in the early design phase. With this procedure, it is possible to carry out rationalization that can improve the company's profit.

It is essential to emphasize that, at present, FEM cannot serve as a substitute for practical laboratory furniture testing. FEM is currently employed solely as a tool to facilitate positive outcomes in real-world testing, application, and the early identification of errors.

This approach to engineering design is especially applicable for newly designed products that incorporate new materials. A prerequisite is knowledge of three-dimensional modeling and good setting of conditions in simulations.

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Design-Built Projects from Wood as Training Tool for Obtaining Complex Skills

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ABSTRACT

The paper deals with the potential of using wood and other local natural materials for architecture, design and engineering education. Wood plays important role in gaining and improving artistic and technical skills by "thinking in material" with environmental, social, participatory and collaborative added value. Paper explores a potential of prefabrication and craftsmanship approach by designing and manufacturing in wood as well, whereas the importance of both is simultaneously rising in contemporary design education. This philosophy is presented on both small scale and large-scale design-build projects – case studies of workshops at the Faculty of Architecture and design, STU in Bratislava, Slovakia, both in cooperation with Bergen School of Architecture, Norway, such as DUNA bird watching or Community kitchen in facility for refugees in Gabčíkovo. There were used wood and wood-based materials in the design and prefabrication and building process on site, to prove the potential of the material, with interdisciplinary methodology, including incorporating of environmental and social context as a tool for obtaining complex skills useful for future praxis.

Key words: architecture, design, skills, social context, training, wood

1. INTRODUCTION

Importance of hands- on methodology is known in many education systhems like Waldorf, Montessori, Dalton or US based Brightworks school, based on project-based learning for school children. It continues on art and technical high schools where working in school workshops is part of curricula. And how about design and architecture education? Own workshops facilities and the opportunity of hands-on modelling and prototyping 1:1 is a must to have in high quality schools.

Importance of hands-on projects were demonstrated on hundreds of good example practice projects from this field. According to Bleibleh *et al.*, (2023) the implications of hands-on introductory courses in architectural engineering (AE) discipline influence students' comprehension of the interdisciplinary nature of the field and help them build basic needed skills and formal visual principles with an emphasis on developing creativity and effective communication.

For architects and designers, it is important to be able to handle tools for processing and forming any kind of material. This means understanding the process with the whole body and thus deeply experiencing a material, a form and a relation to situation and context.

2. WOOD AS TRAINING AND INSPIRATIONAL MATERIAL

Wood has still irreplaceable role by creating sustainable housing and living indoor environment supporting wellbeing. 41 % of Slovakia is covered by forests - mostly spruce and beech. Wood structures and products are part of traditional material culture, but after the second world war wood was massively replaced by other building materials - mostly ceramics, including concrete, and as a material for new structures. After the revolution in the 1990-ties when the building industry has massively transformed and expanded, wood structures experienced a renaissance and found some support from industry and final users. Nonetheless in comparison to Austria, Germany or Scandinavia there is still a gap in architecture education and "the wood agenda" in architecture schools needs improvement. Most of the teaching and learning to design and build with wood is happening in the form of occasional workshops, and a systematic wood structure curriculum is still in development at architecture schools in Slovakia. Despite a progress in the wood engineering and structure, there is still space for experimenting with shapes and constructions. To do so, it has to be managed with knowledge and respect.

Handling, managing and mastering simple and sophisticated woodworking tools brings self-confidence and satisfaction on personal and professional levels that can then be used for designing many other materials.

From the early designing phase up to manufacturing, wood offers a lot of possibilities as training materials for students, but also has a strong position as a "do it yourself phenomena".

Trust in an object is a key issue for creating some relation to it, both in the momentary situation as well as in a long-time interaction. Material consciousness through spatial design and especially product design is extremely important if timeless and body-conscious design is to occur. The key issue is the way the designer has worked with a material, if he/she have shown respect to it and "lead a discussion" with its. Looking at an object where the material was "forced" – shaped into some unnatural form through technological violence also makes our nervous system "suffer". This can be demonstrated by the example of solid wood. While working manually with tools and the material, students better understand how to shape it, mould it, to initiate a dialogue with the material and to together come to a better solution – for both the designer and the material. This skill, the ability to form a material with respect and empathy and to have a creative dialogue, can be cultivated with hands-on projects where students can test ideas and get direct feedback from their designs.

3. HANDS-ON WOOD WORKING WORKSHOPS AND ASIGNEMENTS

Hand on projects including complex research, design and prototyping process are important part of curricula of courses at Faculty of Design and Architecture, STU in Bratislava, whereas usually they are connected to some research-development project.

These principles are demonstrated on case studies: Small Smart Wooden, Wood-wool, Wood as a material for all senses, DUNA bird watching and EMIA, which have been done in recent years, but also in workshops and other forms of lifelong learning platforms managed for the general and expert public by the author.

3.1. 912-**Small scale hands-on projects**

The establishment providing the service of a faculty wood working workshop in the FA STUBA basement was one of the goals of the project Interaction of Man and Wood. Workshop facilities and equipment are used to develop experimental products made from wood within the research and teaching process. Since 2014 the first research concepts and prototypes have been developed and students also have the opportunity to prototype their own designs. Through the hands-on approach, they gained respect for wood and craftsmanship and gained new creative and technical skills. Wood in particular is a material that one needs to become familiar with and to be experienced with one's "own hands" for the design of original and valuable products.

3.1.1. Small smart wooden

A series of small wooden products SMALL SMART WOODEN was restored since 2011 and then continued in 2014 and 2015. In 2016 the subject was enriched by including new material and, under the name WOOD-WOOL and in cooperation with the Dekoma company a number of innovative products combining wood and wool were created. At the same time was created the collection "A Second Life for Oak", in cooperation with the Javorina company, where design students from the newly established course "Application of wood in design", designed and prototyped gifts made of waste oak wood. In the 2016/2017 school year the topic was specified as "Wooden elements furniture for all the senses." These programs are attended by students of architecture and design in the form of workshops and training courses within the subject Furnishing of Interior and Furniture Design, assisted by professional woodworkers. The presence of professionals – experts – was of course very helpful for the students. This resulted in a number of exciting and innovative products made of solid wood which were exhibited at furniture fairs and other professional events (*Figure 1*).

Figure 1. Small smart wooden – WOOD WOOL project, working in faculty workshop and one of the products: Side table for fairy-tales teller- author: Dominika Podolska and Pouf from Katarína Kováčová; Exhibion of students works in 2015 at the furniture fair in Nitra.

The hands-on and complex interdisciplinary approach is present also in our design studio project assignment, whereas between years 2018-2021 there was topic of regional identity implanted in contemporary product and spatial design, where students participated in field research, including wood working hand-on events. In 2022 there was a cooperation with furniture company Drevona within the project DESIRE, where students have designed and prototyped age friendly furniture from laminated particle board.

3.1.2. Restoring the vintage products

Wood has a great potential for redesigning and upcycling, especially. There is a strong interest from the general public in gaining skills for restoring and redesigning old furniture and other interior elements. With wood, repairing and refurbishments are easily manageable. The need is connected not only with arising environmental awareness, but also with a strong need to work manually, by getting direct feedback as a compensation for everyday intangible and abstract working styles – mostly in administration. This is visible in the contemporary nostalgia mirrored in vintage styles in fashion and interior design. We have reflected this potential by organising workshop for the general public on the topic of furniture restoration in Ekocentrum Hruby Šur in March 2017 (*Figure 2*).

Figure 2. Workshop for broad public on topic of redesign and restoration of old furniture, Ekocentrum in Hrubý Šúr

3.2. Big scale hands-on projects

One important aim of the Interaction of Man and Wood project was to become familiar with and bring closer the environmental and humanisation potential of wood in field of interiors, furniture design and civil engineering. Traditional and modern timber engineering, building with wood and traditional carpentry skills, are not as yet included in the standard curricula of architecture education at FA STU, and therefore, it was necessary to make at least occasional workshops for creating experimental small wooden architecture and other wood objects.

3.2.1. DUNA bird watching

In cooperation with a joint project Experimental Wooden Climatic Chamber (EWCC) of the Faculty of Architecture and Norwegian Bergen School of Architecture, with co-funding from EEA Grants and the state budget of the Slovak Republics from the EEA Scholarship Program Slovakia, there the bird watching platform DUNA was built at the Hrušovska reservoir on the Danube River near Kalinkovo, 18 km from Bratislava. During the four workshops and several voluntary working meetings, an experimental microstructure for nature watching and simple recreation was built. This microarchitecture was built by combining modern prefabrication using CNC technology and traditional carpentry, allowing architecture and design students, teachers and volunteers to gain complex skills. The project had educational, research, environmental and social dimensions. Thanks to this project a toolkit "Teaching tool for architects and designers for working with CNC-machines / NESTING in service of architects" was created for working with CNC -techniques for architects and designers, and it is available for the general public. The result is that, in the proximity of Bratislava, there was built a new place to visit and to have a break while cycling or walking along Danube – a new point of interest (Figure 3). It is a place for the wide general public for the promotion of wooden structures and for observing the beauties of nature. It also has the potential to serve as an outdoor testing laboratory for exploring the socio- cultural interaction of man-wood and nature, as well as the behaviour of wood in a demanding outdoor environment.

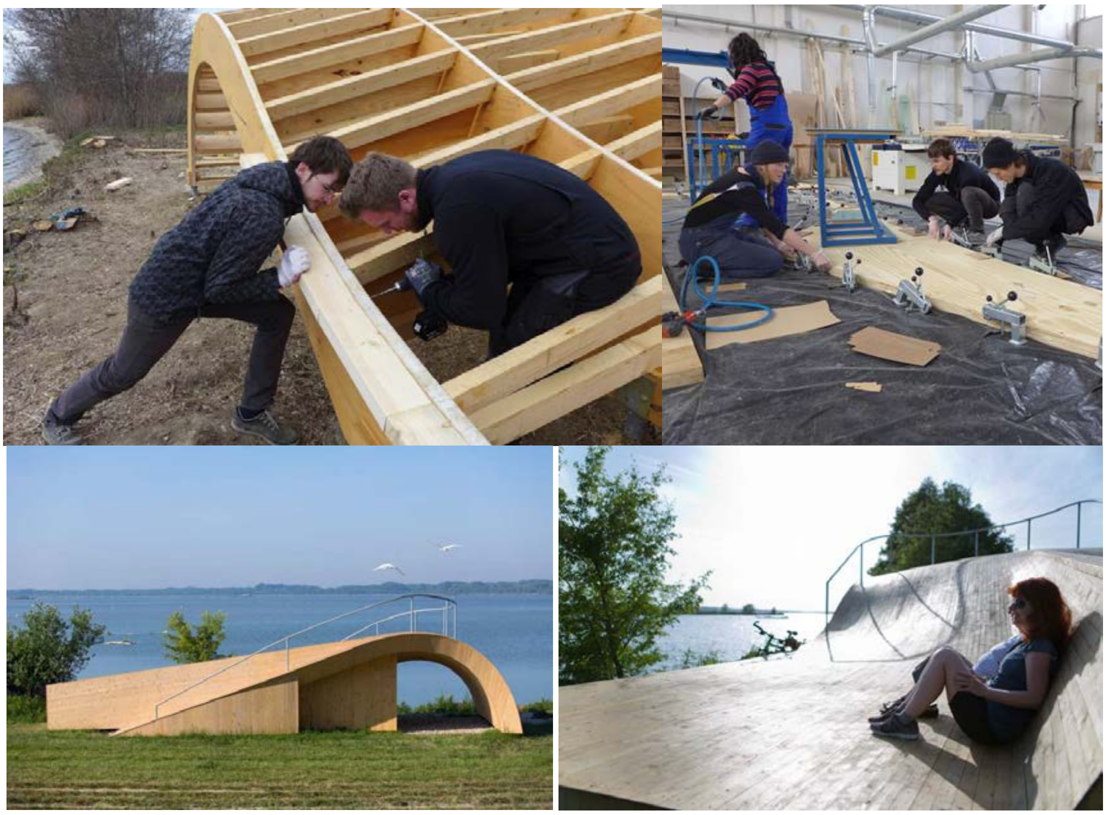

Figure 3. DUNA bird watching combines indoor and outdoor space is result of student´s workshops.

For architects and designers, it is important to be able to handle tools for processing and forming any kind of material. This involves understanding the process with the whole body and thus deeply experiencing the material, its form and its relation to the terrain. That´s why it should be a must to have workshop premises in every design and architecture school. In BAS students get training in working with all kinds of tools, including big stationary machines right from the first year of the study and they have full access to the workshop premises up to late at night. This relates with a high level of trust and leaving a lot of responsibility to them. It is also possible thanks to the small numbers of students in the school. In FA STU in Bratislava the functional woodworking workshop was only established in 2014 and is equipped for building and constructing products from wood and other materials by basic hand and electric table tools, plus some older stationary machines which were repaired and put into operation. From EWCC project funding some tools useful for building on sites not equipped with electricity were added. To have a "tools and machine park" on hand is a basic condition for hands-on or design & build projects at any kind of design and architecture school.

3.2.2. EMIA - Community kitchen in refugee's facility in Gabčikovo

Activity Workhop 1:1 was a part of project Empathy in Art, financed from Norwegian grants. Initial goal was creating an object focused on homelessness. An intensive seminar aimed at promoting empathy for disadvantaged groups and overcoming existing physical and mental barriers between them and society. After beginning of war in Ukraine, we have deciced to orient this activity toards topic of refugees. The inicial task was to involve also representatives of these disadvantaged groups, thus enabling direct contact and enriching students with real experience of working with them and for them…After designing workshop in June 2022 and first contact with refugees, management of facility and NGOs active there, there was less capacity to involve local stakeholders into the designing and building phase. The chosen structure was prepared into construction phase planned for next month in extremely short time.

Figure 4. Working on community kitchen in facility for refugees in Gabčíkovo, foto: author.

The main goal of this structure was to design and build a small wooden pavilion that can focus on the social and cultural act of cooking and eating together. This helps to establish practice that can anchor the refugees to a new place, and eventually build a neighbourhood and to offer spatial gestures that support the family activities and nurtures the local community. Since stays at temporary reception centres tend to be more long term than planned for, it is important to help aid a sense of normality and facilitate for traditions and social gatherings to find place also within the refugees/reception centres. The building is open and inviting towards the entrance to the dormitory and at the same time offers a screen from the parking lot and thus increases the feeling of security inside for the users. The pavilion building placed near the main entrance to the main accommodation building, provides cooking area and bid universal table, with benches that offer public space. Centre of the pavilion is a bread/pizza heated by wood logs.

Designing phase was done during 5-days pre-workshop and preparation works before the start of the prototyping part. Core of the structure was built during the two-week workshop in July 2022 by students and teachers from both schools: Faculty of architecture and design STU in Bratislava, Slovakia and Bergen school of architecture /BAS, Norway; financed by EEA grants project EMIA- Empathy in art. The room structure is made of spruce cut wood, joints were processed by CNC milling machines, covered by metal sheets roof. Wall panels and furnishings are made of spruce wood as well, cut and mounted directly at the site.

Figure 4a. Final appearance of the Community kitchen, photo: N. Knap.

4. RESULTS AND LEARNED KNOWLEDGE AND GAINED SKILLS

During small scale and big scale projects students have gained wide range of knowledge and skills.

According to the teaching and learning method R.A.U (in Slov. riadené aktívne učenie, in Eng. managed active learning) we learn from: 10 % of what we have heard,15 % of what we have seen 20 % of what we have seen and heard, 40 % of what have discussed, 80 % of what we have directly experienced and done and 90 % of what we have taught others (Berová, Z., Bero, P. (2016). The observers on the site also had the opportunity to learn, but more so the active participants who took part in the discussions by brainstorming and bodystorming - by solving every detail that was not planned and solved in the designing phase. But the most important thing was that the students had to teach and train each other. First, they had to find out the most appropriate way to do something and then they had to share this knowledge with the others. This kind of sharing - teaching and learning happened through the whole building process - contributed to the gaining of complex skills.

What we have learned from this project:

- to trust self and fellows, be able to improvise and to find at any time appropriate solutions for each detail on site
- cultural difference is a challenge… all together the Norwegian students spent one month in Slovakia (in DUNA project) during all the workshops within DUNA project and 2 weeks within the EMIA project and they had to embrace Central-east European post-communist culture and to improve their cross-cultural understanding skills; the same for the Slovak students - encountering the Scandinavian way of thinking, of doing, and of taking responsibility. In addition to all the other duties they have in their diploma year, it was not so easy.

- there are many ways to build with wood…during the building process, the students moved in the range between modern wood engineering and artistic craftsmanship, and it gave them a lot of valuable experience, knowledge and skills.
- losing fear of machinery while maintaining respect and creating safe space
- everything takes at least double the time that was planned thus good time management is crucial
- all the projects had also social and environmental context that have broaden students' knowledge and competences.

Acknowledgements: *We wish to thank to EEA grants, project EMIA Empathy in Art; Erasmus+ project 2020-1-SK01-KA202-078245 "DESIRE – DESIgn for all methods to cREate age-friendly housing", supported by the European Commission, APVV 16-0567 Identity SK- common platform of design, architecture and social sciences and APVV-0594-12 Interaction of man and wood.*

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A study on the Environmental Assessment of 3D Printing with Wood-PLA Composites

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ABSTRACT

In recent years, additive manufacturing (AM) has become an integral process in various industries, necessitating an assessment of its impact on the environment. Sustainability in the industry is an ongoing concern, with an expanding focus on increasing production efficiency and minimizing environmental impact. The objective of this study was to comprehensively evaluate different materials and manufacturing methods to produce a chair connector that joins four oak legs to a seat component. A cradle-to-grave life cycle assessment (LCA) was conducted comparing a conventional metal connector with a 3D-printed alternative made of PLA-wood material, following the standard ISO 14044:2006. At LCA, environmental impacts were quantified in 18 categories to determine the feasibility of 3D-printed PLA-wood connectors as a sustainable solution from both a manufacturing and material perspective. The results show the environmental advantage of 3D-printed alternative over conventional metal as renewable materials are considered. However, with biodegradable materials such as wood composites, there are obstacles related to complex handling during processing that affect the stability, fragility, and behaviour of the polymers throughout the manufacturing process.

Key words: 3D printing, carbon footprint, environmental impact, life cycle assessment, wood-PLA composite

1. INTRODUCTION

Sustainable development aims to reduce the environmental impact of production, which can be achieved through AM. 3D printing is associated with potentially strong stimuli for sustainable development, as it is seen as a cost-effective way to reduce manufacturing effort in low-volume, high-value production chains, such as aerospace, automotive and medical component manufacturing. This reduces energy consumption, resource requirements and associated CO_2 emissions throughout the product lifecycle, leading to changes in labor structures and a shift towards more digitized and localized supply chains (Gebler *et al.*, 2014).

Consumers, industry, and governments are increasingly demanding products made from renewable and sustainable resources that are biodegradable, non-petroleum based, carbon neutral, and pose low risks to the environment, human health, and safety (Gardner and Wang, 2019). Direct industrial CO_2 emissions, including process emissions, decreased by 0.6% in 2018 to 8.5 $GtCO_2$ (24 % of global emissions), in line with the trend of relatively flat emissions in recent years. The modest decline occurred mainly in non-energy-intensive industries. To be in line with the Sustainable Development Scenario (SDS), industrial emissions need to decrease by 1.2 % per year to 7.4 $GtCO_2$ by 2030, despite the expected growth in industrial production (IEA - International Energy Agency, 2023). This should be the driving force for the increased use of wood and its components in 3D printing, as it has a positive impact on the environment. Numerous perspective research articles on the use of wood in additive manufacturing AM have already been published and are presented in (Krapež Tomec and Kariž, 2022). In this context, it is also worth promoting life cycle assessment analysis (LCA), a quantitative assessment of the environmental impacts that occur during the life cycle of the product. To improve disposal alternatives and minimize environmental impacts, it is important to study impacts related to emissions and energy consumption, land use, and genotoxicity of residues (Souza *et al.*, 2013). By choosing the right design (less material used, less transport mass, less waste, better efficiency), the right materials (suitable mechanical properties, origin of the material, etc.), and the production technology (time, energy consumption), the environmental impact of the product can be significantly influenced at the design stage.

The industrial sector was directly responsible for emitting 9.0 Gt CO_2 in 2022, equivalent to a quarter of the CO_2 emissions from the global energy system. Annual emissions declined slightly in both 2020 and 2022, but not enough to be consistent with the Net Zero Emissions by 2050 (NZE) scenario, in which industrial emissions decline to about 7 Gt CO_2 by 2030 (IEA - International Energy Agency, 2023). Modest improvements have already been made in energy efficiency and the use of renewable energy, and some positive steps have been taken in the areas of international cooperation and innovation. However, progress is occurring far too slowly. Greater material and energy efficiency, faster adoption of low-carbon fuels, and more rapid development and deployment of near-zero emissions production processes–including carbon capture, utilisation, and storage and hydrogen – are needed if meaningful progress toward the NZE scenario milestones is to be made by 2030 (IEA - International Energy Agency, 2023).

Sustainability of AM processes has become a driving force as environmental concerns increase in manufacturing. This has increased the importance of understanding and characterizing AM processes (Mani *et al.*, 2014). The advanced AM technology used in the manufacture of furniture helps designers to develop new concepts for product design, without restrictions on shape, number of joints, colour or size.

This case study presents a comparative sequence LCA of a part produced by two different manufacturing processes - conventional manufacturing (using milling, drilling, welding) and 3D printing process (FDM – Fused Deposition Manufacturing). FDM technology is the most commonly used 3D printing method due to its simple operating logic and affordability. A particular part – a chair connector - made of metal is analysed from cradle to gate. The site LCA is analysed to provide a framework for selecting the most appropriate manufacturing process in terms of environmental impact.

The environmental impact of each product was quantified for 18 categories. The goal of the LCA was to determine if the use of 3D printed PLA wood products can be a sustainable alternative to a conventional connector from a manufacturing and material perspective.

2. MATERIALS AND METHODS

A connector of a modern household chair was selected for a case study (*Figure 1*). The chair consists of the following components:

- the seat shell and the backrest are made of a plastic composite material and constitute the seat part of the chair. The seat part, which contains four upholstery nuts, is attached to the metal joint with four M6x14 screws.
- another part of the chair set is a metal connector, which is used to attach four oak legs and the seat part. The four oak legs are screwed to the metal connector with eight M6x45 screws and nuts.

The materials used in this case study are a metal-based original, an alternative 3D-printed part made of a wood-PLA filament.

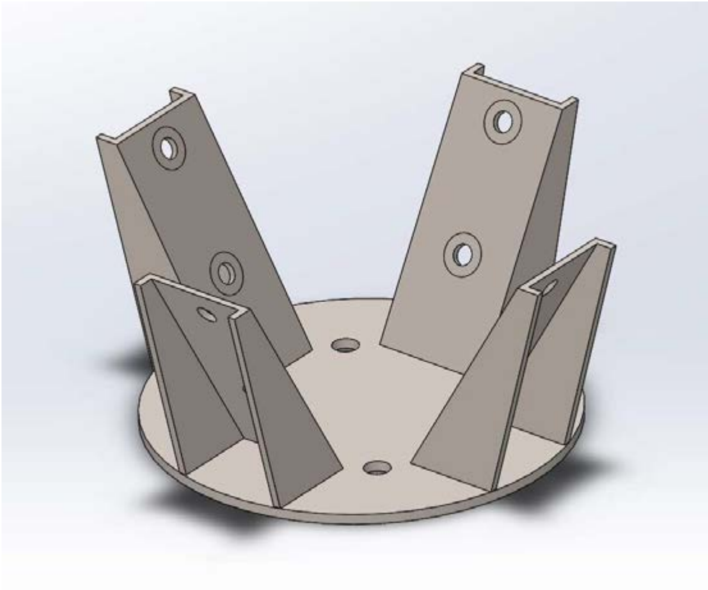

Figure 1. 3D model of connector (SolidWorks)

2.1. 3D printing of wood-PLA connector

Digital model of the 3D part was modelled in SolidWorks software (SolidWorks Corp., Waltham, MA, USA) and exported to STL format. The STL model was sliced and prepared for 3D printing in Z-Suite software (Zorttrax, Olsztyn, Poland).

Wood-PLA filament (with up to 40 % wood flour content according to the technical data), commercially available from Plastika Trcek d.o.o. (Ljubljana, Slovenia), was used. The diameter of the filament was 1.75 mm, the diameter of the printing nozzle was 0.6 mm, the layer thickness was set to 0.4 mm and the infill to 40 %.

2.2. LCA methodology

The study applied the LCA methodology, based on the ISO 14044:2006 standard and comprising four main steps, to quantify the difference in environmental impact between a conventional metal connector and a 3D-printed alternative. A "cradle-to-gate" assessment using SimaPro 9.0 software developed by PRé Sustainability, Amersfoort, 2019. In addition, all stages to the end of life were also considered, based on data from scientific publications. 3D printing is not supported by SimaPro, as it was not yet included in the library at the time of this study. The geography for the manufacturing and distribution phases was set in Slovenia for the 2021 time horizon.

For consistency, it was assumed that the input mass of both versions of the chair connector is 1 kg of raw material.

The classification and characterization process was carried out according to the standard ISO 14040:2006s. For impact assessment, ReCiPe 2016 Midpoint (Hierachist) was applied to calculate environmental impacts and 18 impact categories were included in the LCA. Midpoint characterization factors are calculated based on a consistent environmental cause-and-effect chain, with the exception of land use and resources. The regional scope is Europe; for climate change, ozone depletion, and resources, it is global. Its temporal validity is the present.

3. RESULTS AND DISCUSSION

Sustainability in industry is an ongoing priority, with increasing emphasis on improving production efficiency and harmony with the environment. Sustainable development aims to reduce the environmental impact of production, which can be achieved through AM.

The focus of this case study is to evaluate various materials and manufacturing methods used in the production of a chair connector that joins four oak legs and the seat component.

In Characterization, all results are plotted on a percentage scale.

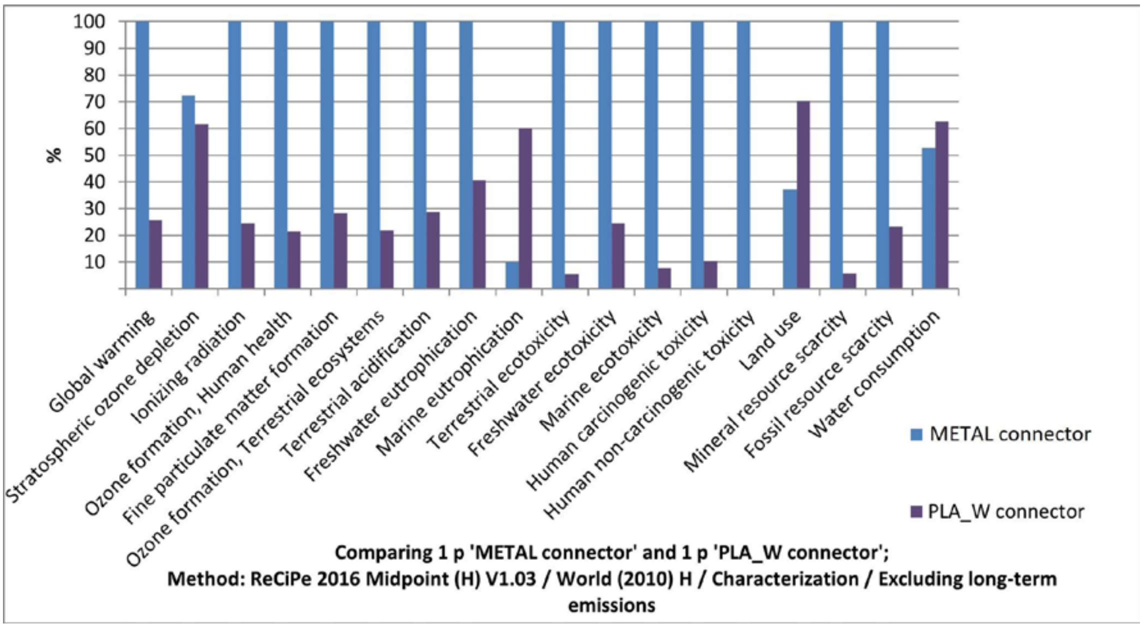

Figure 2. Impact assessment of two versions of chair connectors using ReCiPe 2016 Midpoint (H) method with characterization of results and excluded long-term emissions.

