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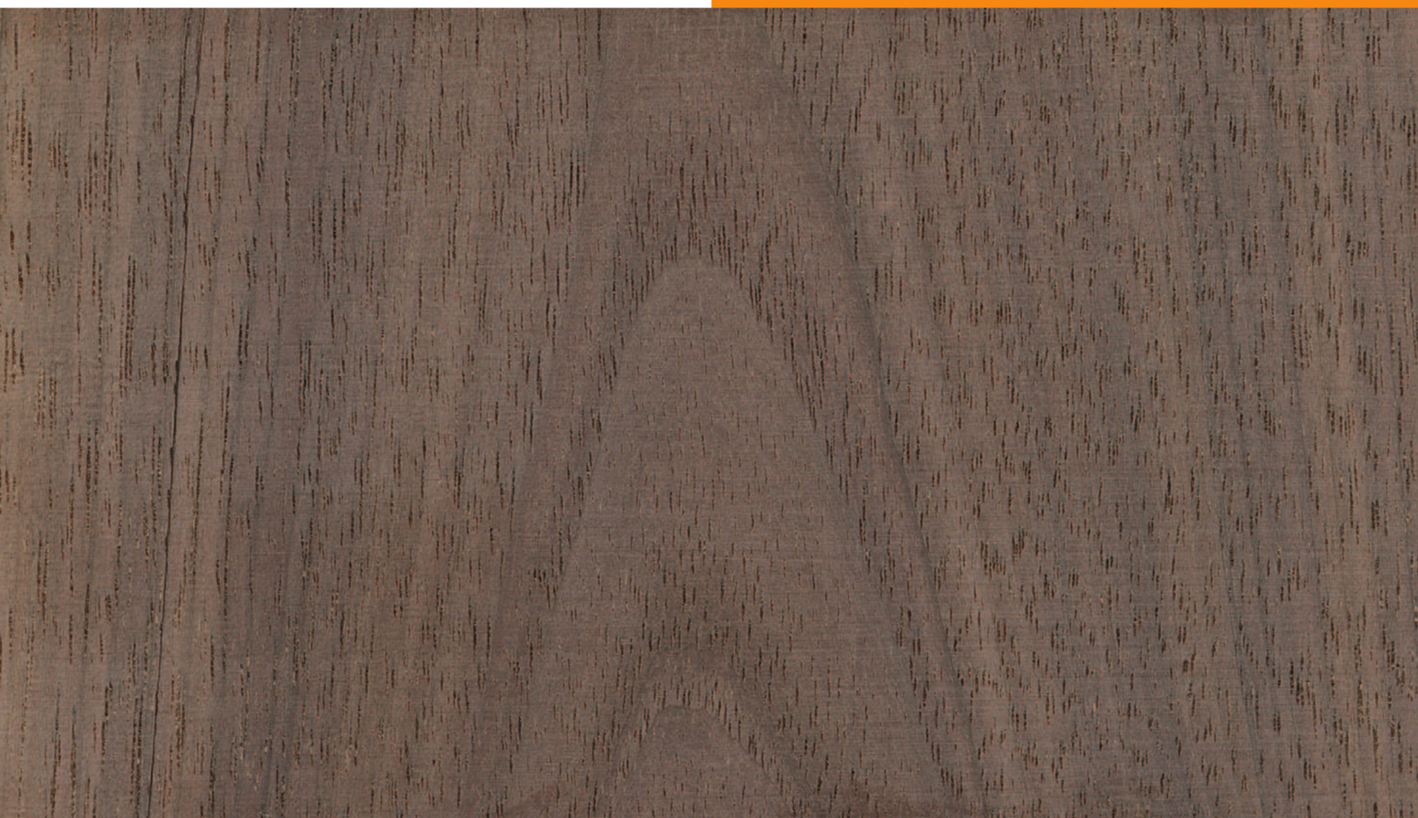

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Kenan Kılıç*[1,2], Uğur Özcan[3], Kazım Kılıç[4,5], İbrahim Alper Doğru[6]

Using Deep Learning Techniques for Anomaly Detection of Wood Surface

Primjena tehnika dubokog učenja za otkrivanje anomalija na površini drva

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ABSTRACT • *The study presents a novel computer-aided vision system for the detection of wood defects using deep learning techniques. Our study utilizes a dataset consisting of over 43000 labelled wood surface defects found in a comprehensive collection of 20276 wood images. To enable rapid decision-making on the production line, a binary classification approach was employed, distinguishing between defective and perfect wood samples. Only flawless wood can be used in production. Wood with one or more defects is not used in production and must be removed from the production line. Deep learning-based convolutional neural networks (CNNs) were optimized and used for the detection of defective and perfect wood. Using the transfer learning approach, experiments were performed with VGG-16, MobileNet, ResNet-50, DenseNet-121, Xception and InceptionV3 architectures. To decide the best optimization, the analysis of Adam, RMSprop, Adagrad, SGD and Adadelta optimization algorithms were tested on CNN architectures. In addition, different numbers of neurons, namely 256, 512, 1024 and 2048 neurons, were used and wood defect detection was performed with optimum parameters. As a result of the experiments, it was found that the RMSprop optimization algorithm of the Xception architecture reached 97.57 % accuracy, which is the most successful result with 512 neurons.*

KEYWORDS: *wood defect; anomaly detection; computer vision; transfer learning image classification*

SAŽETAK • *Predstavljen je novi računalno potpomognuti vizualni sustav za detekciju grešaka drva primjenom tehnika dubokog učenja. Ovo se istraživanje koristi skupom podataka koji se sastoji od preko 43 000 označenih grešaka na površini drva pronađenih u opsežnoj zbirci od 20 276 slika drva. Kako bismo omogućili brzo donošenje odluka na proizvodnoj liniji, primijenili smo pristup binarne klasifikacije, razlikujući uzorke drva s greškama i bez njih. U proizvodnji se može upotrebljavati samo drvo bez grešaka. Drvo s jednom ili više grešaka ne rabi se u proizvodnji i mora se ukloniti s proizvodne trake. Konvolucijske neuronske mreže utemeljene na dubokom učenju (CNN) optimizirane su i primijenjene za otkrivanje drva s greškama i bez njih. Primjenom pristupa transfernog učenja eksperimenti su izvedeni uz pomoć arhitektura VGG-16, MobileNet, ResNet-50, DenseNet-121, Xception i InceptionV3. Kako bi se odabrala najbolja metoda optimizacije, analiza optimizacijskih algoritama Adam,*

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RMSprop, Adagrad, SGD i Adadelta testirana je na CNN arhitekturama. Osim toga, korišteni su različiti brojevi neurona (256, 512, 1024 i 2048), a otkrivanje grešaka drva provodilo se optimalnim parametrima. Kao rezultat istraživanja utvrđeno je da je RMSprop optimizacijskim algoritmom arhitekture Xception postignuta 97,57 %-tna točnost, što je najuspješniji rezultat s 512 neurona.

KLJUČNE RIJEČI: *greške drva; otkrivanje anomalija; računalni vid; transferno učenje klasifikacije slika*

1 INTRODUCTION
1. UVOD

Woodworking industry places great importance on examining defects on the product surface during the quality control process. This step ensures consistent product quality and enhances production efficiency. Defective products must be identified and removed from the production line as early as possible. Wood products require particular attention, as defects can significantly affect their commercial value. These defects can be caused by reasons such as poor-quality raw materials and ineffective production processes. In some countries, the use of raw wood materials is declining due to these defects. Today, wood products are manufactured to strict surface treatment specifications and modern wood processing industries require a robust wood defect detection and identification system. Visual quality audits are currently carried out by trained personnel.

Nevertheless, due to the need for the classification of various types of wood defects and inadequacy of human expertise in practical scenarios, the utilization of convolutional neural networks has become imperative for identifying flaws in industrial products. Although these systems may not be feasible for actual industrial applications, the novel approach has been specifically designed to promptly detect and categorize defects as they occur.

In wood production, computer analysis and image recognition are extensively utilized for identifying surface defects on wooden materials. This method is favored for its cost-effectiveness and lack of additional equipment requirements. Moreover, it seamlessly integrates with operator intervention. Nonetheless, the accuracy of this approach relies on the specific design of the image analysis algorithm, particularly in the realm of digital image processing for wood defect detection. The detection process entails various pre-processing steps such as converting to grayscale, equalizing the histogram, applying spatial or frequency domain filtering, and extracting defect features. Subsequently, machine learning algorithms are employed to classify the images. Overall, the utilization of image analysis and machine learning techniques plays a crucial role in the wood defect detection process (Xie, 2013).

Accurate identification outcomes in wood defect detection rely on the extraction of defect characteristics and making decisions based on these characteristics. Wood surface attributes encompass different elements, such as grayscale co-occurrence matrix, color matrix, color histogram, geometric features, and texture features. However, the intricate nature of wood surfaces makes feature extraction challenging, resulting in heightened complexity in decision-making algorithms. To tackle this issue, Principal Component Analysis (PCA) is frequently used to effectively merge the extracted features, leading to enhanced accuracy in defect recognition.

Various methodologies have been used by researchers to extract features for detecting defects on wood surfaces. In a study by Zhang *et al*. (2015), the wavelet transform and Local Binary Patterns (LBP) algorithm were employed to extract image characteristics associated with both deceased and living knots. Another study conducted by Li *et al*. (2021) used the OTSU algorithm and mathematical morphology to extract characteristics of insect eyes, living knots, and deceased knots on wood surfaces. They also used the Sobel operator to extract edge contours of wood surface defects. Additionally, Li *et al*. (2019) improved the precision of wood surface defect classification by constructing correlated histograms of wood surface image elements and conducting feature extraction. These studies collectively emphasize the importance of feature extraction in detecting wood defects and demonstrate the use of various algorithms and techniques to enhance accuracy and efficiency in recognizing defects on wood surfaces.

These studies emphasize the significance of effectively integrating and extracting characteristics for precise identification and categorization of wood defects. In the realm of examining image features for wood defect detection, convolutional neural networks (CNNs) are frequently used. CNNs enhance decision-making efficiency by utilizing nonlinear discriminant functions (Packianather and Drake, 2005). In a study conducted by Luo (2019), various neural network models, including the backpropagation (BP) neural network, support vector machine (SVM) and CNN, were compared in terms of their effectiveness in classifying wood defects. The findings clearly demonstrated that both the CNN and SVM models outperformed the BP neural network model in terms of accuracy in detecting and categorizing wood defects. This indicates that the CNN and SVM models are more suitable and capable of achieving higher classification accuracy, particularly in the field of wood defect detection. In conclusion, the application of CNNs and SVMs in wood defect detection highlights their effectiveness in accurately classifying wood defects based on image features. The enhanced performance of these models underscores the importance of selecting the appropriate neural network architectures to enhance the accuracy of wood defect detection and categorization (Luo, 2019).

With the advancements in deep learning algorithms, researchers have increasingly turned to CNN models for accurately classifying wood surface defects. Wang *et al*. (2021) have developed diverse frameworks based on CNN models for this purpose. Urbonas *et al*. (2019) achieved a detection accuracy of 96.1 % in identifying wood surface defects through the implementation of the R-CNN method. Shi *et al*. (2020) improved both the speed and accuracy of defect detection by combining the mask R-CNN method with the neural architecture search (NAS) technique when dealing with wood veneer defects. In the context of solid wood panel defect detection, Fan (2020) conducted an extensive analysis utilizing models like R-CNN, Fast R-CNN, and Faster R-CNN. They devised a human-computer interactive system for detecting defects in solid wood panels and used SQL Server software tools to create tables containing image information. These studies underscore the growing utilization of deep learning approaches and CNN models in precisely detecting and categorizing wood surface defects. Table 1 provides a summary of machine learning-based studies on wood defect detection.

Computer vision technology used in wood production is a highly effective tool for the detection and classification of defects on wood surfaces. Properly configured and calibrated computerized vision systems can be used to increase productivity and improve product quality in wood production. Using specialized algorithms including pattern recognition, feature extraction and classification, these systems can quickly and accurately detect defects in wood surfaces. This paper will examine how computer vision technology can be used for wood defect detection and why this technology is important for the wood industry. The highlights of this study are as follows:

– This is the first study in the literature on binary classification for this dataset.
– With the help of deep learning architectures for wood defect detection, binary classification is performed as defective and perfect.
– A high level of success is achieved in wood defect detection with 97.57 % accuracy in two classifications as defective and perfect.
– Within the scope of wood defect detection, six different CNN architectures, five different optimization algorithms and four different neuron numbers are used.
– The structure of well-known CNN architectures is updated by adding batch normalization and dropout layers. The training of the new architecture is started with the transfer learning method and fine-tuned by retraining with the images in the data set.
– Existing wood defect detection methods have been found to have certain limitations, particularly in terms of speed and accuracy on the production line. The distinctive characteristics of wood products, along with the presence of multiple defect types, make image segmentation and feature extraction challenging. To address these issues, a novel approach using a fully convolutional neural network (CNN) has been proposed for classifying imperfect and perfect wood. This method surpasses previous techniques and eliminates the need for extensive image pre-processing and feature extraction. Consequently, it enables faster and more precise detection and identification of wood defects.

The rest of the article is organized as follows: In Section 2, the material and dataset are introduced, and pre-processing, CNN architectures and optimization algorithms used in the method are presented. In Section 3, the findings of the study and their comparison with existing studies are presented. Finally, Section 4 provides conclusions and some recommendations.

Table 1 Studies on wood defect detection, accuracy and defect types
Tablica 1. Istraživanja o otkrivanju grešaka drva, točnosti rezultata i vrste grešaka

Rank *Rang*	**Study** / *Istraživanje*	**Identified defect types** *Utvrđene vrste grešaka*	**Accuracy** *Točnost*
1	Ren *et al*., 2017	“Encased knot, leaf knot, edge knot, and sound knot”	91.55 %
2	Zhang *et al*., 2015	“Live knot, dead knot, and crack”	92.00 %
3	Yu *et al*., 2019	“Live knots, dead knots, pinholes, and cracks”	92.00 %
4	Zhang *et al*., 2016	“Live knot, dead knot, and leaf knot”	93.00 %
5	Li *et al*., 2017	“Live knot, dead knot, and crack”	94.00 %
6	Li *et al*., 2019	“Crack and the mineral line”	94.30 %
7	Ding *et al*., 2020	“Live knots, dead knots, and checking”	96.10 %
8	Urbanos *et al*., 2020	“Branch, core, split, and stain defects”	96.10 %
9	Yang *et al*., 2020	“Dead knot, live knot, worm hole, decay”	96.72 %

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Dataset
2.1. Skup podataka

To address the limited availability of comprehensive databases in the woodworking industry, a large-scale dataset of wood surface defects was collected for experimentation purposes. The dataset consisted of 20276 instances from sawn timber surfaces. Among these instances, 1992 images were defect-free, while 18284 images exhibited one or more surface defects. The dataset encompassed a total of 10 commonly observed wood surface defects. Fused knots and falling knots were the most prevalent defects, accounting for 58.8 % and 41.2 % of occurrences, respectively. This dataset provides a valuable resource for research and development in the field of wood defect detection and analysis (Kodytek *et al*., 2021a).

The dataset comprises over 43000 annotated wood surface anomalies found in a collection of 20276 wood images. The dataset encompasses ten prevalent defect types, namely fused knots, fallen knots, cracked knots, cracks, resins, piths, ures, missing knots, blue stain, and overgrowth defects. The images have a resolution of 2800 × 1024 pixels and are saved in the BMP format. The data was directly gathered from a wood production line during the manufacturing process (Kodytek *et al*., 2021b). Figure 1 presents typical examples of wood defects in the dataset.

2.2 Data augmentation and data preprocessing
2.2. Pojačanje podataka i prethodna obrada podataka

Data augmentation is the process of adding data to increase and stabilize the number of data to be processed (Purnama *et al*., 2019). High-rate sampling and under sampling methods are widely used on unbalanced datasets. Studies show that data augmentation improves success in classification problems performed with deep learning network architectures (Lopez *et al*., 2017; Ayan and Ünver, 2018). In order to prevent imperfect and perfect class imbalance in the dataset and to increase the performance of the deep learning architecture, the number of images in the dataset is increased by applying techniques such as horizontal and vertical rotations, angle changes up to a maximum of 355 degrees, zooming with a minimum value of 1.1 and a maximum value of 1.5, random contrast and brightness enhancement with a maximum value of 0.2. Wood images are converted from 2800 × 1024 pixels bmp format to 300 × 300 jpeg format.

2.3 Deep learning
2.3. Duboko učenje

Deep learning primarily relies on artificial neural networks as its foundation. These architectures can process vast amounts of data by learning from their representations. Consequently, deep neural networks possess more hidden layers in comparison to traditional neural networks (Deng and Yu, 2014). Within deep neural networks, labelled input values are passed through nonlinear activation functions, applying specific weights, to produce an output (Schmidhuber, 2015). The objective of training a deep neural network is to optimize these weights in order to minimize the error value (Ergün and Kılıç, 2021). This study focuses on presenting the deep learning architectures that have been used.

2.3.1 Convolutional Neural Network (CNN)
2.3.1. Konvolucijska neuronska mreža

CNNs are a class of multilayer perceptrons inspired by the visual processing center in animals. These networks have demonstrated remarkable success in a wide range of domains, including image and sound processing, natural language processing, and biomedicine. Notably, CNNs have achieved particularly impressive outcomes in the field of image processing. Their ability to capture spatial dependencies in data has made them a powerful tool for tasks such as image recognition, object detection, and image segmentation. The versatility and effectiveness of CNNs have contributed to their widespread adoption and continued advancement in various fields of study. Forward propagation algorithms in CNNs employ different error rate minimization algorithms, one of which is the back-

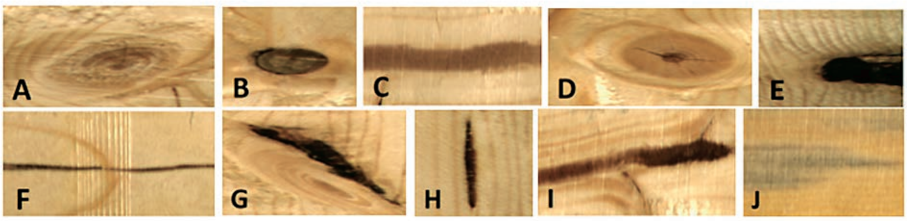

Figure 1 Typical examples of wood defects within the dataset used in the study: (A) Live Knot, (B) Dead Knot, (C) Quartzity, (D) Knot with crack, (E) Knot missing, (F) Crack, (G) Overgrown, (H) Resin, (I) Marrow (J) Blue stain
Slika 1. Tipični primjeri grešaka drva unutar skupa podataka primijenjenih u istraživanju: (A) zdrava kvrga, (B) mrtva kvrga, (C) inkrustacija kvarca, (D) ispucala kvrga, (E) ispala kvrga, (F) pukotina, (G) obrasla kvrga, (H) smolenica, (I) srčika (J) plavilo

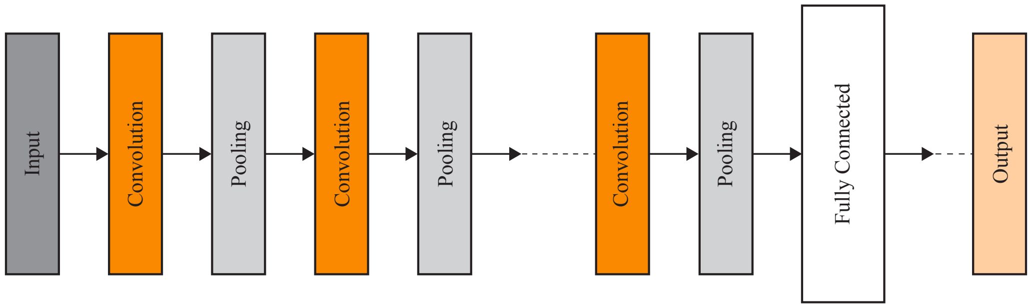

Figure 2 Building block of a typical CNN
Slika 2. Sastav tipičnog CNN-a

propagation algorithm. In the backpropagation algorithm, the error value from the forward propagation stage undergoes derivative operations from the output layer to the input layer, enabling error backpropagation (Tüfekçi and Karpat, 2019). CNNs are deep learning architectures that extract distinctive features from pixel matrices of images, using these features for class prediction (LeCun *et al*., 1998). They have widespread use in computer vision applications including image classification, object detection, image segmentation, voice recognition, text and video processing, and also medical image analysis (Pacal *et al*., 2020).

A CNN is comprised of three primary elements: convolutional layers, pooling layers, and fully connected layers. Figure 2 illustrates the CNN architecture used for image classification. In the convolutional layer, the input image undergoes convolution with kernels or filters to generate feature maps that capture important patterns and features. The pooling layer follows, reducing the size of each feature map to minimize the number of weights, a process also referred to as sub-sampling. Several pooling methods, including general pooling, maximum pooling and average pooling, can be used. As the feature matrix obtained from convolution and pooling layers is typically multidimensional, it is flattened into a one-dimensional vector before being passed to the fully connected layer. The fully connected layer is where the deep neural network is trained using the converted one-dimensional feature vector, enabling classification tasks to be performed (Ergün and Kılıç, 2021).

Convolutional Layer

The convolution layer is a vital component of a CNN and plays a central role in image processing. Since images are usually stationary, the patterns found in one region can also occur in other regions. By taking a small section of a large image and sliding it across the entire image (input), each point can be transformed to a single location (output). These small sections that move over the larger image are referred to as filters or kernels. The filters are constructed using the back-propagation technique. (LeCun and Bengio, 1995).

Sub-sampling or Pooling Layer

Pooling in a CNN refers to the process of down-sampling an image. It involves selecting a portion of the output and subsampling it to obtain a single output value. There are different types of pooling techniques, such as maximum pooling, average pooling and mean pooling. Pooling reduces the computational burden by reducing the number of parameters, while also providing the network with the ability to handle variations in shape, size and scale (Atacak *et al*., 2022).

Fully-connected Layer

The final component of the CNN consists of the fully connected layer (FC Layer). In this layer, each neuron connects to all neurons in the previous layer, and neurons in the current layer collectively contribute to production (Sultana *et al*., 2019).

2.3.2 VGG-16
2.3.2. VGG-16

The VGG-16 architecture is composed of a total of 21 layers. Among these layers, 13 are convolutional layers, five are maximum pooling layers, and three are fully connected layers. One notable characteristic of this network is that all layers have a spatial size of 3×3 pixels. The architecture of VGG-16 can be visualized in Figure 2. For input, the VGG-16 architecture expects a vector of dimensions 224×224×3, representing an image with width, height, and three-color channels. The output of the network is a vector with 1000 values, indicating the predicted class to which the image belongs (Simonyan and Zisserman, 2014).

2.3.3 MobileNet
2.3.3. MobileNet

MobileNet, a compact and highly efficient deep CNN model, is renowned for its outstanding performance and smaller size compared to other popular models. Its exceptional efficiency is achieved by utilizing depth-wise separable convolutions, a technique where a single filter is applied to each input channel, followed by 1×1 point-wise convolutions that merge the outputs of the depth-based layers. This strategy significantly reduces both the model's size and computational requirements. In MobileNet, every layer is accompanied by batch normalization and ReLU activation, except for the fully connected layer, which connects to the softmax layer responsible for classification tasks. MobileNet consists of a total of 28 layers, excluding the depth and point convolutions (Howard *et al*., 2017).

2.3.4 ResNet50
2.3.4. ResNet50

Unlike previous CNN architectures, the ResNet architecture uses residual blocks. In residual blocks, input x passes through the convolution layers to produce the result $F(x)$. This result is added to the input x to obtain the output $H(x) = F(x) + x$. This method ensures that residual values from the previous layer are not ignored. Residual blocks are an important feature that distinguishes the ResNet architecture from others. ResNet is available in versions with different depths, 18-34-50-101 and a maximum of 152 layers, and has a very low error rate (He *et al*., 2016). In this study, a 50-layer architecture is used.

2.3.5 DenseNet121
2.3.5. DenseNet121

DenseNet, a network architecture, is designed to enhance the information flow among layers, allowing each layer to receive supplementary inputs from preceding layers and transmit its feature maps to the subsequent layer. This architecture offers a notable advantage by promoting feature propagation, which facilitates the reuse of learned features and reduces the overall number of network parameters. Specifically, the DenseNet architecture comprises 121 layers, dense blocks, and three transition layers. There are various versions of DenseNet, differing in the number of layers, such as DenseNet121, DenseNet169, and DenseNet201 (Huang *et al*., 2017).

2.3.6 Inception-V3
2.3.6. Inception-V3

The model has undergone training by a top-tier hardware expert in the industry and boasts over 20 million parameters. It comprises both symmetric and asymmetric building blocks, with each block incorporating diverse components like convolutional layers, average and maximum pooling, merging operations, dropout layers, and fully connected layers. Additionally, batch normalization is implemented on the activation layer, and Softmax is used for classification purposes (Ali *et al*., 2021).

2.3.7 Xception
2.3.7. Xception

Xception is a CNN model based on the Inception-V3 architecture. It introduces several improvements to reduce time and space complexity. The model uses a linear stack of depth-wise separable convolution layers and incorporates residual connections. The key feature of Xception is the deeply separable convolution, which separates the learning of channel-based and spatial-based features. This helps capture complex patterns while reducing computational complexity. Additionally, Xception employs residual connectivity to address issues of vanishing gradients and representational bottlenecks by creating shortcuts within the network. Overall, Xception offers improved efficiency and performance compared to Inception-V3, making it a popular choice for various computer vision tasks (He *et al*., 2016).

2.4 Optimization algorithms
2.4. Optimizacijski algoritmi

Optimization techniques are used to minimize errors that can arise during program execution. These techniques are commonly referred to as gradient descent. Optimization methods involve a systematic approach that consists of multiple steps. The number of steps performed during this process is known as the learning rate. It is crucial to select an appropriate value for the learning rate. Choosing a small learning rate extends the solution process, while a large learning rate can result in overshooting the minimum point. SGD, Adagrad, RMSProp, Adadelta and Adam algorithms are among the most widely used optimization methods (Bosch *et al*., 2007; Frome *et al*., 2007; Seyyarer and Aydın, 2017; Cebeci, 2020).

In this study, Adam, Adagrad, Adadelta, SGD and RMSprop algorithms are used.

2.5 Transfer learning
2.5. Transferno učenje

When there is not enough data in image analysis studies, a transfer learning approach is usually preferred for studies with CNN architectures. This approach is to use the parameters of a network that has already been trained on a similar task in the new task. The CNN trained for the new task is initialized using the weights of the pre-trained network, and the parameters are updated by retraining a set number of times (Weiss *et al*., 2016; Fırıldak and Talu, 2019). In this study, six different architectures of the selected CNN, five different optimization algorithms and four different neuron numbers (256, 512, 1024, 2048) were tested. In order to determine the best optimization algorithm compatible with CNN architectures, 30 (6×5) experiments were performed with 256 neurons. Then, after determining the optimization algorithm that gave the best result, 24 (6×4) experiments were performed using 256, 512, 1024 and 2048 neurons. In total, 54 experiments were performed.

2.6 Experimental installation
2.6. Postavljanje eksperimenta

The dataset used for this research was divided into two categories: imperfect and perfect wood images. Due to the limited number of perfect wooden images in the dataset used, the number of images in the training set was increased in order to balance the data distribution and increase the performance of the network. With this increase, the number of perfect wooden images becomes equal to the number of defective wooden images. However, data augmentation is performed only on the training set. The dataset consisted of a total of 20276 images, including 1992 perfect wood images and 18284 defective wood images. The dataset was randomly divided into three subsets: 70 % for training, 15 % for validation, and 15 % for testing.

6 different well-known CNN architectures (VGGNet, ResNet50, MobileNet, DenseNet121, Xception and InceptionV3) were trained for wood defect detection using images. Each of the architectures was trained using the same hyperparameters. Instead of starting education from scratch, the transfer learning method was preferred. With this method, it is aimed to prevent overfitting, save time and increase accuracy. ImageNet weights were used for the weights of the network. Well-known transfer learning architectures have feature extractor layers and an additional classifier softmax layer. It also uses the "adam" activation function for activation within the network. For the experiments, first the batch normalization layer, the fully connected layer and the dropout layers with a ratio of 0.25 were added to the softmax layer of these architectures. The purpose of this is to prevent overfitting of the network.

In order to provide comparative and comprehensive analysis, different optimizers such as Adam, RMSprop, Adadelta, Adagrad and SGD were used in the experiments. At the same time, for the most successful optimizer, 256, 512, 1024 and 2048 neurons are added to each of the architectures and their performances are measured separately.

The learning rates of the networks at the beginning of the training were determined as standard 0.0001, and the validation loss was checked in each training cycle, and if the loss did not decrease for 5 epochs, the learning rate was reduced by 50 %. Thus, it is aimed to use dynamic learning rate. Since the study involved many experiments and comparative analysis, the number of epochs was determined as 20, considering the training times. Batch size was set to 64, considering the ram and graphics card capacity and data size.

Experiments were carried out in the Kaggle kernels cloud environment using Google. The infrastructure is on the Nvidia Tesla P100 graphics card. Python programming language was used in the application software.

2.7 Evaluation metrics
2.7. Mjerni podatci za ocjenjivanje

Accuracy

Chicco and Jurman (2020) presented that the accuracy metric is a ratio between correctly estimated data points and all the data points in the dataset. Eq. 1 expresses the formula of accuracy metrics.

$$accuracy = \frac{TP - TN}{n^{+} + n^{-}} = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

TP, TN, FP, and FN are abbreviations that represent the terms true positive, true negative, false positive, and false negative.

Precision

The precision score is expressed as a score between true positive and all the predicted number of samples which are presented as positive (Power, 2020). Eq. 2 indicates that precision score.

$$precision = \frac{TP}{TP + FN} \quad (2)$$

Recall

Power (2020) defined the recall score which is a ratio between true positive instances and the actual number of samples represented as positive. Eq. 3 illustrates the recall score.

$$recall = \frac{2}{TP + FP} \quad (3)$$

F1 Score

According to Chicco and Jurman (2020), the F1 score is a metric that calculates the harmonic mean of precision and recall, as described in Eq. 4.

$$F1score = \frac{2 \cdot TP}{2 \cdot TP + FP + FN} = 2 \cdot \frac{precision \cdot recall}{precision + recall} \quad (4)$$

Regarding all evaluation metrics, the worst value is 0, whereas the best value is 1.

AUC

The Area Under the Curve (AUC) quantifies the extent of discrimination ability of a classification architecture by measuring the area beneath the ROC Curve. It provides a measure of how well the architecture can differentiate between positive and negative examples. As the AUC value increases, indicating a larger area under the curve, the discrimination ability of the architecture improves (Adegun and Viriri, 2020).

Error Rate

Error Rate indicates the ratio of the absolute difference between the true value and the value obtained by the classifier (Ergün and Kılıç, 2021).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

This section contains wood defect classification results of 6 different transfer learning architectures. Experimental results are performed with different

Table 2 The best results of CNN architectures and optimization algorithms after 20 epochs
Tablica 2. Najbolji rezultati CNN arhitekturâ i optimizacijskih algoritama nakon 20 epoha

CNN model *CNN model*	**Optimization algorithm** *Optimizacijski algoritam*	**Precision** *Preciznost*	**Recall** *Opoziv*	**F1-score**	**ROC**	**Time** *Vrijeme*	**Accuracy** *Točnost*
VGG16	Adam	0.9706	0.9698	0.9701	0.9884	309.44 s	0.9698
VGG16	RMSprop*	0.9754	0.9747	0.9750	0.9914	309.19 s	0.9747*
VGG16	Adagrad	0.9705	0.9711	0.9707	0.9918	309.92 s	0.9711
VGG16	SGD	0.9549	0.9566	0.9530	0.9885	308.92 s	0.9566
VGG16	Adadelta	0.9616	0.9586	0.9597	0.9833	312.30 s	0.9586
MobileNet	Adam	0.9720	0.9701	0.9708	0.9866	148.97 s	0.9701
MobileNet	RMSprop*	0.9749	0.9737	0.9742	0.9880	156.01 s	0.9737*
MobileNet	Adagrad	0.9633	0.9612	0.9620	0.9840	146.99 s	0.9612
MobileNet	SGD	0.9542	0.9533	0.9537	0.9781	145.91 s	0.9533
MobileNet	Adadelta	0.9316	0.9316	0.9316	0.9565	145.02 s	0.9316
ResNet50	Adam	0.9709	0.9684	0.9693	0.9899	260.55 s	0.9684
ResNet50	RMSprop*	0.9740	0.9734	0.9736	0.9920	258.28 s	0.9734*
ResNet50	Adagrad	0.9715	0.9701	0.9706	0.9851	259.85 s	0.9701
ResNet50	SGD	0.9695	0.9635	0.9653	0.9880	264.58 s	0.9635
ResNet50	Adadelta	0.9567	0.9556	0.9561	0.9817	260.07 s	0.9556
DenseNet121	Adam*	0.9715	0.9714	0.9715	0.9911	268.23 s	0.9714*
DenseNet121	RMSprop	0.9653	0.9648	0.9651	0.9878	267.61 s	0.9648
DenseNet121	Adagrad	0.9689	0.9668	0.9676	0.9868	266.89 s	0.9668
DenseNet121	SGD	0.9692	0.9665	0.9665	0.9882	266.62 s	0.9665
DenseNet121	Adadelta	0.9580	0.9536	0.9553	0.9797	267.39 s	0.9536
XCeption	Adam	0.9711	0.9678	0.9689	0.9892	389.93 s	0.9678
XCeption	RMSprop*	0.9756	0.9756	0.9734	0.9911	383.37 s	0.9724*
XCeption	Adagrad	0.9662	0.9635	0.9645	0.9823	384.23 s	0.9635
XCeption	SGD	0.9626	0.9579	0.9596	0.9828	383.87 s	0.9579
XCeption	Adadelta	0.9585	0.9464	0.9501	0.9774	385.66 s	0.9464
InceptionV3	Adam	0.9699	0.9691	0.9695	0.9887	200.64 s	0.9691
InceptionV3	RMSprop*	0.9732	0.9717	0.9723	0.9915	198.71 s	0.9717*
InceptionV3	Adagrad	0.9649	0.9619	0.9630	0.9873	199.61 s	0.9619
InceptionV3	SGD	0.9643	0.9615	0.9626	0.9852	199.06 s	0.9615
InceptionV3	Adadelta	0.9444	0.9352	0.9386	0.9676	199.59 s	0.9352

numbers of fully connected layer neurons and different optimization algorithms added to the architectures, and the results are presented comparatively. First, architectures were trained with optimization algorithms and the most successful optimizer was determined. In the next stage, experiments were carried out by combining the most successful optimizer with different fully connected layer neurons. The performance of the architectures used to classify imperfect and perfect timbers is shown in Table 2. Experiments are performed with the augmented and balanced dataset.

Table 2 shows that the most successful results of the different architectures used for the experiments were obtained with the RMSprop optimizer. The most successful result was obtained as 97.47 % with the VGGNet-16 architecture with 256 neurons. The results show that SGD and Adadelta optimizers produce lower results and fail more than others. Adagrad is the optimizer that provides results closest to RMSprop in all architectures. Although Adam provided the most successful performance in large-scale image classification competitions such as ImageNet, it fell behind RMSprop and Adagrad in this study for the detection of wood defects.

Experiments were conducted with four different variables, 256, 512, 1024 and 2048 neurons, with the RMSprop optimization algorithm that gives the best result as shown in Table 3.

In the experiments conducted with different neuron numbers using the RMSprop algorithm, the following accuracy was found: VGG16 1024 neurons - 97.50 %, Mobilenet 256 - neurons 97.37 %, Resnet50 256 - neurons 97.34 %, DenseNet121 2048 neurons - 97.34 %, Inceptionv3 2048 neurons - 97.24 %. Increasing the ResNet50 architecture with 256 neurons did not improve accuracy. The Xception architecture achieved the highest accuracy at 512 neurons. In Densenet121 and InceptionV3 architectures, the highest accuracy was achieved at 2048 neurons. Among all experiments, the Xception architecture RMSprop optimization algorithm gave the highest accuracy result of 97.57 % with 512 neurons.