The carbon footprint is the sum of greenhouse gas emissions caused directly or indirectly by an organization, product, service, or other activity that causes or contributes to greenhouse gas emissions over a period of time. It is defined in units of CO_2 equivalents (CO_2e) (Le Treut *et al.*, 2007). Impacts are calculated per unit of CO_2e of the six major greenhouse gasses (GHGs). The average of all these gasses causing global warming is known as Global Warming Potential (GWP) and is usually given in the time frame of 100 years.

The 3D-printed alternative from wood-PLA filament showed 73 % lower GWP than the conventional metal part. However, the results of the cradle-to-gate life cycle assessments suggest that the 3D-printed PLA alternative may cause greater environmental impacts than the conventional products in some impact categories – Stratospheric ozone depletion, Marine eutrophication, Land use and Water consumption. However, there is always the option to recycle 3D-printed materials into usable filament that can produce parts with properties comparable to those made with virgin filament. This has the potential to save significant amounts of raw materials, reduce costs, save energy, and decrease CO_2 emissions in the production of 3D-printed components (Anderson, 2017).

The results show that a metal part produced by conventional subtractive processes (milling, drilling, welding, etc.) has a higher environmental impact than the 3D-printed alternative made from renewable materials. Nevertheless, the steel industry is responsible for around 2.8 gigatons of CO_2 emissions per year, which corresponds to 10 % of the total emissions of the energy system (IEA - International Energy Agency, 2023).

To sum up, in the context of LCA, 3D-printed wood-PLA alternative would therefore be much more environmentally friendly compared to conventional products, although the environmental benefits might be insignificant from the manufacturer's point of view.

These observations are due to the fact that 3D printing uses much smaller amount of material because it is additive manufacturing - in other words, it creates less waste during manufacturing, it is possible to optimise geometries and create lightweight components that reduce material consumption during manufacturing and energy consumption during use, it reduces transportation in the supply chain, and an inventory waste due to the ability to manufacture replacement parts as needed. However, the wood-PLA material has lower strength than metal. The adapted geometry that can withstand the external loads of the connector must be taken into account, and with it the higher material consumption. Nevertheless, the supply chain, feedstock and production protocols remain the same, so all in all the results with a more solid 3D-printed connector are similar to those presented in this study.

In addition, it has been shown that the material used can strongly influence the environmental footprint in other impact categories, leading to important trade-offs. Challenges in AM with biodegradable materials, such as wood composites, include processing issues during extrusion and part fabrication, particularly with respect to dimensional stability of parts and brittleness of the material depending on the degree of stress on the wood components, as well as effects on the crystallisation behaviour of the polymer during processing (Gardner and Wang, 2019). In some instances, 3D-printed parts can exhibit mechanical and physical properties that are similar to traditional wood composites like particleboard, fiberboard, and wood-thermoplastic composites. By effectively integrating wood fibers, nanocellulose, and utilizing continuous fiber printing techniques, it's possible to further enhance these properties.

Nevertheless, 3D printing technology has the potential to fill the gaps created by the limitations of traditional subtractive manufacturing technologies. It offers a number of advantages, including improved surface quality, shorter production time, and reduced tool wear. Its potential is even more significant when biobased and biodegradable materials are used, making the process more efficient and environmentally friendly.

***Acknowledgements**: The authors acknowledge the support of the Slovenian Research Agency within the framework of research program No. P4-0015 "Wood and lignocellulosic composites".*

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Determination of Thermal Insulation properities of the Developed Material based on Foamed Wood

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ABSTRACT

This work deals with the determination of the thermal insulation properties of the developed insulation material, based on a foamed wood mixture. As part of the effort to develop environmentally friendly material, the main raw material is wood fibers from wood waste, which is generated in the wood processing industry. The main goal of this work is to determine the coefficient of thermal conductivity λ, the coefficient of thermal resistance and the coefficient of heat transfer U of this developed material. The results are graphically processed. The results are compared with selected commercially produced thermal insulation materials.

Key words: Agglomerated material, Foamed wood, Thermal insulation, Wood-based insulation, Wooden waste

1. INTRODUCTION

Globally, the acceleration of climate change due to carbon dioxide emissions is beginning to have a direct impact on people's lives. Construction sector generates almost 40 % of the global annual volume of carbon dioxide emissions (Sovacool *et al*., 2021). As a result, the global reduction of carbon dioxide emissions and the reform of the construction sector are essential. There are many significant trends in sustainable architecture that help reduce the carbon footprint caused by the construction sector (Ali *et al*., 2020). One of the key aspects of these challenges is the issue of building materials, especially thermal insulation (Yildiz *et al*., 2021).

Thermal insulation plays a key role in thermal protection of buildings. Properly insulated buildings can significantly reduce the amount of energy needed for heating and cooling, thereby reducing greenhouse gas emissions (Almusaed *et al*., 2023). Traditional insulation materials, although effective, often require high energy and water consumption and are difficult to recycle (Scrucca and Palladino, 2023).

However, despite the many advantages of natural-based insulation materials, we still face many challenges, including technological limitations, lack of standards and regulations, and insufficient awareness of the possibilities of these materials by consumers and construction professionals. Therefore, it is important to continue research and development of these materials and work to overcome these obstacles (Hellová *et al*., 2020).

The transition to natural insulation is not only a question of sustainability, but also a question of the future in environmental protection (Ulutaş *et al*., 2023). This is the step we must take if we want to achieve goals such as changing the negative impact on the climate and sustainable development (Pescari *et al*., 2022).

Foamed wood presents a host of advantages that make it an innovative and environmentally friendly material. Its lightweight nature, resulting from the incorporation of air into its structure during the foaming process, grants it exceptional insulating properties (Fendt *et al*., 2004). This translates to improved energy efficiency in construction, reducing heating and cooling costs. Additionally, foamed wood exhibits enhanced strength and durability while being sustainable, as it is often derived from renewable sources (*Ferreira et al.*, 2023). Its capacity for sound absorption and fire resistance further adds to its appeal, making it a versatile and promising material for a wide range of applications in various industries, particularly in construction and manufacturing.

2. MATERIALS AND METHODS

2.1. Materials

A test sample with dimensions of 500 mm x 500 mm and a thickness of 40 mm was made. The test body of thermal insulation material based on foamed Wood fiber is conditioned at 65 ± 5 % relative humidity and 20 ± 2 °C air temperature for 168 hours. The moisture content of the thermal insulation material is determined by a moisture analyzer type MB23 (OHAUS Europe GmbH) on samples taken from individual parts of the test material.

The percentage moisture content (u) was determined as the weight difference between the wet (m_w) and dry (m_0, dried at 105°C ± 2°C for 6 hours) sample according to the relationship:

$$u\ (\%) = \frac{m_w - m_0}{m_0} . 100 \qquad (1)$$

u – moisture content (%)
m_w – weight of the wet sample (kg)
m_0 – weight of the dry sample (kg)

2.2. Measurement

The examined material was inserted into the device for determining thermal insulation characteristics, which enables the measurement of thermal insulation characteristics by the method of protected warm plates TAURUS TLP 900-GS (TAURUS Instruments GmbH, Germany). The principles of the design of the methodical procedure, the test equipment and the basic requirements that must be met for the laboratory determination of the heat transfer properties of parts of buildings follow from the EN 12939 standard.

One plate sample with defined dimensions determined by the EN 12667 standard was placed between the hot and cold plates of the measuring device of the chamber with applied temperature sensing sensors. Subsequently, the chamber was closed and started in measurement mode, the measurement took place for 30 hours until the temperature reached a steady state in the density profile of the measured sample. The necessary parameters for measuring the heat transfer coefficient λ were set on the device. Sensing probes were applied to the examined sample and then the sample was isolated with polystyrene plates so that the examined material was tested in the most precise conditions.

Table 1. Device characteristics of a calibrated box with an integrated hot plate TLP 900 (G)S

Characteristics	Technical data	
Measurement range	0.005 – 2.0 $W.m^{-1}.K^{-1}$	
Test sample size (mm)	500x500 – 800x800 mm	
Sample thickness (mm)	10 – 240 mm	
Temperature range	Plate for cooling	-10 – +50°C
	Heating plate	0 – +60°C
Voltage	110 – 230 V 50/60 Hz	

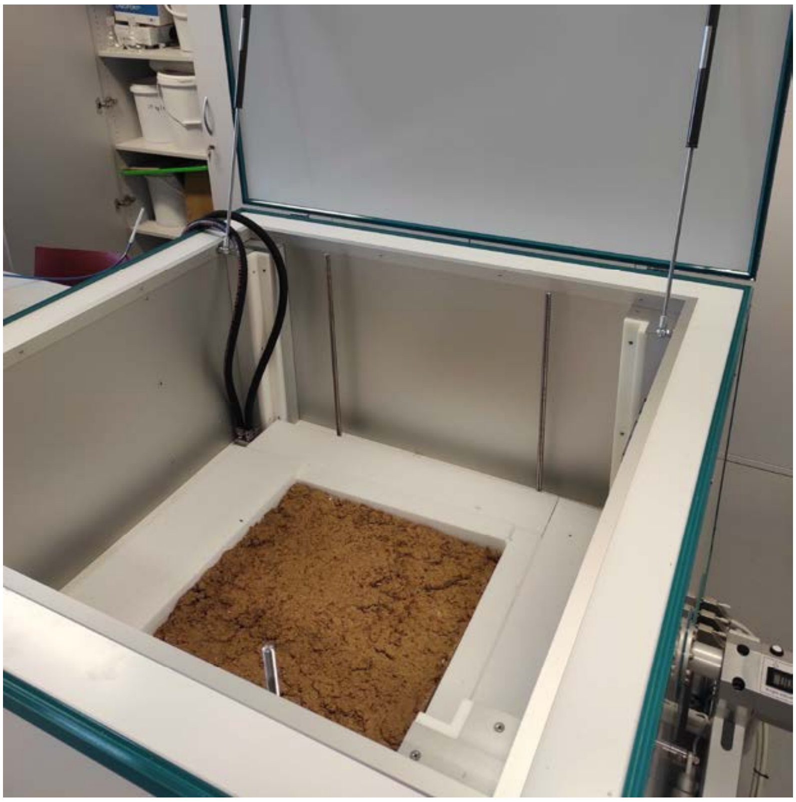

Figure 1. Samples applied in calibrated box with an integrated hot plate TLP 900 (G)S

2.2.1. Principle of calculation of thermal conductivity λ

Thermal conductivity characterizes the ability of the tested material to conduct heat. It represents the rate at which heat spreads from one heated part to a cold part. The device measures thermal conductivity with an accuracy of ± 0.1 %.

The calculation is given by the relation (EN 12667):

$$\lambda = \frac{\varphi\, d}{A\,(T_1 - T_2)} \tag{2}$$

λ – coefficient of thermal conductivity (W.m^{-1}.K^{-1})
T_1 – average temperature on the warm side of the sample (K)
T_2 – average temperature on the warm side of the sample (K)
d – thickness of the tested material (m)
A – specific area of the sample (m^2)
φ – average heat flow (W)

2.2.2. Calculation of thermal resistance R

Thermal resistance characterizes the amount of heat, how much heat passes through a structure with an area of 1 m^2 when the temperature difference of its surfaces is 1 K.

The calculation is given by the relationship (EN ISO 6946):

$$R = \frac{d}{\lambda} \tag{3}$$

R – thermal resistance of the structure (m^2.K.W^{-1})
d – thickness of the tested material (m)
λ – coefficient of thermal conductivity (W.m^{-1}.K^{-1})

3. RESULTS AND DICUSION

The measured values of the developped new Foamed Wood material were compared with selected commercially produced materials. Materials such as STEICO ISOVER (Wood fiber insulation) (Steico AG, Germany), ISOVER UNI (Mineral wool) (Saint-Gobain Construction Products CZ a.s., Czech Republic), KOBE ECO HEMP FLEX (Hemp fiber insulation)(KOBE-cz s.r.o., Czech Republic), EKOPANEL (straw insulation) (EKOPANELY CZ s.r.o., Czech Republic) were selected. The resulting values of the material parameters are shown in the following *Table 3.*

Table 2. Comparison of Foamed Wood (FW) with selected thermal insulations

Specimen	λ ($W.m^{-1}.K^{-1}$)	R ($m^2 \cdot K.W^{-1}$)	ρ ($kg.m^{-3}$)
FOAMED WOOD	0.0412	0.97	97.8
STEICO ISOVER	0.0400	1.00	160.0
ISOVER UNI	0.0350	1.14	40.0
KOBE ECO HEMP FLEX	0.0400	1.00	0.35
EKOPANEL	0.0990	0.40	379.0

The goal was to determine the basic thermal-insulating characteristics of the new thermal-insulating material based on foamed wood fibers for the potential of its application when it is implemented in the structure of the perimeter shell. The resulting parameters were compared with four other types of thermal insulation materials from commercial manufacturers.

The value of the coefficient of thermal conductivity was determined, for Foamed Wood material λ = 0,0412 ($W.m^{-1}.K^{-1}$), the results show that, compared to other commercially produced thermal insulation materials, it has comparable parameters as insulation materials based on wood or straw fibers, it shows worse parameters than insulation materials based on Mineral wool.

The same results are confirmed by the assessment of thermal resistance R = 0,97 ($m^2 \cdot K.W^{-1}$), where the results show that, compared to other commercially produced thermal insulation materials, it has comparable parameters as insulation materials based on wood or straw fibers, it shows worse parameters than insulation materials based on Mineral wool.

Acknowledgements: *We wish for the support of the project "Development and analysis of thermal insulation materials based on cellulose fibers", No. A-09-23, financed by the Internal Grant Agency (IGA) of the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Czech Republic.*

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Characterization of Particleboards Produced with Orange (*Citrus sinensis* L.) and Turkey Oak (*Quercus cerris* L.) Wood Species Using Modified Starch as Adhesive

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ABSTRACT

The rise in raw material prices forced the panel industry to search for new raw materials with low economic competition. This study focused on developing particleboards (PBs) using wood branches of Orange tree (*Citrus sinensis* L.) from crops and Turkey oak (*Quercus cerris* L.) wood residues from forest stands. The management of both wood species produces an undervalued biomass. PBs were produced using Urea-Formaldehyde (UF) adhesive and Modified Starch (MS) promoted as a low environmental impact adhesive, and evaluated in terms of modulus of elasticity (MOE), modulus of rupture (MOR), internal bond strength (IB), thickness swelling (TS) and water absorption (WA). The obtained data were statistically analyzed using analysis of variance (ANOVA) and Duncan's mean separation tests. Panels produced with the mixture of UF and MS comply with the minimum requirements of the standard EN 312:2004 for P2 panels type, namely non-structural panels including furniture for use in dry areas. TS values met the requirement for P3 panels type intended for use in humid conditions only in the case of the panels produced with UF adhesive. MS has negatively affected dimensional stability. However, the produced panels were suitable for indoor applications, where dimensional stability is not a strict requirement.

Key words: alternative raw materials; modified starch; particleboard; wood

1. INTRODUCTION

Wood-based panels (WBP) are engineered composite-type panels made from chips, fibers, or veneers, adhered with thermosetting resins. Due to their high performance and low cost, WBP have revolutionized the woodworking industry, leading to the creation of wood-based products in accordance with the furniture industry demands (Rossi and Spallazzo, 2021). Technological development, new market requirements, and the steadily changing raw material situation led to continuous improvements in WBP and their manufacturing processes (Irle and Barbu, 2010). Depending on the type of the starting wooden material, WBP aim to cover specific needs of the modern industry. Biomass materials for panel production typically consist of unprocessed forest products, industrial residues from wood processing, or agricultural waste in various forms like fibers, shavings, chips, or particles (Maloney, 1993).

A particleboard (PB) is defined as a wood-based panel manufactured under pressure and heat from wood particles including wood chips, shavings, and/or other lignocellulosic material with the addition of an adhesive (EN 309, 2007). The physical and mechanical properties of the final panel are significantly influenced by the wood species and the type of adhesive used (Irle and Barbu, 2010). The main sources of raw material for PBs are regenerated forest land or plantation, however, the increasing demand for PBs and the growth in wood consumption led to an increase in wood raw material prices. Raw material costs represent a significant proportion of the total panel manufacturing costs. To overcome this issue, less expensive lignocellulosic materials considered a waste, or other unused wood species, could be reused as alternative raw materials for the panel industry (Solt *et al*., 2019).

Tons of wood residues produced from both agricultural and forest utilization are not considered valuable feedstock for the material sector. Fruit orchards require annual pruning which leaves abundant residual biomass on the ground. Cataldo *et al.* (2022) have estimated that in Italy around 6 million tons (over dry basis) of pruning biomass is available from the main orchards each year. Among Italian orchards, the orange tree (*Citrus sinensis* L.) is one of the most representative crops, with 76 042.20 ha (Bruno *et al.*, 2020). In Basilicata region, located in southern Italy, orchards occupy 50 281.00 ha and 12 % of this area is occupied by orange crops (Istat, 2017). The cultivation of orange trees requires at least one pruning per year, producing a woody biomass estimated to be about 1800 kg ha year^{-1}(Cotana and Cavalaglio, 2008). At the moment, the main strategy to manage the pruning biomass is to use it for fuel or, sometimes, it is chopped and left on the soil to improve the organic matter for farm needs or it is used for energy purposes (Cichy *et al.*, 2017). The scenario regarding oak forest stands is somehow similar. Turkey oak (*Quercus cerris* L.) is widespread in the Mediterranean area and represents one of the forest species with the largest planted area in Italy, especially in the Apennines Mountain range system (INFC, 2015). The management of oak stands produces a large amount of wood residues mainly used for energy purposes (*i.e.,* firewood) without any additional economic value (Todaro *et al.*, 2012). The technological limitations of this wood species arouse indifference from wood markets and the research world (Giordano, 1981). Burning residues is not always permitted due to concerns about the emission of CO_2 into the atmosphere. The European Strategy aims for waste prevention and a circular economy, requiring alternative management methods for agro-forestry biomass with minimal environmental impact (D'Adamo *et al.*, 2022). In addition, adhesives have been always an important topic of discussion for the panel industry. Most panels are manufactured using urea-formaldehyde (UF) for its low cost. The issue with this adhesive is its formaldehyde emission, a dangerous substance that poses significant health risks to humans and the environment. The interest in eco-friendly products has highlighted the potential of modified starch (MS) as a sustainable alternative adhesive for producing PBs (Chotikhun and Hiziroglu, 2017).

The study aimed to evaluate the applicability of orange wood branches from pruning operations and oak wood from forest thinning as raw materials for PBs manufacture, predicting high polyphenol content inside the oak wood may limit the bonding performances.

Two adhesives were used: UF and MS. The effect of using two different wood species and two adhesives on mechanical properties, such as Modulus of elasticity (MOE), Modulus of rupture (MOR), Internal bond strength (IB), and physical properties, such as Thickness swelling (TS) and Water absorption (WA) was studied. Results were compared with the requirements imposed by the European Standard that define wood-based panels according to their commercial use.

2. MATERIALS AND METHODS

2.1. Biomass Material

Orange wood residues came from a Mediterranean Italian Region (Basilicata), and Turkey oak wood chips from Meridiana Legnami Company. The chips were air-dried to a moisture content of 12 % for 60 days, reduced into particles using a multi-functional ensilage crusher, and screened using horizontal vibrating sieves to remove oversized and dust particles.

The fraction of particles that passed through the sieve with opening sizes of 4 mm and remained on the sieve with opening sizes of 0.8 mm was chosen for the production of homogenous single-layer PBs. A micrometer was used to measure the dimensions of approximately 30 randomly selected particles. The particles had a length ranging from 3 to 10 mm, width from 0.5 to 1.5 mm, and thickness from 0.3 to 1 mm. Slenderness ratio (SR) (length/thickness) and flatness ratio (FR) (width/thickness), were also determined (*Table 1*).

Table 1. Average particles dimensions. Slenderness ratio (SR), Flatness ratio (FR) of wood particles. Values in parenthesis are Standard deviation

Dimension characteristic	Average value
Length (mm)	7.05 (2.54)
Width (mm)	1.12 (0.31)
Thickness (mm)	0.56 (0.24)
Slenderness ratio (SR)	12.58 (7.79)
Flatness ratio (FR)	6.26 (4.38)

The particles were stored in a chamber to maintain a moisture content (MC) of 10 % at 22 % relative humidity (RH) and 21 ± 1°C until they were used.

2.1.1. Particleboard Manufacture

The produced panels were divided into three categories based on the wood species used: PBs with 100 % Orange wood particles, PBs with 100 % Turkey oak wood particles, and PBs with 80 %-20 % Orange-Turkey oak wood particles. Each of these categories is divided according to two adhesives used: UF at amount of 10 % and UF mixed with MS at amount of 2 % and 15 %, respectively (*Table 2*). A total of thirty-six panels, six for each trial, were produced for the experiments.

Table 2. Experimental design: panel types, proportion of raw material, and adhesive amount. O UF-Orange particleboards with Urea-Formaldehyde; TO UF-Turkey oak particleboard with Urea-Formaldehyde; O+TO UF-mixed Orange and Turkey oak particleboards with Urea-Formaldehyde; O (UF+MS)-Orange particleboards with Urea-Formaldehyde and Modified Starch; TO (UF+MS)-Turkey oak particleboards with Urea-Formaldehyde and Modified Starch; O+TO (UF+MS)-mixed Orange and Turkey oak particleboards with Urea-Formaldehyde and Modified Starch.

	Raw material		Adhesive	
	Orange	Turkey Oak	UF	MS
Panel type	(%)	(%)	(%)	(%)
O UF	100	_	10	_
TO UF	_	100	10	_
O+TO UF	80	20	10	_
O (UF+MS)	100	_	2	15
TO (UF+MS)	_	100	2	15
O+TO (UF+MS)	80	20	2	15

The percentages of adhesive and the production parameters were decided based on a previous study (Chotikhun and Hiziroglu, 2017). A target density level of 780 Kg/m^3 was assumed. The nominal dimension of the panels was 300mm×400mm×10mm (width×length×thickness). *Tables 3* and *4* detail the production parameters for panels made with UF and UF+MS adhesives.

Table 3. Production parameters of panels made with UF adhesive

Parameter	Value
Press temperature (°C)	160
Pressing time (min)	5
Pressure (Bar)	60
Dimensions (mm)	300×400
Thickness (mm)	10

Table 4. Production parameters of panels made with UF+MS adhesives

Parameter	Value
Press temperature (°C)	160
Pressing time (min)	20
Pressure (Bar)	60
Dimensions (mm)	300×400
Thickness (mm)	10

The pressure value was determined considering the density of the wood species used. Therefore, 60 Bar of pressure was deemed necessary to ensure a good interaction between wood particles and adhesive. Particles were oven-dried at 70±3 °C to achieve a MC value below 5 %. Based on the oven dry particles weight, 10 % UF resin in liquid form (65 % solid content) was applied. As a hardener, ammonium chloride (NH_4Cl, 2 % based on the resin weight) in powder form was previously added to the UF solution. Regarding the panels produced with 2 % of UF combined with 15 % of MS, the procedure was as follows: corn starch in powder form modified with glutaraldehyde in solution form in a ratio of 1:2 (w/w) was used as a binder at amount of 15 % based oven dry particle weight. Finally, 2 % of UF was added to the MS solution. The adhesive and wood particles were blended for 5 minutes using a hand mixer. The resinated particles were placed in a wooden frame for mat formation and manually pre-pressed. The frame was previously placed on a 3 mm thick steel sheet, covered with heat-resistant paper. After pre-pressing the mat, the frame and the panel were removed and new heat-resistant paper was used for the top of the mat. The obtained mat was hot pressed using an automatic laboratory press (P 600 LAB 100 TON | Nicem SpA). The produced panels were trimmed to avoid edge effects and conditioned at a temperature of 20 °C and RH of 65 % for two weeks. The specimens obtained from each panel were conditioned at a temperature of 20 °C and RH of 65 % before testing. MC (EN 322:1993) and density (EN 323:1993) were also determined.

2.1.2. Mechanical Properties Evaluation

Universal testing machine (INSTRON, Model 5567) was used for both bending and IB tests. Three-point flex measurements of MOE and MOR were performed on rectangular specimens (250×50 mm) (EN 310:1993). Results were calculated using the following Equations (1) and (2):

$$MOE = \frac{l_1^3(F_2 - F_1)}{4bt^3(a_2 - a_1)} \quad (1)$$

MOE – modulus of elasticity (N/mm^2)
l_1 – distance between the centers of the supports (mm)

b – width of the test piece (mm)
t– thickness of the test piece (mm)
F_2– F_2 – increment of load in the straight-line portion of the load-deflection curve (N)
a_2– a_1 – increment of deflection at the mid-length of the test piece (mm)

$$MOR = \frac{l_1^3(F_2 - F_1)}{4bt^3(a_2 - a_1)} \tag{2}$$

MOR – modulus of rupture (N/mm^2)
F_{max} – maximum load (N)
l_1 – distance between the centers of the supports (mm)
b – width of the test piece (mm)
t – thickness of the test piece (mm)

Square-shaped specimens (50×50 mm) were then used for IB measurement (EN 319:1993). The faces of the specimens were glued to the auxiliary wooden devices and subjected to a uniformly distributed tensile stress, until breaking. The tensile stress perpendicular to the panel faces (IB) is calculated as the ratio between the maximum load and the squared specimen surface according to the following Equation (3):

$$IB = \frac{F_{max}}{a \times b} \tag{3}$$

IB – internal bond (N/mm^2)
F_{max} – maximum load (N)
a – length of the test piece (mm)
b – width of the test piece (mm)

2.1.3. Physical Properties Evaluation

Square-shaped specimens (50×50 mm) were used for TS and WA measurements (EN 317:1993). The same specimens were used for physical properties evaluation. Specimens were fully soaked in distilled water at room temperature (20±2 °C) for 2 and 24 h to determine short- and long-term water resistance, respectively. The thickness and weight were measured before and after soaking. Results, calculated according to Equations (4) and (5), are reported as percentage values before soaking.

$$TS = \frac{t_2 - t_1}{t_1} \times 100 \tag{4}$$

TS – thickness swelling (%)
t_1 – thickness of the test piece before immersion (mm)
t_2 – thickness of the test piece after immersion (mm)

$$WA = \frac{w_2 - w_1}{w_1} \times 100 \tag{5}$$

WA – water absorption (%)
w_2– weight of the test piece after immersion (g)

w_I– weight of the test piece before immersion (g)

Duncan's mean separation tests and analysis of variance (ANOVA) were applied to determine the statistical significance between the various treatments (Duncan, 1955). A 5 % difference ($p<0.05$) was considered to be statistically significant.

3. RESULTS AND DISCUSSION

3.1. Moisture content and density of the panels

The MC values of the panels ranged from 8.70 % to 8.55 %. The actual density values were found to be slightly lower than the intended target density as displayed in *Table 5*.

Table 5. Mean values of the actual density for each panel type. Values having the same letter are not significantly different based on Duncan's test at the 0.05 significant level. Values in parentheses are standard deviations.

Panel type	N	Actual density[I] (Kg m^{-3})	X_{min}[II]	X_{max}[III]
O UF	30	684^{c} (0.03)	0.625	0.769
TO UF	30	718^{b} (0.04)	0.651	0.850
O+TO UF	30	740^{ab} (0.05)	0.600	0.816
O (UF+MS)	42	724^{b} (0.06)	0.623	0.822
TO (UF+MS)	42	762^{a} (0.05)	0.600	0.869
O+TO (UF+MS)	42	767^{a} (0.06)	0.600	0.900

IMean values of the actual density
IIMinimum value
IIIMaximum value

The resulting low densities could be due to the weight loss of the particles during the mixing process (Kelly, 1977).