Although the Xception architecture reaches 97.57 % accuracy, the training and testing time is more than 2 times that of the MobileNet architecture. MobileNet architecture reaches 97.37 % accuracy, which is close to the highest result in the shortest time. At the same time,

Table 3 CNN architectures, RMSprop optimizer and neuron count performances
Tablica 3. CNN arhitekture, RMSprop optimizator i performanse brojenja neurona

CNN model *CNC model*	**Optimization algorithm / number of neurons** *Optimizacijski algoritam / broj neurona*	**Precision** *Preciznost*	**Recall** *Opoziv*	**F1-score** *F1-rezultat*	**ROC**	**Time** *Vrijeme*	**Accuracy** *Točnost*
VGG16	RMSprop / 256	0.9754	0.9747	0.9750	0.9914	309.19 s	0.9747
VGG16	RMSprop / 512	0.9730	0.9730	0.9730	0.9905	308.68 s	0.9730
VGG16	RMSprop / 1024*	0.9754	0.9750	0.9752	0.9920	309.74 s	0.9750*
VGG16	RMSprop / 2048	0.9729	0.9724	0.9726	0.9906	308.78 s	0.9724
MobileNet	RMSprop / 256*	0.9749	0.9737	0.9742	0.9880	156.01 s	0.9737*
MobileNet	RMSprop / 512	0.9704	0.9698	0.9700	0.9813	145.78 s	0.9698
MobileNet	RMSprop / 1024	0.9722	0.9704	0.9711	0.9883	145.86 s	0.9704
MobileNet	RMSprop / 2048	0.9751	0.9734	0.9740	0.9910	147.48 s	0.9734
ResNet50	RMSprop / 256*	0.9740	0.9734	0.9736	0.9920	258.28 s	0.9734
ResNet50	RMSprop / 512	0.9628	0.9632	0.9630	0.9885	258.92 s	0.9632
ResNet50	RMSprop / 1024	0.9741	0.9724	0.9730	0.9910	259.27 s	0.9724
ResNet50	RMSprop / 2048	0.9726	0.9717	0.9721	0.9906	259.00 s	0.9717
DenseNet121	RMSprop / 256	0.9653	0.9648	0.9651	0.9878	267.61 s	0.9648
DenseNet121	RMSprop / 512	0.9697	0.9684	0.9689	0.9893	266.79 s	0.9684
DenseNet121	RMSprop / 1024	0.9734	0.9724	0.9728	0.9909	267.34 s	0.9724
DenseNet121	RMSprop / 2048*	0.9748	0.9734	0.9739	0.9915	267.08 s	0.9734*
XCeption	RMSprop / 256	0.9756	0.9756	0.9734	0.9911	383.37 s	0.9724
XCeption	RMSprop / 512*	0.9769	0.9757	0.9761	0.9870	383.81 s	0.9757*
XCeption	RMSprop / 1024	0.9755	0.9753	0.9754	0.9923	383.54 s	0.9753
XCeption	RMSprop / 2048	0.9636	0.9642	0.9639	0.9737	383.84 s	0.9642
InceptionV3	RMSprop / 256	0.9732	0.9717	0.9723	0.9915	198.71 s	0.9717
InceptionV3	RMSprop / 512	0.9737	0.9714	0.9722	0.9928	198.73 s	0.9714
InceptionV3	RMSprop / 1024	0.9706	0.9691	0.9697	0.9871	198.59 s	0.9691
InceptionV3	RMSprop / 2048*	0.9720	0.9724	0.9721	0.9901	199.45 s	0.9724*

the InceptionV3 architecture, which is low in terms of time, reaches 97.24 % accuracy with 2048 neurons.

The confusion matrix of the test set of the Xception architecture, which achieved the most successful accuracy rate according to the experiments, is shown in Figure 3.

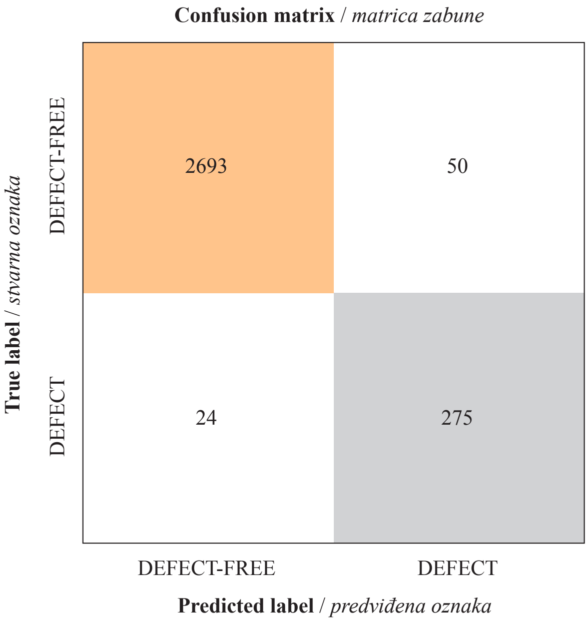

Figure 3 Confusion matrix of the most successful Xception architecture
Slika 3. Matrica zabune najuspješnije Xception arhitekture

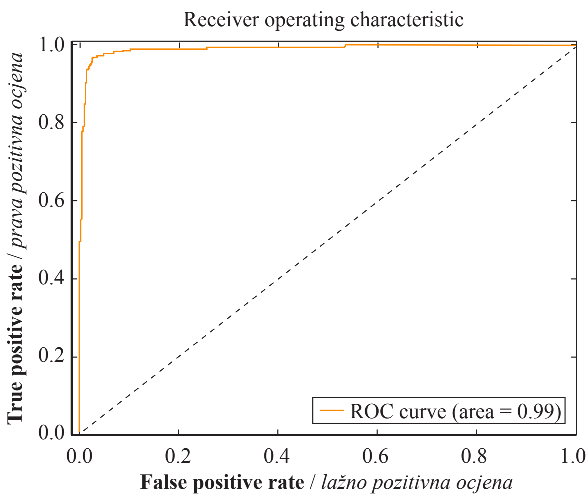

Figure 4 ROC curve showing discernment ability of Xception architecture
Slika 4. ROC krivulja koja pokazuje sposobnost razlučivanja Xception arhitekture

The ROC curve shows how well classifiers separate positive and negative examples. One side of the ROC curve gives the true positive rate, and the other side gives the false positive rate. The area under the curve shows the AUC score. The ROC curve showing the discrimination ability of the Xception architecture, which achieved the most successful results, is shown in Figure 4.

4 CONCLUSIONS
4. ZAKLJUČAK

Wood defect detection is an important issue in quality and production processes in the woodworking industry worldwide. In this study, deep learning-based classification is performed for the detection of imperfect and perfect wood images, and the performance of the architectures used for classification is compared. Deep learning architectures are classified by learning features from the representation of the data. The size and diversity of the data set increases the classification performance. For this reason, the data is divided into 70 % training, 15 % validation and 15 % testing. In the dataset set, 12798 imperfect and 12798 perfect wood images are separated for training. 25596 images are allocated for training. For validation, 2473 images are separated into 15 % of the defective wood images. For validation, 299 images are reserved as 15 % of the perfect wood images. For the test, 2473 images are allocated as 15% of the defective wood images. For testing, 299 images are allocated as 15 % of perfect wood images. Data balancing is done only in training. Data augmentation is done to equalize the number of perfect wood images to the number of imperfect wood images to make the data balanced. Horizontal and vertical flips, angle changes, zooming, random contrast and brightness enhancement techniques are used in the training phase to improve the performance of the classification architecture and prevent overfitting.

VGG-16, MobileNet, DenseNet-121, ResNet-50, Xception, InceptionV3 architectures are used for the experiments. To determine the best optimization algorithm for the architectures, Adam, RMSprop, Adagrad, SGD, Adadelta are used. Experiments are performed with 256, 512, 1024, 2048 neurons to determine the performance of the architecture and optimization algorithms.

Experiments on the dataset used Xception architecture - RMSprop algorithm - 512 neurons with 97.57 % classification accuracy and 99.11 % ROC score. The most unsuccessful result was achieved by the MobileNet architecture - Adadelta optimization algorithm - 93.16 % classification accuracy with 256 neurons. These results could not be compared since no binary classification has ever been done in the literature for this dataset. In the light of the results, it can be said that a very successful performance was obtained for defect detection in wood with heterogeneous and 10 different defects. In future studies, it is aimed to increase the classification success by automatically segmenting the defect region due to the noise in the images to be used in wood defect detection, enabling deep learning architectures to better see distinctive features and improving the classifier hyper-parameters.

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Effects of DES and Chlorite Delignification Methods on Properties of Transparent Wood Materials

Učinci dubokih eutektičnih otapala i metodâ delignifikacije kloritom na svojstva prozirnih drvenih materijala

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ABSTRACT • *Wood has many uses as raw material and after being processed. Since the use of wood as raw material is limited, the interaction of physical and chemical processes with technological developments has led to new products and new areas of use. Transparent wood production, for example, has emerged to provide maximum efficiency from heat and light. In this study, sodium chlorite and deep eutectic solvents (DES) obtained from choline chloride and lactic acid were used. In the production of transparent wood, 1- and 2-mm thick beech wood veneers (Fagus orientalis L.) and two-component transparent epoxy resin were used as filler. As a result of delignification processes, the highest delignification rate was obtained with 59 % in wood samples treated with $NaClO_2$. Transparent wood production was obtained from the samples where the most delignification took place. The adhesion of the epoxy used in the production of transparent wood in the wood cells was determined by SEM analysis. The tensile strength of the transparent wood samples increased by 31 % compared with the control samples. The study results contribute to the literature on the efficiency of different delignification methods.*

KEYWORDS: *deep eutectic solvent; delignification; transparent wood; beech wood*

SAŽETAK • *Drvo ima široku primjenu kao sirovina i nakon različitih procesa prerade. Budući da je uporaba drva kao sirovine ograničena, interakcija fizikalnih i kemijskih procesa s tehnološkim je razvojem dovela do pojave novih proizvoda i područja uporabe. Na primjer, proizvodnja prozirnog drva pojavila se kako bi se osigurala maksimalna učinkovitost topline i svjetlosti. U ovom su istraživanju korišteni natrijev klorit i duboka eutektična otapala (DES) dobivena od kolin klorida i mliječne kiseline. U izradi prozirnog drva korišteni su bukovi furniri (Fagus orientalis L.) debljine 1 i 2 mm i dvokomponentna prozirna epoksidna smola kao punilo. U procesu delignifikacije najveća je stopa delignifikacije od 59 % postignuta na uzorcima drva tretiranima s $NaClO_2$, te su ti uzorci rabljeni za proizvodnju prozirnog drva. Adhezija epoksidne smole u stanicama drva, koja je upotrijebljena*

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u proizvodnji prozirnog drva, određena je SEM analizom. Vlačna čvrstoća prozirnih uzoraka drva povećala se za 31 % u usporedbi s kontrolnim uzorcima. Rezultati istraživanja pridonose literaturnim podatcima o učinkovitosti različitih metoda delignifikacije.

KLJUČNE RIJEČI: *duboka eutektična otapala; delignifikacija; prozirno drvo; bukovina*

1 INTRODUCTION
1. UVOD

Wood structures vary according to wood type (softwood and hardwood) and growing zones. Softwoods generally grow fast, and their cells are larger than hardwoods, whereas hardwoods generally grow slowly, and their cells are smaller; however, hardwood densities are higher than those of softwoods (Russel and Richard, 1984).

The lumens and cell wall, which are formed by the porous structure of wood, have an important place in the reflection of light. Lignin, which is one of the elements composing wood, has a complex structure and a brown color. Hemicellulose and cellulose, the other essential elements of wood, have a white color (Fink, 1992; Zhu *et al*., 2014). Therefore, research on the optic properties cannot be conducted in the current form of wood, and lignin must be removed from inside the cell wall. The status requires pretreatments and chemical processes. After lignin is removed via several methods from the wood structure, cellulose and hemicellulose become individual forms. Li *et al*. (2016) treated wood with poly (methyl methacrylate) after delignification of wood under vacuum, obtaining 85 % transparent wood. Zhu *et al*. (2016a) modified a $NaOH/Na_2SO_3$ solution to remove the lignin in the wood, and the wood without lignin was impregnated with polyvinylpyrrolidone (PVP) to obtain high transparency. The results showed wood obtained with high transparency of 90 %. Zhu *et al*. (2016b) modified the wood material with $NaOH/Na_2SO_3$, and later the modified wood was treated with hydrogen peroxide (H_2O_2). The delignified wood was impregnated with epoxy under vacuum, and the obtained wood was found to have high transparency in the range of 75 – 90 %.

According to the literature review, chemicals generally provide high transparency of wood; however, the chemicals are petroleum-based materials and can cause environmental pollution. With increased interest in the environment, the use of chemicals is often decreased in many applications due to legal regulations. For the delignification of wood materials, green chemicals such as deep eutectic solvents (DES) have started to be used in the same applications. Deep eutectic solvents are a new class of solvents that have gained significant attention in recent years. Their unique properties make them attractive for a wide range of applications in fields such as chemistry, materials science, and biotechnology. These solvents are formed from the complexation of a hydrogen bond donor (such as a quaternary ammonium salt) and a hydrogen bond acceptor (such as a metal salt or organic compound). They exhibit a eutectic behavior, which means they have a lower melting point compared with the individual components. This property allows them to be used as low-temperature solvents, making them suitable for processes that require low temperature conditions. Some of the advantages of deep eutectic solvents include their biodegradability, non-toxicity, and low volatility (El Achkar *et al*., 2021).

Traditional delignification methods have been used for many years in various industries, such as pulp and paper production and biofuel production. These methods involve the use of chemicals, such as sodium hydroxide, to break down and remove lignin from cellulose fibers. This process is known as “delignification” and is essential for separating lignin from cellulose to obtain high-quality cellulose fibers for different applications, such as papermaking or producing biofuels (Sivasubramanian *et al.,* 2008).

Previous studies showed that DES can provide a good delignification in wood materials as compared with conventional chemicals and it generally does not affect cellulosic materials (Francisco *et al*., 2012; Lynam *et al*., 2017). The extraction mechanism of lignin from wood with DES occurs with the breaking of phenyl propane units in a lignin structure as occurring in the conventional chemicals (Alvarez-Vasco *et al*., 2016).

The building sector (electrical devices, heating, air conditioning, and hot or cold-water vb.) generally accounts for the highest energy consumption in the world (about 30 – 40 %) (Rotzetter *et al*., 2012). Therefore, world demand for sun energy, i.e., a clean, low-cost, and sustainable resource, has been increased to meet the increase of energy consumption amounts in accordance with the economic development. The demands for artificial light sources can be reduced via natural light sources with transparent buildings (He *et al*., 2014). Further, transparent wood can be used as transparent construction materials, and sun battery staffs due to its optic properties and high mechanical strength (Yaddanapudi *et al*., 2017). The aims and objectives of this study are to determine the results of delignification with DES, i.e., to determine transparency by obtaining transparent wood as well as to determine the morphological and mechanical properties of transparent wood.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

In the study, beech wood veneers with 1- and 2-mm thickness were used. The veneers have dimensions of 5 x 5 cm and moisture content of 12 %. The hybrid methods, including DES, sodium chlorite ($NaClO_2$), and their mixes (50/50 wt.), were used for the delignification of the veneers. Choline chlorite (ChCl) with a molecular weight of 139.62 g/mol and lactic acid (LA) with a molecular weight of 90.8 g/mol were used to obtain the DES. After the delignification with 1.7 mol/L $NaClO_2$, 30 % H_2O_2 was used to provide higher transparency in the wood. The variations and material properties for the delignification of the wood are given in Table 1.

2.2 Preparation of DES
2.2. Priprema dubokih eutektičnih otapala

DES was prepared by mixing ChCl with LA at 1:10 (mol: mol). The blends were made at a temperature of 60 °C under a magnetic mixer until the blends were homogenous and the final blends were transparent. The production mechanism of the DES is given in Figure 1.

To determine the optimum DES activity, the veneers were treated with ten-fold DES at 120 °C for 1, 2, 3, and 4 h.; images of the resulting solvents after the treatment of the veneers are given in Figure 2. In treatments of more than 4 h (5-6 h), it was determined that the dissolved lignin was reabsorbed by the wood. In this case, the main purpose of the delignification process is lost.

2.3 Delignification of wood materials
2.3. Delignifikacija drvnih materijala

In this study, the delignification process with DES was conducted on the four wood samples having a moisture content of 12 %. The ratio of sample to solvent was 1:10 (w/w). The delignification was applied to the wood samples at 120 °C for 4 h; after the treatment, the samples were dried with distilled water. The washing process was continued for 5 min under running water. The washed samples were kept in distilled water for 12 h. The delignification process with sodium chlorite ($NaClO_2$) is a commonly used method in the pulp and paper industry. This study followed the same method, and the samples with the dimensions of 5 mm × 5 mm were put into a beaker containing 1.7 mol/L $NaClO_2$ with the tenfold weight of each wood sample. The beaker was kept in the water bath at the temperature of 80 °C under an air cabinet, and 0.5 mL acetic acid (CH_3COOH) and 1.5 g $NaClO_2$ were added to the beaker for each 160 mL $NaClO_2$ solvent per hour (total 6 h). After the delignification, the whitened samples were cleaned for 6 h with distilled water. After the delignification of the samples, the whitening process with 30 % hydrogen peroxide (H_2O_2) was applied to the samples in the water bath at 80 °C for 30 min. Four types of the delignification process were applied, including DES, $NaClO_2$, $NaClO_2$+H_2O_2, DES+$NaClO_2$+H_2O_2. After the delignification, all samples were put in a beaker containing ethyl alcohol for 12 h; further, some of the delignified samples were dried and then ground for determining residue lignin. Table 1 shows the delignification type and formulations of the wood samples.

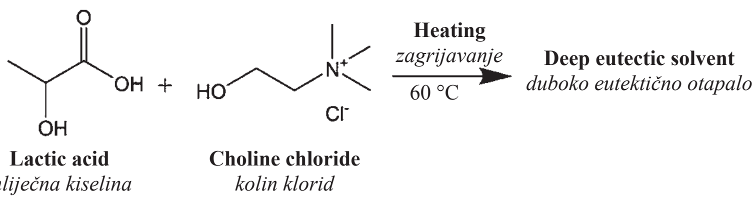

Figure 1 Production of lactic acid-based DES (Li *et al*., 2019)
Slika 1. Proizvodnja dubokih eutektičnih otapala na bazi mliječne kiseline (Li *et al*., 2019.)