3.2. Mechanical properties

The average values of MOE, MOR, and IB are presented in *Table 6*.

*Table 6. Mean values of Modulus of elasticity (MOE), Modulus of rupture (MOR), and Internal bond (IB) for each panel type. Values having the same letter are not significantly different based on Duncan's test at the 0.05 significant level. Values in parentheses are standard deviations. *Each IB value is an average of 18 measurements*

		Bending properties (N mm^{-2})		
Panel type	N	MOE	MOR	IB (N mm^{-2})*
O UF	30	2028.7^{bc} (666.8)	13.8^{b} (2.7)	1.79^{a} (0.34)
TO UF	30	1790.9^{c} (625.7)	16.9^{a} (4.5)	1.59^{ab} (0.38)
O+TO UF	30	2042.8^{bc} (517.4)	15.8^{a} (3.4)	1.52^{b} (0.45)
O (UF+MS)	42	2380.6^{b} (829.4)	6.1^{d} (2.6)	0.65^{d} (0.10)
TO (UF+MS)	42	3630.1^{a} (1051.4)	8.5^{c} (2.7)	0.63^{d} (0.18)
O+TO (UF+MS)	42	3385.1^{a} (1253.2)	9.1^{c} (3.5)	0.90^{c} (0.24)
Minimum value imposed by EN 312:2004 for panel type P2	-	1800 N mm^{-2}	13 N mm^{-2}	0.40 N mm^{-2}

Statistical analysis found some significant differences (P<0.05) between some groups means for MOE, MOR, and IB values. An increase in MOE values of UF+MS panels did not mean a substantial increase in MOR values. Due to the prolonged exposure of 20 minutes at high pressure temperature of 160 °C, the outer layers of the panels became stiffer than in the case of pressing UF panels (5 minutes), which led to high MOE but low MOR (Bekhta 2021, personal communication). The presence of the bio-adhesive (UF+MS) resulted in significantly higher MOE values for panel types TO (UF+MS) and O+TO (UF+MS) compared to UF panels. Ye *et al*. (2018) observed that when starch dosage exceeded 8 %, the rigidity of the panels increased, resulting in a decrease in the resistance to deflection. All the tested panels, except for TO UF panel type, were shown to have MOE values higher than the minimum requirement stated in EN 312:2004, which set up a MOE minimum value of 1800 N/mm^2 for panel type P2, namely non-structural panels including furniture for use in dry areas. The presence of UF adhesive at the amount of 10 % resulted in significantly higher MOR values compared to the other ones (UF+MS) and this could be due to the better strength properties of the UF adhesive itself (Shalbafan and Thoemen, 2022). Panels produced with UF adhesive met and exceeded MOR minimum requirements for panel type P2, as stated in EN 312:2004, which imposes a minimum value of 13 N/mm^2. The highest IB values were achieved by UF panels and the lowest values by MS panels. As expected, starch-based adhesives have low bonding strength (Chotikhun and Hiziroglu, 2017). However, all panels exceeded the requirements of the EN 312:2004 standard for panel type P2, which imposes a minimum bonding strength value equal to 0.40 N/mm^2.

3.3. Physical Properties

After 24 h of immersion, UF+MS panels swelled four times more compared to UF panels (*Table 7*).

Table 7. Mean values of Thickness swelling (TS) and Water absorption (WA) for each panel type. Values having the same letter are not significantly different based on Duncan's test at the 0.05 significant level. Values in parentheses are standard deviations.

		TS (%)		WA (%)	
Panel type	N	2 h	24 h	2 h	24 h
O UF	60	3.78^c (1.48)	9.98^d (2.22)	16.68^c (6.08)	41.86^c (7.18)
TO UF	60	3.75^c (1.48)	12.03^d (2.64)	12.75^d (5.64)	31.34^d (6.38)
O+TO UF	60	5.10^c (1.90)	11.98^d (2.27)	17.41^c (6.31)	41.89^c (6.82)
O (UF+MS)	60	35.46^b (5.36)	40.57^c (7.05)	50.65^b (5.38)	67.43^b (4.40)
TO (UF+MS)	60	36.22^b (8.90)	46.59^{bc} (10.73)	52.41^b (5.82)	69.34^b (5.22)
O+TO (UF+MS)	60	41.84^a (6.69)	54.97^a (9.30)	66.58^a (4.83)	88.00^a (5.45)
Maximum value imposed by EN 312:2004 for panel type P3		-	14 %	-	-

The poor dimensional stability is due to the nature of starch itself which is hydrophilic, thus it tends to absorb water (Robit, 2008). UF panels comply with panels maximum property requirement of 14 % for 24 h of water immersion based on EN 312 type P3 (2004) for non-structural panel for use in humid conditions.

4. CONCLUSIONS

The study examined the effectiveness of Orange and Turkey oak wood species in producing single-layer PBs. Two dosages of adhesives were used: 10 % UF, and 2 % UF combined with 15 % MS. All panels with UF adhesive showed good mechanical performances, meeting the minimum specifications of the standard EN 312:2004 for P2 panels type for use in dry areas. TS values also met the requirement for P3 panel type intended for use in humid conditions, but only in the case of the panels produced with UF adhesive. The presence of MS has negatively affected the physical properties. However, the panels showed good performance for indoor applications, where dimensional stability is not a strict requirement. The results proved that Orange and Turkey oak residues might be useful innovative raw materials, and the bio-based adhesive could be an industrially viable bio-based solution. The idea of using starch as adhesive meant giving further efficiency to the wood raw material, allowing minor wood species to satisfy the future demand for eco-friendly products.

Acknowledgements: *The authors express gratitude to the National Research Council of Sesto Fiorentino and the Department of Wood Processing and Wood Products of Brasov University for providing the equipment necessary for this study. The study was carried out within the Agritech National Research Center and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.*

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Assessing the Impact of Forest Management in Life Cycle Assessment: Wooden Table Case Study

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ABSTRACT

Life cycle assessment (LCA) has become a valued method for analysing the environmental impact of a wood products across all life cycle stages - from raw material extraction to end-of-life disposal scenarios. Although the concept of LCA covers all stages of the life cycle, forest management is not normally considered for wood products. As many of the impacts of forest management are difficult to quantify but are particularly important in the long term, we wanted to investigate the possibilities of including the long-term impacts of forest management, such as deforestation, in the LCA. The aim of this LCA study is therefore to compare the cradle-to-gate approach for a simple wood product (a wooden table) from "close-to-nature" forest management with a product from "generic" forest management. The input data for the calculation of the environmental impact of a wooden table are extended by the parameter's silviculture and timber harvesting. The results of this study show possible differences in the overall environmental performance of products made from wood originating from differently managed forests. It also highlights the challenges that need to be considered when developing a suitable LCA method for the assessment of wood products.

Key words: climate change, deforestation, forest management, forest-wood chain, LCA, life cycle analysis

1. INTRODUCTION

The European Green Deal (European Commission, 2019) promotes the most important strategies to achieve the common goal of making Europe the first climate-neutral continent by 2050. An important part of the Green Deal is the Green Deal Industrial Plan for the Net-Zero Age (European Commission, 2023), that promotes development of technological and industrial sphere in the context of sustainable circular bioeconomy, which represent a complex intertwine of environmental, economic and social considerations. As a key element for a climate-neutral industry, the forest-wood chain is considered promising, especially in countries with large forest areas or where woody biomass is the most abundand biomass source. The forest-wood chain has become one of the most important value chains in the EU (Đuka *et al.*, 2017). It is not only a supplier for long-established industries such as carpentry, civil engineering or the paper industry, but also offers many promising opportunities for the development of wood-based industries with added value, such as biochemistry. The EU Forest-based Industries 2050 (FBI, 2019) emphasize that EU's forests and wood-based industry industries significantly reduce the carbon footprint within the EU. Carbon stocks and the CO_2 balance are usually assessed in the context of the carbon cycle, often focussing on the carbon stored in forests (Straka and Layton, 2010). Greenhouse gasses (GHG), particularly carbon dioxide, appear to be responsible for climate change. Therefore, it is not surprising that the contribution to GHGs, together with global warming potential, is the most commonly assessed metric category (Klein *et al.*, 2015; Røyne *et al.*, 2016). The increase of CO_2 in the atmosphere is closely linked to the combustion of fossil fuels. Therefore, the inclusion of a larger share of woody biomass in the industry seems to be a solution for the development of the bioeconomy, which aims to replace fossil resources with bio-based ones (D'Amato *et al*., 2020, Klein *et al*., 2015). Furthermore, the energy equation shows us that the potential energy gain from wood far exceeds the energy consumption from fossil fuels in the forest-wood chain (Abbas and Handler, 2018).

On the one hand, wood products are generally considered carbon neutral as they can store carbon throughout their life cycle. However, the net impact of wood products on the carbon cycle and the carbon balance in the atmosphere is much more complex than just the amount of carbon stored in products (Klein *et al*., 2015; Røyne *et al*., 2016; Straka and Layton, 2010). On the other hand, the imbalance of the carbon cycle is also caused by deforestation, as trees represent a sink for CO_2 through photosynthesis processes and the ability to store excess carbon as biomass (Đuka *et al*., 2017). It could be argued that the energy demand for the production of wood products is much lower than for the production of steel products and that the use of wood biomass as a fuel enables the use of less fossil fuels. Nevertheless, the timeframe to which we relate the carbon neutrality of wood products should be considered more carefully, as any land change or even just forest management can lead to much larger changes in the long-term carbon cycle. For example, the hundreds or thousands of years old trees that are cut down may never grow back and the same amount of biomass may never be stored in the trees again. There are many different scenarios as to why this could happen. The forest areas could be converted or degraded, and plantation trees or fast-growing trees combined with rapid consumption store a much smaller amount of carbon than old, slow-growing trees (Straka and Layton, 2010; Zhang *et al*., 2020). Young, fast-growing trees cannot reduce atmospheric carbon and cannot improve the balance of the carbon cycle (Đuka *et al*., 2017). Furthermore, industrial processes can cause long-term (or short-term) damage to ecosystems, and without close monitoring, we often do not know how a chemical or process is damaging forests and biodiversity until the damage has already occurred (D'Amato *et al*., 2020. In addition to the uncertainty about how the direct and indirect effects of land use change will play out in the future (Đuka *et al*., 2017; Røyne *et al*., 2016), the temporal distribution of GHG emissions and carbon sequestration is also uncertain.

1.1. Inclusion of deforestation in the life cycle assessment

As promising as wood may be as a raw material for various applications, two aspects of the strategy for the development of the wood-based bioeconomy still need to be considered. The first is the quality of the forests in the future and thus the carbon pools. The second aspect is the emissions generated by the processes in the forest-wood chain. While the first aspect is more difficult to define and accurately assess, the second is much easier to quantify and measure and is often assessed using the life cycle assessment (LCA) method. LCA is a standardised method that assesses the entire life cycle of a product or process using the "cradle-to-grave" approach. The impact assessment considers scenarios for raw material sourcing, manufacturing, transport, distribution, use/reuse, maintenance, recycling, waste management and final disposal (Sinkko *et al*., 2023). However, a life cycle assessment does not necessarily have to cover the entire life cycle from cradle to grave, but can instead focus on different stages of the process flow or even on a single processing facility in the life cycle of a product. This is often the case with life cycle assessments of wood products, where the origin of the wood, forest management and harvesting are often not included in the assessment system. Some researches that discuss wooden products and focus on wooden panels (Schwarz *et al*., 2023), furniture (Sakib *et al*., 2024), wood used in construction (Duan *et al*., 2022) or in biorefineries/wood-based chemistry (Shahzad et al.; 2023) do consider the impacts of forestry, but do not include it in the calculations. However several previous researches have shown, that the operations prior to the sawmill or even factory gate are not significant (PE INTERNATIONAL AG, 2012; Puettmann *et al*., 2013). Klein *et al*., 2015, described the most important processes in the silvicultural activities as final felling, forwarding, thinning, site preparation and transportation. That being said we cannot consider this without some uncertainty and understanding the carbon cycle and the dynamics of it (Røyne *et al*., 2016). Concepts such as biological diversity, social factors, and economic aspects related to forest sustainability are often qualitative and challenging to quantify. In a large number of studies on the life cycle assessment of forestry operations, the fuel consumption of machinery is repeatedly cited as a significant environmental impact (Mirabella *et al*., 2014). This emphasises the central role of efficient and sustainable forest management practises in reducing the environmental footprint of forestry. Nevertheless, the wider application of LCA in forestry research has its limitations, as some studies lack rigorous mathematical methods and use narrow system boundaries, which can make comparability with modern LCA studies difficult.

The aim of this study is to assess a simple wood product with the help of the LCA and to evaluate the possibilities of including the long-term results of forest management, such as conservation and biodiversity, in the system boundaries.

2. LCA CASE STUDY OF A WOODEN TABLE

To assess the ability of LCA tools to integrate deforestation and low-quality forest management into the environmental impact of a wood product, we conducted an LCA case study using SimaPRO 9. 5. 0. 1. together with Ecoinvent 3.9.1. and the USLCI database. The USLCI database (U.S. Life Cycle Inventory Database) was used in addition to Ecoinvent, as it more accurately maps the processes created specifically for the forest-wood chain and thus avoids many simplifications. The main objective of this LCA study was to compare the environmental impact of a wooden table originating from a "close-to-nature" and a "generic" managed forest. The evaluated system included forest management, logging, sawmill activities and activities related to furniture production. The functional unit of this study was a simple table made of spruce wood weighing 16.45 kg. The evaluated process was divided into four working blocks: A – forest management, B – logging, C – sawing the log and D - furniture production.

The LCA analysis was carried out in accordance with EN ISO 14040:2006, EN ISO 14044:2006 and the ILCD Handbook. However, the system included mass allocation. We used the cut-off criteria for our calculations, which means that energy and mass, which account for less than 1 % of the system, were not included in the final calculations. For the life cycle impact assessment (LCIA) phase, the ReCiPe 2016 method (Mirabella *et al*., 2014; Sahoo *et al*., 2019) was used for both the Midpoint (H) and Endpoint (H) categories. The Midpoint categories assessed using the ReCiPe method are: Global warming; Stratospheric ozone depletion; Ionizing radiation; Ozone formation, Human health; Fine particulate matter formation; Ozone formation, Terrestrial ecosystems; Terrestrial acidification; Freshwater eutrophication; Marine eutrophication; Terrestrial ecotoxicity; Freshwater ecotoxicity; Marine ecotoxicity; Human carcinogenic toxicity; Human non-carcinogenic toxicity; Land use; Mineral resource scarcity; Fossil resource scarcity; Water consumption. These categories and the assigned emissions are summarised in endpoint categories, which are important indicators for protecting the well-being of people and ecosystems.

2.1. Life cycle inventory (LCI)

Forest management block A was divided into two possible scenarios: the "generic" (sub-block A1) and the "close-to-nature" forest management scenario (sub-block A2). Both represent the activities and inputs required to produce the output parameter "standing spruce". The first block included forest management activities described in some previous studies (Mirabella *et al*., 2014; PE INTERNATIONAL AG, 2012; Puettmann *et al*., 2013; Zhang *et al*., 2020), so that we could compare and adjust the input parameters from the databases. Sub-block A1 therefore comprised (1) the growing of the spruce seedlings in the greenhouse; (2) the preparation of the site for planting the seedlings, taking into account a slight slope of the site in this and all other work steps; (3) the planting of the seedlings; (4) fertilisation with inorganic nitrogen fertiliser; (5) thinning. Sub-block A2, which is considered "close-to-nature" forest management, only included thinning. Thinning was carried out with a chainsaw, the cut biomass and sawdust were defined as avoided products in the system and managed according to the forest management regulations and completely decomposed on site. For both A1 and A2, we took into account that the decomposition of wood releases pollutants such as nitrogen, phosphorus and calcium into the soil (Røyne *et al*., 2016) and gases such as carbon dioxide and methane into the atmosphere (Rowell *et al*., 2012). The construction and management of forest roads were not included in the system. In sub-block A1, the use of pesticides was also not considered, although some studies (Zhang *et al*., 2020) provide evidence of pesticide use. For both sub-blocks, we specify the land transformation according to the area of the needed forest growth (SiStat, 2023).

Block B, which focussed on feeling the tree, included: (1) hand felling and delimbing the tree with the chainsaw; (2) skidding; (3) loading the log onto the timber lorry; (4) transport to the sawmill, estimated to be 50 km from the felling site. The stumps with the roots and sawdust were left to decay on site. Here, too, we took into account the emissions to soil and air. The branches were to be loaded onto the lorry, processed (shredded) and used in the sawmill to generate energy, while the other half was to be left to decay in the forest. In addition to defining the land tranformation, we divided block B into B1 and B2, with B1 taking into account the "generic" forest management and thus also the damage to the forest when converting about a quarter of the area under consideration from forest to arable land. B2 remained unchanged. This method of assessing the clear-cutting criteria to the forest management system was adopted from De Schryver *et al*. (2013).

Block C was the same for both scenarios and included sawmill operations and the production of sawn timber, fine residues, coarse residues and bark. Activities included: (1) on-site manipulation using a forklift; (2) debarking, where the bark was used on-site for energy recovery; (3) sawing the debarked log, which produced some fine and coarse residues that were used for energy recovery; (4) Drying the sawn timber to the correct moisture content – approximately 20 %; (5) Bundling the sawn timber with plastic strapping; (6) Transporting the sawn timber to the furniture manufacturer, estimated to be 50 kilometres from the sawmill.

Block D included the production of a simple wooden table. The tasks included: (1) on-site manipulation using a forklift; (2) the activities required for furniture production such as planning, sawing, milling and sanding; (3) gluing the parts together. The fine and coarse residues generated during the process were taken into account for energy recovery on site.

3. RESULTS WITH DISCUSSION

The results for the Midpoint categories are shown in *Figure 1*. The categories with the highest impacts are Human carcinogenic toxicity, Land use and Freshwater eutrophication. »Generic« scenario shows higher values for almost all categories, but for some categories the difference between the scenarios is insignificant. These categories are: Water consumption, Mineral resource scarcity, Human non-carcinogenic toxicity, Marine eutrophication and Ionizing radiation. The Land use category is the same for both scenarios, which is particularly interesting as it shows that land use in our scenarios is only influenced by wood consumption and no activities related to soil change or land modification influence this criterion, as neither the activities in Block A nor the activities in Block B influence land use in any way. The biggest differences between the scenarios can be seen in Human carcinogenic toxicity, Global warming, Fine particulate matter formation and Ozone formation (Terrestrial ecosystems). The differences in these categories are mainly due to land changes when the net primary productivity of carbon was taken into account, as well as the energy used in wood processing or forest management in the case of the global warming category. The results of the Endpoint categories show similar signs. The greatest impacts and differences between the scenarios can be seen in the "Human helath" indicator. The estimated damage to the ecosystem is also almost identical, while the damage to tar resources tends towards zero in both scenarios. De Schryver *et al*., 2013; Klein *et al*., 2015, emphasise that the most important impact category to be addressed in forest-related studies is Global warming. This is because this is the category where there is a clear difference with the actual parameters and does not need to be reassessed in the interpretation phase, unlike, for example, toxicity to human health, which is calculated very rigorously and is often emphasised as a critical point because some chemicals or energy consumption are included in the parameters.

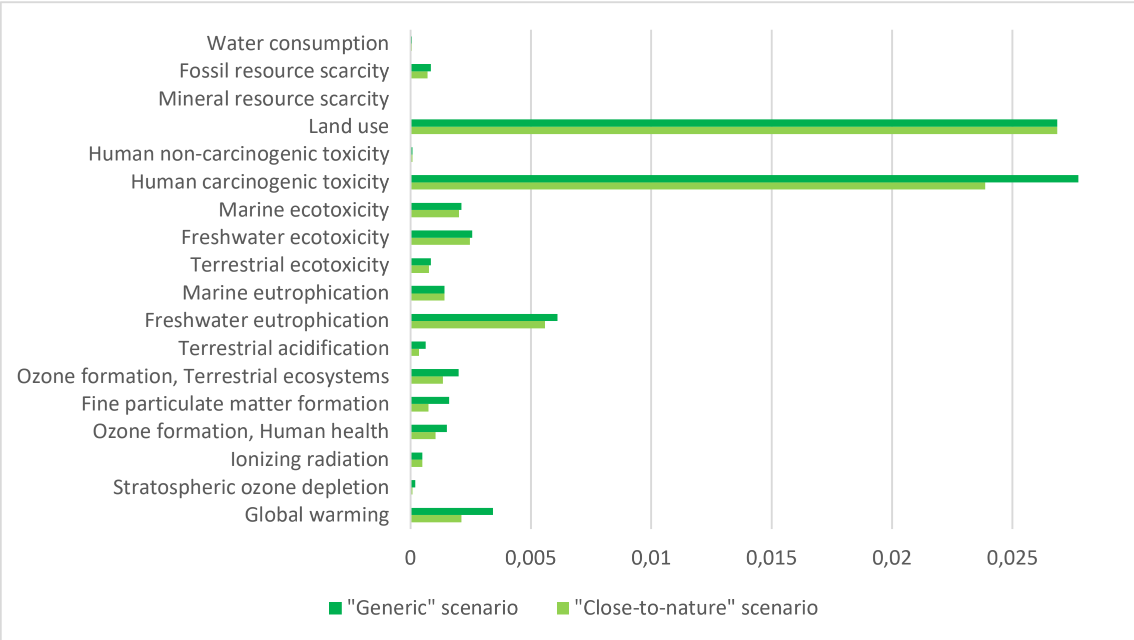

Figure 1. Results of the Midpoint categories for the scenarios compared.

The results of the inputs and activities described in blocks C and D are identical for both scenarios. In both blocks, the processes for which energy was required had the highest load values. The most notable impact category was Human carcinogenic toxicity, which was especially due to the sawing process in Block C and the furniture processing activities in Block D. This could be explained by the fact that we used the input parameters from the database, which were generalised for the European Union region. The energy consumed in the plant therefore represents the European energy mix, which also includes nuclear energy, natural gas and coal, that are in LCA calculated with special consideration of human health. According to the International Energy Agency, in 2020, 24.5 % of electricity in the EU27 was generated from nuclear energy, 20.1 % from natural gas, 14.3 % from wind energy, 13.7 % from coal, 13.4 % from hydropower, 5.2 % from biofuels and solar energy, 1.7 % from oil, 1.4 % from waste, 0.2 % from geothermal and other sources and less than 0.02 % from tidal energy.

Since blocks C and D were the same for both scenarios, the differences in the results can be attributed to blocks A and B. The results of the scenario comparison of block A showed more negative impacts for the »generic« scenario. Interestingly the results for the »close-to-nature« scenario showed positive impacts on the environment in several categories (*Figure 2*). The greatest positive impacts are seen in ozone formation. Most likely the benefits of replacing fossil fuels with woody biomass are taken into account. The benefits far outweigh the consumption of fossil fuels and energy, e.g. diesel, burnt during thinning. These results could support the claim that wood products are »carbon neutral«, as they show that naturally managed woody biomass has no negative impact on the ozone layer or the CO_2 balance in the atmosphere. Positive effects are also shown in the categories of ecotoxicity, soil acidification, human toxicity and depletion of fossil resources, which also speaks in favour of the preliminary positive effects of woody biomass. The impact categories related to soil quality could also benefit from the chemical elements that are likely to be released into the soil as the biomass decay on site. The impacts to the remaining categories are similar for both scenarios. Impacts on Mineral resource scarcity and Ionizing radiation are almost zero, the impacts on Land use are the same, and the impacts on Marine eutrophication, Freshwater eutrophication and Global warming are slightly higher in the »generic« scenario.

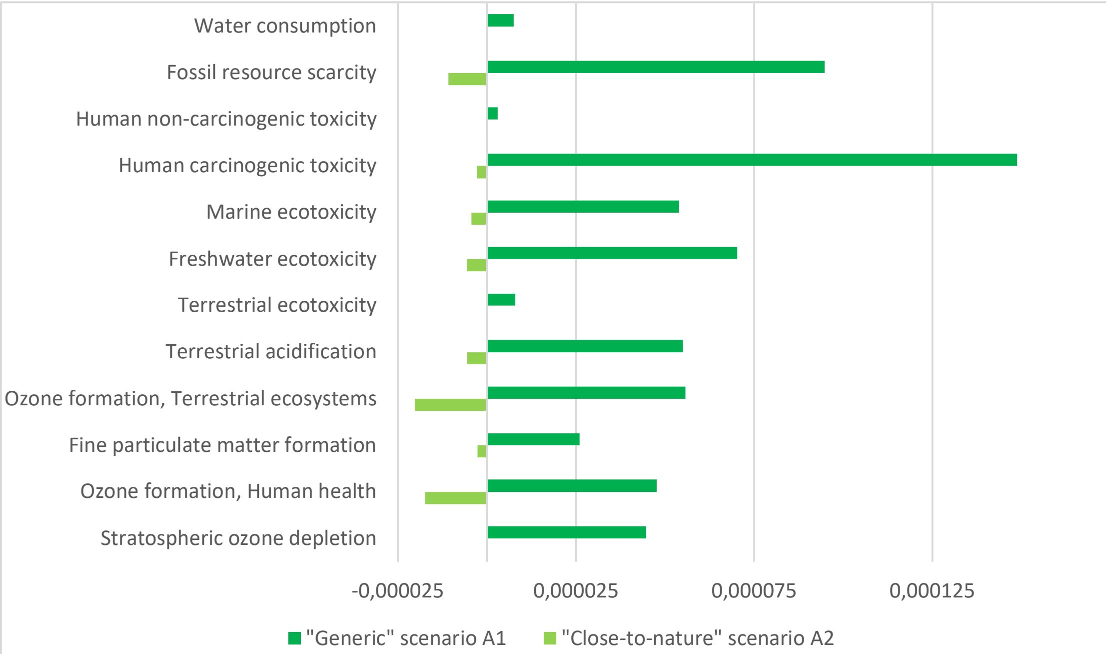

Figure 2. Results of the compared scenarios for block A.

The results of the comparison of sub-block B1 and sub-block B2 are shown in *Figure 3*. Here, the effects of land-use change in B1 were integrated as an input parameter indicating the degree of deforestation. Since all other parameters were identical between the scenarios, the difference is due to this parameter, which takes into account the carbon fluxes in aboveground biomass, belowground biomass and dead organic matter in deforestation. However, this parameter had no influence on the Land use category, where a strong correlation can be assumed. Instead, the negative impacts affect practically all other categories. This input parameter makes it possible to include clear-cutting of primary wood in the assessment, but can also be used to assess overall forest degradation if we can estimate the ratio of degradation area to deforestation area.

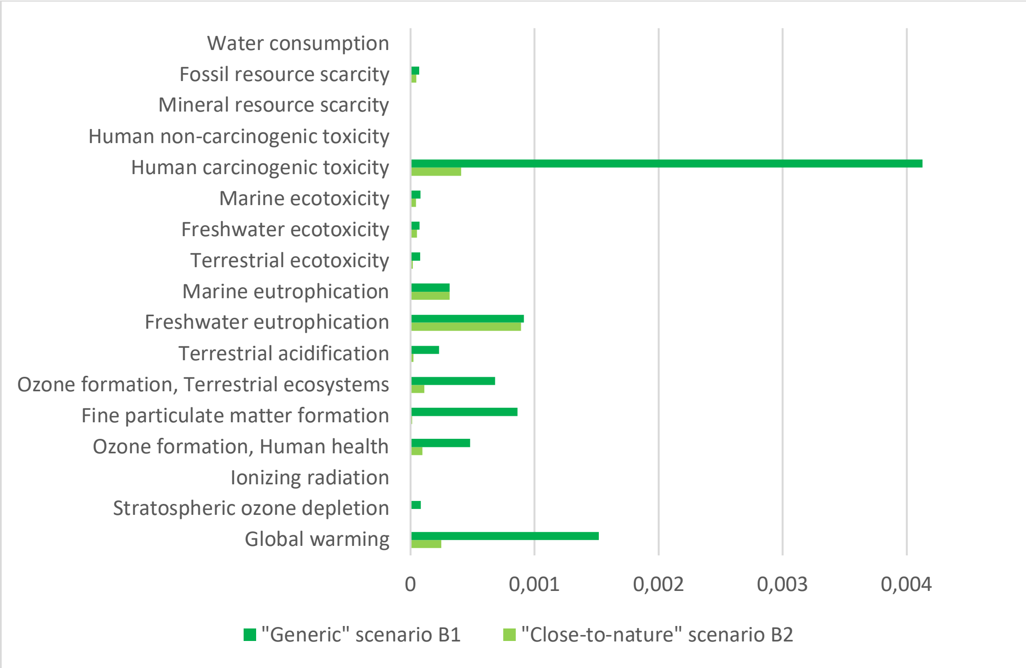

Figure 3. Results of the compared scenarios for block B.