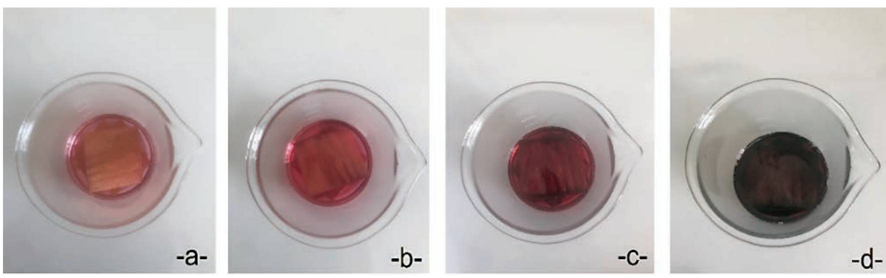

Figure 2 Resulting solvents after treatment of veneers (a=1 hour, b=2 hours, c=3 hours, d=4 hours)
Slika 2. Dobivena otapala nakon tretiranja furnira (a=1 sat, b=2 sata, c=3 sata, d=4 sata)

Table 1 Delignification type and formulations
Tablica 1. Vrste i formulacije delignifikacije

Variations / *Varijacije*	**Delignification process** / *Proces delignifikacije*	
DES	1st stage	1:10 DES at 120 °C for 4 h
$NaClO_2$	1st stage	1.7 mol/L $NaClO_2$ at 80 °C for 6 h
	2nd stage	30% H_2O_2 at 80 °C for 2 h
DES+$NaClO_2$	1st stage	1:10 DES at 120 °C for 4 h
	2nd stage	1.7 mol/L $NaClO_2$ at 80 °C for 6 h
	3rd stage	30% H_2O_2 at 80 °C for 2 h
Control / *Kontrola*	No action taken / *nije poduzet nikakav postupak*	

2.4 Determination of residue lignin percentages
2.4. Određivanje postotnog sadržaja lignina nakon delignifikacije

The Klason method, according to the TAPPI T222 om-66 standard, was used to determine the amount of residue lignin in wood veneers with 1-mm thickness. Lignin amount was calculated according to the following Eq. 1:

$$Lignin\ amount\,(\%) = \frac{A}{W} \cdot 100 \qquad (1)$$

where A is residue lignin amount (g), and W is oven-dried wood weight (g).

2.5 Transparent wood production
2.5. Proizvodnja prozirnog drva

Wood veneers with dimensions of 5 cm × 5 cm were impregnated via immersion into epoxy resin with two components (2:1 wt. %, resin/hardener) in a silicon plate under a vacuum cabinet, after the delignification and H_2O_2 treatment. A stainless-steel web was covered on the top of the silicon plate during the immersion to prevent the movement of the wood veneers in the vacuum cabinet. The vacuum process was applied at 0.1 mbar for 40 min. After the vacuum process, the immersed wood veneers were put inside two silicon mats for 24 h to obtain a smooth surface.

2.6 Methods
2.6. Metode

2.6.1 Scanning electron microscope (SEM) analysis
2.6.1. Analiza skenirajućim elektronskim mikroskopom (SEM)

Morphology and fractured sections of the transparent woods were examined with a Tescan MAIA3 XMU-SEM at various magnitudes. For SEM analysis, sections were taken from the samples at equilibrium moisture (12 %). The samples were coated with a mixture of palladium/gold particles to enhance the flow of electrons.

2.6.2 Fourier transform infrared (FTIR) analysis
2.6.2. Analiza Fourierovom infracrvenom spektroskopijom (FTIR)

The transparent wood was scanned with a Shimadzu IRAffinity-1 FTIR (Kyoto, Japan). The spectra of the samples were recorded by 16 scans from 800 to 3800 cm^{-1} with a resolution of 4 cm^{-1}. This analysis was carried out to determine whether the treatments caused changes in the chemical structure of the samples.

2.6.3 X-Ray diffraction (XRD) analysis
2.6.3. Analiza difrakcijom X-zraka (XRD)

The XRD pattern was obtained with a Philips PANalytical Empyrean X-ray diffractometer using Ni-filtered Cu Kα (1.540562 Å) radiation at scales from 10° to 80° 2 θ range, and the crystallinity was determined using the Segal and curve-fitting methods. XRD analysis was used to determine the differences in the crystal structure of the samples.

2.6.4 Tensile strength tests
2.6.4. Ispitivanja vlačne čvrstoće

A U-test mechanical tester was used to characterize the mechanical properties of the transparent wood. The tensile test was conducted according to ASTM D 638-03 Type I at 5 mm/min of test speed. Elongation during the test was measured with an extensometer.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Delignification results
3.1. Rezultati delignifikacije

The delignification process of lignin from structural components of the wood was conducted prior to transparent wood production. In this study, various delignification methods including DES, $NaClO_2$, and DES+ $NaClO_2$, were used. Delignification processes determined by the ultrasound method according to TAPPI T122-om-66 were compared with control samples. Table 2 shows 19.5 % of lignin for the control beech wood in the delignification with the Klason method. The delignification with DES was provided 13 % of lignin in beech wood. The minimum amount of lignin of 8 % wt. was found in the delignification with $NaClO_2$. With the chlorite method, 59 % of the existing lignin (19.5 %) in the control sample was removed, leaving 8 % lignin. After combining DES and $NaClO_2$, the amount of lignin was found to increase from 8 % to 12 %. On the other hand, the use of DES in combina-

Table 2 Delignification rate and lignin amount obtained with different methods
Tablica 2. Stopa delignifikacije i količina lignina dobiveni različitim metodama

Methods / *Metode*	**Amount of lignin before delignification, wt. %** *Količina lignina prije delignifikacije,* tež. %	**Amount of lignin after delignification, wt. %** *Količina lignina nakon delignifikacije,* tež. %	**Delignification rate, %** *Stupanj delignifikacije,* %
Control	19.5		-
DES (in veneers)		13	33.3
$NaClO_2$ (in veneers)		8	59.0
DES+$NaClO_2$ (in veneers)		12	38.5

tion with sodium chloride did not cause a significant change in the delignification process. As a result, it has been seen that using delignification methods alone will be more efficient and economical.

In a study, Yaşar and Tanrıverdi (2008) grounded the beech wood and researched the lignin amount in the wood after delignification conducted with DES; the lignin amount was determined as 26.1 % wt. In this study, the lignin amount was lower due to the wood veneers, according to Yaşar and Tanrıverdi (2008), because of lower contact surface of the solvents. The reason might be that the veneers were produced with the pretreatments of hot water or by water steaming, and the methods might have been affected by the lignin percentages in wood (Cristescu and Karlsson, 2013). Yang *et al*. (2020) studied with DES the effect of ChCl/oxalic acid (1:1) on the delignification of balsa wood, and the delignification rate was determined as 60 %; further, Hou *et al*. (2018) found the delignification rate as 84.7 % via similar DES (2:1) with ChCl at higher percentages. In this study, the delignification rate was generally lower than found in the literature, i.e., the studies in the literature review were generally conducted on grounded wood; therefore, the contact surface and efficiency of the solvents were higher. However, this study was conducted on wood veneers, and both the contact surface and efficiency of the DES were lower than them.

Therefore, in this study, the lignin amount was lower than that of the studies in the literature review. Although the minimum lignin amount was obtained with the DES delignification, the maximum delignification rate was determined as 59 % for the $NaClO_2$. In another study, Yang *et al*. (2020) studied the lignin amount and the delignification rate of balsa wood with DES; the delignification rate was determined to be 77 %. The rate was found to change according to the wood anatomical structure and solvent contact surface. However, the data obtained and the literature have differences, as the solvents were applied to the coating in the study; therefore, the solvent could not penetrate into the inner parts of the wood sufficiently.

On the other hand, in the literature studies where high delignification was achieved, solvents were used after grinding the wood, which resulted in a more efficient delignification process. Figure 3 shows 1-mm thick wood veneers delignified with $NaClO_2$ - (a) veneers before and (b) veneers after delignification. Generally, appearances of the samples after all delignification processes were similar to each other.

a) b)

Figure 3 1-mm thick wood veneers delignified with $NaClO_2$: a) veneers before and b) veneers after delignification
Slika 3. Furniri drva debljine 1 mm delignificirani s $NaClO_2$: a) furniri prije delignifikacije, b) furniri nakon delignifikacije

The delignification with DES+$NaClO_2$ was provided at 12 % of the lignin amount and 38.5 % of the delignification rate. As a result, DES efficiency on the delignification of the veneers was higher than the efficiency of $NaClO_2$, and it can be said that only DES treatment is a good method for the lignin delignification. As shown in Figure 2, the treatment time was an important factor in the delignification with DES, and it can be said that the best delignification parameters were determined at 120 °C for 4 h due to the black color of DES after the delignification. After the delignification with DES, the veneers were softened, and the dimensional integrity of the veneers was broken down. This status might be caused by the removal of lignin, as a filling material in the wood.

In another study, Fu *et al.* (2018) provided a high lignin-removing rate during the delignification with DES. Weakening of bonds between wood cells and then loosening of the cytoskeleton of veneers were found to occur with too high lignin delignification, which decreased the mechanical properties with the dimensional integrity of the veneers. Consequently, it can be said that treatment time and temperatures were important factors in the delignification rate. Although the minimum lignin amount was determined with the delignification with $NaClO_2$, the best delignification rate was obtained with the delignification with $NaClO_2$; therefore, this study

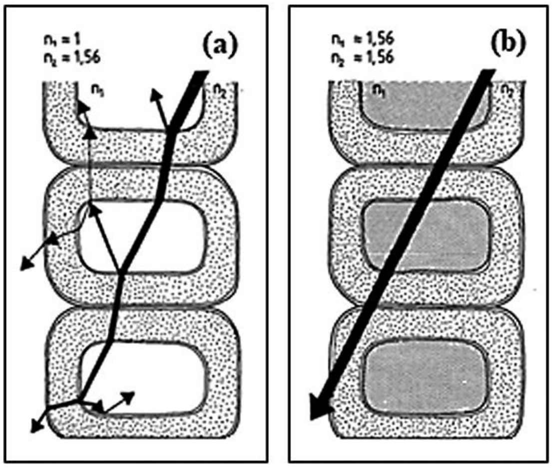

Figure 4 Light reflection and direction in (a) empty lumen and (b) lumen filled with epoxy (Fink, 1992)
Slika 4. Refleksija i smjer svjetlosti u praznom lumenu (a) i u lumenu ispunjenom epoksidom (b) (Fink, 1992.)

a)

b)

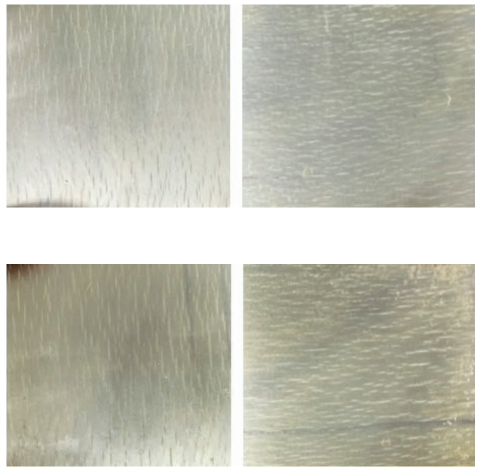

Figure 5 Transparent veneers with 1-mm (a) and 2-mm (b) thickness before impregnation with epoxy
Slika 5. Prozirni furniri debljine 1 mm (a) i debljine 2 mm (b) prije impregnacije epoksidom

was conducted on the properties of the 1- and 2-mm samples delignified with $NaClO_2$.

3.2 Transparency results
3.2. Rezultati prozirnosti

After filling the wood cells with epoxy, the appearance of the delignified wood changed from white to transparent; however, the transparency of the samples may generally not be enough due to low filling rate with the epoxy as given in Figure 4a; further, the good transparency can be provided with good filling rate in the wood cells, as seen in Figure 4b. This status might be caused due to the areas with different densities and the different light reflections in the wood inside (Fink, 1992).

Refractive index is the ratio of the speed of light in a vacuum to its speed in a given medium. The speed of light in a medium depends on the properties of the medium. The reflective material (epoxy) and lumen refractive index (n) play an important role in the light reflection. Increasing the difference between the lumen refractive index ($n_1 = 1$) and the wood cell refractive index ($n_2 = 1.56$) causes the scattering of the light (a decrease in the light intensity), as seen in Fig. 4 (a). If the optical properties of the filling material and wood cells were similar to each other, the scattering of the light would not occur, and the materials would have transparency properties due to good light reflection, as seen in Figure 4b. The transparent wood with 1-mm (a) and 2-mm (b) thickness is shown in Figure 5. For providing transparency, the differences between refractive indexes must be little or similar, as presented by Fink (1992). For example, neat cellulose is white in color and is not transparent. When cellulose is saturated with water ($n_c = 1.3$), wet cellulose exhibits transparency properties, as opposed to dried cellulose. In this study, the delignified wood was impregnated with epoxy, including two components, and epoxy filling under vacuum exhibited the transparency properties in the veneers due to similarity in the refractive indexes of epoxy and delignified samples as seen in Figure 5 and 6.

After the delignification process of the veneers, lightening was found to occur in the colors of the rays, and their visibility did not disappear, as seen in Figure 5. It can be said that this situation provides a natural appearance to transparent woods. On the other hand, if the desired look is not achieved, various softwoods or tree species, including high sapwood, can be selected to produce transparent wood. According to the SEM images in Figure 7, the epoxy resin filled many wood cell lumens; therefore, transparency was ensured. In the empty lumens, transparency remained at a certain level due to high light diffraction. Less dense epoxy or stronger vacuum can be applied to fill the empty lumens.

According to SEM images, it was determined that the epoxy generally filled the wood cells very well. Furthermore, SEM images show that the cell filling ability of epoxy is quite high (60-70 %). The empty lumens are presumably latewood trachea (thick cell walls, narrow lumens).

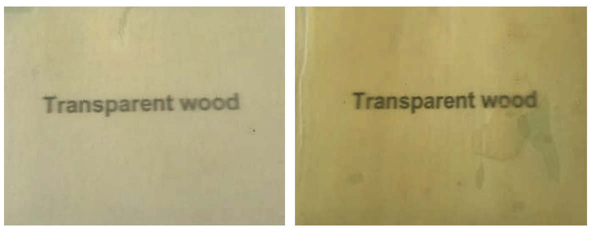

Figure 6 Transparent samples with 1-mm (a) and 2-mm (b) thickness after impregnation with epoxy
Slika 6. Prozirni uzorci debljine 1 mm (a) i debljine 2 mm (b) nakon impregnacije epoksidom

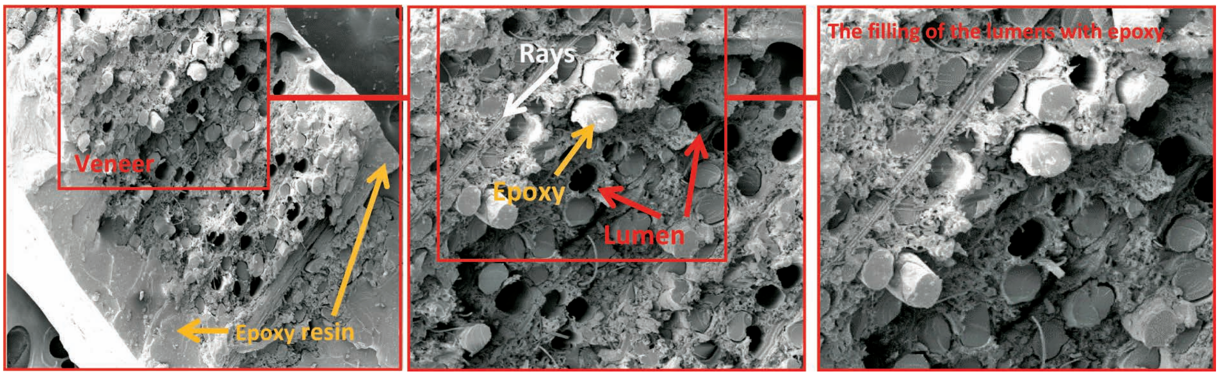

Figure 7 SEM images of transparent veneers prepared with epoxy resin
Slika 7. SEM slike prozirnih furnira s epoksidnom smolom

3.3 FTIR results
3.3. FTIR rezultati

After the delignification, most of the lignin in the veneers is removed with the delignification solvents. This turns the veneers into a cellulosic-structured material. The changes in the structure of the cellulosic material were investigated as given in Figure 8. FTIR analysis was conducted from 800 to 4600 cm^{-1}. FTIR results generally exhibited the wavenumbers belonging to holocellulose, and hemicelluloses were detected at the wavenumber of 1734 cm^{-1} (Cheng *et al.*, 2016). However, the aromatic rings of the lignin and C = C bonds were found at the wavenumbers of 1595 and 1603 cm^{-1}, respectively. The vibration of the aromatic rings was detected at 1509 cm^{-1} (Popescu *et al.*, 2007; Zhou *et al.*, 2015), and C –O bonds of the guaiacyl and syringyl lignin were detected at 1240 and 1670 cm^{-1} (Popescu *et al.,* 2007; Chen *et al.*, 2010, Traoré *et al.,* 2018) and 1215 cm^{-1} (Zhou *et al.*, 2015).

As seen in Figure 8, especially in the veneers treated with $NaClO_2$ and DES+$NaClO_2$, the bonds at 1245 and 1215 cm^{-1} for guaiacyl and syringyl units, and the bonds at 1425 and 1465 cm^{-1} for C–H asymmetrical deformation of methoxyl/aromatic skeletal vibrations were determined to be of low intensity (Kaur *et al.*, 2023). However, the lignin content in the veneers treated with DES was found to be high. Consequently, it can be said that the lignin delignification rate conducted with $NaClO_2$ and DES+$NaClO_2$ was found to be higher than the delignification made with DES. These results are supported by the data in Table 2.

3.4 XRD results
3.4. XRD rezultati

XRD was used to determine the structural analysis and crystallinity of the veneers at two thickness (1-

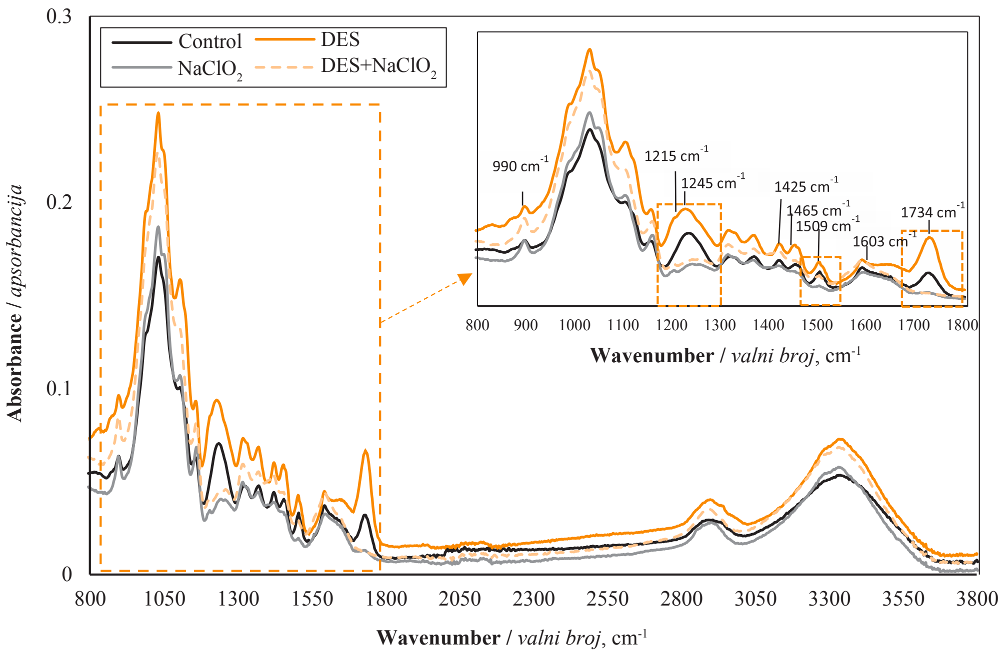

Figure 8 FTIR spectra of control and delignified woods
Slika 8. FTIR spektri kontrolnoga i delignificiranog drva

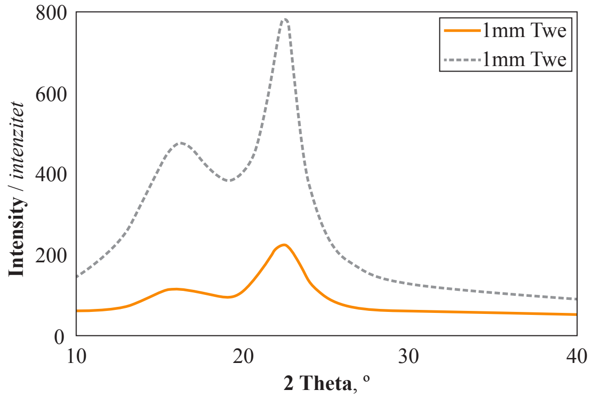

Figure 9 XRD patterns of transparent veneers with 1- and 2-mm thickness
Slika 9. XRD dijagrami prozirnih furnira debljine 1 i 2 mm

Table 3 Peak points and crystallinity of transparent veneers with 1- and 2-mm thickness
Tablica 3. Vršne točke i kristaliničnost prozirnih furnira debljine 1 i 2 mm

Samples *Uzorci*	**2 Theta, °**	**Crystallinity, %** *Kristaliničnost, %*
1-mm Twe	15.8, 22.4	45
2-mm Twe	16.4, 22.6	65

and 2-mm), as given in Figure 9. As seen in the XRD patterns, the highest peak was detected at 16.4° and 22.6° for the transparent veneers with 2-mm thickness. For the transparent veneers with 1-mm thickness, two peaks were determined at 15.8° and 22.4°, but the peak at 15.8° was found to be weaker than the peak at 22.4°. The crystallinity index was measured according to the Gauss method and calculated at 65 % and 45 % for the transparent veneers 2-mm and 1-mm thick, respectively, as given in Table 3. Epoxy has an amorphous peak at 20°-23° (Alhumade *et al.,* 2019), and it can be seen that the veneers 1-mm thick absorbed the epoxy resin better than the veneers 2-mm thick (2-mm Twe). This status means that the veneers 1-mm thick (1mm Twe) had better transparency.

3.5 Mechanical results
3.5. Rezultati mehaničkih ispitivanja

The tensile strength of the transparent veneers with 2-mm thickness was compared with beech wood veneers of the same dimension. Five specimens were tested for both veneers, and the obtained results are given in Table 4.

After the tensile test, the mean deformation and maximum load were found as 1.2 and 1.5 mm and 606 and 795 N for the control wood and the transparent wood, respectively. Tensile strength was calculated as 95 N/mm^2 for the control wood and 125 N/mm^2 for the transparent wood. The tensile strength of transparent wood was found to be higher (31 %) than the control

Table 4 Tensile strength values of transparent and control veneers
Tablica 4. Vrijednosti vlačne čvrstoće prozirnih i kontrolnih furnira

Values / *Vrijednosti*	**Control wood** *Kontrolno drvo*	**Transparent wood** *Prozirno drvo*
Force, N *sila,* N	606	795
Tensile strength, N/mm^2 *vlačna čvrstoća,* N/mm^2	95	125
Deformation, mm *deformacija,* mm	1.2	1.5

wood. The tensile strength of beech wood in the literature varies between 90-120 N/mm (Efe and Kasal, 2007; Çetin and Gündüz, 2017). As a result, the transparent veneers were found to have better mechanical performance than those presented in the literature.

Based on the above, the performance of the epoxy used as a filler has an important effect on the increase of the tensile strength of the transparent veneers. The literature reported that the used filling materials increase the mechanical properties depending on their structure (Li *et al*., 2016; Zhu *et al*., 2016b). From these results, it can be said that transparent wood can be an alternative material to wood in decorative structural applications for which high tensile strength is demanded.

4 CONCLUSIONS
4. ZAKLJUČAK

The sustainable, natural, and widespread availability of wood makes it a preference in many applications. This situation continues today, as in the past, with scientific studies and technological advances. The production and use of energy have strategic importance. Therefore, the interest in natural and renewable energy sources such as heat, light, and wind is quite high. The increase in delignification in the production of transparent wood obtained within the scope of this study naturally increased the transparency. It was observed that the deep eutectic solvent provided delignification at a lower rate than the chlorite method.

The structure of wood cells was also found to be important in the production of transparent wood. Large lumens are easier to fill with epoxy. More favorable results are obtained in materials with refractive indices close to each other. It has been determined that the voids in the material reduce the transmittance by reducing the intensity of light.

It was observed that the applied epoxy was effective in the higher mechanical resistance of the transparent wood samples compared with the control samples. Since it is possible to affect many stages in the production of transparent wood, luminous materials and decorative products and materials can be obtained during the production phase. Larger surface transparent wood materials can be preferred especially in smart buildings to obtain maximum benefit from light. Transparent wood applications can be carried out in the division of office and private areas and in areas where privacy is required. Again, with different disciplines, their potential to be used as a panel for the production of electricity from solar energy and the storage of the produced electricity can be increased.

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Comparing Wettability and Surface Free Energy of False Heartwood, Ripe Wood and Sapwood in Beech (*Fagus sylvatica* L.)

Usporedba stupnja kvašenja i slobodne površinske energije lažne srži, zrelog drva i bjeljike bukovine (*Fagus sylvatica* L.)

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ABSTRACT • *False heartwood is a common defect in beech wood. If the false heartwood is healthy and without microbial attacks, it is possible to utilize such material. Application of adhesives and coatings is an important part of the wood furniture industry. Studying wood surface properties provides answers to problems in application of glues, coating materials, and similar. Comparing wettability and surface free energy of false heartwood, ripe wood, and sapwood zones of beech was the focus of this paper. Two-way ANOVA with Duncan post-hoc test of multiple comparison was used for testing of the hypotheses and statistical evaluation of the results. The zones were also examined with light microscopy. Two testing liquids were used in wettability experiment – redistilled water and diiodomethane. Ripe wood showed the best wettability for both testing liquids among the wood zones. Significant differences in contact angles at the beginning of the wetting process, equilibrium contact angles, and surface free energies were found in almost all pairwise comparisons of the wood zone and testing liquid factors. The pairs where significant difference was not found were as follows: false heartwood and ripe wood in testing with redistilled water, and ripe wood and sapwood in testing with diiodomethane. Equilibrium times in all wood zones for both testing liquids were also statistically evaluated. Significant differences were found in all wood zones in testing with redistilled water. In testing with diiodomethane, equilibrium time for false heartwood was significantly different from ripe and sapwood zone equilibrium times.*

KEYWORDS: *beech; false heartwood; light microscopy; surface free energy; wettability*

SAŽETAK • *Lažna srž česta je greška bukovine, ali je i to drvo moguće iskoristiti ako je zdravo i nije napadnuto mikrobima. Primjena ljepila i premaza važni su postupci u drvnoj industriji i proizvodnji namještaja. Proučavanje svojstava površine drva daje odgovore na probleme u primjeni ljepila, premaznih materijala i sl. Fokus ovog rada je na usporedbi stupnja kvašenja i slobodne površinske energije drva u zoni lažne srži, zrelog drva i bjeljike bukovine. Za testiranje hipoteza i statističku procjenu rezultata primijenjena je dvosmjerna ANOVA s Duncanovim*

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post-hoc testom višestruke usporedbe. Zone drva istražene su i svjetlosnim mikroskopom. Pri ispitivanju stupnja kvašenja upotrijebljene su dvije ispitne tekućine – redestilirana voda i dijodometan. Zrelo drvo pokazalo je najbolju sposobnost kvašenja s obje ispitne tekućine. Značajne razlike u kontaktnim kutovima na početku kvašenja, ravnotežnim kontaktnim kutovima i slobodnim površinskim energijama zabilježene su u gotovo svim usporedbama zona drva i različitih ispitnih tekućina. Parovi u kojih nije utvrđena značajna razlika jesu lažna srž i zrelo drvo u ispitivanju redestiliranom vodom te zrelo drvo i bjeljika u ispitivanju dijodometanom. Također, statistički su procijenjena ravnotežna vremena u svim zonama drva za obje ispitne tekućine. U ispitivanju s redestiliranom vodom utvrđene su značajne razlike među ravnotežnim vremenom u svim zonama drva. U ispitivanju s dijodometanom ravnotežno vrijeme za lažnu srž značajno se razlikovalo od ravnotežnog vremena u zoni zrelog drva i bjeljike.

KLJUČNE RIJEČI: *bukovina; lažna srž; svjetlosni mikroskop; slobodna površinska energija; stupanj kvašenja*

1 INTRODUCTION
1. UVOD

Defects in wood are irregularities or abnormalities in wood structure. They usually change physical and mechanical properties of wood and therefore limit the use of such wood (Čunderlík, 2009). Nonetheless, defects in wood can create an interesting and aesthetically pleasing structure and are sought after for the manufacture of unique products. False heartwood is a hidden wood defect, and it is difficult to detect in a growing tree (Kúdela, 2011).

Other terms such as true heartwood, red heartwood, discoloured wood, wounded wood, pathological heartwood are also used for the different wood colourations found in hardwoods (Hörnfeldt *et al.,* 2010). The term "false heartwood" is used throughout this paper to cover all variants of wood colourations found in beech, in opposition to the normal heartwood colouration that beech does not produce (Hörnfeldt *et al.,* 2010; Shigo, 1986). Požgaj *et al.* (1993) divide false beech heartwoods according to their visible shape on the cross section. Round (simple, double, mosaic) red brown to pale brown heartwoods are considered "healthy" false heartwoods. Star shaped, flame shaped false heartwoods, and round false heartwoods with a different coloured zone and a sharp margin are "unhealthy" false heartwoods. Unhealthy and decayed false heartwood has significantly worse mechanical properties and it is not suitable for production of solid wood furniture (Požgaj *et al.,* 1993).

Numerous theories and interpretations of the formation of false heartwood are hypothetical even today (Prka *et al*., 2009). Many authors (Nečesaný, 1958; Bosshard, 1967; Paclt, 1953; Račko and Čunderlík, 2006) agree on the opinion that the primary cause of the false heartwood formation is a trunk injury during tree growth and the age of the beech tree. The trunk injury together with age influence the size and type of false heartwood. According to Chovanec (1969, 1974 and 1989) and Nečesaný (1958), the extent of false heartwood in the trunk depends on the age in which the wound was formed, the extent of the wound and the velocity of wound occlusion (Račko and Čunderlík, 2006). A healthy false heartwood is formed when parenchyma cells in the ripe wood zone die away. With the dyeing parenchyma cells, a film is created on the scalariform perforation plates. The false heartwood is then changing colour due to oxidization of extractives and tyloses form inside vessels (Kúdela, 2011).

Račko and Čunderlík (2006) evaluated the qualitative structure of beech logs produced in seven harvest areas in Slovakia, as well as the quality and quantity of beech false heartwood. The false heartwood was found in 30.7 % of the harvested logs. The average age of the logs ranged from 66.3 to 115.6 years. Račko and Čunderlík (2010) also investigated ripe wood as a limiting factor of false heartwood formation in beech. False heartwood started to form in approximately the 40th cambial age of the trunk, when there was already a 2.5 cm thick ripe wood zone present. Most of the trunks (89.5 %) had a smaller false heartwood zone compared to the size of ripe wood zone.

Another such research on the share of false heartwood in beech was performed by Prka *et al*. (2009) in central Croatia. In the respective cut classes, the share of logs containing false heartwood was as follows: 11.7 % in thinning cut, 54.7 % in preparatory felling, 71.3 % in seeding felling, and 84.6 % in final felling. The average age of the logs ranged from 76 to 106 years.

False heartwood often has a beautiful colour and texture (Hörnfeldt *et al*., 2010), which can be used as an aesthetic element in furniture. Some timber processors started looking for classical false heartwood timber to use its decorative characteristics. Furniture made of beech false heartwood is already well established and can be found in the individual production by carpenters as well as in the industrial production of kitchens, living- and bedrooms (Hansmann *et al*., 2009). Colour of the false heartwood can be effectively utilized for the production of decorative veneers (Kúdela, 2011).

According to Koch (2004), the industrially relevant properties of false heartwood are not adversely affected, except for the formation of tyloses. Požgaj *et al.* (1993) stated that, aside from colour and permeability, the physical and mechanical properties of healthy beech heartwood are the same as physical and mechanical properties of beech wood without false heartwood.

According to Pöhler *et al.* (2006), the mechanical and technological properties of red hearted beech give no evidence of different behaviour in comparison with the normal beech wood.

Applying adhesives or coating materials on beech boards or veneers with false heartwood, ripe wood, and sapwood might bring forth problems in woodworking processes. Differences in wood surface properties can cause different behaviour of coating materials on the wood substrate, different absorption of the adhesive or coating material, and this can cause defects in the final products. Therefore, it is important to study and understand wood surface properties, to ensure a final product of high quality.

Wetting of the wood surface with liquids is a very complex process. It depends on the chemistry and behaviour of liquids, substrate behaviour, and interactions between the wood substrate and liquids used (Kúdela *et al*., 2016). A good wettability is often a predictor of high-quality adhesive bonding (Piao *et al*. 2010). Contact angles measured at the interface with a liquid standard serve as a base for deriving wood surface thermodynamic characteristics – surface free energy and its components. Contact angles are also an important indicator to predict the adhesion performance of coating materials and glues to the substrate (Kúdela *et al*., 2016). The surface free energy of wood is a useful parameter that provides information on the interaction between the wood surface and an adhesive. Additionally, it has a great influence on the bonding strength of wood composites (Qin *et al*., 2015).

Evaluation of the relative wettability of a surface can be helpful for predicting or controlling the outcome of various industrial processes. Wettability can be generally defined as the tendency of a selected liquid to spread out and make intimate contact with a surface of interest (Hubbe *et al*., 2015). The best measure of wetting process quality is the contact angle between the solid substrate and the wetting liquid (Liptáková *et al*., 1998). Studying of wood wetting with liquids is obligatory for understanding interactions at the interface between wood and coating material, wood and gluing materials, and similar (Scheikl *et al*., 2001; Piao *et al*., 2010). Measurement of the contact angle formed by a droplet of a liquid placed on wood surface is a widely used method for the assessment of surface wettability and calculation of surface free energy (Štrbová *et al*., 2013). The contact angles are also useful for the assessment of other properties of the solid – liquid – gas system (Liptáková *et al*., 1998).

The aim of this study is to compare wettability and surface free energy of false heartwood, ripe wood, and sapwood zones of beech wood. In addition, microscopic structure of each zone was examined with light microscopy. The contact angle and surface free energy results were analyzed with a two-way ANOVA method and Duncan's post-hoc test of multiple comparison.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Four beech trees were harvested in September 2022, in the locality Štiavnické vrchy (Štiavnické mountains, in Slovakia). The logs were cut through into planks. From each log, planks containing false heartwood, ripe wood, and sapwood were selected (from here, false heartwood, ripe wood, and sapwood will be referred to as FHW, RW, and SW, respectively). These planks were cut into rectangular timber, separating the FHW, RW, and SW zones. Rectangular timber from each zone was selected and sawn into smaller samples with dimensions 150 mm x 20 mm x 40 mm, in longitudinal, radial, and tangential direction, respectively. From each log, one sample per FHW, RW, and SW was used. Twelve samples in total were used for this experiment. The average oven dried density of the samples was: 683 kg/m^3 in FHW, 669 kg/m^3 in RW, and 653 kg/m^3 in SW. All sides of the samples were milled.

The samples were oven dried at a temperature of (103±2) °C. After drying, the samples were weighed on a Radwag laboratory scale (model XA 60/220/X, Radwag, Radom, Poland) and measured with a digital slide calliper. The samples were then placed into a climatic chamber (relative air humidity was set to 45 % and air temperature to 20 °C), until they reached an equilibrium moisture content of 7.5 %. When the samples reached the equilibrium moisture content, they were weighed again, and the moisture content was calculated using the gravimetric method.

2.1 Wettability with liquids and wood surface free energy
2.1. Stupanj kvašenja tekućinama i slobodna površinska energija drva

Wood surface wetting process and contact angle measurement were performed with a Krüss DSA30 Standard drop shape analyzer (Hamburg, Germany) and the attached software package (Fig. 1). Following Kúdela (2014), two testing liquids with different polarities were used – redistilled water and diiodomethane. Redistilled water is a polar-apolar liquid with a polar component of surface free energy higher than the polar component of wood. Diiodomethane is a nonpolar liquid with a nonpolar component of surface free energy higher than the disperse component of wood (Kúdela *et al*., 2019). Parameters of both liquids are listed in Table 1.