4. CONCLUSIONS

The study presents a system for assessing the environmental impact of a simple wood product – a wooden table made of spruce wood. Two scenarios were compared: one that includes forest management measures such as seedling planting and fertilisation in addition to thinning, and one that considers close-to-nature practises and only includes thinning. The impact of forest management measures has no significant environmental impact, with the exception of the use of fertilisers, where the impact on the soil should be taken into account. Overall, the environmental impacts in both scenarios of wood use are low and the production of wooden products can be considered environmentally friendly. The biggest difference was found when including the aspects of clear-cutting and land use change, which have significant negative impacts in most categories. We can conclude that the database already provides us with some kind of input data for the impact of deforestation. However, since the parameter is modelled for clear-cutting that converts land use to agricultural land, for example, it is difficult to quantify this parameter according to the estimated forest degradation when it is not clear-cutting but practises whose temporal distribution and impacts are questionable. The challenge lies not only in the modelling of the parameter, but also in the core of the problem. How can the temporal effects of forest activities be estimated at all? How are we destroying the soil and what are the consequences? Are we planting the »wrong« species that will not survive in the near future due to the climate changes already taking place? Are we emitting the chemicals that are affecting the forest on a global scale? These are just some of the questions that need to be answered in order to improve the eco-balance of wood products and avoid greenwashing.

Acknowledgements: *The research was financially supported by the Slovenian Research and Innovation Agency (ARIS), under the Wood and Lignocellulosic Composites Programme (P4-0015).*

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Change in Physical Properties at Different Humidity Levels During Laser Wood Processing

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ABSTRACT

Laser machining is not used much for woodworking, this is mainly due to the fact, that at the moment it is not possible to cut higher dimensions, the burned area and, last but not least, the still high acquisition costs. This puts more emphasis on research dealing with this issue.
The research is focused on the evaluation of some physical properties of wood. Change in color and gloss with different moisture content through processing (8 and 30 %). Furthermore, a comparison was made with a conventional machining method - cutting on a circular saw. Research should help to better describe the machining process and help its better implementation in practice. We chose oak (*Quercus robur*, L.) as the wood, which has a higher price per m^3 than most European woods, and it could pay off earlier to buy a laser when processing this or a similar wood. For gloss, a significant statistical dependence was shown for all variables. In the same way, the change in moisture content during machining had a significant effect on the color change. The results confirmed the general assumptions. Different moisture content and the description of its effect on the change of physical properties can help not only in secondary wood-production, but also in primary wood-production.

Key words: Gloss; Laser Cutting; Moisture Content; Oak Wood; Wood Colour.

1. INTRODUCTION

Laser technology is still in development and there are still more ways of possible implementation in industry. The wood processing industry is no exception, and therefore also in our area of scientific interest is laser cutting of wood. (Aniszewska *et al.*, 2020; Yusoff *et al.*, 2008). Laser technology has been known for a long time. Research dealing directly with cutting wood and materials based on it began to appear in abundance in the 70s, 80s and especially in the 90s of the last centuries. (Powell, 1998; McMillin *et al.*, 1984; Barnekov *et al.*, 1989; Peters, 1975).

Wood as a material is inhomogeneous and from the point of view of laser cutting, this inhomogeneity is quite problematic. It was not only a problem of the material, but also the most suitable type of laser for cutting wood, the location of the focal point, etc. had to be determined. In terms of setting the cutting conditions such as power and cutting speed, this issue was carried over to today's research (Liu *et al.*, 2020; Fukuta *et al.*, 2016).

In this area we can find a whole range of them and they usually deal with the given material and optimize the setting of the aforementioned conditions. Already today, this optimization is very beneficial, in terms of ecological and economic impact on production. All these researches support the introduction of progressive technology into the woodworking process and practically evaluate the possibilities of its use (Fukuta *et al.*, 2016; Hernandez-Castaneda *et al.*, 2011; Eltawahni *et al.*, 2011).

From the point of view of today's wood processors, the laser technology that can be used to cut wood and wood-based materials is relatively expensive to purchase and service. Currently, the biggest problem with laser cutting is the ratio of its power and energy consumption, as well as its relatively low efficiency. All this, together with high energy prices, slows down the introduction of laser technology into production (Madić *et al.,* 2018; Gyasi *et al.,* 2022).

Today, in practice, mainly engraving and marking lasers are used on a larger scale, which are also used at lower powers, where the CO_2 laser proves to be very good for engraving and cutting workpieces of small thickness (Muangpool and Pullteap, 2018; Badoniya, 2018).

An integral part of the issue of wood processing using a laser is also the cutting surface, which is blackened, but above all partially charred. This phenomenon can be eliminated precisely by optimal settings and also by optimizing the material itself (e.g., humidity). (Hernandez-Castaneda *et al*., 2011; Kubovský *et al.*, 2020).

The development of the laser in other areas does not stop, and with increasing competition, it will be increasingly introduced in wood processing as well. By eliminating the current disadvantages compared to conventional cutting, advantages such as smaller cutting joints, flexibility of cutting (curvilinear, etc.) and easy possibility of full automation will remain to a greater extent.

2. EXPERIMENTAL

In the research, we investigated the effect of the type of tool and the change in moisture content on the change in color and gloss of the cut surface. The cutting surface was created using unconventional machining (laser) and the machined surface created after machining with a circular saw was chosen as a reference (*Figure 1*).

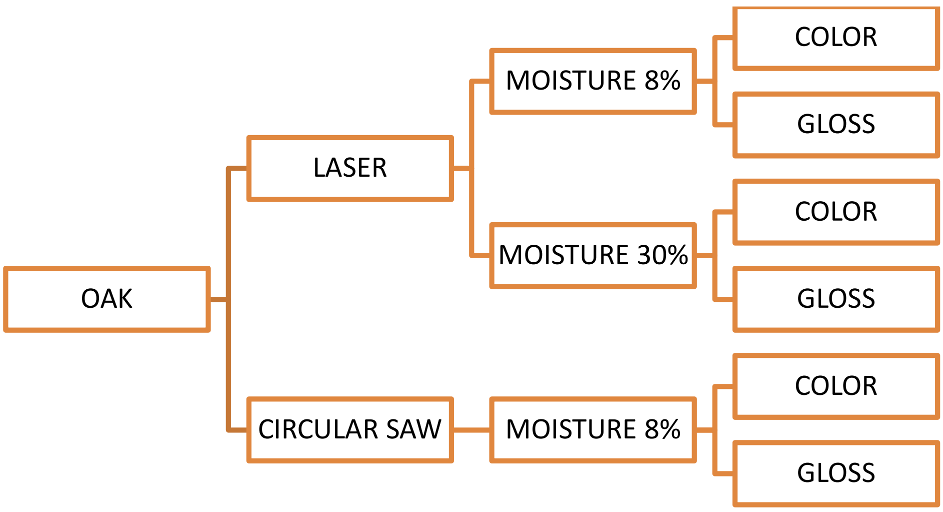


Figure 1. Research scheme.

2.1. Materials

The material chosen for the research was standard oak lumber (*Quercus robur*, L.), from which 40 samples with dimensions of 40 x 100 x 30 mm were cut. The first set of samples at 8 % moisture content and the second at 30 % moisture content. The lumber was flawless due to the elimination of measurement and evaluation errors (*Figure 2*).

For the production of reference samples, a standard circular saw fitted with a newly sharpened saw blade was used. The machine revolutions were set at 4000 per minute and the feed rate was manual.

Laser production line from Biatec Laser Technology s.r.o. was set to a power of 5 kW with a speed of movement of the cutting head of 3 $m \cdot min^{-1}$ with a focal point in the upper third of the cut material. The same setting was used for both determined wood moistures.

Figure 2. Samples produced using a laser

2.2. Methods

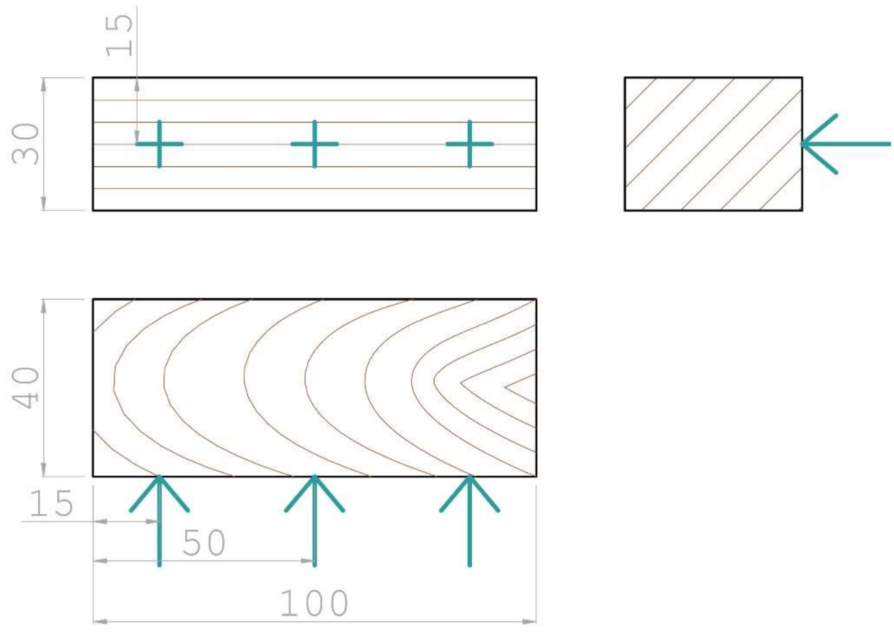
After the density of the samples was determined, the colour was measured. A Konica Minolta CM600d handheld spectrophotometer was used for the measurements. The CIELAB trichromatic system was chosen to interpret the results. The measurement was carried out according to figure 3. under standard conditions in the laboratory.

To calculate the colour, change of cut surfaces according to the formula (1).

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (1)$$

ΔL – brightness
a – coordinates of red colour

b – coordinates of yellow colour



Figur 3. Scheme of colour measurement.

Gloss was measured in the same way as for colour changes. KSJ MG268-F2 gloss meter was used for measurement. The gloss was always measured at all angles (20°, 60°, 85°) respecting the recommendations given in ČSN EN ISO 2813 (2016). The measurement was carried out according to figure 4. under standard conditions in the laboratory.

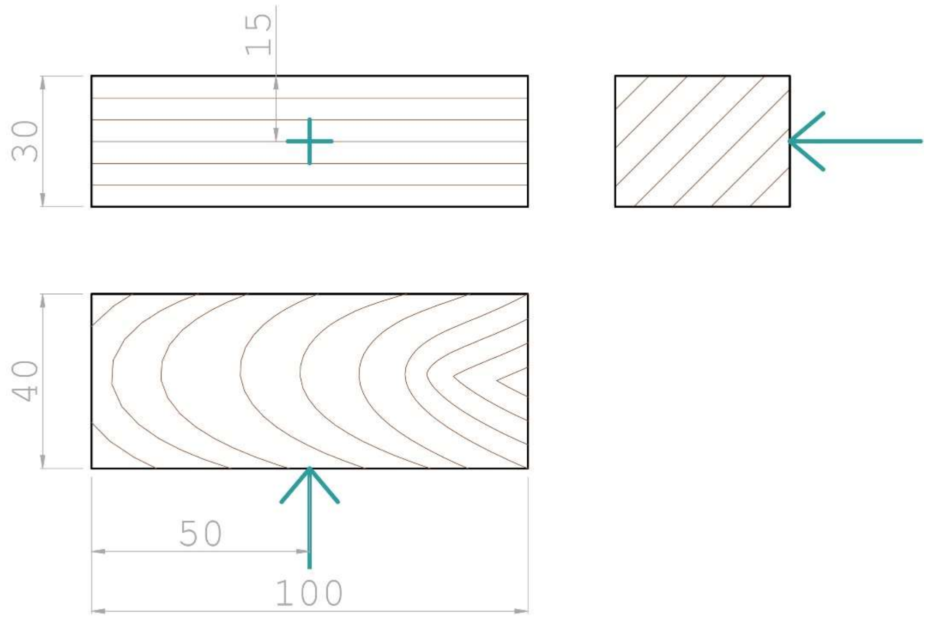


Figure 4. Scheme of gloss measurement.

2.3. Statistical data processing

All tests were evaluated at a significance level of α = 0.05. The Shapiro-Wilks test was used to confirm the normality of the data. Elimination of outliers was performed using the Dean-Dixon test. Further data processing was performed using ANOVA and Duncan's test.

3. RESULTS AND DISCUSSION

From the results presented below, it follows that the type of cutting had the most significant effect on the color change of the cut surfaces of the samples. The effect was also demonstrated in laser-cut wood at different moisture content levels. In the following pictures *(Figure 5* and *Figure 6*) and tables (*Tables 1 to 6*) we can see the change of individual coordinates in the CIELAB trichromatic system.

Regarding the values of the L* coordinate, we can observe a very significant difference between the types of cutting, where the circular saw shows the highest values. This result is logical because the L parameter determines the colour change between black and white. Incontrast, the initial moisture content of the laser-cut samples appears to be almost negligible here.

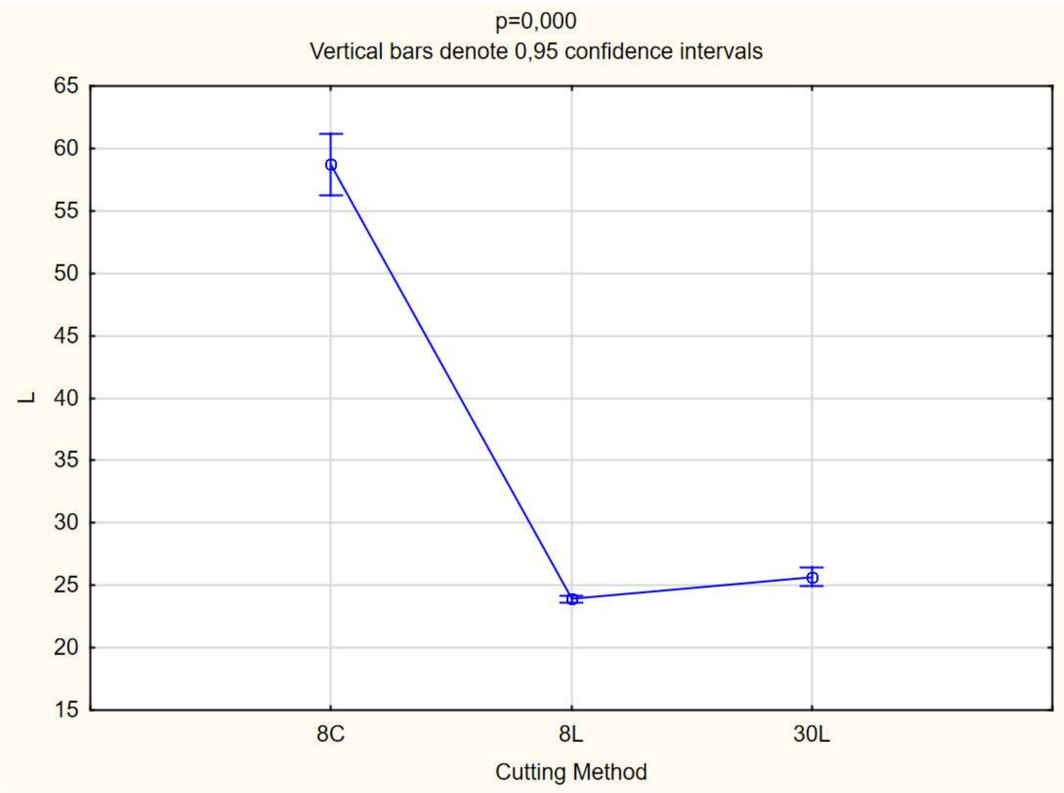


Figure 5. Statistical evaluation of the parameter L in the colour spectrum.

Table 1. Statistical evaluation of the parameter L in the colour spectrum

Num.	Cutting Method	L Mean	L SEM	L -95.00 %	L +95.00 %	N
1	8C	58.708	1.177	56.244	61.172	20
2	8L	23.903	0.132	23.625	24.180	20
3	30L	25.678	0.365	24.912	26.443	20

The total change in the colour of the cut surface ΔE is shown in the following *figure 6* and *table 2*, where it can be noted that it reaches the highest values for samples cut by a laser at a moisture content of 8 % and 30 %. Not only humidity, but also other parameters of the laser cutting process have an effect on the colour change (blackening) of the cut surface. According to research (Aniszewska *et al*., 2020) where they investigated the optimization of laser head power and sliding speed. The research showed that it is necessary to optimize the parameters together and no definite conclusions can be made. This generally makes it difficult to optimize inhomogeneous material.

The fact that the optimization itself will be a very demanding process is also confirmed by research (Eltawahni *et al*., 2011; Kubovský *et al*., 2020; Li *et al*., 2021), where they express the need to optimize all factors, even on a much more homogeneous material (MDF).

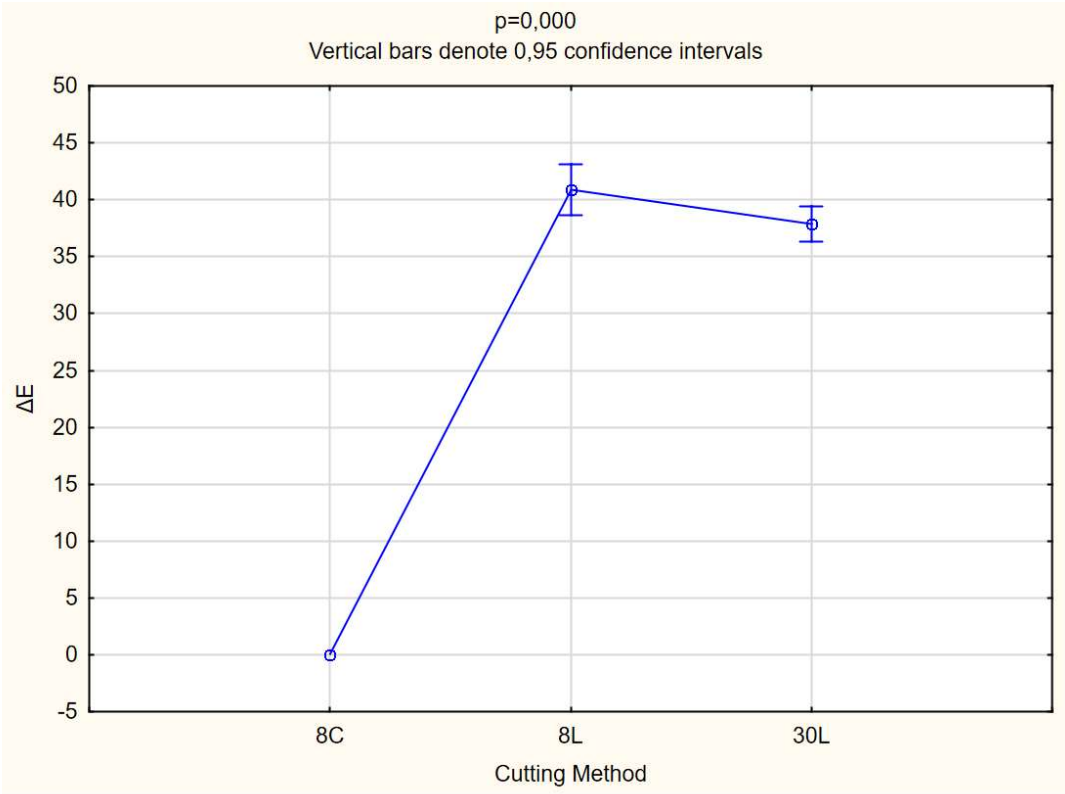


Figure 6. Statistical evaluation of the ΔE of the colour measurement.

Table 2. Statistical evaluation of the ΔE of the colour measurement.

Num.	Cutting Method	ΔE Mean	ΔE SEM	ΔE -95.00 %	ΔE +95.00 %	N
1	8C	0				20
2	8L	40.907	1.064	38.679	43.134	20
3	30L	37.848	0.731	36.317	39.379	20

In the following tables (*Tables 3* to *6*) we can see that the type of cutting was manifested as a statistically significant difference for most of the monitored parameters. The exception is the aforementioned L* value, which reaches similar values when cutting dry and wet wood with a laser. The type of cutting at moisture content of 8 % manifests itself as a statistically very significant difference.

Table 3. Duncan's test for the dependence of the L value on cutting method*

Num.	Cutting Method	{1} 58.709	{2} 23.903	{3} 25.678
1	8C		0.000	0.000
2	8L	0.000	0.000	0.085
3	30L	0.000	0.085	

Table 4. Duncan's test for the dependence of the a value on cutting method*

Num.	Cutting Method	{1} 7.201	{2} 1.513	{3} 3.452
1	8C		0.000	0.000
2	8L	0.000		0.000
3	30L	0.000	0.000	

Table 5. Duncan's test for the dependence of the b value on cutting method*

Num.	Cutting Method	{1} 22.505	{2} 1.976	{3} 4.848
1	8C		0.000	0.000
2	8L	0.000		0.000
3	30L	0.000	0.000	

Table 6. Duncan's test for the dependence of the ΔE value on cutting method*

Num.	Cutting Method	{1} 0.000	{2} 40.907	{3} 4.150
1	8C		0.000	0.000
2	8L	0.000		0.005
3	30L	0.000	0.005	

When cutting with a laser, the gloss values are essentially identical at both moisture content levels (8 % and 30 %), when measured at an angle of 20° and 60°. In contrast, the measurements performed showed a significant difference in gloss values when measured at an angle of 85°, depending on the moisture content of the wood. Gloss values at 30 % moisture content were up to double the values at 8 % moisture content. The results obtained for samples cut with a circular saw showed a very significant increase in gloss values, gradually from an angle of 20°, through an angle of 60° to an angle of 85°, in this ascending order (*Figure 7; Tables 7* and *8*). Samples cut with a circular saw achieve the highest gloss values at all measured angles.

Overall, the wood that was cut with a laser at its initial moisture content of 8 % achieves the lowest gloss.

The largest dispersion of the measured values was achieved when measuring the gloss at an angle of 85° for both types of cutting, on the contrary, the values measured at an angle of 20° showed the smallest dispersion.

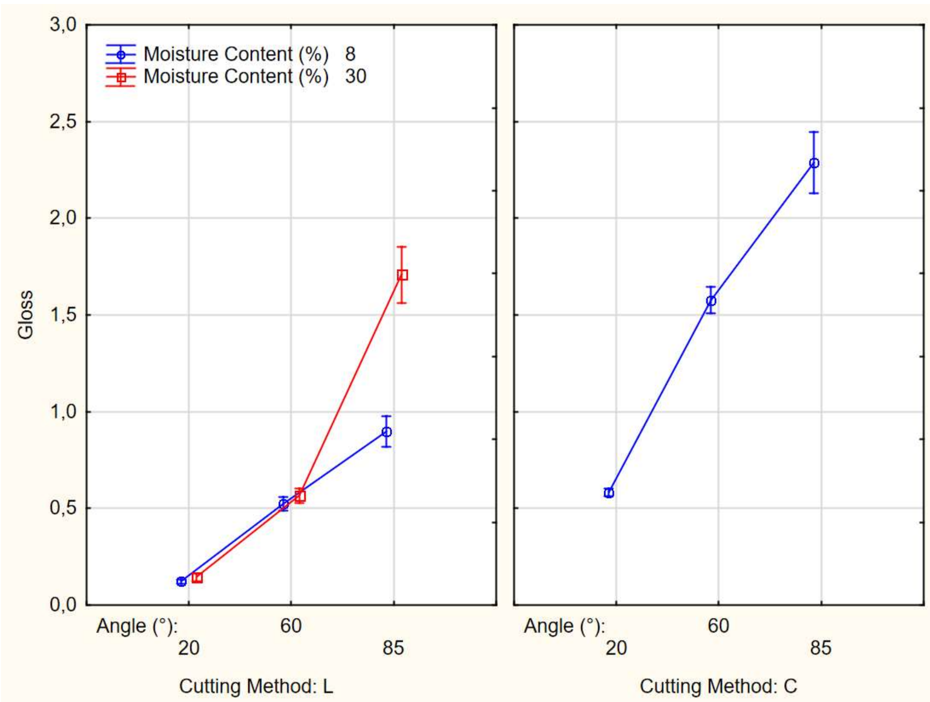


Figure 7. Dependence of gloss on individual parameters.

Table 7. Statistical evaluation of gloss on individual parameters

Num.	Cutting Method	Moisture content (%)	Angle (°)	Gloss Mean	Gloss SEM	Gloss -95.00 %	Gloss +95.00 %	N
1	L	8	20	0.121	0.006	0.108	0.134	20
2	L	8	65	0.523	0.017	0.488	0.559	20
3	L	8	85	0.898	0.037	0.820	0.975	20
4	L	30	20	0.145	0.009	0.124	0.165	20
5	L	30	60	0.567	0.017	0.530	0.605	20
6	L	30	85	1.709	0.069	1.563	1.854	20
7	C	8	20	0.583	0.009	0.564	0.601	40
8	C	8	60	1.576	0.033	1.508	1.645	40
9	C	8	85	2.288	0.078	2.129	2.447	40

After evaluating the dependence of all variable factors, i.e. type of cutting (laser or circular saw), moisture content during cutting (8 % and 30 %) and measuring angles (20°, 60°, 85°) in relation to each other, some conclusions can be made. While when measuring the gloss of the cut surface of samples cut with a laser at angles of 20° and 60°, the variable (moisture) shows a negligible effect, at an angle of 85 % a statistically significant difference with a value of P = 0.000 was demonstrated (*Table 8*).

There is not much research dealing purely with gloss and its change after laser enamel processing, there is a whole range of research that deals with the change in morphology after laser processing, or on the contrary, the change in gloss during thermal modification of wood (Hernandez-Castaneda *et al*., 2011; Rezaei *et al*., 2022). Laser cutting itself affects the cutting surface to a certain depth, and similar processes take place in this part of the workpiece as during thermal modification. Unfortunately, controlled heat modification creates wood with predefined properties. As for laser cutting, the burning or sublimation of wood material occurs and this process is more or less uncontrolled. What we can control is primarily the setting of individual factors and thus reduce the depth and intensity of the burned area (Fukuta *et al*., 2016; Madić *et al*., 2018; Rezaei *et al*., 2022).

Table 8. Duncan's test for the dependence of the gloss value on cutting method, moisture content and angle.

Num.	Cutting Method	Moisture content (%)	Angle (°)	{1} 0.121	{2} 0.523	{3} 0.898	{4} 0.145	{5} 0.567	{6} 1.709	{7} 0.583	{8} 1.576	{9} 2.288
1	L	8	20		0.000	0.000	0.744	0.000	0.000	0.000	0.000	0.000
2	L	8	65	0.000		0.000	0.000	0.537	0.000	0.436	0.000	0.000
3	L	8	85	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000
4	L	30	20	0.744	0.000	0.000		0.000	0.000	0.000	0.000	0.000
5	L	30	60	0.000	0.537	0.000	0.000		0.000	0.828	0.000	0.000
6	L	30	85	0.000	0.000	0.000	0.000	0.000		0.000	0.064	0.000
7	C	8	20	0.000	0.436	0.000	0.000	0.828	0.000		0.000	0.000
8	C	8	60	0.000	0.000	0.000	0.000	0.000	0.064	0.000		0.000
9	C	8	85	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

4. CONCLUSIONS

- The colour is very significantly influenced mainly by the cutting method. Whereas laser-cut samples have low values of the L parameter and saw-cut samples have high values.
- Regarding the moisture content during machining, it does not have a significant effect on the colour change.
- For gloss, the highest values are for wood cut with a circular saw. Classically cut wood is therefore higher gloss value than laser, burnt, wood.