Syringes were used to apply drops of the testing liquids on the wood surface. For each testing liquid, separate syringes were used. The drop volume was set to 1.8 μl. Testing liquids were applied on tangential

Table 1 Surface free energy and its components of the testing liquids
Tablica 1. Slobodna površinska energija ispitnih tekućina i njihove komponente

Testing liquid *Ispitna tekućina*	γ_L, mJ/m²	γ_L^d, mJ/m²	γ_L^p, mJ/m²	γ^+, mJ/m²	γ^-, mJ/m²	η, Pa·s	**References** *Reference*
Redistilled water / *redestilirana voda*	72.80	21.80	51.00	25.50	25.50	0.010	Gardner (1996)
Diiodomethane / *dijodometan*	50.80	50.80	0.00	0.00	0.00	0.028	van Oss *et al.* (1998)

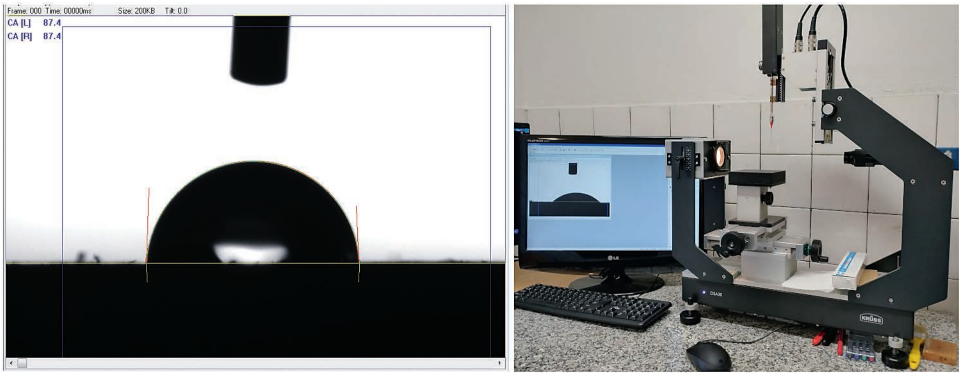

Figure 1 Contact angle measurement by the circle method on the left side of the figure; Krüss DSA30 Standard drop shape analyzer on the right side of the figure
Slika 1. Mjerenje kontaktnog kuta kapi (lijeva slika); Krüss DSA30 standardni analizator oblika kapi (desna slika)

surfaces of the samples. The drop shape analyzer recorded spreading and soaking of the testing liquids from the moment they were applied on the tangential surface until their complete soaking into the substrate. Spreading of the testing liquids along the fibres was analyzed. Scanning frequency (number of recorded frames per second) was set and adjusted according to the wetting intervals in FHW, RW, and SW. Measurement of the contact angles was computed in the DSA30 software, using the circle method.

Contact angles θ_0 were measured right after the drop application, in the very first moment of the testing liquid spreading. Equilibrium contact angles θ_e were determined according to Liptáková and Kúdela (1994), at a moment of spreading of the testing liquids, when the contact angle changed from an advancing angle to a receding angle. This equilibrium state was matched with the moment when the liquid stopped spreading onto the surface and started to recede. This moment was determined through the drop base diameter (Kúdela *et al.*, 2015). Contact angles θ_0 and θ_e were used to calculate θ_w, the contact angle corresponding to an ideal smooth surface (Liptáková and Kúdela, 1994). The contact angle θ_w was calculated according to Eq. 1, 2, and 3 (Liptáková and Kúdela, 1994):

$$\cos\theta_0 = f_1 \cdot \cos\theta_w - f_2 \quad (1)$$

$$\cos\theta_e = f_1 \cdot \cos\theta_w + f_2 \quad (2)$$

Where:

θ_0 – contact angle at the beginning of the wetting process,

θ_e – equilibrium contact angle,

θ_w – equilibrium contact angle corresponding to a wood substance with surface characterized by roughness of molecular dimensions,

*f*1 – proportion of the substance at the spot occupied by the testing liquid,

*f*2 – proportion of void pores and cell capillaries and of cell walls under the drop (Kúdela, 2014).

Surface free energy values of the substrate γ_S were calculated according to the equation modified by Neumann *et al.* (1974), Eq. 4:

$$\cos\theta = \frac{(0.0137 \cdot \gamma_S - 2.00)\sqrt{\gamma_s \cdot \gamma_L} + \gamma_L}{\gamma_L \cdot (0.0137 \cdot \sqrt{\gamma_S \cdot \gamma_L} - 1)} \quad (4)$$

Dispersion and polar components γ_S^d and γ_S^p of the substrate surface free energy were calculated according to Kloubek (1974), Eq. 5 and 6:

$$\sqrt{\gamma_S^d} = \sqrt{\gamma_L^d} \cdot \frac{1+\cos\theta}{2} \pm \sqrt{\gamma_L^p} \cdot \sqrt{\frac{\gamma_S}{\gamma_L} - \left(\frac{1+\cos\theta}{2}\right)^2} \quad (5)$$

$$\sqrt{\gamma_S^p} = \sqrt{\gamma_L^p} \cdot \frac{1+\cos\theta}{2} \mp \sqrt{\gamma_L^d} \cdot \sqrt{\frac{\gamma_S}{\gamma_L} - \left(\frac{1+\cos\theta}{2}\right)^2} \quad (6)$$

According to Kúdela *et al.* (2016), a combined value of the surface free energy γ_{SC} was calculated by addition of the dispersion component γ_S^d, calculated from measurements with diiodomethane and polar component γ_S^p, calculated from the measurement with redistilled water. In total, 72 measurements were done per each zone, 18 measurements per one sample were done with both testing liquids. The spots where the testing liquid drop was placed did not overlap.

2.2 Data analysis
2.2. Analiza podataka

A two-way ANOVA was used for testing whether the variability of the results among samples was due to chance or was the effect of the observed factors or their

Table 2 Two-factor ANOVA design used for estimating how the mean of a quantitative variable changes according to the levels of two categorical variables
Tablica 2. Dvofaktorska ANOVA za procjenu promjene srednje vrijednosti kvantitativne varijable prema razinama dviju kategoričkih varijabli

Source of variation *Izvor varijacije*	**Sum of squares** *Zbroj kvadrata*	**Degree of freedom** *Stupanj slobode*	**Mean square** *Srednja vrijednost kvadrata*	***F*-test**	***p*-level**
Factor A effect / *utjecaj faktora A*	SS_A	df_A	MS_A	F_A	p_A
Factor B effect / *utjecaj faktora B*	SS_B	df_B	MS_B	F_B	p_B
Interaction AB effect *utjecaj interakcije faktora A i B*	SS_{AB}	df_{AB}	MS_{AB}	F_{AB}	p_{AB}
Error / *pogreška*	SS_E	df_E	MS_E		
Total / *ukupno*	SS_{Total}	df_{Total}			

Figure 2 FHW (A), RW (B), and SW (C) zone samples. Small blocks to cut out for microscopic examination are marked on the pictures on the right-hand side.
Slika 2. Uzorci zona FHW (A), RW (B) i SW (C). Mali blokovi za izrezivanje za mikroskopsko ispitivanje označeni su na slikama desno.

interaction. The null hypothesis of equal samples means was tested. The test criterion was *F*-statistic representing the ratio of two estimates of variance – an estimate of the variance among samples (*MS* effect) and an estimate of variance within samples (*MS* error). The design of the two-factor ANOVA is presented in Table 2.

If *MS* effect is significantly greater than *MS* error, then the null hypothesis is rejected in favour of the alternative hypothesis - de facto the given factors are responsible for differences among sample means. Subsequently, Duncan post-hoc test of multiple comparison was applied to identify significant pairwise differences. Sample means and 95 % confidence intervals for population means are presented graphically by box and whisker charts.

The analyses were carried out using statistical software STATISTICA 12. An alpha level of 0.05 traditionally used in similar studies as decision rule was applied. The output tables were edited in the Microsoft Excel spreadsheet editor.

2.3 Microscopic observation
2.3. Mikroskopska analiza

For microscopic observation, FHW, RW, and SW samples from one log were selected randomly. From each of the selected 150 mm × 20 mm × 40 mm samples, a 4 mm thick slice was sawn from the 20 x 40 mm side. This was done after the samples were oven dried. Two 7 mm × 4 mm × 3 mm small wood blocks were carefully cut from these slices. Radial and tangential microsections were our main object of observation; therefore, each of the small wood blocks was cut accordingly. In Figure 2, small wood blocks are marked on the FHW, RW, and SW zones.

The small wood blocks were embedded in epoxy resin and left to cure for two weeks. Approximately 15 μm thick microsections were cut from the wood-resin blocks on a sledge microtome (Reichert, Wien, Austria). The microsections were stained with a combination of Astra Blue and Safranin stains. This stain combination was used to detect axial parenchyma and nutrients inside ray parenchyma cells (Slováčková and Mišíková, 2023). Astra Blue and Safranin stain combination can also be used to distinguish cellulose from lignified cells (de Baerdemaeker *et al*., 2018). Safranin stains lignin regardless of whether cellulose is present, whereas Astra Blue stains cellulose only in the absence of lignin (Srebotnik and Messner, 1994; Schwarze and Engels, 1998). A combination of Safranin and Astra Blue is used to detect early stages of white rot, i.e., selective delignification (Srebotnik and Messner, 1994). With this stain combination, a fungal attack could be discovered, so it also confirmed that the false heartwood did not have a fungal attack. After staining, the microsections were mounted in Euparal (BioQuip Products Inc., Rancho Dominguez, CA, USA).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Wettability and surface free energy
3.1. Stupanj kvašenja i slobodna površinska energija

Soaking of the testing liquids into the wood zone samples is presented Figure 3. One characteristic measurement per each wood zone for both testing liquids was selected to be presented in the figure. Measurements with average contact angles θ_0 and average soaking times (from the time of the placement of the testing liquid drop until the time of complete soaking into the wood substrate) were selected. Figure 3 presents the decrease of contact angles over time. The longest average soaking times for both testing liquids were observed in FHW, and the shortest times were observed in RW.

The mean values of θ_0 and θ_e contact angles measured in the respective wood zones are presented in Table 3 and Table 4. In measurement with redistilled water, the lowest mean contact angles were measured in FHW, and the highest values were measured in SW. In measurement with diiodomethane, the highest mean contact angles were measured in FHW, and the lowest in RW.

Concerning θ_0, detailed results of two-way ANOVA experiment are presented in Table 3. Based on computed p-values, the null hypothesis that there is no difference among the means was rejected. The observed differences of θ_0 among samples are the result of the interaction effect of the investigated factors – testing liquid and wood zone. In the detailed pairwise comparison, significant differences in mean θ_0 values were confirmed for most pairs based on the presented p-values.

Similarly in Table 4, when evaluating θ_e, significant differences of mean values among samples were tested (p=0.000), which is the result of the influence of the investigated factors. In a detailed pairwise comparison, the null hypothesis of equality of θ_e was ac-

Table 3 Results of Duncan post-hoc test of pairwise differences for dependent variable θ_0
Tablica 3. Rezultati Duncanova post-hoc testa razlikâ između parova za zavisnu varijablu θ_0

Two-way ANOVA with interaction: testing liquid*wood zone, *F* = 7.48, *df* = 2, *p* = 0.001 *Dvosmjerna ANOVA s interakcijom: ispitna tekućina* zona drva, F = 7,48, df = 2, p = 0,001*								
Testing liquid *Ispitna tekućina*	**Wood zone** *Zona drva*	**Mean value, °** *Srednja vrijednost, °*	(1) FHW	(2) RW	(3) SW	(4) FHW	(5) RW	(6) SW
Redistilled water *redestilirana voda*	(1) FHW	80.45		0.892	0.013	0.000	0.000	0.000
	(2) RW	80.58	0.892		0.014	0.000	0.000	0.000
	(3) SW	82.97	0.013	0.014		0.000	0.000	0.000
Diiodomethane *dijodometan*	(4) FHW	41.15	0.000	0.000	0.000		0.002	0.005
	(5) RW	37.97	0.000	0.000	0.000	0.002		0.654
	(6) SW	38.40	0.000	0.000	0.000	0.005	0.654	

Note: The pairs without a significant difference are printed in black. / *Napomena: parovi bez značajne razlike otisnuti su crnom bojom.*

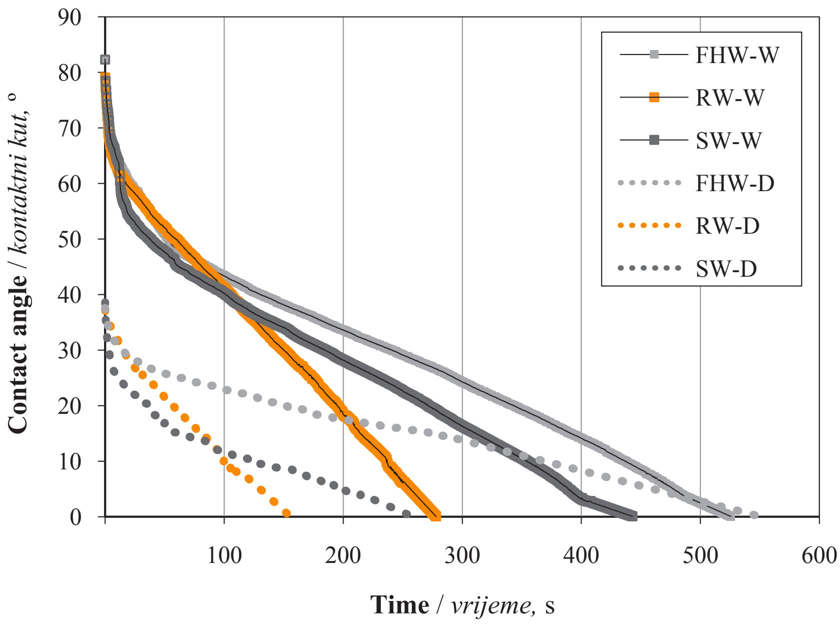

Figure 3 Contact angles over soaking time. Testing liquids are denoted next to wood zone abbreviations: W - measurement with redistilled water, D - measurement with diiodomethane.
Slika 3. Kontaktni kutovi tijekom kvašenja. Ispitne su tekućine označene uz kratice zone drva: W – mjerenje redestiliranom vodom, D – mjerenje dijodometanom.

Table 4 Results of Duncan post-hoc test of pairwise differences for dependent variable θ_e
Tablica 4. Rezultati Duncanova post-hoc testa razlikâ između parova za zavisnu varijablu θ_e

Two-way ANOVA with interaction: testing liquid*wood zone, *F* = 7.64, *df* = 2, *p* = 0.000 *Dvosmjerna ANOVA s interakcijom: ispitna tekućina* zona drva, F = 7,64, df = 2, p = 0,000*								
Testing liquid *Ispitna tekućina*	**Wood zone** *Zona drva*	**Mean value, °** *Srednja vrijednost, °*	(1) FHW	(2) RW	(3) SW	(4) FHW	(5) RW	(6) SW
Redistilled water *redestilirana voda*	(1) FHW	23.90		0.042	0.000	0.000	0.000	0.000
	(2) RW	25.55	0.042		0.043	0.000	0.000	0.000
	(3) SW	27.19	0.000	0.043		0.000	0.000	0.000
Diiodomethane *dijodometan*	(4) FHW	37.69	0.000	0.000	0.000		0.051	0.230
	(5) RW	36.03	0.000	0.000	0.000	0.051		0.393
	(6) SW	36.72	0.000	0.000	0.000	0.230	0.393	

Note: The pairs without a significant difference are printed in black. / *Napomena: parovi bez značajne razlike otisnuti su crnom bojom.*

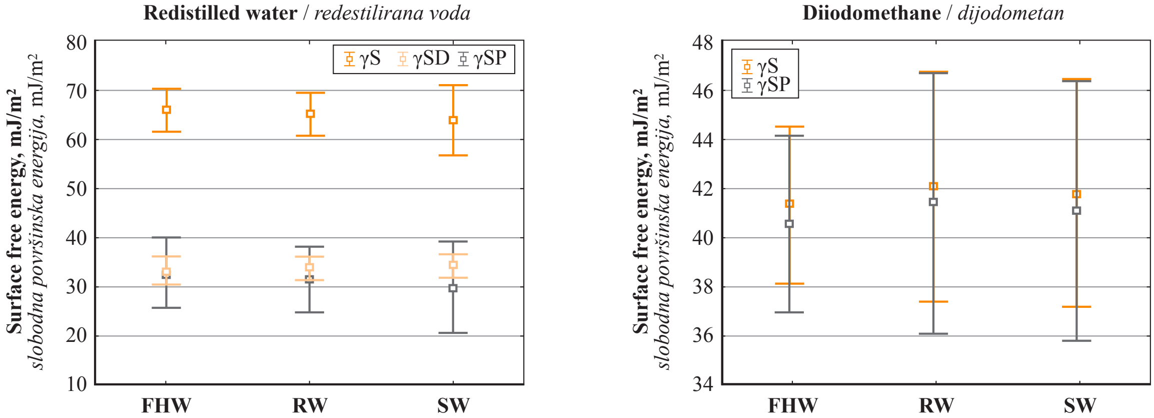

Figure 4 Box and whisker plot (sample mean ± 2·standard deviation) of surface free energy calculations with both testing liquids
Slika 4. Prikaz rezultata (srednja vrijednost uzorka ± 2·standardna devijacija) izračuna slobodne površinske energije s obje ispitne tekućine

cepted in only two cases – redistilled water FHW versus RW, and diiodomethane RW versus SW.

Results of surface free energy and its polar and disperse components are presented in Figure 4. In measurement with redistilled water, surface free energy and its polar component showed a decreasing trend through the wood zones. The highest surface free energy was found in FHW and the lowest surface free energy in SW. Disperse component of the surface free energy in measurement with redistilled water had a moderately increasing trend through the wood zones.

In measurement with diiodomethane, the highest surface free energy and its disperse components were found in RW. The lowest values were found in FHW. Since diiodomethane is a nonpolar liquid with only a disperse surface free energy component, the polar component of surface free energy in wood zones was zero and is therefore not included in Figure 4.

Results of analysis for surface free energy are presented in Table 5. The *F*-test of the interactive effect of the two investigated factors – testing liquid and wood zone – confirmed their significant influence (p=0.000) on the surface free energy values. Even in a simultaneous pairwise comparison using Duncan's test, almost all pairs were significantly different. As pairs with the same mean surface free energy values, the combinations - re-

Table 5 Results of Duncan post-hoc test of pairwise differences for dependent variable of surface free energy
Tablica 5. Rezultati Duncanova post-hoc testa razlikâ između parova za zavisnu varijablu slobodne površinske energije

Two-way ANOVA with interaction: testing water*wood zone, *F* = 10.20, *df* = 2, *p* = 0.000 *Dvosmjerna ANOVA s interakcijom: ispitna tekućina* zona drva, F = 10,20, df 2, p = 0,000*								
Testing liquid *Ispitna tekućina*	**Wood zone** *Zona drva*	**Mean value, mJ/m²** *Srednja vrijednost*, mJ/m²	(1) FHW	(2) RW	(3) SW	(4) FHW	(5) RW	(6) SW
Redistilled water *redestilirana voda*	(1) FHW	65.94		0.031	0.000	0.000	0.000	0.000
	(2) RW	65.05	0.031		0.002	0.000	0.000	0.000
	(3) SW	63.82	0.000	0.002		0.000	0.000	0.000
Diiodomethane *dijodometan*	(4) FHW	41.26	0.000	0.000	0.000		0.083	0.265
	(5) RW	42.01	0.000	0.000	0.000	0.083		0.475
	(6) SW	41.72	0.000	0.000	0.000	0.265	0.475	

Note: The pairs without a significant difference are printed in black. / *Napomena: parovi bez značajne razlike otisnuti su crnom bojom.*

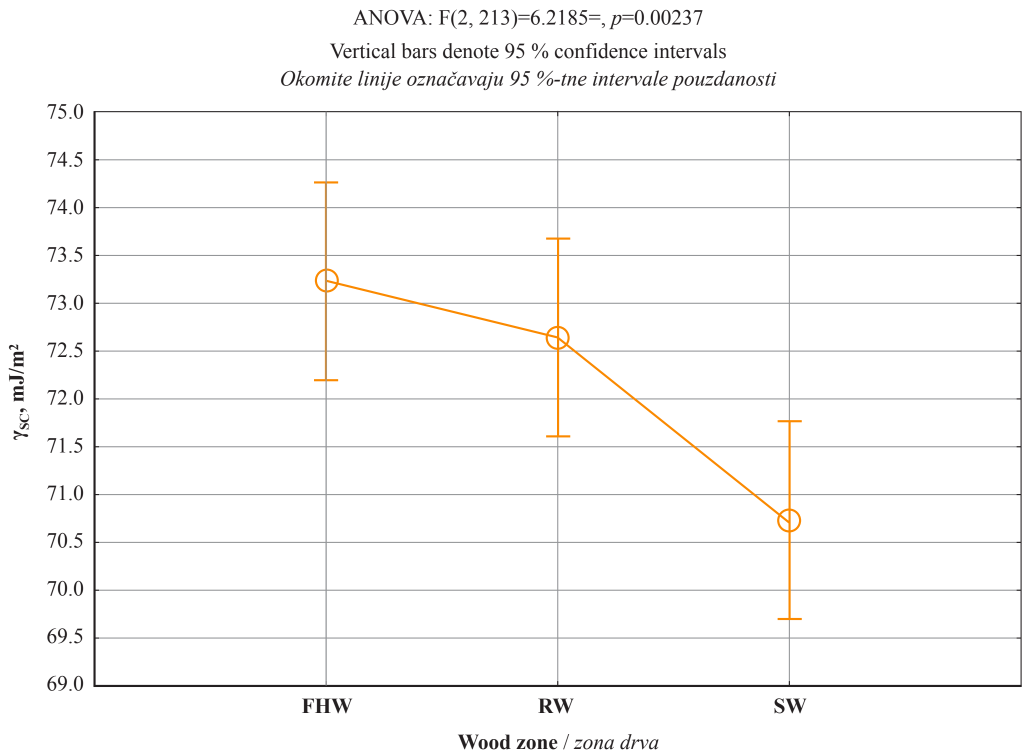

Figure 5 Result of One-way ANOVA and 95 % confidence intervals: dependence of combined surface free energy on wood zone
Slika 5. Rezultat jednosmjerne ANOVA analize i 95 %-tnog intervala pouzdanosti: ovisnost kombinirane slobodne površinske energije o zoni drva

distilled water FHW versus RW, and diiodomethane RW versus SW- were proven by the test.

Following Kúdela *et al*. (2016), the combined surface free energy values γ_{SC}, calculated by addition of the average value of dispersion component γ_S^d, calculated from measurements with diiodomethane and average value of polar component γ_S^p, calculated from the measurement with redistilled water, were as follows: 73.23 mJ/m^2 in FHW, 72.64 mJ/m^2 in RW, and 70.73 mJ/m^2 in SW. These values are slightly lower than the surface free energy value of normal beech wood of 78.3 mJ/m^2 reported by Kúdela *et al*. (2016). The surface of the samples used in the cited research was milled. The authors did not state the moisture content of the normal beech wood; a different moisture content value could have had an influence on the surface free energy value. The combined surface free energy values calculated on beech wood with FHW and normal beech wood confirm that the adhesion behaviour of beech wood with FHW is similar to normal beech wood. ANOVA was used for the analysis of the combined surface free energy values. The result is presented in Figure 5. The investigated factor wood zone showed that SW was significantly different (p=0.002) from FHW and RW.

Studies on adhesion behaviour of beech false heartwood show that the results of the adhesion behaviour of beech false heartwood are the same as those of normal beech wood (Pöhler *et al*., 2006). Aicher and Reinhardt (2007) examined delamination and dry shear strength tests on glued beech false heartwood. It was found that false heartwood did not have an influence on shear strength. Delamination tests revealed a distinct dependency of the glue line integrity on false heartwood and width of the adherents (Aicher and Reinhardt, 2007).

3.2 Microscopic observation
3.2. Mikroskopska analiza

The results of microscopic observation of FHW, RW and SW are presented in Figure 6 and Figure 7. The FHW zone microsection (shown in Figure 6A and 6B) absorbed only Safranin from the stain combination Astra Blue and Safranin. The formation of FHW is closely connected with the production of tyloses inside the vessels (Kúdela and Čunderlík, 2012). Numerous tyloses were observed inside the vessels of the samples used in this experiment. The tyloses are denoted in Figure 6A and 6B with black arrows. Tyloses were observed only in the FHW zone. Oxidized extractives were also observed; they are visible in the ray parenchyma cells in Figure 6A as a dark looking compound inside the ray parenchyma cell. Similar observation of the extractives inside ray parenchyma cells was made by Požgaj *et al.* (1993). Ray parenchyma cells containing oxidized extractives are denoted with a white arrow (outlined with black).

The RW microsections are shown in Figure 6C and 6D. RW microsections absorbed also blue stain

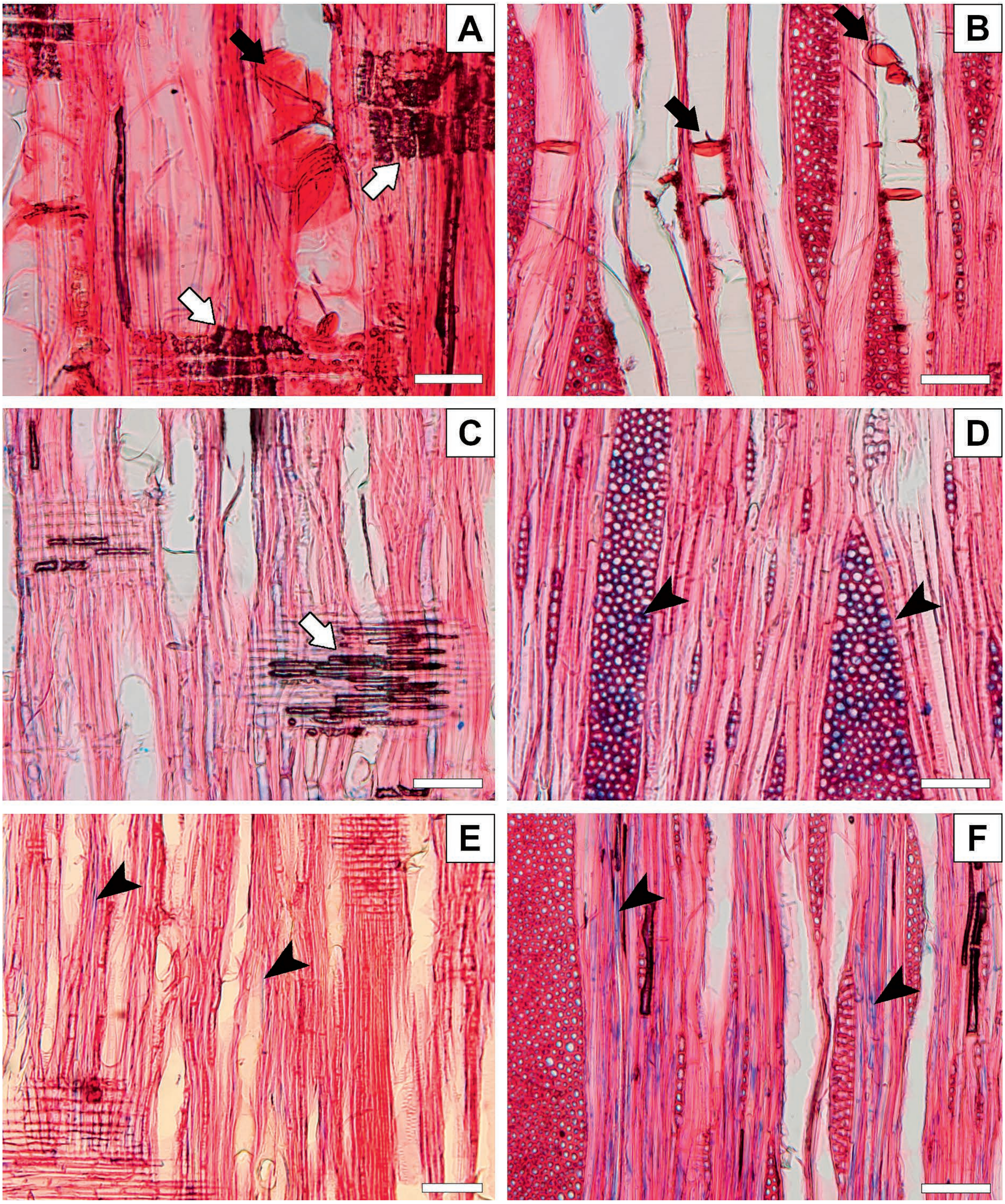

Figure 6 FHW (A and B), RW (C and D) and SW (E and F) microsections stained with Astra Blue and Safranin stain combination. A, C and E are radial microsections and B, D and F are tangential microsections. Scales are denoted with a white stripe in the lower right corners of the figures – 50 µm in 5A and 100 µm in the other figures.
Slika 6. FHW (A i B), RW (C i D) i SW (E i F) mikrografije obojene kombinacijom boja Astra Blue i Safranin. A, C i E radijalni su presjeci, a B, D i F tangentni presjeci. Skale su označene bijelom prugom u donjem desnom kutu slikâ – 50 µm u 6A i 100 µm u ostalim slikama.

from the stain combination. The axial parenchyma and ray parenchyma cells absorbed Astra Blue stain (denoted with arrow heads in Figure 6D, visible also in 6C). Because of the staining, both types of parenchyma cells can be clearly distinguished from the rest of the wood structure. The rest of the microsection absorbed red from Safranin stain. In Figure 6D, the blue stained ray parenchyma cells are dispersed throughout the wide ray. Figure 7 shows that in some rays, only the parenchyma cells on the outer part of wide rays absorbed the blue colour from the stain combination. Oxidized extractives in ray parenchyma cells appeared in radial RW microsections, Figure 6C. The oxidized extractives in RW microsections were

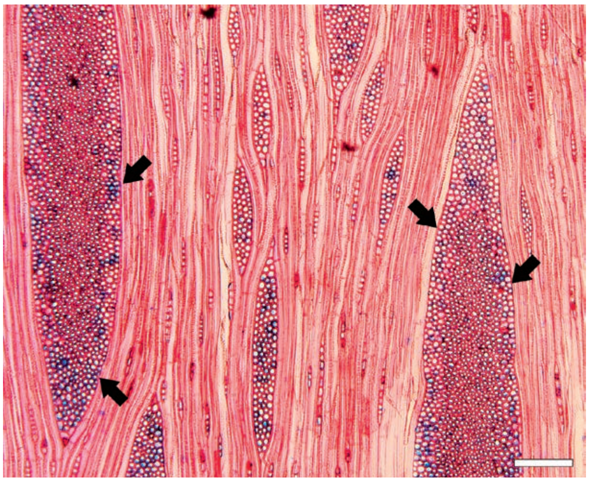

Figure 7 Tangential microsection of RW zone with blue stained ray parenchyma cells on the outer edges of the wide ray. Scale is denoted with a white stripe in the lower right corner of the figure and its size is 150 µm.
Slika 7. Mikrografija tangentnog presjeka RW zone s plavo obojenim stanicama parenhima na vanjskim rubovima širokih trakova. Skala je označena bijelom prugom u donjem desnom kutu slike, a veličina je 150 µm.

less pronounced than in FHW microsections. When a healthy FHW is formed, still active parenchyma cells in the RW zone become inactive. During the formation of FHW, extractives inside the parenchyma cells oxidize (Požgaj *et al*., 1993). The occurrence of oxidized extractives in ray parenchyma cells in RW could be a sign of FHW formation.

SW microsections (shown in Figure 6E and 6F) also absorbed blue stain from the stain combination and revealed axial parenchyma. This is denoted in Figure 6E and 6F with black arrowheads. The axial parenchyma in SW microsections appeared to be more saturated with the blue stain than in RW microsections. Extractives in ray parenchyma cells were not observed in SW microsections.

The difference between RW and SW zones is in the vitality of parenchymatic cells. This has a significant influence on the occurrence of defects in the wood structure. Parenchymatic cells in SW have a high vitality whereas parenchymatic cells in RW have a low vitality (Kúdela and Čunderlík, 2012).

Jankowska *et al*. (2018) studied the effect of extractives on wettability on 13 tropical wood species, European beech, and oak. The influence of extractives relative to wettability and surface free energy was confirmed. Oxidized extractives were observed in FHW and RW (Figure 6A and C). The results of Duncan's pairwise comparison suggest that there could be an influence of oxidized extractives on wettability and surface free energy of beech in FHW and RW, however further research needs to be performed to confirm this statement.

The research (Jankowska *et al*., 2018) also determined that a higher content of axial parenchyma resulted in a higher contact angle. Axial parenchymas were visible in RW and SW microsections (Figure 6C and 6F). They absorbed the blue stain from the Astra Blue – Safranin stain combination. Axial parenchyma was not visible in FHW microsections. The presence of axial parenchyma can possibly influence wettability and surface free energy of beech; the results of the Duncan's test for θ_0, θ_e, and for FHW and SW pair in redistilled water measurement, and all pairs in diiodomethane measurement support this statement. In measurement with redistilled water, the contact angles in RW and SW were higher than in FHW. However, in measurement with diiodomethane, the contact angles were higher in FHW than in RW and SW. To firmly confirm the statement, further research needs to be done.

3.3 Equilibrium time
3.3. Ravnotežno vrijeme

Equilibrium time is the time passing from the measurement of the contact angle θ_0 until the contact angle θ_e is described as the equilibrium time t_u. During the sessile drop experiments, different equilibrium times in different wood zones were noticed. Therefore, the effect of wood zone on the equilibrium times was analyzed. The analysis was performed using ANOVA, especially in the case of redistilled water and diiodomethane. In both cases, the investigated factor significantly affected the values of equilibrium time (p=0.000). Figure 8 presents the 95 % confidence intervals for equilibrium time means of individual wood zones. In the case of the redistilled water, significant differences were tested in all three wood zones. In the case of diiodomethane, FHW differed significantly from RW and SW.

In measuring with diiodomethane, the drop often showed only the receding angle; it started to soak into the wood substrate immediately after placing the diiodomethane drop. The equilibrium times were 0 seconds in 5.5 % of FHW measurements, 40 % of RW measurements, and 28 % of SW measurements. The average equilibrium time for FHW measured with diiodomethane was ten times higher than that for RW and SW. The significant differences in equilibrium time of FHW for both testing liquids were caused by the numerous tyloses present in FHW (Figure 6A and 6B). Tyloses obstruct the pass ability of vessels, hence false heartwood permeability for liquids is significantly decreased (Babiak *et al.*, 1990; Kúdela and Čunderlík, 2012).

Kúdela *et al*. (2015) stated that the equilibrium time t_u depends on the liquid polarity, as well as on wood moisture content, polar share, and viscosity of the testing liquids. The variability of t_u values in one testing liquid is the result of unevenness of the wood surface and the random placement of the testing liquid drop on the wood surface (Kúdela *et al*., 2015).

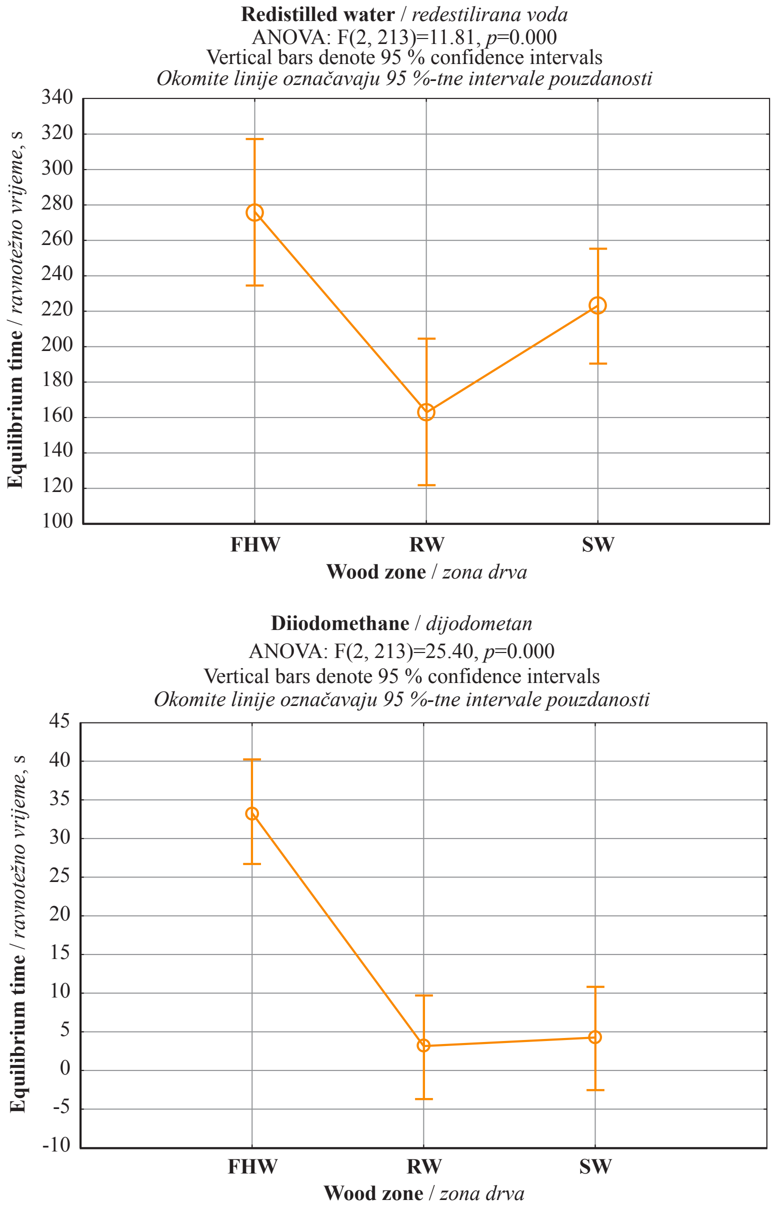

Figure 8 Result of One-way ANOVA and 95 % confidence intervals: dependence of equilibrium time on wood zone using two testing liquids - redistilled water and diiodomethane
Slika 8. Rezultat jednosmjerne ANOVA analize i 95 %-tnog intervala pouzdanosti: ovisnost ravnotežnog vremena o zoni drva za dvije ispitne tekućine – redestiliranu vodu i dijodometan

According to Kúdela *et al.* (2016), a poorer wetting performance is associated with a longer time necessary for the testing liquid drop to spread over the surface and higher contact angles. Significantly enhanced wettability with standard polar and non-polar liquids was reflected in higher surface free energy (Kúdela *et al.,* 2022). In our experiment, FHW had the longest average soaking and equilibrium times, a high combined surface free energy, lowest contact angles in measurement with redistilled water and highest contact angles in measurement with diiodomethane. FHW had also tyloses inside vessels and extractives in ray parenchyma. RW had the lowest average soaking times, lowest equilibrium time, higher combined surface free energy than SW, and low contact angles in both testing liquids. The average soaking times of SW were between RW and FHW average soaking times, SW had low equilibrium times, the highest contact angles in measurement with redistilled water and lowest combined surface free energy values. Out of the tested wood zones in beech wood, RW had the best wettability for both testing liquids. SW had the worst wettability for redistilled water; wettability for diiodomethane was similar to that of RW. It is difficult to state whether FHW had good or bad wettability. The combined surface free energy values and contact angles measured with redistilled water suggest that the wettability of FHW is similar to that of RW. However, the average soaking and equilibrium times were the longest among the wood zones.