- Moisture content as such proved to be a significant factor only for gloss measured at an angle of 85°, where higher values were shown at 30 % of moisture content.

Acknowledgements: *We wish to thank to project: Advanced research supporting the forestry and wood-processing sectors adaptation to global change and the 4th industrial revolution", No. CZ.02.1.01/0.0/0.0/16_019/0000803 financed by OP RDE".*
We also wish to thank to Department of Wood Processing and Biomaterial from Czech University of Life Sciences Prague for co-financing of research.

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Analysis of Yield and Sawing Methods During Processing Low Value Pedunculate Oak (*Quercus robur* L.) Logs to Sawmill Products

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ABSTRACT

One of the most important places in sawmill industry is reserved for logs prices. Base on this view, it is obligatory to look for and choose the correct method for log sawing. That method should increase measuring factors, optimize technological process, and increase yield of material. Main aim of this research is to determine the influence of the different method of sawing (live and modified Slavonian method), on quantitative, qualitative and value yields of oak timber. This paper, theoretically and through experimentally researches the performance indicators of sawmill processing of Pedunculate oak (*Quercus robur* L.) lower qualitative classes logs in sawn boards. Also, this paper is a continuation of the previously started research on the efficiency indicators of oak logs sawmill processing. The research covered logs classified according to the Croatian standards HRN D. B4.028 into two qualitative classes. Diameter of processed logs were in range between 30 to 39 cm and 4 m long. Logs were sawn up in the 50 mm nominal thickness of sawn boards. Technological line based on vertical log band saw with hydraulic carriage was used for primary sawing up. It was found that live sawing method, yielded the least favourable results comparing with modified Slavonian sawing method.

Key words: live sawing, low quality and small-sized diameter logs, log quantity yield, pedunculate oak (*Quercus robur* L.), quality yield, Slavonian sawing method, value yield

1. INTRODUCTION

Oak species is the most used, most valuable, and important wood in Europe. Sawmill processing in Croatia is mostly based on traditional processing of Slavonian oak. Quantitative yield significantly depends of diameter and quality of oak logs. Value yield of logs increase with increasing quality and diameter of the logs (Prka, 1988a; Prka 1988b). Methods of sawing also have a strong influence on the final quantity of small sawn products (Smajic *et al*., 2021). The yield of raw material, as well as the quality and dimensional structure of sawn products, depends on the method of sawing. Raw material and quality of raw material are the most important factors for yield of logs (Petutschnig and Katz, 2005). The dimensions of the log (Tanušev *et al*., 2009) also is important for yield. The volume yield decreases with increasing logs length, however, less, when the top end diameter is less. While analysing the impact of top end diameter it is obvious, that the intensity of changes in volume yield increases with greater log length and taper (Baltrušaitis *et al*., 2001). The Oak logs processing by live method is usually carried out on log band saws. Generally, the yield of raw material, as well as the quality and dimensional structure of sawn products, depends on method of sawing (Skakić, 1985). Main goal of this research is to determine the influence of the different method of sawing (live and modified Slavonian method), on quantitative, qualitative and value yields of oak timber. This paper also theoretically and through experimentally researches the performance indicators of sawmill processing of Pedunculate oak (*Quercus robur* L.) lower qualitative classes logs and lower diameters of logs in sawn boards.

2. MATERIAL AND METHODS

The oak saw logs, 30–39 cm in diameter and 4 m long, were used in this research (*Figure 1*). Ten logs were prepared for live method of sawing (*Figure 2*) and the other ten for Slavonian sawing method (*Figure 3*).

Figure.1. Oak logs processed in research

Saw logs were made with almost the same quality and dimensions according HRN D.B4.028. Sawing pattern was not predefined but it was adapted according to quality, dimensions, and shapes of logs (visually identifying of logs). The main aim of processing those logs was to make products with highest quality and highest possible value. Before processing on log band saw measurements has been taken: length of log (l), diameters without bark (top end - d, mid length – dm, butt end – D).

Volume of logs without bark (V_l) was calculated according to the formula 1. (Šoškić *et al*., 2010).

$$V_1 = \frac{\left(\frac{d + d_m + D}{3}\right)^2 \pi}{4} \times l \quad (1)$$

Figure.2. Sawing pattern for live sawing method.

Figure.3. Sawing pattern Slavonian sawing method.

Values of diameters were calculated as the mean value of two cross measurements. All dimensions were rounded to the nearest centimetre without bark. The thickness of bark was measured with a precision of 0.2 mm, and the mean value of four sample measurements on each log was used. The volume of bark was calculated as the difference between volumes of each log with and without bark.

Primary sawing was carried out on a log band saw (Artiglio, ST110, flywheels diameter 1100 mm). Logs were sawn into 50 mm thick sawn boards, parallel to the central log axis. Blade parameters were: width - 140 mm (band saw), thickness – 1.47 mm (band saw), and breadth of swage set on one side – 0.3 mm.

Long and short edged sawn boards, half edged and un-edged sawn boards were produced. Standard applied in this process were HRN EN 975-1. Different kind of products, which were produced are presented by Figure 5. The quantitative yield was calculated by dividing the volume of sawmill products by the volume of logs without bark. Analysis of the sawmill product structure was done for each group of products (unedged and edged sawn boards), calculated as the share in the total volume of products. Due to its irregular shape, the total volume of large wood waste was calculated as a ratio of waste wood mass and wood density.

Based on five randomly chosen products from each log, by measuring their mass and dimensions average wood density was calculated. The difference between the log volume, sum of product volume and large wood waste volume obtained as the volume of sawdust.

A B C

Figure 5. A - Edged and half edged sawn boards, B – Un-edged and half edged sawn boards C - Large wood waste

Quantitative yield is a very important indicator of sawmill processing success. The objective assessment of the effects of production is often made by the value yield. This is often calculated by using the value of production, expressed in a currency per unit of the area or volume (Shepley et al., 2004).

This is a simple and practical method and it was used as one of the indicators of value yield in this research. Factors that can be included in the calculation of quantity, quality, and value yield and which in this research used were:

$Y_{Quantity}$ – quantity yield in form of sawn board and small sawn wood products

$\sum V_{sawn\ board}$ – total sawn board and small sawn wood products volume (m^3)

V_{log} – total log volume (m^3)

$V_{sawn\ board\ 1\ldots n}$ – single sawn board and small sawn wood products volume (m^3)

$N_{sawn\ board\ 1\ldots n}$ – number of sawn boards and small sawn wood products of the same volume

$Y_{Quality}$ – sawn board and small sawn wood products quality yield

$k_{sawn\ board\ 1\ldots n}$ – quality index of sawn board and small sawn wood products of the same quality group

$Y_{Quality\ €/m3\ sawn\ board}$ – monetary value of the sawn board and small sawn wood products quality yield (€/m^3)

cp – price of sawn board and small sawn wood products whose quality index is selected as 1 (€/m^3)

Y_{Value} – log value yield in the form of sawn board and small sawn wood products

$Y_{Value\ €/m3}$ log – monetary value of the log value yield in the form of sawn board and small sawn wood products (€/m^3)

Calculation was done according to the *Equations 2 to 6* (Brežnjak, 1997):

$$Y_{Quantity} = \frac{\sum V_{sawn\ board}}{V_{log}} \tag{2}$$

$$Y_{Quality} = \frac{V_{sawn\ board_1} \cdot k_{sawn\ board_1} + V_{sawn\ board_2} \cdot k_{sawn\ board_2} + \ldots + V_{sawn\ board_n} \cdot k_{sawn\ board_n}}{V_{sawn\ board_1} + V_{sawn\ board_2} + \ldots + V_{sawn\ board_n}} \tag{3}$$

$$Y_{Quality €/m3 sawnboard} = Y_{Quality} \cdot c_p \tag{4}$$

$$Y_{Value} = Y_{Quantity} \cdot Y_{Quality} \tag{5}$$

$$Y_{Value\ €/m3\ log} = Y_{Value} \cdot c_p \tag{6}$$

3. RESULTS AND DISCUSION

The values of calculated yield are shown in *Table 1* and *Table 3* and structures of sawmill products made of oak saw logs are shown in *Table 2* and *Table 4*. The data show quantitative yield of live and Slavonian method of sawing. The structure of quantity yield (%) for both sawing methods is shown also graphically (*Figures 6* and *7*). However, in this research differences were not statistically confirmed due to high variation within the groups.

Based on the product structure, Slavonian sawmill method clearly differed from live sawing, especially in the number of small sawn products.

Table 1. Calculated yield (%) based on the live sawing method

Yield	Method of sawing Live	
	Value	Unit
$Y_{quantity}$	62.24	%
$Y_{quality}$	68.57	%
$Y_{quality€/m^3}$	334.63	€
Y_{value}	42.68	%
$Y_{quality€/m^3\ log}$	208.27	€

Table 2. Structure of quantitative yield (%) based on the live sawing

Wood products	Live (%)
Un-edged boards	39.47
Half edged boards	0.00
Total, un-edged and half-edged wood	39.47
Edged boards L≥2m	3.77
Edged boards L<2m	6.50
Total, edged wood	10.27
Raw material yield	62.24
Large waste	12.90
Sawdust	14.86
Total Waste	27.76
Oversize	10.00
Total	100.00

Table 3. Calculated yield (%) based on the Slavonian sawing method

Yield	Method of sawing Live	
	Value	Unit
Y quantity	53.71	%
Y quality	82.48	%
Y quality€/m3	402.51	€
Yvalue	44.30	%
Y quality€/m3 log	216.19	€

Table 4. Structure of quantitative yield (%) based on the Slavonian sawing method

Wood products	Live (%)
Un-edged boards	5.65
Half edged boards	41.55
Total, un-edged and half-edged wood	47.20
Edged boards L≥2m	5.90
Edged boards L<2m	7.70
Total, edged wood	13.60
Raw material yield	53.71
Large waste	11.40
Sawdust	17.80
Total Waste	29.20
Oversize	10.00
Total	100.00

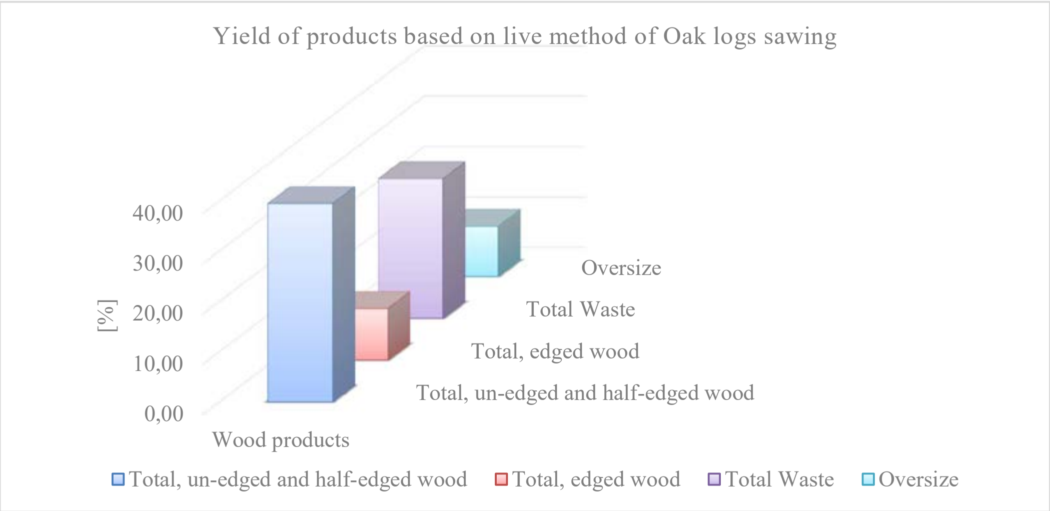

Figure.6. Yield of products for live method of Oak logs sawing.

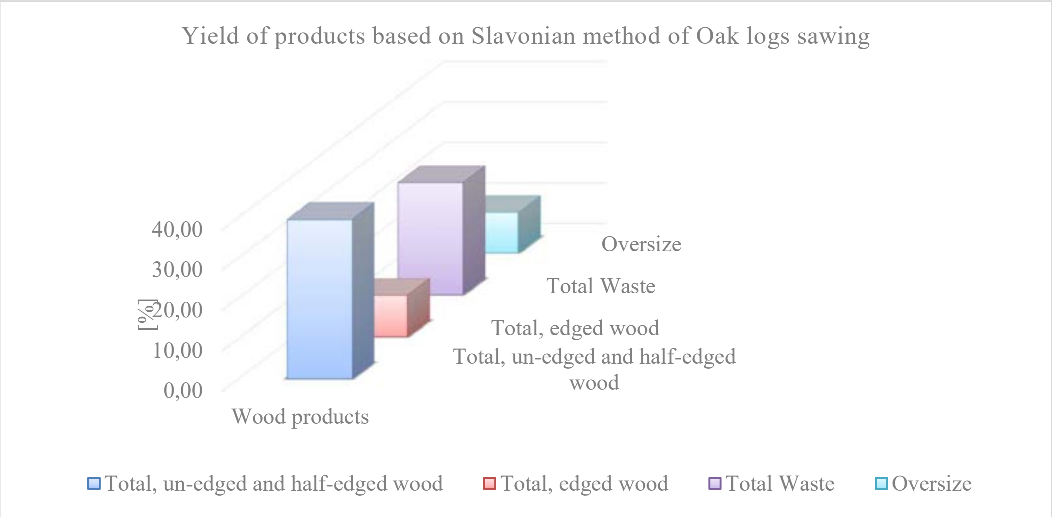

Figure.7. Yield of products for Slavonian method of Oak logs sawing.

4. CONCLUSIONS

Sawing methods have a strong influence on the final quantity of sawn products. Quantitative yield in live sawing of the oak logs observed in this research was around 62,24 %, quality yield 68,57 % (334,63 €/m³) and value yield 42,68 % (208,27 €/m³). Quantitative yield in Slavonian method sawing of the oak logs observed in this research was around 53,71 %, quality yield 82,48 % (402,51 €/m³) and value yield 44,30 % (216,19 €/m³). Structure of the sawn products was strongly depended by method of sawing. It can be concluded that live sawing yielded the least favourable results comparing with Slavonian sawing method and with some previous research works. Radial sawn boards were dominantly obtained by Slavonian method of sawing. Considering the market status of oak wood and sawmill products, greater attention should be given to economic indicators of the success of sawmill processing into this form of sawmill products.

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*** HRN D. B4. 028, HRN D. B4. 028/1 *Proizvodi iskorištavanja šuma, Trupci za piljenje, Listopadno drvo*

*** EN 975-1 2009: *Sawn timber Sawn timber. Appearance grading of hardwoods. Oak and beech.*

Comparison of Log Taper in Different Wood Species

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ABSTRACT

The rational yield of the sawlogs is one of the key factor for the prosperity of the sawmill capacity. One of the factors that significantly influence the maximum quantitative yield of sawlogs is the diameter taper. The diameter taper is an inevitable sawlogs occurrence and it is determined by the geometry of the logs. The diameter taper is defined as the difference between the diameters of the two ends of the log, alongside its length. Great differences between these two diameters adversely affect the percentage of maximum quantitative yield. This parametar plays a fundamental role in the classification of logs into quality classes. The aim of the paper is to compare the diameter taper in different wood species. Wood species of interest are: beech (*Fagus sylvatica* L.), pine (*Pinus sylvestris*, *Pinus nigra*), oak (*Quercus sessiliflora*), and fir/spruce (*Abies alba/Picea excelsa*). Log length is of important influence in the value of log taper. Therefore, the analysis for the different wood species will also present different groups of lengths, in order to determine the different values for the log taper. The selection of wood species is for the purpose of comparison of the taper values in deciduous and coniferous wood species.

Key words: diameter, length, log taper, quality class, sawlogs, wood species.

1. INTRODUCTION

The basic source of the raw material for processing in the wood industry facilities are the forest potentials, which are an important branch for the economic life of the human population. Of particular interest for the primary processing of wood are commercial and private forests, the way of managing them and the production of forest assortments, in order to obtain sawmill products of the highest class of quality after cutting and processing the raw material. Of particular importance for the primary processing of wood are the logs intended for mechanical processing.

The quality of the sawn lumber is determined by the quality of the sawlogs. In addition to the quality of the lumber, of particular importance for the technological process of primary processing, is the rational use of sawlogs. Sawlogs yield is defined as yield in the form of sawn lumber or as complex yield of sawlogs. The use of sawlogs is considered from the point of view of maximum quantitative, qualitative and valuable yield. Of particular interest is the maximum quantitative yield. Maximum quantity yield is defined by the amount of sawn lumber obtained from processing of the sawlogs. In practice, the maximum quantitative yield depends on several factors, such as: wood species, log profile, diameter taper, etc.

The diameter taper is defined as the difference between the diameter of the thick end and the diameter of the thin end of the sawlog. The drop in values of the diameters is determined by the geometry of the logs, the deviation from the ideal cylindrical shape. The shape is defined by the rapid or slow increasement of log thickness, in the direction from the thin end to the thick end. From that aspect, the large difference between the diameters of the two ends of the log lead to lower yields and this causes a greater number of cuts in order to obtain lumber with a constant width.

The paper analyzes the diameter taper in 4 wood species, 2 deciduous and 2 coniferous species, for the purpose of comparison.

1.1. Previous research

Saw logs with a constant length of 4,20 m from beech (*Fagus sylvatica* L.), distributed in thickness classes, as follows: 26,0 – 30,0 cm, 31.0 – 34.0 cm, 36.0 – 40.0 cm, 41.0 – 45.0 cm, 51.0 – 55.0 cm have a constant diameter taper of 1.0 cm/m. The sawlogs belong to I/III quality class. (Rabadziski, 1991)

The diameter taper of live stems, in trunk region, is greater in oak (*Quercus robur* L.) than in pine (*Pinus sylvestris* L.). The diameter taper varies along the length of the trunk, and is most pronounced in the lower parts. In the lower parts of the trunk, the dimeter taper is 3.5 times greater in oak than in pine. (Bilous *et al*., 2021)

In pine (*Pinus pinaster* Ait.), the diameter of the thick end, in 80 samples, ranges from 15.0 cm to 25.0 cm, and in 56 % of the samples, the diameter of the thick end ranges from 25.0 cm to 52.0 cm. The diameter of the thick end of the logs varies depending on the position in the trunk. In the logs from the lower part of the trunk, the average diameter of the thick end was 36 cm, and in the logs from the upper parts of the trunk, this diameter was 24.0 cm. Therefore, it is concluded that the diameter taper depends on the position of the logs in the trunk. The diameter taper of all logs from the trunk was an average of 9.0 mm/m, and ranged from 4.0 mm/m to 22.0 mm/m. Logs from the lower part of the trunk had a mean diameter taper of 13.0 mm/m, and logs from the upper part of the trunk had a mean diameter taper of 11.0 mm/m. Logs from the middle part of the trunk showed a diameter taper of 6.0 mm/m. (Pinto *et al*., 2003)

In pine logs (*Pinus sylvestris*) with a constant length of 5.0 m, the mean diameter was 48.3 ± 2.38 cm, and the diameter taper was 1.1 ± 0.091 cm/m. In 6.0 m long pine logs, the mean diameter was 42.2 ± 1.204, and dimeter taper was 1.1 ± 0.093 cm/m. Logs belonged to 1st, 2nd and 3rd quality class. (Rabadziski *et al*., 2017).

2. MATERIALS AND METHODS

The research was carried out under industrial conditions in the sawmill named "Tri Reki", village of Ratevo, Berovo. The research was conducted on the territory of the Republic of North Macedonia. In the analyzed sawmill, on an annual level, logs of conifer and hardwood origin are processed. The annual number of processed logs from beech is 3000 m^3, from oak 1000 m^3, from pine 3000 m^3, and from fir/spruce 1500 m^3. Part of the raw material for research originates from the Maleshevo mountain, territory of the Republic of North Macedonia, and part originates from the Republic of Bulgaria.

The classification of logs was carried out according to Macedonian standards MKC EN D.B4.028/1:1990, MKC EN D.C1.022 and MKC EN 1316-1:2013.

The work method consisted of:

– measuring logs,
– calculation of the mean diameter, the volume of the log and the diameter taper, and
– processing of the obtained data using statistical methods.

The measurement of the logs was carried out at the log warehouse. A wooden log rule caliper and steel tape were used to measure the dimensions of the logs. The diameters of both ends of the logs intended for processing were measured with a wooden log rule caliper. The log rule caliper was graduated in centimeters (*Figure 1*). The steel tape was 10 meters long, divided into meters, centimeters and decimeters, and the first meter is divided into millimeters. The length of the logs was measured with the steel tape. All measured parameters were registered in pre-prepared log tables.

The diameter was measured on each log separately. First the diameter of thin end, then the diameter of the thick end. The value of the mean diameter is the arithmetic mean of the measured values of the thin and the thick end of the log. The mean log diameter was calculated according to the formula:

$$D_m = \frac{d_1 + d_2}{2} \quad (1)$$

D_m – mean diameter of the log (cm)
d_1 – thin end diameter (cm)
d_2 – thick end diameter (cm)

The volume of the log is calculated according to the formula:

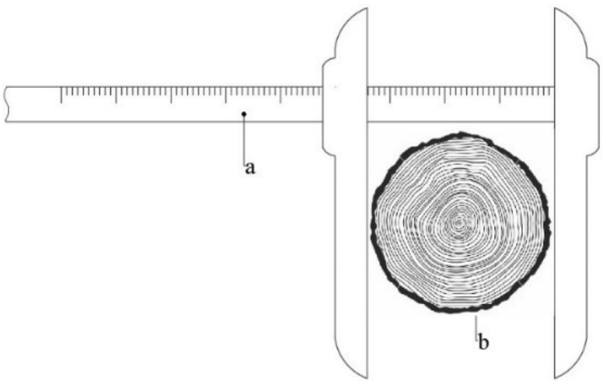
$$V = \frac{D_m \cdot \pi}{4} \cdot l \quad (2)$$

V – log volume (m^3)
l – log length (m)

The diameter taper represents a gradual increase in the diameter of the log along its length, from the thin end to the thick end. It is expressed in cm/m or in %. The diameter taper is shown in *Figure 2*. It is calculated according to the formula:

$$S = \frac{d_2 - d_1}{l} \quad (3)$$

S – diameter taper (cm/m)



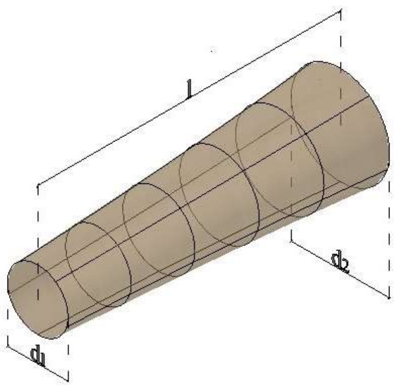


Figure 1. Log rule caliper for measuring the log diameters a – rule caliper, b – log.

Figure 2. Diameter taper.

Mihajlov (1968) suggested a model that divides the diameter taper into 5 thickness degrees of wood mass (*Table 1*).

Table 1. Thickness degrees according to Mihajlov (1968)

Thickness degree	Diameter taper (cm/m)
A	up to 0,5
B	0,5 ÷ 1,0
C	1,1 ÷ 1,5
D	1,51 ÷ 2,0
E	above 2,0

3. RESULTS AND DISCUSSION

A total of 120 beech logs were analyzed, 40 for each length group. Logs were divided into three length groups (2,3 and 4 m). Logs were classified within 1st, 2nd and 3rd quality class. A total amount of 55.789 m^3 of wood mass was analyzed. Regarding the diameter of the thin end, the smallest mean value occurred in the logs with a length of 3.0 m, while the largest value was found in the logs of 4.0 m. The diameter of the thick end had the smallest mean value for logs of 3.0 m, and the largest for logs of 4.0 m. The diameter taper was most pronounced in logs of 2.0 m, and the least in logs of 3.0 m. According to Mihajlov (1968), logs of 2.0 and 4.0 m length, coinciding with the mean value, associated with grade C, and logs with a length of 3.0 m associated with grade B. It can be concluded that for beech sawlogs, the most favorable diameter taper occurred in logs with a length of 3.0 m (*Table 2*). The obtained values for mean value, standard deviation and coefficient of variation show fairly equal values for all length groups. The data accuracy values shown (*Table 3*) are greater than 3 in all cases, indicating reliability of the data.

Table 2. Beech (Fagus sylvatica L.) sawlogs

Length group (m)	2.0	3.0	4.0
d_1 (cm)	27.0 ÷ 53.0	27.0 ÷ 52.0	28.0 ÷ 56.0
d_{1m} (cm)	4.,0	39.0	46.0
d_2 (cm)	29.0 ÷ 55.0	29.0 ÷ 58.0	30.0 ÷ 60.0
d_{2m} (cm)	44.5	44.0	48.0
d_m (cm)	28.0 ÷ 54.0	28.0 ÷ 55.0	29.0 ÷ 58.0
d_{mm} (cm)	42.5	42.0	47.0
S (cm/m)	1.00 ÷ 3.50	0.67 ÷ 3.00	0.25 ÷ 3.00
S_m (cm/m)	1.50	1.00	1.25
V (m^3)	12.495	17.466	25.828
K (Quality class)	1st, 2nd, 3rd	1st, 2nd, 3rd	1st, 2nd, 3rd
N (Total number of logs)	40	40	40

Table 3. Statistical data regarding beech (Fagus sylvatica L.) sawlogs

Length group (m)	Statistical values			Data accuracy			Normal distribution N		
	$x_m \pm f_{xm}$ (cm/m)	$\sigma \pm f_\sigma$ (cm/m)	$v \pm f_v$ (%)	$x_m/f_x > 3$ (cm/m)	$\sigma/ f_{\sigma} > 3$ (cm/m)	$v/f_v >$ 3 (%)	$x_m \pm \sigma$ (68.3 %)	$x_m \pm 2\sigma$ (95.4%)	$x_m \pm 3\sigma$ (9.7%)
2.0	1.81 ± 0.13	0.83 ± 0.09	45.77 ± 0.68	13.18 > 3	8.94 > 3	67.16 >3	0.98 ÷ 2.64	0.15 ÷ 3.47	0.67 ÷ 4.30
3.0	1.39 ± 0.12	0.75 ± 0.08	53.82 ± 0.84	11.75 > 3	8.94 > 3	63.65 > 3	0.64 ÷ 2.14	0.10 ÷ 2.89	0.85 ÷ 3.64
4.0	1.35 ± 0.12	0.75 ± 0.08	55.57 ± 0.90	11.24 >3	8.83 > 3	61.32 > 3	0.60 ÷ 2.10	0.15 ÷ 2.85	0.90 ÷ 3.60

x_m – mean, $f_{x,}$ - standard error of the mean, σ – standard deviation, f_σ – standard error of the standard deviation, v – coefficient of variation, f_v – standard error of the coefficient of variation

Table 4 shows the data regarding oak logs. A total number of 30 logs with a length of 3.0 m and 30 logs with a length of 4.0 m were analyzed, that is, 60 logs in total. The total volume of the logs was 36.962 m^3. Logs were graded within to 1st, 2nd and 3rd quality class. The analyzed logs were divided within two length groups, 3.0 m and 4.0 m logs. The thin end diameter and mean diameter were with a greater value in the case of 4.0 m logs. A greater diameter at the thick end was observed in the 3.0 m logs. The diameter taper was smaller for logs with 4.0 m length, and they belonged to grade C, while according to the diameter taper, logs with 3.0 m belonged to grade D (Mihajlov, 1968). The accuracy of the data (*Table 5*) was, in all cases greater than 3, which shows the reliability of the data. The data regarding the oak sawlogs was the smallest in comparison with the data for the other analyzed wood species. Oak logs showed a greater value for the mean diameter in comparison with the beech logs. In oak logs there was an occurrence of greater diameter taper in comparison with the beech logs.

Table 4. Oak (Quercus sessiliflora) sawlogs

Length group (m)	3.0	4.0
d1 (cm)	27.0 ÷ 62.0	28.0 ÷ 56.0
d1m (cm)	42.0	46.5
d2 (cm)	29.0 ÷ 7.0	30.0 ÷ 60.0
d2m (cm)	48.5	48.0
dm (cm)	28.0 ÷ 74.0	29.0 ÷ 58.0
dmm (cm)	45.0	46.5
S (cm/m)	0.67 ÷ 2.67	0.25 ÷ 3.00
Sm (cm/m)	2.00	1.37
V (m3)	16.441	20.521
K (Quality class)	1st,2nd,3rd	1st,2nd,3rd
N (Total number of logs)	30	30

Table 5. Statistical data regarding oak (Quercus sessiliflora) sawlogs

Length group (m)	Statistical values			Data accuracy			Normal distribution N		
	$x_m \pm f_{xm}$ (cm/m)	$\sigma \pm f_\sigma$ (cm/m)	$v \pm f_v$ (%)	$x_m/f_x > 3$ (cm/m)	$\sigma/ f_\sigma > 3$ (cm/m)	$v/f_v > 3$ (%)	$x_m \pm \sigma$ (68.3%)	$x_m \pm 2\sigma$ (95.4 %)	$x_m \pm 3\sigma$ (9.7 %)
3.0	1.63 ± 0.13	0.71 ± 0.09	43.26 ± 0.84	12.66 >3	7.74 > 3	51.17 >3	0.93 ÷ 2.34	0.22 ÷ 3.04	0.40 ÷ 3.75
4.0	1.43 ± 0.13	0.73 ± 0.09	51.60 ± 1.06	10.61 > 3	7.74 > 3	48.46 > 3	0.69 ÷ 2.17	0.04 ÷ 3.91	0.78 ÷ 3.65

x_m – mean, f_x, - standard error of the mean, σ – standard deviation, f_σ – standard error of the standard deviation, v – coefficient of variation, f_v – standard error of the coefficient of variation

A total number of 107 pine logs were analyzed. The pine sawlogs were divided according to their length. There were total of 27 saw logs with a length of 3.0 m, 40 saw logs with a length of 4.0 and 5.0 m each. The logs belonged to the 1st, 2nd and 3rd quality classes. A total of 70.14 m^3 of wood mass was analyzed. According to the log mass, pine sawlogs prevailed the analysis concerning this paper. The 4.0 and 5.0 m logs showed equal mean values for thin and thick end diameter and mean diameter. The diameter taper was most favorable in logs with a length of 5.0 m, and all three length groups showed a decrease in diameter of degree C (Mihajlov, 1968) (*Table 6*). The data showed accuracy in all cases (*Table 7*).

Table 6. Pine (Pinus sylvestris) sawlogs

Length group (m)	3.0	4.0	5.0
d_1 (cm)	28.0 ÷ 54.0	28.0 ÷ 53.0	28.0 ÷ 53.0
d_{1m} (cm)	38.0	43.0	43.0
d_2 (cm)	32.0 ÷ 57.0	30.0 ÷ 59.0	30.0 ÷ 59.0
d_{2m} (cm)	42.0	48.5	48.5
d_m (cm)	30.0 ÷ 55.0	29.0 ÷ 56.0	29.0 ÷ 56.0
d_{mm} (cm)	40.0	47.0	47.0
S (cm/m)	0.66 ÷ 3.00	0.50 ÷ 2.50	0.40 ÷ 2.20
S_m (cm/m)	1.33	1.37	1.20
V (m^3)	11.598	25.975	32.567
K (Quality class)	1st, 2nd, 3rd	1st, 2nd, 3rd	1st, 2nd, 3rd
N (Total number of logs)	27	40	40

Table 7. Statistical data regarding pine (Pinus sylvestris) sawlogs

Length group (m)	Statistical values			Data accuracy			Normal distribution N		
	$x_m \pm f_{xm}$ (cm/m)	$\sigma \pm f_\sigma$ (cm/m)	$v \pm f_v$ (%)	$x_m/f_x > 3$ (cm/m)	$\sigma/ f_{\sigma} > 3$ (cm/m)	$v/f_v > 3$ (%)	$x_m \pm \sigma$ (68.3 %)	$x_m \pm 2\sigma$ (95.4 %)	$x_m \pm 3\sigma$ (9.7%)
4.0	1.61 ± 0.13	0.65 ± 0.09	40.83 ± 0.87	12.73 > 3	7.34 > 3	46.76 > 3	0.95 ÷ 2.27	0.29 ÷ 2.93	0.36 ÷ 3.59
5.0	1.24 ± 0.09	0.49 ± 0.06	53.02 ± 0.89	13.26 > 3	7.48 > 3	47.84 > 3	0.74 ÷ 1.73	0.25 ÷ 2.23	0.24 ÷ 2.72
6.0	1.24 ± 0.09	0.49 ± 0.07	43.02 ± 0.90	13.26 > 3	7.48 > 3	47.84 > 3	0.74 ÷ 1.73	0.25 ÷ 2.23	0.24 ÷ 2.72

x_m – mean, f_x, - standard error of the mean, σ – standard deviation, f_σ – standard error of the standard deviation, v – coefficient of variation, f_v – standard error of the coefficient of variation

Fir/spruce sawlogs were divided into three length groups (*Table 8*). A number of 30 logs with a length of 3.0 m, 35 logs with a length of 4.0 m and 40 logs with a length of 5.0 m were analyzed. A total number of 105 fir/spruce logs were analyzed. Logs belonged to 1st , 2nd and 3rd quality class. The total wood mass of the logs was 67.377 m^3. Equal values for the mean thin end diameter ware observed for the 3.0 m and 5.0 m long logs. The highest value for the diameter of the thick end was observed for logs with a length of 3,0 m, and the lowest for logs with a length of 5.0 m. The mean diameter was the same for the 3.0 m and 5.0 m logs. The diameter taper was the lowest for the 5.0 m logs and they belonged to grade B (Mihajlov, 1968), as do the 4.0 m long logs, while the 3.0 m long logs belonged to grade D. The diameter taper of the 5.0 long fir/spruce sawlogs showed the most favorable values in the analyzed logs of coniferous origin. *Table 9* shows close values for the mean, standard deviation, and coefficient of variation for all length groups. It can be concluded that the data regarding the fir/spruce sawlogs is accurate.

Table 8. Fir/spruce (Abies alba Mill./Picea abies L.) sawlogs

Length group (m)	3.0	4.0	5.0
d_1 (cm)	27.0 ÷ 70.0	28.0 ÷ 56.0	28.0 ÷ 53.0
d_{1m} (cm)	42.0	44.0	42.0
d_2 (cm)	29.0 ÷ 72.0	30.0 ÷ 60.0	30.0 ÷ 59.0
d_{2m} (cm)	48.5	48.0	46.0
d_m (cm)	28.0 ÷ 71.0	29.0 ÷ 58.0	29.0 ÷ 55.0
d_{mm} (cm)	45.0	46.0	45.0
S (cm/m)	0.67 ÷ 3.00	0.25 ÷ 3.00	0.40 ÷ 2.20
S_m (cm/m)	2.00	1.25	1.00
V (m^3)	17.226	22.916	27.235
K (Quality class)	1st, 2nd, 3rd	1st, 2nd, 3rd	1st, 2nd, 3rd
N (Total number of logs)	30	35	40

Table 9. Statistical data regarding fir/spruce (Abies alba Mill./Picea abies L.) sawlogs

Length group (m)	Statistical values			Data accuracy			Normal distribution N		
	$x_m \pm f_{xm}$ (cm/m)	$\sigma \pm f_\sigma$ (cm/m)	$v \pm f_v$ (%)	$x_m/f_x > 3$ (cm/m)	$\sigma/ f_{\sigma} > 3$ (cm/m)	$v/f_v > 3$ (%)	$x_m \pm \sigma$ (68.3 %)	$x_m \pm 2\sigma$ (95.4 %)	$x_m \pm 3\sigma$ (9.7%)
4.0	1.60 ± 0.14	0.78 ± 0.10	47.53 ± 0.95	11.24 > 3	7.74 > 3	49.79 > 3	0.82 ÷ 2.38	0.04 ÷ 3.17	0.74 ÷ 3.95
5.0	1.42 ± 0.12	0.74 ± 0.08	52.25 ± 0.93	11.32 > 3	8.36 > 3	56.30 > 3	0.68 ÷ 2.74	0.06 ÷ 2.92	0.81 ÷ 3.67
6.0	1.06 ± 0.08	0.51 ± 0.06	48.46 ± 0.84	12.21 > 3	8.37 > 3	57.74 > 3	0.55 ÷ 1.58	0.03 ÷ 2.09	0.48 ÷ 2.61

x_m – mean, $f_{x,}$ - standard error of the mean, σ – standard deviation, f_σ – standard error of the standard deviation, v – coefficient of variation, f_v – standard error of the coefficient of variation

4. CONCLUSION

Diameter taper is defined as the difference between the diameter of the thick end and the diameter of the thin end of the sawlog. This parameter is determined by the geometry of the logs, precisely by the deviation from the ideal cylindrical shape. The shape is defined by the rapid or slow increase in the thickness of the log in the direction from the thin end to the thick end. The paper analyzed the diameter taper in 4 tree species, 2 deciduous tree species (beech and oak) and 2 coniferous tree species (pine and fir/spruce). In total, logs with a volume of 230.268 m^3 (392 logs) were analyzed.

Logs with a length of 3.0 m had the most favorable diameter taper in beech sawlogs. For oak, the most favorable values were for logs of 4.0 m. Beech sawlogs showed a smaller diameter taper than oak sawlogs. Pine sawlogs with a length of 5.0 m showed the most favorable diameter taper. Fir/spruce sawlogs with a length of 5.0 m had the lowest diameter taper value. The diameter taper in fir/spruce was smaller compared to pine. From the analyzed wood species, the smallest values (equal to S_m = 1.00 cm/m) of the mean diameter were present in oak and beech, while the largest values were present in oak sawlogs (S_m = 2.00 cm/m). Logs of coniferous origin (pine, fir/spruce) had lower values of the mean diameter taper compared to logs of hardwood origin (beech, oak).

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MKC EN 1312:2010 Round and sawn timber -- Determination of the batch volume of sawn timber

MKC EN 1313-2:2010 Round and sawn timber -- Permitted deviations and preferred sizes -- Part 2: Hardwood sawn timber.

MKC EN 1316-1:2013 Hardwood round timber -- Qualitative classification -- Part 1: Oak and beech.

Bio-Based Adhesives Made From Liquefied Wood, Tannin and Lignin

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ABSTRACT

Many of the wood adhesives are formaldehyde-based, which makes them harmful to health and the environment. Nowadays, there are many efforts to develop new bio-based adhesives that could at least partially replace formaldehyde adhesives. Three materials - liquified wood (LW), tannin (T) and lignin (L) - have been used to produce bio-based adhesives for wood bonding. Urea-formaldehyde (UF) was used as a reference adhesive. The curing process of the adhesives and the development of bond strength were observed using the Automated Bonding Evaluation System (ABES). In addition, shear tests (EN 205) were performed on the bonded joints. The ABES results confirmed UF as the fastest curing adhesive, followed by bio-based adhesives from T, L and LW. The average shear strength for an LW adhesive was 6.8 N/mm^2 and did not reach the minimum value of 10 N/mm^2 required for durability class C1 (EN 12765). The T and L adhesives met this limit with average values of 11.4 and 10.3 N/mm^2, respectively. However, the UF adhesive showed the best bonding performance with an average value of 14.0 N/mm^2.

Key words: Adhesive, lignin, liquified wood, tannin, urea-formaldehyde

1. INTRODUCTION

Various biocomponents such as tannin, lignin, liquefied wood, etc. can be used to produce adhesives (Pizzi, 2016). Due to their phenolic origin and large natural occurrence, tannins and lignins are considered the most promising solutions among the above-mentioned biocomponents for the replacement of synthetic formaldehyde-based adhesives in wood panels (Saražin *et al.*, 2020). Several attempts to produce different tannin or/and lignin adhesive formulations have been successful on a laboratory scale; some of them have also proven successful in industrial applications.

Another natural substitute for synthetic adhesives for bonding wood are liquefied lignocellulosic materials (Pizzi, 2006). Liquefied wood (LW) has been successfully used several times as a raw component for the synthesis of LW-based adhesives (Kobayashi *et al.*, 2000; Kishi *et al.*, 2011), as an additive to commercially available synthetic resins (Hassan *et al.*, 2009; Esteves *et al.*, 2015) or as a stand-alone wood adhesive (Wan *et al.*, 2017; Ugovšek and Šernek, 2013). The main problem associated with LW adhesives is the low resistance of the adhesive compounds to decomposition due to increased relative humidity or water.

The application of these bioadhesives in the wood industry requires detailed knowledge of the mechanical properties of the bonded joints and the determination of suitable pressing parameters. The characterization of the curing process of an adhesive makes it possible to determine the optimal pressing parameters, which is essential for the economical production of wood-based composites. Various laboratory-scale techniques provide insight into the curing process of adhesives by measuring the differences in various adhesive parameters.

In this study, the curing process of tannin-based adhesives, lignin-based adhesives and liquefied wood- based adhesives was investigated using the Automated Bonding Evaluation

System (ABES). Urea-formaldehyde (UF) was used as a reference adhesive. Standardised shear tests were also carried out on the bonded joints.

2. MATERIALS AND METHODS

2.1. Adhesives

The curing process of three bio-based adhesives and one synthetic adhesive (*Table 1*) was observed with ABES.

Table 1. List of studied adhesives

Label	Adhesive	Basic component	Other components
T	Tannin	Pine tannin	Hexamethylenetetramine
L	Lignin	Organosolv lignin	Dimethyl carbonate and Hexamethylenediamine
LW	Liquefied wood	Wood - tree of heaven	Ethylene glycol and Sulfuric acid
UF	Urea-formaldehyde	Urea	Formaldehyde

2.1.1 Tannin adhesive (T)

The tannin-hexamine adhesive mixture was prepared in the following steps: (1) First, 40 units by weight of pine tannin powder was dissolved in 60 units by weight of distilled water. (2) The pH was adjusted from 6.5 to 7.0 with NaOH. (3) 6 units by weight of a 40 % aqueous solution of hexamine was added (as 6 % hexamine dry weight to tannin dry weight). The density of the prepared adhesive was determined to be 1.04 g/cm³ and the solids content 35.6 %. This adhesive was presented in detail in a previous study (Saražin *et al.*, 2021a).

2.1.2 Lignin adhesive (L)

First, 25.9 units by weight of organosolv lignin powder were poured into a three-necked flask with a reflux condenser and thermometer. Then, 17.5 units by weight of dimethyl carbonate and 21.6 units by weight of distilled water were added and stirred with a magnetic stirrer at 50 °C for 40 minutes and then cooled to room temperature. A total of 35.1 units by weight of hexamethylenediamine was then added to the mixture and stirred at 90 °C for 120 minutes with a magnetic stirrer. The resin was then cooled to room temperature and was ready for use. The pH of the adhesive produced was determined to be 12.0 and the solids content 46 %. This adhesive was presented in detail in a previous study (Saražin *et al.*, 2021b).

2.1.3 Liquefied wood adhesive (LW)

The LW was obtained by liquefying the sieved particles of the wood of the tree of heaven (*Ailanthus altissima* (Mill.) Swingle) with a maximum size of 0.237 mm; 200 g of the oven-dried (103 °C, 24 h) wood particles were placed in a three-neck glass reactor containing 600 g of ethylene glycol (Honeywell, Charlotte, USA) and l8 g of 96 % sulfuric acid (KEMIKA d.d., Zagreb, Croatia).

The glass reactor was immersed in an oil bath heated to 180 °C and equipped with a water condenser. The liquefaction process was carried out in 120 minutes under mechanical stirring (500 min^{-1}). The liquefied product was decanted into a glass, diluted with a mixture (4:1) of 1,4-dioxane and distilled water, and filtered through paper filter disks (grade 388, Sartorius, Göttingen, Germany) to remove the insoluble parts.

The mixture of 1,4-dioxane and water was evaporated at 55 °C under vacuum (10 mbar) using a rotavapor apparatus (R-210, Büchi Labortechnik AG, Flawil, Switzerland) and a vacuum pump (PC 3003 Vario, Vaccubrand GmbH & Co. KG, Wertheim, Germany). Ethylene glycol was then evaporated from the liquefied product at 120 °C and 10 mbar using the same equipment. Evaporation was stopped when the gravimetric ratio between wood and ethylene glycol reached approximately 1:1. This adhesive was described in detail in a previous study (Žigon *et al.*, 2023).

2.1.4 Urea-formaldehyde adhesive (UF)

A commercial urea-formaldehyde adhesive (W-leim plus 3000, Dynea, Lillestrøm, Norway) was tested as a reference; 59 units by weight of urea-formaldehyde powder were mixed with 41 units by weight of distilled water. The density of the adhesive produced was determined as 1.183 g/cm³, the pH value as 6.4 and the solids content as 53.7 %.

2.2 Determination of the adhesive bond strength development with ABES

Adhesive bond strength development was evaluated with ABES (Adhesive Evaluation Systems Inc., Oregon, USA) in accordance with ASTM D7998-19 and previous studies (Saražin *et al.*, 2022; Žigon *et al.*, 2023). ABES is a combination of a small hot press and a tensile testing machine (*Figure 1*), which makes it possible to determine the adhesive bond strength immediately after the desired pressing time or regime.

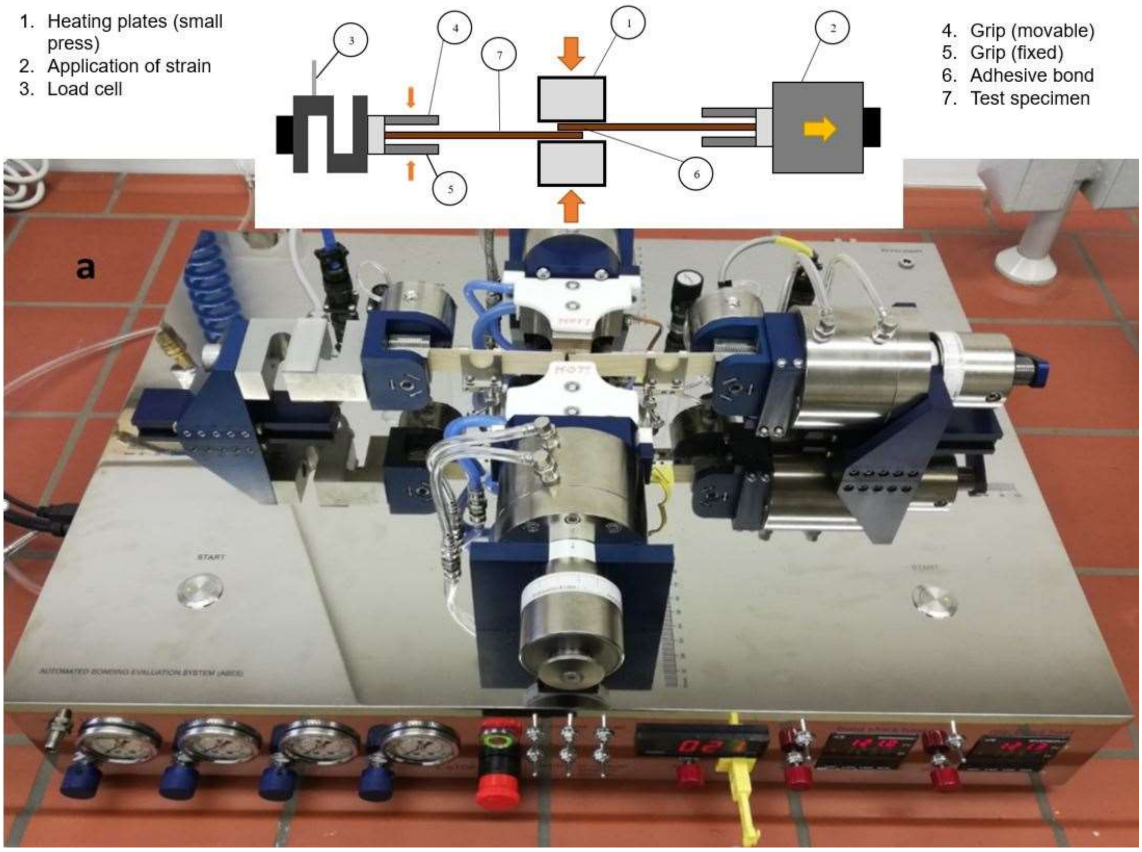

Figure 1. Automated Bonding Evaluation System (ABES)

Two 0.84 mm thick beech veneers (*Fagus sylvatica* L.) (*Figure 2*) were bonded in the ABES hot press at selected temperatures and different pressing times. The geometry of the bonded area of the veneer overlap joints was 5 mm × 20 mm. The mass of the tested adhesive was approximately 20 mg (i.e., the application rate was 200 g/m^2).

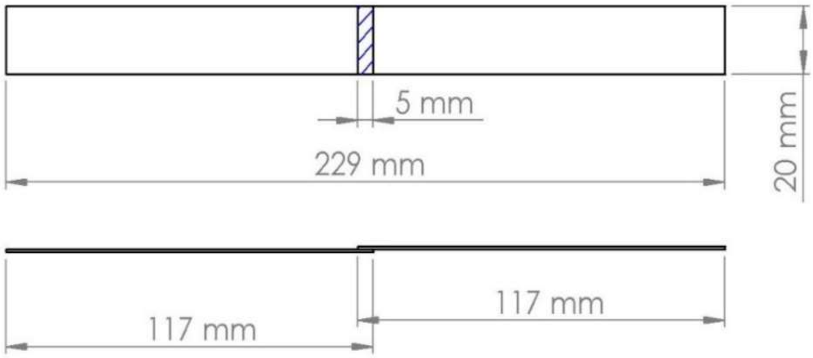

Figure 2. Test specimen for ABES, consisting of two veneers with bonded overlap of 5 mm × 20 mm area

Different pressing times between 10 s and 600 s (10 to 12 per observed temperature) were chosen to determine the development of bond shear strength over time. The pressing temperatures varied for the different adhesives and ranged from 75 °C to 225 °C.

After opening the hot press, the bonded joint was cooled for 5 s with compressed air. The actual temperature transition to the bond line was observed with a type K thermocouple for each of the temperatures tested.

The final step was to test the shear strength of the bonded joint. The overlap joint was pulled until it broke (approx. 10 s after opening the hot press). The maximum force achieved was compared to the bonded area and the resulting shear strength was expressed in N/mm².

Each of the tested sequences with ABES was modelled with a three-parametric logistic function (Eq. 1) with non-linear regression (Saražin *et al.*, 2022).

$$f(t) = \frac{\beta}{1+\exp(-\kappa(t-\gamma))} \quad (1)$$

where f(t) is the shear strength of the bonded joint, t is the time from the start of pressing (s), β determines the upper asymptote of the shear strength, κ is the slope of the curve and γ is the time at which the maximum growth occurs.

2.3 Tensile shear strength test

The performance of the adhesives was also evaluated using a tensile shear strength test described in the EN 205 (2016) and EN 12765 (2016) standards. Beech wood lamellas conditioned to 10 % moisture content with a length of 600 mm, a width of 135 mm and a thickness of 5 mm were used as a substrate. Two two-layer assemblies were bonded with each adhesive mixture (200 g/m^2) using a conventional hot press at 180 °C for 15 min. Twenty single-lap joint specimens (*Figure 3*) with a length of 150 mm and a width of 20 mm were cut out of the bonded assemblies one day after completion of bonding and stored in a climate chamber (20 ± 2 °C, relative humidity of 65 ± 5 %) for 7 days (conditioning procedure C1). Half of the specimens were additionally immersed in cold (20 ± 5 °C) water for 24 hours (conditioning procedure C2). Finally, the tensile shear strength of the lap joints was determined using a Z005 universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany).

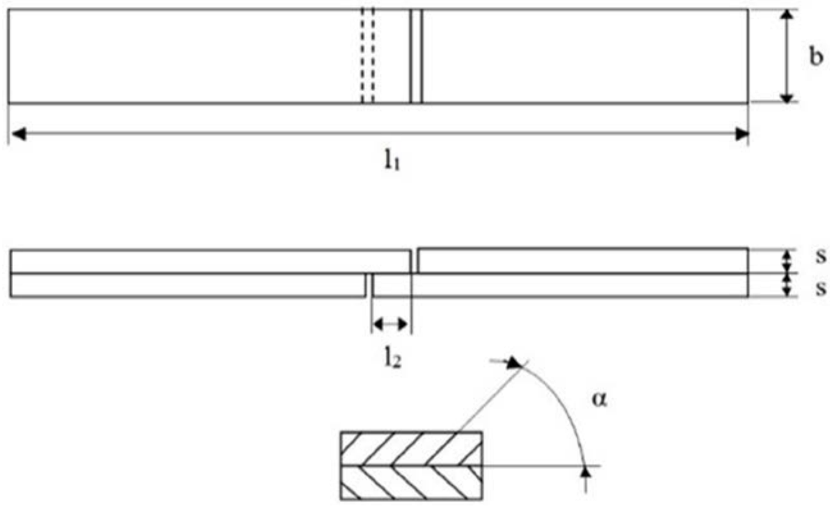

Figure 3. Lap joint shear test specimen (l_1 = 150 mm, b = 20 mm, s = 5 mm, l_2 = 10 mm and α = 30-90°)

3. RESULTS AND DISCUSSION

3.1 Adhesive bond strength development

The development of bond strength (i.e., shear strength as a function of pressing time) was determined with ABES at different pressing temperatures for each of the adhesives tested, as shown in Figures 4, 5, 6 and 7.

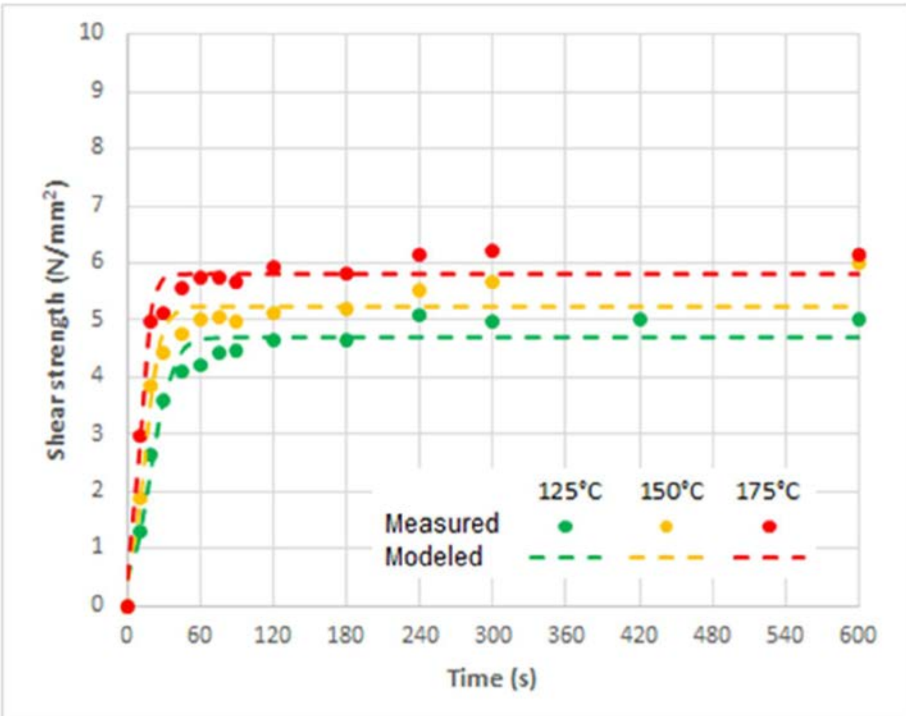

Figure 4. Development of the shear strength of tannin (T) adhesive bonds (Saražin et al., 2022)

The pressing temperature significantly influenced the development of the shear strength of the tannin adhesive bond. The highest shear strength of the tannin adhesive bonds was around 6 N/mm^2.

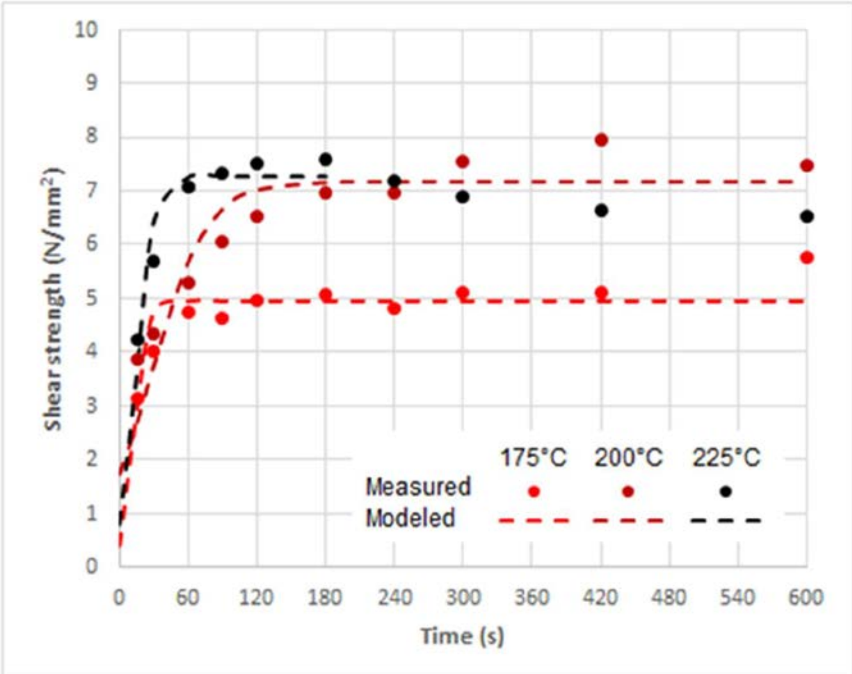

Figure 5. Development of the shear strength of lignin (L) adhesive bonds (Saražin et al., 2022)

The lignin adhesive required a much higher pressing temperature for sufficient strength. The highest shear strength of the lignin adhesive bonds was about 8 N/mm^2.

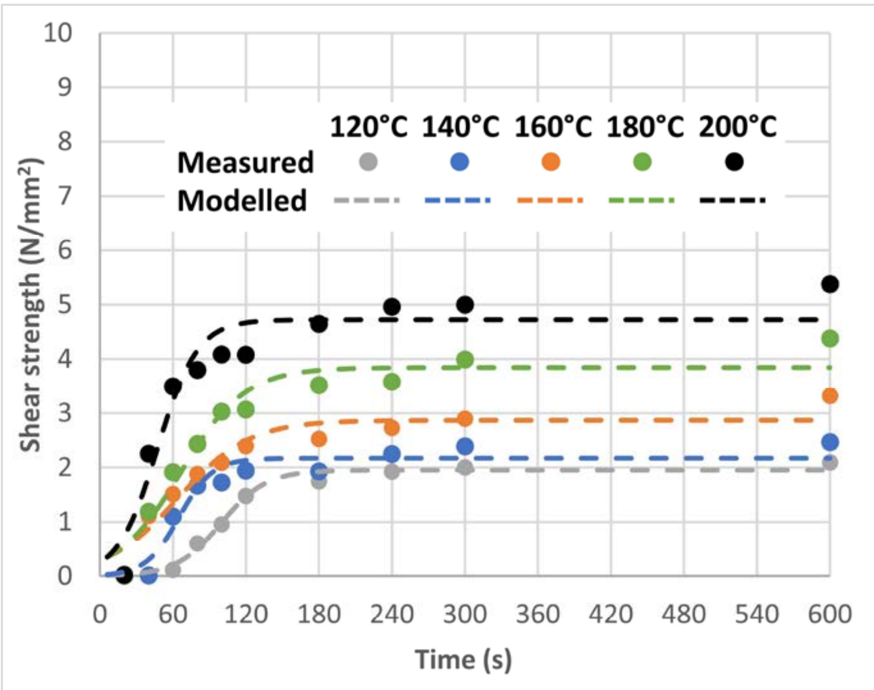

Figure 6. Development of the shear strength of liquified wood (LW) adhesive bonds (Žigon et al., 2023)

It has been shown that a higher pressing temperature leads to stronger LW adhesive bonds. The higher the pressing temperature, the shorter the pressing time required to achieve a maximum increase in bond strength. The highest shear strength of the LW bonds was around 5 N/mm^2.

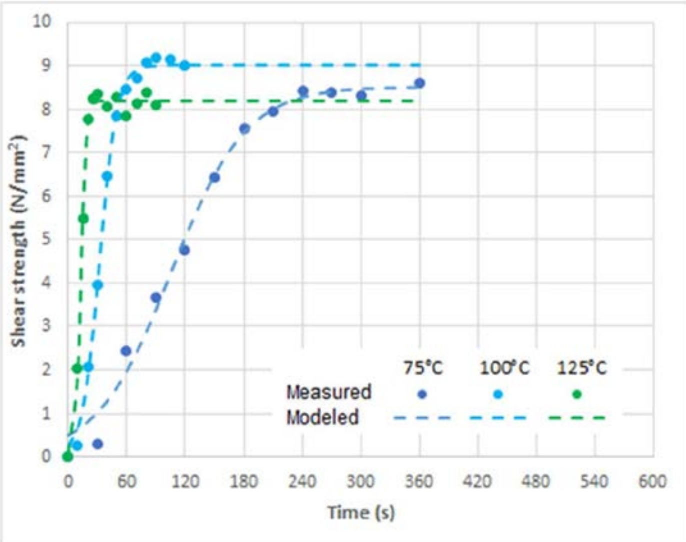

Figure 7. Development of the shear strength of urea-formaldehyde (UF) adhesive bonds (Saražin et al., 2022)

The ABES results confirmed that UF was the strongest (9 N/mm^2) and fastest adhesive tested. The optimum pressing for UF adhesive would be 1.5 min at 100 °C, for T adhesive 4 min at 175 °C, for LW adhesive 4 min at 200 °C and for L adhesive 7 min at 200 °C.

3.2 Tensile shear strength

The results showed that T, L and UF adhesives achieved the minimum tensile shear strength value of 10 N/mm^2 (durability class C1) prescribed by the EN 12765 standard, whereas the adhesive based on LW did not (*Table 2*). None of the adhesives tested met the requirements of durability class C2 (7 N/mm^2). The comparison of the shear strength achieved with the ABES and the standardised shear test showed that the strength values of the tensile shear test were higher than those of the ABES. The reasons for this lie in the different thickness of the wood substrate for bonding (the standardised shear test uses 5 mm thick solid wood, while the ABES uses 0.84 mm thin veneer) and in the time between the pressing and testing steps (the standardised test requires a 7-day conditioning of the specimens, while in the ABES hot specimens are tested immediately after pressing).

Table 2. Average shear strength (N/mm^2) of adhesive bonds after different pre-treatments

Adhesive	Conditioning procedure C1	Conditioning procedure C2
T	11.4	3.7
L	10.3	3.1
LW	6.8	0.5
UF	14.0	3.2
Standard requirement	10.0	7.0

4. CONCLUSION

The ABES results confirmed UF as the fastest curing adhesive, followed by bio-based adhesives from T, LW and L. The pressing temperature significantly influenced the dynamics of strength development of adhesive bonds. The average shear strength for an LW adhesive was 6.8 N/mm^2 and did not meet the minimum shear strength value (10 N/mm^2) required for durability class C1. The T and L adhesives met this limit with average values of 11.4 and 10.3 N/mm^2, respectively. However, the UF adhesive showed the best bonding performance with an average value of 14.0 N/mm^2.

Acknowledgements: *This research was financed by the ERA-CoBioTech project WooBAdh and by the Slovenian Ministry of Education Science and Sport; the Slovenian Research Agency within the framework of the programs P4-0015 and P4-0430; and ASFORCLIC project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°952314.*

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Maximizing Process Efficiency in the Wood Industry: A Case Study of FMEA in GoSoft ERP

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ABSTRACT

Failure Modes and Effects Analysis (FMEA) is a systematic approach traditionally employed to identify and prevent failures and risks in manufacturing and business environments. This research explores the application of the FMEA method using the GoSoft software for Enterprise Resource Planning (ERP) in wood industry companies. The primary objective of this study is to explore how the FMEA method can be integrated and implemented within the GoSoft ERP system to improve quality management, risk management, and process optimization. The study analyses the steps involved in applying FMEA within this ERP context and assesses how this integration can support organizations in achieving better operational control, minimizing risks, and optimizing product or service quality. Practical examples of FMEA implementation in the GoSoft software are explored, providing insights into both benefits and challenges during the implementation process. This paper provides valuable insights into the advantages of integrating FMEA with the GoSoft ERP system, encouraging further exploration and application of this strategy for improving business processes and quality across various industries.

Key words: Enterprise Resource Planning, Failure Modes and Effects Analysis, GoSoft, Wood Industry

1. INTRODUCTION

The wood industry holds crucial significance in promoting sustainability, climate action, economic growth, and making an integral contribution to the construction sector (EOS, 2023). The wood-based industries significantly contribute to the EU's manufacturing landscape, encompassing woodworking, furniture, pulp and paper, and printing. In 2020, these industries constituted one in five manufacturing enterprises in the EU, emphasizing their widespread presence, particularly among small or medium-sized enterprises. The wood-based industries employed 3.1 million persons across the EU in 2020 or 10.5 % of the manufacturing total (Eurostat, 2022). Regarding economic impact, the Gross Value Added - GVA of wood-based industries in the EU reached €136 billion in 2020, comprising 7.2 % of the total manufacturing industry (Eurostat, 2022).

In today's saturated market, there has been a notable shift in production strategies in the wood industry, moving away from the sole emphasis on increasing volume recovery. Unlike older research, which primarily focuses on volume-optimized solutions, contemporary approaches prioritize the quality of final products (Hosseini and Peer, 2022). More than ever, quality has become affecting a company the competitive advantages and financial performance (Zhang *et al.*, 2022). One extensively utilized methodology for addressing these challenges is Failure Mode and Effects Analysis (FMEA). This structured approach is designed to systematically identify and analyse potential failure modes within a system, subsequently developing strategic measures to mitigate or eliminate them proactively before they manifest (Wu *et al.*, 2021). FMEA has garnered broad applicability across various industries, including healthcare, aerospace, and automotive manufacturing, underscoring its efficacy as a tool for augmenting the safety and reliability of manufacturing processes. The application of the FMEA method is suitable for every business process within the company's IPO (Input, Process, and

Output) chain, covering the entire spectrum from initiation to completion. Monitoring risks in business processes enables the reduction of malfunctions and economic losses. At the same time, preventive measures are intended to avert the occurrence of risks and their impact on business performance across economic, technological, technical, social, and environmental dimensions (Teplická *et al.*, 2022).

In conjunction with the increasing complexity of products, services, and customer expectations, strong market pressures prompt companies to use sophisticated software to sustain their operations (Baykasoğlu and Gölcük, 2017). Enterprise Resource Planning (ERP) software is one solution that assists companies in integrating all business functions for operational efficiency and effectiveness. Notably, the integration of Failure Mode and Effects Analysis (FMEA) within the ERP system can further enhance operational efficiency by proactively addressing and mitigating potential failure modes during the implementation process. Given that ERP implementations are risky and challenging endeavours, companies should be supported with appropriate risk management tools, including the integration of FMEA, to eliminate potential failures and increase overall effectiveness. It is evident that awareness of the importance of ERP risk management tools, including the integration of FMEA, is growing for the success of implementation projects.

This research explores the integration and implementation of the FMEA method within the GoSoft Enterprise Resource Planning (ERP) system for wood industry companies. The primary objective is to investigate how FMEA, implemented through GoSoft ERP, can enhance quality management, risk management, and overall process optimization. The study will analyse the steps involved in applying FMEA within the ERP context, evaluating its impact on operational control, risk reduction, and product/service quality. Practical examples of FMEA implementation in the GoSoft software will be examined, providing insights into both benefits and challenges during the implementation process. This paper contributes valuable insights into the advantages of integrating FMEA with the GoSoft ERP system, encouraging further exploration and application of this strategy for improving business processes and quality across various industries.

2. RESEARCH METHOD

The Failure Mode and Effects Analysis (FMEA) is a systematic methodology for identifying potential failures in a product or process, assessing their impact, and developing measures to prevent or mitigate them (Wanas and Ramadan, 2018). FMEA typically involves a team of experts analysing the system or product in question by breaking it down into its components and sub-components. For each component, the team identifies potential failure modes (i.e., ways in which the component could fail), their effects on the system or product, and the likelihood of occurrence and detection. Based on this analysis, the team then develops recommendations for reducing the risk of failure, such as redesigning components, improving testing procedures, or adding redundancies.

Traditionally, FMEA prioritizes potential failures through the Risk Priority Number (RPN), a product of severity, occurrence, and detection (Stamatis, 2019). Severity assesses the seriousness of potential consequences, occurrence estimates the frequency of failure causes, and detection gauges the ability to identify errors before production or customer notice. FMEA utilizes the RPN score, which is determined by multiplying the probability of occurrence (O), the severity of the failure (S), and the likelihood of detection (D) (Kushwaha *et al.*, 2020). Severity, occurrence, and detection are evaluated on a 10-point scale, leading to an RPN value between 0 and 1000. Failure modes are then categorized as low, medium, or high risk, guiding necessary actions, with corresponding colours in GoSoft indicating risk significance levels (low - green, medium - yellow, or high risk - red). Low-risk scenarios require no corrective actions, medium-risk scenarios involve limited actions, while high-risk scenarios demand substantial changes in system, design, product, and process. Prioritization within the same RPN involves addressing greater severity first, followed by detection and occurrence (Sartor and Cescon, 2019).

The FMEA methodology is implemented in the GoSoft ERP, offering a systematic approach to identify, analyse, and manage potential risks in wood industry processes. In this paper, the key functions of the FMEA method integrated into the GoSoft ERP system are studied. The method, applied within GoSoft ERP, involves a gradual investigation of potential flaws in construction, production, assembly, or the product or service itself, applied in a wood industry company.

3. FMEA IN THE GOSOFT ERP SYSTEM

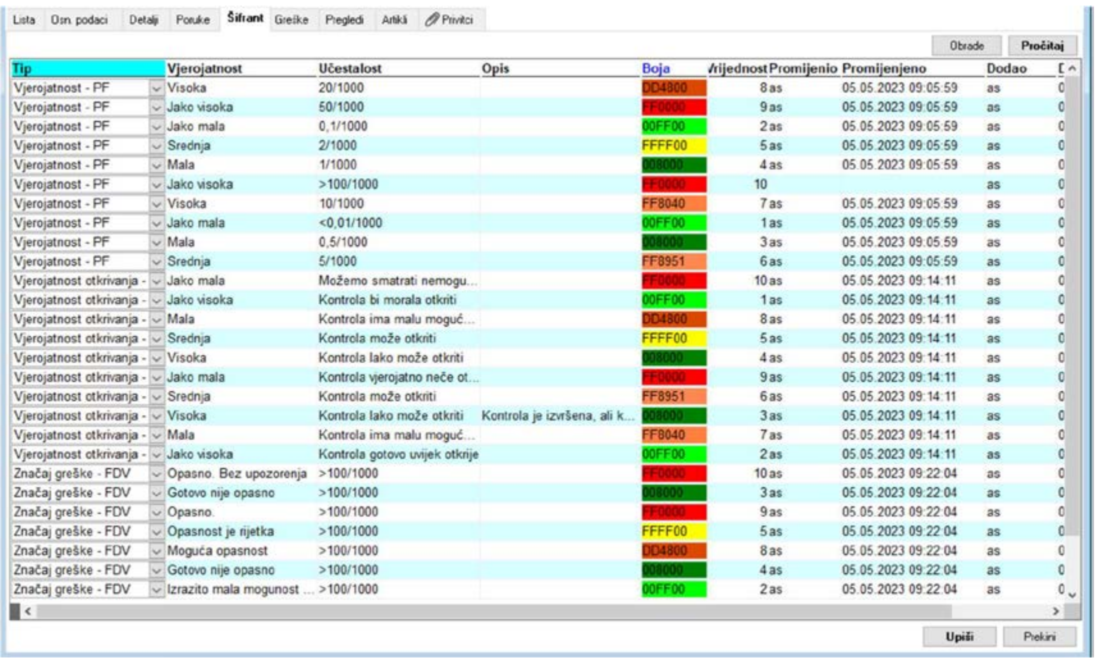
One of the key functions of the FMEA method in the ERP system is risk identification. The ERP system may contain a module or functionality that identifies potential risks at various stages of business processes. Users within the organization can create lists of potential failures, rank them according to the FMEA method, and assign them to responsible individuals for further analysis and action. Additionally, FMEA functionality can be linked to other modules within the ERP system to ensure the integrity and consistency of information. For instance, information about identified risks and action plans can be linked to quality management, procurement, or human resources management modules, contributing to more effective risk management throughout the organization. Teams using FMEA within the ERP system include quality experts, risk management teams, and process engineers. Their responsibilities encompass the implementation and improvement of the ERP system, failure analysis, impact assessment, and proposing preventive measures to ensure continuous quality and reduce risks within the ERP system. The application of the FMEA method within the ERP system aims to reduce risks, improve quality, optimize processes, and increase customer satisfaction. By identifying potential failures, assessing their effects, and taking preventive measures, a company can minimize the risk of failures, enhance operational efficiency, and ensure high-quality services or products it offers.

In this academic article, we will look at the GoSoft information system, shedding light on its use for control using FMEA as a key component within the system. Perić *et al.* (2022) conducted a study illustrating how FMEA can be leveraged to assess the severity, occurrence, and detection of potential failures while implementing ERP systems in the wood industry. The study highlights the critical success factors that contribute to successful ERP implementation, including IT infrastructure, consultant support, ERP performance assessment, and employee training. By utilizing FMEA, organizations can proactively manage risks and measure performance at each stage of ERP implementation, facilitating continuous improvement and ensuring the system meets intended goals and delivers positive business outcomes (Perić *et al.,* 2022). GoInfo is a prominent computer engineering, services, and consulting company with a presence in Nova Gorica (Slovenia), and Zagreb (Croatia). GoInfo has leveraged its expertise to develop software tailored to the specific needs of manufacturing companies, rooted in the Manufacturing Resource Planning (MRP) II principle. Under the name „GoSoft“ the company's information system has emerged as a leading solution for the management of manufacturing enterprises. Notably, GoSoft has earned acclaim from businesses across Croatia, Slovenia, Bosnia and Herzegovina, and Serbia for its remarkable adaptability and applicability as an ERP system. Its exceptional quality and user-friendliness make it a standout choice in the industry. The system is used by a variety of companies in different sectors, with manufacturing companies being the primary users. Basic modules that are an integral part of GoSoft include sales, logistics, technical data on items, technologies, and workplaces, production, quality control, and various analyses that show the movement of goods in warehouses, sale of individual items costs, production costs, procurement costs, and many other analyses based on collected and saved data within the database that can be used as support for making timely and correct business decisions. GoSoft is an interactive information system that covers all major functions required by manufacturing companies or public institutions. It helps in planning and managing the production process from raw materials to finished products, while also reducing costs, improving quality, and optimizing resources.

As part of implementing the GoSoft information system, a specialized Quality Control Error Type has been developed to address imprecise measurements and systematic input of important data such as basic information, details, messages, codes, and identified errors. This data is collected meticulously as part of the FMEA and requires the assimilation of foundational information related to construction, production, assembly processes, or the specific product/service. To facilitate comprehensive analysis, the critical data sets are systematically entered into the ERP system. Creating basic FMEA data involves steps such as selecting the analysis type (process or construction/design), assigning a unique identification code, and specifying the version for tracking alterations.

Other essential details include determining the analysis status, providing a descriptive overview, inputting relevant identifiers, designating responsible individuals, and establishing dates for analysis execution, creation, and approval. Once these fundamental steps are completed, the analysis progresses to a detailed examination, in which potential deficiencies and their corresponding effects are identified within the FMEA framework. This detailed examination is crucial to identify and address any potential issues before they can escalate into more significant problems.

In the encryption scheme, the most important step establishing classes of frequencies or influences of errors and assigning them specific scores. Additionally, each class is associated with a designated colour, and on the detailed page (*Figure 1*), the corresponding column is shaded in this specific colour. It's important to calculate the column Grade, which is the product of the three preceding columns, based on the settings specified in the key.



Tip	Vjerojatnost	Učestalost	Opis	Boja	Vrijednost	Promijenio	Promijenjeno	Dodao	[
Vjerojatnost - PF	Visoka	20/1000		DD4800	8	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Jako visoka	50/1000		FF0000	9	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Jako mala	0,1/1000		00FF00	2	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Srednja	2/1000		FFFF00	5	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Mala	1/1000		008000	4	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Jako visoka	>100/1000		FF0000	10			as	0
Vjerojatnost - PF	Visoka	10/1000		FF8040	7	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Jako mala	<0,01/1000		00FF00	1	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Mala	0,5/1000		008000	3	as	05.05.2023 09:05:59	as	0
Vjerojatnost - PF	Srednja	5/1000		FF8951	6	as	05.05.2023 09:05:59	as	0
Vjerojatnost otkrivanja -	Jako mala	Možemo smatrati nemogu...		FF0000	10	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Jako visoka	Kontrola bi morala otkriti		00FF00	1	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Mala	Kontrola ima malu moguć...		DD4800	8	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Srednja	Kontrola može otkriti		FFFF00	5	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Visoka	Kontrola lako može otkriti		008000	4	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Jako mala	Kontrola vjerojatno neće ot...		FF0000	9	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Srednja	Kontrola može otkriti		FF8951	6	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Visoka	Kontrola lako može otkriti	Kontrola je izvršena, ali k...	008000	3	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Mala	Kontrola ima malu moguć...		FF8040	7	as	05.05.2023 09:14:11	as	0
Vjerojatnost otkrivanja -	Jako visoka	Kontrola gotovo uvijek otkrije		00FF00	2	as	05.05.2023 09:14:11	as	0
Značaj greške - FDV	Opasno. Bez upozorenja	>100/1000		FF0000	10	as	05.05.2023 09:22:04	as	0
Značaj greške - FDV	Gotovo nije opasno	>100/1000		008000	3	as	05.05.2023 09:22:04	as	0
Značaj greške - FDV	Opasno.	>100/1000		FF0000	9	as	05.05.2023 09:22:04	as	0
Značaj greške - FDV	Opasnost je rijetka	>100/1000		FFFF00	5	as	05.05.2023 09:22:04	as	0
Značaj greške - FDV	Moguća opasnost	>100/1000		DD4800	8	as	05.05.2023 09:22:04	as	0
Značaj greške - FDV	Gotovo nije opasno	>100/1000		008000	4	as	05.05.2023 09:22:04	as	0
Značaj greške - FDV	Izrazito mala mogunost ...	>100/1000		00FF00	2	as	05.05.2023 09:22:04	as	0

Figure 1. The main interface of the "Encryption scheme" in FMEA (source: GoInfo).

The FMEA analysis in GoSoft comprises a "Details" module that enables comprehensive examination of data on potential errors and their consequences. This module displays columns based on the type of analysis being conducted. The "Details" tab contains various fundamental columns such as detail number, standard operation selection, function definition, error consequences, severity classification, potential error causes, frequency classification, preventive measures, control options, detection classification, Risk Probability Number (RPN), work order selection, control procedure choice, measurement code, preventive actions, standard operation description, responsible person, action completion date, severity, frequency, detection ratings after preventive measures, and Action Priority (AP). The "Details" module facilitates systematic data collection, analysis, and documentation of potential errors and their impacts. It also allows for proposing and implementing preventive measures to mitigate risks.

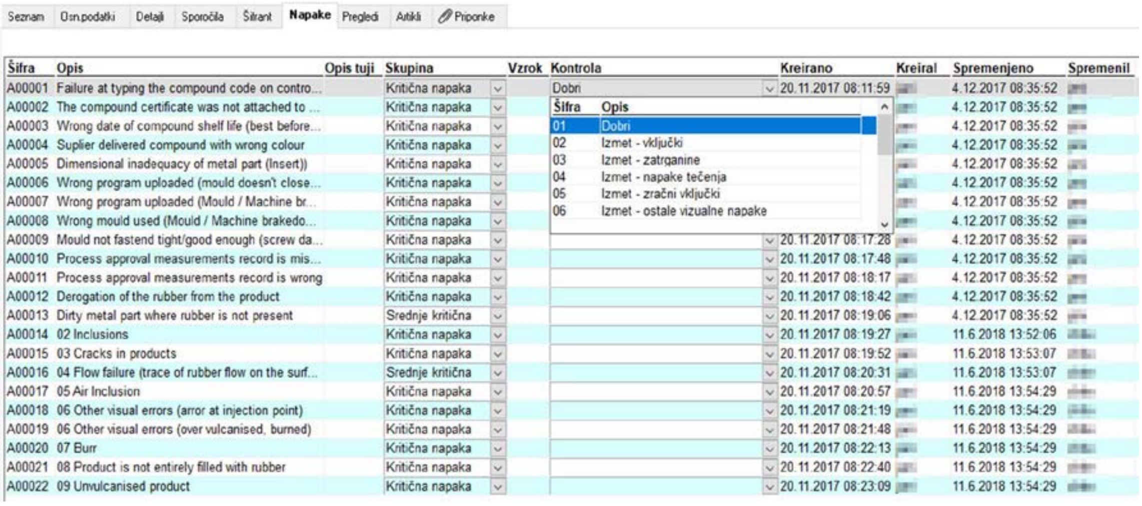


Figure 2. The main interface of "Errors" in FMEA (source: GoInfo).

In the GoSoft ERP system, the "Errors" module enables users to create and modify records of errors with a unique code. This module includes descriptions of each error, the selection of an appropriate error group, the cause of the error, and the choice of an appropriate control. Control data is linked to the control code in the Technical Data -> Codes -> Control database, which can be expanded as needed. At the end of each month or year, GoSoft offers the option to visually represent the status of quality control in production. This feature can provide technical experts with detailed insights into the quality of products during different stages of production.

A practical demonstration of how the FMEA methodology operates within the GoSoft ERP system is conducted by thoroughly examining potential failure modes and their impacts on wooden furniture production, with a specific focus on panel furniture manufacturing. The following practical example outlines specific failure modes, their potential effects, severity (S), occurrence (O), detection (D) ratings, Risk Probability Number (RPN), and proposed corrective measures. This example is drawn from real-world scenarios encountered during the implementation and use of the GoSoft ERP system in the context of the wooden furniture industry, specifically in the procurement *(Table 1),* and production processes *(Table 2)*. The following examples highlight specific scenarios, and we have emphasized only a subset that can serve as illustrative instances for implementing FMEA in GoSoft.

One identified risk within the procurement process (*Table 1*) is the "Supply Shortage of Edge Strips". This potential failure mode could result in a delay in production, missed deadlines, and customer dissatisfaction. The severity (S) of this failure is rated at 4, occurrence (O) at 7, and detection (D) at 6, yielding a Risk Probability Number (RPN) of 168. To address this, proposed corrective measures include expanding the supplier market for edge bands to cover all décors and implementing periodic audits and quality checks. Another risk in procurement is the "Delayed Production and Missed Deadlines." The potential effects encompass delayed order fulfilment and customer dissatisfaction. The severity here is higher, rated at 8, with an occurrence of 8 and detection of 7, resulting in a higher RPN of 448. Proposed corrective measures involve confirmation and verification of orders by project and procurement managers, and improved communication and coordination with the supplier.

Table 1: FMEA Analysis for Procurement Process

Process Step	Potential Failure Mode	Potential Effects of Failure	(S)	(O)	(D)	RPN	Proposed Corrective Measures
Procurement	Supply shortage of certain edge strips	Delays in production, missed deadlines, and unsatisfied customers	4	7	6	168	Expand supplier market for edge bands to cover all décors Implement periodic audits and quality checks
Procurement	Delayed production and missed deadlines	Delayed order fulfilment and unsatisfied customers	8	8	7	448	Confirmation and verification of orders by project and procurement managers Improved communication and coordination with the supplier
Procurement	Delayed delivery to customers	Delayed order fulfilment and unhappy customers	7	7	8	512	Timely organization and communication with transport companies Implement multiple transport options and alternatives

In production *(Table 2),* an identified risk is "Inadequate Pallet Packaging," potentially causing customer complaints, increased costs, and damaged products during transport. Rated at severity 6, occurrence 7, and detection 8, the resulting RPN is 336. Corrective measures involve using proper materials, applying appropriate production parameters, and training employees in effective packaging techniques. Another significant risk is "Downtime Due to Equipment Failure" in production, posing potential delays and increased costs. Rated at severity 7, occurrence 8, and detection 8, the RPN is 448. Proposed corrective measures include using quality materials, maintaining production parameters, regular equipment maintenance, and having a backup plan. Lastly, the risk of "Incorrect Storage of Finished Products" is identified, potentially causing incorrect shipments and customer complaints. Severity, occurrence, and detection are rated at 7, resulting in an RPN of 343. Corrective measures include using proper documentation for marking (load orders) and providing employee training on documentation procedures.

Table 2: FMEA Analysis for Production Process

Process Step	Potential Failure Mode	Potential Effects of Failure	(S)	(O)	(D)	RPN	Proposed Corrective Measures
Production	Inadequate pallet packaging	Customer complaints, increased costs Damaged products during transport	6	7	8	336	Use of adequate materials and tools Application of appropriate production parameters Employee training on proper packaging techniques
Production	Downtime Equipment failure	Delays in production, increased costs	7	8	8	448	Use of quality materials Appropriate production parameters Regular maintenance of equipment and tools Implementation of backup plan
Production	Storage of finished products	Marking of finished work orders Incorrect shipment	7	7	7	343	Use of appropriate documentation for marking (load orders) Employee training on proper documentation procedures

In these practical examples, we have outlined specific risks within the procurement and production processes, detailing potential effects, severity, occurrence, detection, RPN, and proposed corrective measures for each identified failure mode. This provides a thorough understanding of how FMEA is applied in the GoSoft ERP system, particularly in the context of wooden furniture manufacturing.

4. CONCLUSIONS

This research explores the integration and implementation of Failure Mode and Effects Analysis (FMEA) within the GoSoft Enterprise Resource Planning (ERP) system for companies in the wood industry. The crucial role of the wood industry in sustainability, economic growth, and the EU's manufacturing landscape underscores the significance of optimizing operational efficiency and quality management. In response to evolving market dynamics, modern wood industry production strategies emphasize quality over volume, necessitating robust methodologies like FMEA for proactive risk management.

Integrating the FMEA methodology into the ERP system offers a systematic approach to identifying, analysing, and managing potential risks in wood industry processes. The study demonstrates that the GoSoft ERP system provides a comprehensive platform for implementing FMEA, enabling risk identification, analysis, and control across various business processes.

The research highlights the role of FMEA in the ERP system, emphasizing risk identification as a key function. The systematic integration of FMEA within the ERP system enables users to create, rank, and assign potential failures for analysis and action. This interconnectedness extends to other modules, ensuring a holistic approach to risk management.

The practical example presented in this research, focusing on risks in the procurement and production processes, serves as a tangible illustration of how FMEA operates within the GoSoft ERP system. The detailed analysis, including the Risk Probability Number (RPN) and proposed corrective measures, elucidates the methodology's effectiveness in addressing potential failures and optimizing operational efficiency.

This research encourages further exploration of FMEA integration in ERP systems, emphasizing the importance of risk management tools for successful implementation projects. The insights provided underscore the role of FMEA in continuous improvement, ensuring the achievement of intended goals and delivering positive business outcomes. The study's findings contribute valuable knowledge to wood industry companies and other sectors by fostering a culture of proactive risk mitigation, quality enhancement, and a comprehensive understanding of utilizing FMEA for quality control, risk management, and process optimization within the broader context of enterprise resource planning.

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Wood Formation to Evaluate Tree Species Adaptation Capacity and Productivity in Drought-prone Forests

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ABSTRACT

Climate change-induced natural disturbances such as droughts and heat waves have profound implications for wood and phloem development in forest tree species, especially in semi-arid ecosystems. Understanding the growth responses of trees in such environments is central to assessing the adaptive capacity and productivity of tree species and to developing sustainable management strategies. Our research examines the wood and phloem characteristics of tree species that thrive in semi-arid environments to answer questions about tree performance and adaptability in climate change scenario. We provide a comprehensive overview of our recent research efforts and the results obtained. We studied wood and phloem formation of mature trees of *Pinus pinea*, *Pinus halepensis*, and *Quercus ilex* from drought-prone forests in Italy and Spain by collecting microcores containing phloem, cambium, and xylem tissue. Thin sections of the microcores were analysed through microscopy to identify cambium cells and wood and phloem cells at different stages of differentiation. Our results suggest that under stress, there is high plasticity in the control of water use. The occurrence of Intra-Annual Density Fluctuations (IADFs) indicates a high degree of plasticity and rapid response to climatic variations. Higher cambium and xylem plasticity leads to higher wood production and influences wood properties and quality.

Key words: xylogenesis, wood plasticity, wood productivity, drought stress

Research Needs for European Species in a Scenario of Increasing Structural Wood Demand in a Bioeconomy Based Model

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ABSTRACT

The building sector is the second largest in the EU industrial ecosystem in economic terms, and activities associated with buildings (construction, usage, renovation, and demolition) are responsible for 36 % of greenhouse gas emissions. Building materials will dominate resource consumption in fast-growing developing economies, and associated greenhouse gas emissions are expected to double by 2060. The current construction sector model is far from complying with the EU Green Deal initiatives for climate neutrality by 2050, so, the emissions associated with materials and construction processes need to be addressed soon. Forests and wood-based products become an opportunity to contribute to this challenge. Forests are carbon reservoirs, and wood is a sustainable material that stores carbon during its entire service life. Including long-life wood products in buildings, the whole value chain from the forest to the built environment becomes a major carbon sink. The current sawnwood production worldwide is mainly focused on softwood species, of which only a few are available for structural purposes. In addition, global softwood production is expected to increase at an annual rate of 1.8 % by 2030, with 50 % of the wood volume destined for construction purposes as a substitute for steel, concrete and masonry. In Europe, the use of wood, which was concentrated in residential housing and long-span structures during the last years, is gaining acceptance for multistorey buildings. The aim to contribute to the decarbonisation of the built environment from timber construction requires research and innovation which supports the structural safety requirements. Since wood is an anisotropic material, physical and mechanical properties vary not only with the species but also with the origin and forest management, the research and innovation need to provide the construction sector with knowledge about resources and products with the necessary technical information to design and build safely and efficiently. The objective of this paper is, therefore, to present the state of the art of the European wood species and their properties available nowadays for structural design and to identify the need for additional research to boost the efficient use of wood in the construction sector. Firstly, a brief analysis on how climate change is affecting the availability of wood will be presented. Secondly, the current wood species and engineered wood products graded for structural uses in Europe will be identified. And, finally, the research needs to fill te information gaps in the European standards to design with underused species, reused and salvage wood, and for finite element modeling of wood will be identified.

Key words: timber structures, construction, forests, climate change, decarbonisation, design codes, finite element modelling, reused wood, salvage wood, mechanical properties

***Acknowledgements**: European research projects funded by the European Union: Horizon Europe EUFORE No. 101081788, and Horizon 2020: BASAJAUN No. 862942.*

Captain Vlaho Podic's sea Chest from 1871

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ABSTRACT

The paper represents a brief overview of sea chests in general with particular interest into the sea chest from 1871 found in the attic of the devastated house of captain Vlaho Podic in Kupari, Župa Dubrovačka. Sea chest constructions are usually made of hewn massive wood boards connected by slanted dentils similar to stitches. Sea chest has painted decorations on the front, of a steam-powered sailing ship, as well as on the sides while its inside is ornate with two smaller paintings and a mirror. Apart from the ornaments, the inside also contains five small hidden drawers. The paintings as well as the type of the sailing ship have been analysing and the type of wood that the chest is made of has been identified. An FT-IR analysis of the wood from which the chest was made was also conducted, alongside microscopic imaging of the deteriorated wood structure. The discovery of the sea chest, documentation, analyses, conservation and restoration treatments will make sure that chest finds its place in the rich cultural heritage of Dubrovnik and its surroundings.

Key words: sea chest, sailing ship, junction for wood, wood anatomy identification

Influence of the Focal Length Position of the Focusing Lens on the Plywood Discoloration under Different Modes of CO2 Laser Engraving

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ABSTRACT

This paper presents the results of a study of the laser engraving process on plywood samples. The influence of the focal distance of the focusing lens at different positions relative to the surface of the material on the discoloration of plywood samples, at different power and scanning speed of a CO_2 laser beam, was investigated. The change in the color shades of the plywood was studied with an LS173 calorimeter. For this research ZnSe lens with focal length F = 50.8 mm was used; a position of the focal plane of the focusing lens relative to the surface of the material ΔF = 4, 6, and 8 mm; laser beam power P = 4.0, 5.6 and 7.2 W; feed rate of the laser beam V_f = 250, 260 and 270 mm/s.

The color shade difference of the plywood samples was measured in the L*, a* and b* color space. The results allow to offer modes for surface treatment with laser beam in the construction of complex graphic images on plywood products.

Key words: CO_2 laser beam, focal distance, calorimeter, discoloration, colour space, plywood, surface treatment

Empowering Advancement of the Wood and Furniture Sector Through Key Digital and Sustainability Competencies

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ABSTRACT

In the context of the growing importance of sustainable development and digitalization, our study examines the crucial digital and sustainability competencies for wood science and technology graduates. By surveying experts and companies in the wood sector, we have conducted a comprehensive analysis of the competencies expectations at various levels of education. In this way, we were able to map the development of competencies across all vertical levels of education and in addition reveal disparities in industry expectations that indicate an inconsistent approach to the adoption of digital technologies and the prioritization of sustainability. Nonetheless, we have identified the scope and type of competencies required for the sustainable and digital transformation of the wood industry that graduates of different educational levels should possess. It highlights the importance of ensuring that graduates are well equipped to navigate the evolving technological and sustainable landscape, and the importance of designing educational programs to meet both the immediate and future needs.

Key words: key competencies, DigComp, GreenComp, digital and sustainable transition, wood and furniture sector

Frequency Spectrum of Roughness Signal Obtained on Machined Surface of Solid Oak Wood After Sawing on the Circular Saw

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ABSTRACT

In the evaluation of surface quality after machining of solid wood there are no clear and unanimous standards of surface quality evaluation and quantification. Usually, in the scientific work, standard parameters defined in ISO 4287 are used for surface quality assessment. There is still no clear recommendation which parameters, or combination of parameters should be used, to get good enough assessment of surface quality after machining solid wood. One complimentary method in signal analysis, that can be used to provide better assessment of surface quality is frequency analysis of provided machined surface profile. To distinguish between inherent anatomical roughness of workpiece material and other contributing factors to overall surface roughness by means of frequency analysis, an experiment was conducted. Experiment consisted of surface roughness measurements on hand planed surface of solid oak (*Quercus robur* L.) wood, which were considered as "ideally" cut and representative of measured anatomical roughness, and same type of measurements on the machined surface after sawing with circular saw. From the obtained results, it is obvious that frequency analysis is valuable, additional tool for surface quality assessment of solid wood after machining.

Key words: machined surface roughness; anatomical roughness; frequency analysis; solid wood

Determination of Flexible Pipe Pressure Loss in a Chip and Dust Suction System

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ABSTRACT

The suction system is most efficient when it works with as little pressure drop in the system as possible. The resistance to the flow of the mixture of air and wood particles must be minimal. An insufficiently researched part of the system for suction and transport of wood particles is flexible pipes. They enable correction of the position of the machines themselves and connection to hard-to-reach places. The aim of this paper is to determine the resistances of the most commonly used diameter of flexible pipes and to determine those with the smallest pressure drop. The resistances that occur in flexible pipes are significantly higher than those in straight metal pipes. After the research, it was established that the pipes with the highest market price have the smallest pressure drop per length meter and the smallest drop in air velocity.

Key words: wood particle suction system, pressure loss, flexible pipe, resistance in pipe, flow rate, dynamic pressure, static pressure

Possibilities for using Artificial Intelligence in Furniture/Woodworking industry.

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ABSTRACT

The use of artificial intelligence (AI) in various fields has attracted a lot of attention in the past year, especially after the release of ChatGPT, a freely available intelligent online system. Several advanced software solutions that incorporate AI are becoming available on a larger scale and could help improve every aspect of our lives. The use of AI has great potential in several areas also in the woodworking industry, from the design phase of the product, the product construction phase and optimization, to the optimization of production, product forecasting and maintenance of production machinery, as well as market analysis, marketing activities and the sales process. An overview of the solutions currently available has been made in order to discover new opportunities for the use of AI in the wood industry as an important aspect of digital transformation.

Key words: Artificial intelligence, woodworking industry, furniture design, digital transformation

Analysis of Primary Value Chains in the Slovenian Forest and Wood Bioeconomy

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ABSTRACT

Green value chains are becoming very important due to the current European and global strategic directions. Wood and wood-related value chains are one of them. In Slovenian forest and wood bioeconomy there are many challenges to face with in order to make it stronger and more efficient. One of the biggest challenges is the increasing share of deciduous trees in Slovenian forests. The question here is how to build or strengthen forest-wood value chains whose basic raw material is hardwood of different qualities. The most important thing for the whole forest and wood bioeconomy is effective and functioning primary value chains in order to have a strong basis for multiplying the impact and value in the whole forest-wood value chain. The objective of this study was to analyse the primary value chains in the Slovenian forest-wood bioeconomy, focusing on hardwood processing.

Key words: value chains, forest-wood chain, bioeconomy, hardwood

Life Cycle Assessment (LCA) Study for Early Design Stages of Wooden Wall Coverings with Enhanced Aesthetics and Functionality

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ABSTRACT

As climate change, pollution, resource depletion and waste management require an urgent action on a global scale, the transition to the usage of sustainable materials and processing technologies in product design is becoming an inevitable requirement. Imposing environmental issues could be partially mitigated with transition to more sustainable materials like wood. From the numerous benefits that can be gained from wood it is important to point out its most valuable advantages such as renewability, carbon storage capacity and biodegradability. Incorporating sustainability principles into the early stages of product design is often more cost-effective and environmentally friendly than retrofitting existing products or processes. In cases such as these it is necessary to identify best available tools on the market that could back up such concepts, such as Life Cycle Assessment (LCA). LCA is a vital tool in sustainable product design that helps evaluate the environmental impact of a product throughout its entire life cycle. For the purpose of this study different versions of a product – wooden wall coverings, in its early design stages, are being analysed and compared using LCA methodology. The goal is to present wooden products with enhanced aesthetics and functionality while offering a range of design options and environmental considerations.

Key words: Life Cycle Assessment, product comparison, wood product design, sustainable resources, wooden wall coverings

Chemical Characterization of Liquefied Forest Biomass of Common Spruce (*Picea abies* L.) and Oak (*Quercus robur* L.)

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ABSTRACT

The aim of this work was to investigate the group chemical composition of the biomass of two forest species, common spruce (*Picea abies* L.) and oak (*Quercus robur* L.), and their chemical properties after liquefaction with the polyhydric alcohol glycerol ($C_3H_8O_3$) in the presence of sulfuric acid (H_2SO_4) as an acid catalyst under well-defined liquefaction conditions. The degree of liquefaction, the percentage of insoluble residue and the dry matter were determined as values indicating the polymer properties of the liquefied forest biomass. Depending on the different ratios between sample and solvent, the degree of liquefaction of spruce biomass ranged from 71.98 to 88.12 % and that of oak from 76.91 to 90.25 %. The insoluble residue ranged from 11.88 to 28.02 % for spruce and from 9.75 to 23.09 % for oak. The percentage of dry matter ranged from 53.01 to 65.29 % for spruce and from 51.45 to 61.16 % for oak.

Key words: spruce, oak, group chemical composition, liquefied biomass, percentage of liquefaction, dry matter

Formaldehyde Free Particleboard Bonded with Imidazole Citric Acid Adhesive System

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ABSTRACT

Last decades a lot of effort was oriented towards searching for an adhesive which would/could replace synthetic, formaldehyde-based adhesive used for production of particleboards. Such adhesive has to fulfil few demands, such as comparable or better mechanical properties, high moisture resistance and most importantly, it should be made without formaldehyde, hence can be classified as E0 panels. Tannin and starch-based adhesives are the ones where panels with E0 formaldehyde emission and relatively good mechanical properties can be made. Their downside is low moisture resistance. In the literature, there are a range of substances with binding abilities, including ionic liquids, which often contain imidazole in their composition. However, imidazole in combination with citric acid has, to our knowledge, not intensively investigated as an adhesive system for particleboard. In presented research imidazole solution in combination with citric acid was used as binder for producing lignocellulosic based panels made from spruce wood (Picea abies) Five different 16 mm thick with density between 0.7 and 0.75 g·cm-3 were produced. The resin load was 15 %. The difference in panels was related to the share of imidazole and citric acid. Determined properties (bending strength, modulus of elasticity, internal bond, thickness swelling, formaldehyde emission and formaldehyde emission) were compared to panel made with urea-formaldehyde (UF) resin. Although strength properties are lower compared to UF bonded panel there is a positive impact on moisture resistance, which is higher at panels made with imidazole/citric acid adhesive system. The impact of the resin composition (imidazole/citric acid ratio) was also determined.

Key words: particleboard, imidazole, citric acid, mechanical properties, thickness swelling, formaldehyde emission

Structural Based Analysis of Moisture Resistance of Different Wood-Based Panels

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ABSTRACT

Wood-based panels differs in the morphology of used constituents, adhesive used and in their structure. This difference also, partially explains the resistance against moisture and water of different wood-based panels. But this is only a fraction, when considering the moisture and water resistance of wood-based panels. When considering plywood, there is a big difference in reactivity of veneer towards water related to its orientation in plywood but small difference when considering differences in compaction of individual plywood. But, looking at wood-based panels from particles and fibre the difference in density (compaction) in thickness is significant, core layer having lower and surface layer having higher density. When comparing the swelling of dense materials, we often consider higher density acts as a barrier against water absorption resulting in lower panel thickness swelling. But when the panels are exposed to water or moisture so that it can enter from the edge, more variable surface, the differences in core and surface layer becomes more evident. The aim of this paper is to show the anti-swelling efficiency of individual layer of OSB, particleboard, MDF as well as plywood when edges and surfaces are in contact with water or moisture. The paper presented will show that water is quicker absorbed by more dens surface layer compared to less dense core layer, as well as it will show the differences in absorption potential of differently oriented veneers.

Key words: wood-based panels, moisture resistance, core layer, surface layer, density

Modelling of Peripheral Wood Milling Power Using Design of Experiment Approach

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ABSTRACT

For efficient production planning, it is necessary to know the power consumption of a particular woodworking operation in advance. In the past, many power measurement tests have been carried out based on a large number of different combinations of technological parameters. However, in this paper, the effects of technological parameters and wood properties on the power magnitude of peripheral milling are analysed using modern experimental design methods, where the effects of the different factors can be tested with a much smaller number of combinations. Therefore, a central composite experimental design was used to plan the experiments. Three different tree species with different densities were milled with three different numbers of teeth and three depths of cut at constant feed and revolution speed. For each milling combination, the power was measured continuously and then the average power was calculated. Based on the measurements, a suitable model was determined that allowed the magnitude of the power to be determined for each combination of technological parameters and wood species tested. The model proved to be suitable and promising, as the deviations between the measured and modelled power values are minimal.

Key words: wood, milling, power consumption, design of experiment, central composite design

Colouring of Oak Wood Veneers with Water-based Stains

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ABSTRACT

Staining of wood is the oldest variant of wood colouring and different types of stains are used to enhance the natural colour and to increase contrasts in the wood grain. Furthermore, in order to preserve the wood raw material, emphasis is placed on the use of veneer in the interior. Although veneer has all the characteristics of solid wood, it should be considered that during the production of veneer, a large number of factors affect the veneer sheets and consequently the colouring of the veneer. The aim of this study was to level out colour differences of the oak wood veneers and to determine the differences between heartwood and sapwood colouring. Three types of stains were used: water-based direct dye stain, water-based reactive dye and water-based positive stain. The colouring process was performed in a water bath at two temperatures: 30 and 80 °C. The colour of the oak veneer samples was measured with a spectrophotometer after colouring and after rinsing the veneer samples. The results showed that the sapwood and heartwood were both coloured differently, and that the temperature had influence on colouring results. Furthermore, differences were also found in the coloration of veneers after rinsing veneer samples with water.

Key words: dye stain, colour change, veneer, wood stain

Market Trend Analysis of Wood Products and Wood Waste in the EU Towards a Better Understanding of Environmental Sustainability and Climate Change

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ABSTRACT

With the increasing global emphasis on sustainability, the wood industry and its by-products have come under the spotlight in terms of their environmental impact. This study investigates the market trends and relations between the production of sawnwood, the trade dynamics of wood residues, and the subsequent production of boards from particles in the EU. The overarching goal was to understand the interactions and influences between these sectors, especially in light of the EU's climate change mitigation strategies. Using a dataset spanning over two decades, we performed correlation analyses and linear modelling to assess the relationships between sawnwood production, wood waste trade among EU states, and the production of boards from particles. Additional emphasis was placed on understanding the impact of wood waste imports from non-EU countries on board production.

Key words: market trends analysis, wood-products, wood residues, climate change

Impact of Ultrasonic Waves on the Synthesis of ZnO Nanoparticles for Wood Modification.

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ABSTRACT

Wood has various limitations, including susceptibility to decay, moisture absorption, and dimensional instability. Various wood modification techniques have been developed to address these issues by not only prolonging the lifespan of wood products but also promoting sustainable resource utilization.

Our research aims to create in-situ zinc oxide (ZnO) nanoparticles for enhanced hydrophobicity. Initially, we modify wood samples without ultrasonication, followed by the same modification process with ultrasonication. Our study highlights the pivotal role of ultrasonic waves in improving wood's hydrophobic properties during ZnO nanoparticle impregnation. Ultrasonication significantly increases hydrophobicity, resulting in a superhydrophobic wood surface with around 150° contact angle while preserving primary particle characteristics. The results depict a notably increased contact angle and uniformly distributed nanoparticles in wood samples that underwent modification with ultrasonication compared to others.

To summarize, the promising potential of using ultrasonic waves in revolutionizing wood modification depicts exciting opportunities for advancing wood modification techniques and their wide-ranging applications.

Key words: Wood modification, Nanoparticles, ZnO, Ultrasonication.

Acoustic Properties of Certain Types of Wood from Croatia

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ABSTRACT

Despite the new materials, wood still remains the material of choice for a wide range of applications. The reason for this is the peculiar and desirable range of mechanical and physical properties of wood. The acoustic properties of wood have been the subject of research for many decades, however, the development of more precise and sophisticated experimental devices makes such research attractive even today. In this work, the sound coefficients of absorption and reflection of oak, beech and fir wood were determined in the frequency range from 50 Hz to 6300 Hz using an impedance tube kit.

Key words: acoustic properties, coefficient of sound absorption, coefficient of sound reflection

Study on the Natural Aging Process of Old Fir (*Abies alba* Mill.) Structural Timber

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ABSTRACT

Wood as a building material undergoes an ageing process during its lifetime in a given local environment, due to the influence and variations of various environmental factors. To study this process, samples of naturally aged historical silver fir (*Abies alba* Mill.) wood, dated between 1772 and 1858, were taken from the roof of St. Barbara's Church (Ravnik nad Hotedrščico, Slovenia) during its renovation phase. The historic wood was examined microscopically, subjected to chemometric analysis (FT-IR) and some of its physical and mechanical properties were determined. Inside the examined structural timber, we found colour changes and, as a result of hydrolytic effects, a decreased relative amount of hemicelluloses, which reduced the hygroscopicity of the wood. Local cracks and delamination of the cell walls were observed in the cell structure. In historic structural timber, some mechanical properties such as tensile strength and hardness, as well as dynamic stiffness along the wood fibres, increased slightly but not significantly. However, for historic wood, we confirmed a significant decrease in impact bending strength and lower hardness and stiffness in the transverse direction. The damping of mechanical vibrations was also lower in historic wood.

Key words: structural timber; aging; dendrochronology; microscopy; FT-IR spectroscopy; physical properties; mechanical properties

Addition of Rotten Wood with the Aim of Improving the Wood Pellet Properties

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ABSTRACT

In this research, the impact of adding rotten wood to the oak raw material with the aim of improving the properties of wood pellets was examined. Wood material infected with brown and white rot fungi found in nature were separately added to the oak raw material, without the addition of other additives. Rotten wood was added to the oak raw material in the amount of 10 and 20 %, and the mixtures were then pelletized in a laboratory pellet press KAHL 14-175. After pelletizing, their influence on the ash content, bulk density, mechanical durability, calorific value and dimensions of the wood pellet was tested according to HRN EN ISO 17225.

Key words: wood pellets, white and brown rot fungi wood, lab scale pellet press, wood pellet properties

Impact of Feed Rate on Energy Consumption During Cutting Dry Beech Wood with a Circular Saw

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ABSTRACT

The feed rate during mechanical processing of wood is one of the factors that has a high impact on energy consumption. Energy consumption is an indicator of cutting resistance and depends directly proportionally, that is, inversely proportionally when the thickness of the sawdust is less than 0,1 mm. At the same time, the teeth do not cut the wood, i.e., they do not create sawdust but wood dust. The friction of the teeth on the wood is increased, the temperature in the contact zone increases and the teeth blunted quickly. For this purpose, this paper investigates the dependence of the feed rate on the energy consumption of beech wood, when cutting dry wood with a circular saw, with the intention of determining the optimal cutting conditions for obtaining optimal values of energy consumption. In this research, three different feed rates were applied (U_1=12 mmin^{-1}, U_2=16 mmin^{-1} and U_3=20 mmin^{-1}) for a constant cutting height of 45 mm in dry beech wood with humidity of W=10±1 %. The measurements were made with a circular saw with a diameter of D=250 mm, number of teeths Z=80 and width of the cut b=3,2 mm. The number of revolutions is n=5500 min^{-1}. Measurement data for energy consumption were taken with a clamp ampermeter. The obtained results show a pronounced significance, i.e., directly proportional dependence of the energy consumption on the feed rate.

Key words: beech wood, circular saw, the feed rate, energy consumption.

Sustainability Through FSC Recycling: An In-Depth Assessment of European Adoption and Trends

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ABSTRACT

The Forest Stewardship Council (FSC) is a global forest certification system, and its importance is undeniable. It advocates for sustainable forest management, helping to preserve forest ecosystems and biodiversity. FSC certificates confirm that products originate from responsibly managed sources, enhancing ecological awareness and market competitiveness. Recycling plays a crucial role in conserving resources and reducing the environmental footprint, and within the FSC framework, recycled materials hold significant importance. FSC Recycled denotes products containing materials from the FSC supply chain, promoting the sustainable use of wood resources. For our research, we utilized data from the FSC database to analyse the prevalence of FSC recycling in European countries. Data on the economic and production indicators of European countries were collected from the Eurostat database. The objective of the study is to explore how specific economic and production factors affects the number of FSC Recycled certificates in European countries and to understand the links between economic dynamics, production capacities, and ecological certifications in the wood industry. The results of this study provide a significant scientific contribution by revealing insights into European FSC recycling behaviours and the application of sustainable wood product practices.

Keywords: Economic Factors, FSC Recycled, Forest Stewardship Council, Sustainable Wood Products

NOTES


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GALEKOVIČ
kvaliteta u tradiciji
PARKETI I PODOVI
MASIVNI PARKETI, MULTILAYER,
CHEVRON, MAXI RIBLJA KOST, DECKING
MASIVNE PLOČE
TERMO FASADE
PELETI
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Unleashing The Potential of Wood-based Materials