4 CONCLUSIONS
4. ZAKLJUČAK

This paper focused on wettability and surface free energy of false heartwood, ripe wood, and sapwood in beech. Measurement of contact angles was performed with two testing liquids – redistilled water and diiodomethane (a polar-apolar and a nonpolar liquid). Two-way ANOVA and Duncan's post-hoc test of multiple comparison were used for statistical analysis of the results. False heartwood, ripe wood, sapwood wood zones and testing liquids were the main factors in Duncan's pairwise comparison test.

Ripe wood showed the best wettability for both testing liquids with a high surface free energy, lowest contact angles among the researched wood zones and shortest average soaking and equilibrium times. Sapwood showed the worst wettability in measurement with redistilled water. False heartwood showed similar wettability to ripe wood in measurement with redistilled water, although the average soaking and equilibrium times were the longest. The long times are caused by the presence of tyloses in false heartwood. These findings were supported by Duncan's post-hoc test. The false heartwood and ripe wood pair did not differ significantly, while sapwood was significantly different from ripe wood and false heartwood in measurement with redistilled water.

In measurement with diiodomethane, false heartwood showed the worst wettability, while the wettability of sapwood was similar to that of ripe wood. These results were also supported by Duncan's post-hoc test; the sapwood and ripe wood pair did not show a significant difference.

The long average soaking time of false heartwood needs to be taken into consideration in furniture production. An incorrect application of adhesives on veneers containing false heartwood could affect the glue line integrity of the final product.

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Determination of Fire Resistance, Mechanical Property and Physical Stability of Boron Phosphate Containing Wood Polymer Composites

Određivanje vatrootpornosti, mehaničkih svojstava i fizičke stabilnosti drvno-plastičnih kompozita koji sadržavaju bor-fosfat

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ABSTRACT • *This study presents the improvement in flame retardancy of wood polymer composites (WPCs) by boron phosphate (BPO_4) additive. The WPCs were manufactured by phenol formaldehyde and wood flour of Oriental beech (Fagus orientalis L.) using compression molding. Polydiphenylmethane-4,4'-diisocyanate (PMDI) was also added to enhance the compatibility of hydrophilic wood flour and hydrophobic polymer resin. The strengthening of interfacial adhesion by PMDI incorporation resulted in better mechanical (flexural) and physical (water absorption, thickness swelling) properties. The BPO_4 flame-retardant additive in WPCs formulation was first reported and thermal behaviors of composites were investigated by thermogravimetric analysis (TGA), limiting oxygen index (LOI) and UL-94 tests. The BPO_4 compound promoted the char formation of WPCs, and the LOI values of composites were increased from 28.7 to 35.6. The UL-94 tests also showed that the flame retardancy of composites were improved by changing the V-2 rating to V-0 with the addition of 5 wt.% BPO_4.*

KEYWORDS: *boron phosphate; wood polymer composite; flame-retardant; polydiphenylmethane- 4,4'-diisocyanate (PMDI) compatibilizer*

SAŽETAK • *Ovo istraživanje opisuje poboljšanje vatrootpornosti drvno-plastičnih kompozita (WPC) dodavanjem bor-fosfata (BPO_4). Drvno-plastični kompoziti proizvedeni su od fenol formaldehida i drvnog brašna bukovine (Fagus orientalis L.) kompresijskim lijevanjem. Usto, smjesi je dodan polidifenilmetan-4,4'-diizocijanat (PMDI) kako bi se poboljšala kompatibilnost hidrofilnoga drvnog brašna i hidrofobne polimerne smole. Jačanje međupovršinske adhezije dodavanjem PMDI-ja rezultiralo je boljim mehaničkim svojstvima (na savijanje) i boljim fizičkim svojstvima (upijanje vode, debljinsko bubrenje). Prvi je put u formulaciji WPC-a upotrijebljen BPO_4 kao usporivač gorenja, a toplinska su ponašanja kompozita ispitana termogravimetrijskom analizom (TGA), mjerenjem graničnog indeksa ki-*

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sika (LOI) i UL-94 testovima. Spoj BPO_4 pospješio je stvaranje pougljenjenih WPC-ova, a LOI vrijednosti kompozita povećane su s 28,7 na 35,6. Provedeni UL-94 testovi također su pokazali da je vatrootpornost kompozita poboljšana jer je nakon dodavanja 5 težinskih postotaka BPO_4 ocjena V-2 promijenjena u V-0.

KLJUČNE RIJEČI: *bor-fosfat; drvno-plastični kompozit; polidifenilmetan-4,4'-diizocijanat (PMDI) kompatibilizator*

1 INTRODUCTION
1. UVOD

Wood processing wastes have been considered as natural and renewable resources for fabrication of wood plastic composites (WPC). Woodworking wastes can be shifted to a new material for construction, furniture, garden products and also for automotive applications (Li, 2011; Schwarzkopf and Burnard, 2016; Clemons, 2008). WPCs have been classified as plywood, particleboard, oriented strand board (OSB), fiberboard (MDF, HDF), etc. These composites are commercial products obtained by mixing thermoplastic/thermoset polymer matrix wood flour. WPCs are designed to meet the needs of specific usage, and they are formulated for high mechanical, physical and thermal properties and long durability. Additives/fillers can be added into WPCs or different functionalities can be incorporated to improve their properties. Crosslinkers, coupling agents/compatibilizers, flame-retardants, dye pigments and fungicides are commonly used as admixtures.

Boron based additives can serve both as a wood preservative against fungi/insects and as a flame-retardant filler for fire resistance (Marney and Russell, 2008). Boric acid, borax, zinc borate and disodiumoctaborate tetrahydrate were mostly used due to the colorless, odorless, non-toxic and cheap additives (Mohareb *et al.,* 2011). Many researchers showed that, as a flame-retardant additive, boron compound has two effects on wood materials. First, it can form a glassy layer insulating the surface of wood and block the further diffusion of oxygen into the material. Second, it increases the char yield by acidic dehydration mechanism (Roth *et al.,* 2007; Yang, Y. *et al.,* 1999; Simsek *et al.,* 2010). Ammonium polyphosphate (APP) is another well-known flame-retardant additive and can be used alone or in synergy with boron compounds such as boric acid (BA), borax (BX), zinc borate, etc. When BA/BX mixture and APP were used together, the observed char acted first as an insulator to keep condensed phase at lower temperatures, and second as a barrier to prevent the volatile fuel from reaching the flame front (Kurt and Mengeloğlu, 2011). Similarly, with different contents of boron compounds, phosphate compounds were added to wood flour/polypropylene composites and results showed that 4/8 wt.% formulations of the flame-retardants have optimum physical, mechanical and fire resistance properties of composites (Ayrilmis *et al*., 2012). Synergistic effect of various boron compounds and APP has been revealed for improved flame retardancy of a polypropylene (PP) intumescent system. Cone calorimeter and TGA results demonstrated that the boron compounds showed their synergistic effect by reinforcing and increasing the barrier effect of the char (Doğan *et al*., 2010).

Based on the above studies, it can be concluded that the new flame-retardant to be designed should contain both boron and phosphate constituents. Hence, in this study boron phosphate (BPO_4) was synthesized by hydrothermal and microwave-assisted technique and then the effects of BPO_4 on physical, mechanical and thermal properties of WPCs were investigated. BPO_4 previously imparted flame retardancy to PET and Nylon fibers (Kilinc *et al*., 2015; Doğan *et al*., 2011), but boron phosphate was used for the first time as a flame-retardant in wood polymer composites made of phenol formaldehyde resin and Oriental beech (*Fagus orientalis* L.) flour. Many organic thermoplastic and thermoset polymers are of hydrophobic nature, and they are not compatible with hydrophilic wood. Hence, compatibilizers are used that can bond with the hydrophilic and hydrophobic parts at the interfaces. Organic based compatibilizers used in WPCs are generally maleic anhydride and isocyanate functional group compounds containing two or more functional groups. In the present study, polydiphenylmethane- 4,4'-diisocynate (PMDI) is used as compatibilizer in WPC composition. This study focuses on the effects of BPO_4 additive on flame retardancy, thermal stability, physical and mechanical properties of WPCs. It also provides scientific data for the utilization of BPO_4 in WPCs production. The secondary aim of this study is to investigate the effect of PMDI compatibilizer on the properties of WPCs together with BPO_4 flame-retardant.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Phenol formaldehyde resin (ALFEN 74 resol, density 1.12 g/cm^3 at 20 °C, viscosity 350 cP at 20 °C) was purchased from GENTAŞ Chemical Co. The liquid phenol formaldehyde resin with 47 % solid content was used as polymer matrix and a gel time of 6 min at 130 °C. Oriental beech wood (*Fagus orientalis* L.)

flour was sieved (40 mesh) and dried in an oven, first at 80 °C for 24 hours and then dried at 35 °C until it reached a constant weight. The sieved and dried wood flour was kept in a desiccator at (23±2) °C and (50±5) % relative humidity for subsequent use. Boric acid (99.5 %, Merck), o-phosphoric acid (85 %, Merck) and poly-diphenylmethane- 4,4'-diisocynate (PMDI, Ravago Petrochemical Co.) were used as received.

2.2 BPO_4 synthesis
2.2. Sinteza bor-fosfata (BPO_4)

Boron phosphate (BPO_4) was synthesized by thermal and microwave-assisted methods (Hauf *et al.*, 1998). Equal molar of H_3BO_3 (0.03 mol) and H_3PO_4 were mixed in an ultrasonic bath for 30 minutes and then exposed to microwave irradiation at 800 watt for 10 minutes. The reaction mixture was then calcined at 600 °C for 5 hours. The reaction between boric acid and o-phophoric acid is given below as chemical equation.

$$H_3BO_3(s) + H_3PO_4(aq) \rightarrow BPO_4(s) + H_2O(g) \quad (1)$$

FT-IR spectroscopy and XRD analysis were performed for the characterization of the obtained product. The BPO_4 powder XRD patterns were recorded between 5°<2θ<90°, with 0.05° step and 1°/min rate on a Rigaku-Miniflex diffractometer. The measurements were made by using monochromatic CuKα (30 kV, 15 mA and λ=1.54051 Å) radiation at room temperature. The FTIR spectrum of BPO_4 was recorded using a Thermo Scientific Nicolet iS10 FTIR spectrometer to verify its chemical structure. The spectrum was obtained within the wavenumber range of 600-4000 cm^{-1}, using the ATR mode of operation.

2.3 Composite preparation
2.3. Priprema kompozita

WPCs were manufactured based on the recipe given in Table 1. Phenol-formaldehyde resin, beech flour, BPO_4 flame-retardant and PMDI compatibilizer were mixed homogeneously by mechanical stirrer. Compression molding was performed for curing the mixtures, and stainless-steel molds were filled with mixtures and then inserted into the hot press. The press temperature, pressure and time were 160 °C, 10 bar and 12 min, respectively. The mold was then removed from the hot press and cooled to ambient temperature. 10 specimens from each sample were prepared in-situ for physical, mechanical and thermal tests.


a)

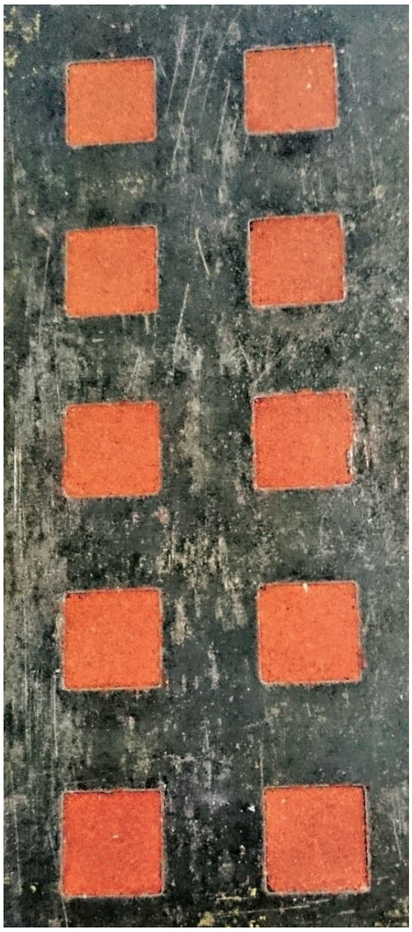
b)

Figure 1 Photos of experiment samples: a) for mechanical tests, b) for water absorption tests
Slika 1. Fotografije ispitnih uzoraka: a) za mehanička ispitivanja, b) za ispitivanja upijanja vode

Table 1 Composites components ratios (wt.%), codes and densities
Tablica 1. Omjeri komponenata u kompozitu (tež.%), oznake i gustoća

Sample codes *Oznake uzoraka*	**Resol, %**	**Wood flour, %** *Drvno brašno, %*	**PMDI, %**	**BPO_4, %**	**Density, g/cm³** *Gustoća, g/cm³*
PF (Control)	68.3	31.7	-	-	0.64
PFI	64.9	30.1	5	-	0.72
PFB	64.9	30.1	-	5	0.75
PFBI	61.5	28.5	5	5	0.71

Figure 1 shows the photos of the samples used in mechanical and water absorption tests. Figure 1a was used for mechanical tests, while Figure 1b was used for water absorption

2.4 Physical properties
2.4. Fizička svojstva

Densities of composites with standard deviations were determined by dry weight and volume, as shown in Table 1. To obtain the mean values of air-dry densities, five specimens of each group were prepared with dimensions 50 mm × 50 mm × 5 mm. The specimens were weighed with an accuracy of 0.0001 g on analytical balance and the volumes were measured by digital micrometer. Density values were calculated by the following equation.

Water absorptions of WPCs were examined, and ASTM D 1037 and standard procedure was followed for preparing the specimens and measurements. Samples with dimensions 50 mm × 50 mm × 5 mm were weighed on a 0.0001g precision analytical balance, and then the specimens were immersed in pure water for the duration of the experiment. The measurements were made periodically for 2, 24, 48, 72, 96, 120, 144, 168 hours, 2, 3, 4 weeks, 2, 3, 4, 5, 6 months. At the end of these periods, the surface water of the samples was wiped off with a cloth and then weighed again with the same precision. Ten replicates were tested for all test groups and the water uptakes were calculated by the equation below.

$$\%\ WA = (W_w - W_o) / (W_o) \times 100 \quad (g/cm^3) \qquad (2)$$

Where;
WA – water absorption (%)
W_o – dry weight (g)
W_w – wet weight given in the formula (g)

The thickness swelling tests were carried out according to EN 317 standard and samples conditioned at a relative humidity of (60±5) % and a temperature of 25 °C. Thicknesses of specimens prepared in 50×50×5 (mm) plate dimensions were measured with a micrometer sensitive to 0.01mm from the exact mid-point. The conditioned samples were entirely immersed for 2, 24, 48, 72, 96, 120, 144, 168 hours, 2, 3, 4 weeks, 2, 3, 4, 5, 6 months. Then, the excess water was removed with a clean dry cloth and their thickness was measured again from the first measured point. Ten replicates were tested for all test groups and the thickness swelling ratio was calculated according to Eq. 3.

$$TS\% = (T_w - T_c)/T_c \times 100 \qquad (3)$$

Where:
$TS\%$ – thickness swelling in percentage
T_w – thickness of the wet sample at certain time
T_c – initial thickness of the conditioned sample.

2.5 Mechanical properties
2.5. Mehanička svojstva

Since the components are used in different proportions in the production of wood polymer composites, three point bending tests were performed to examine the effect of the addition of PMDI compatibilizer and boron phosphate flame-retardant on the mechanical properties of the composites. 10 samples with dimenssions of 3.2 mm × 12.7 mm × 125 mm were prepared from each composition according to ASTM D790-92 standard and measured on Zwick Z250 with a crosshead speed of 2 mm/min. The modulus of elasticity (MOE) and modulus of rupture (MOR) of specimens were determined by three point bending test.

2.6 Thermal analysis
2.6. Toplinska analiza

Thermogravimetric analysis (TGA) has been carried out to determine the thermal stability, the decomposition temperature and degradation mechanism, which is the investigation of main degradation peaks and shoulders (Badji *et al.*, 2016) of composites. Approximately 10 mg of the sample was heated in a thermogravimetric analyzer (Perkin Elmer TGA 4000 instrument) from room temperature to 750 °C with a heating rate of 10 °C/min under nitrogen atmosphere. The temperature and corresponding mass loss (%) of the samples were monitored. The rate of weight loss as a function of time was derived from TG curve resulting in a derivative TG curve.

2.7 Fire resistance tests
2.7. Test vatrootpornosti

The flame retardancy of WPCs was determined by UL-94 vertical burning test and limiting oxygen index (LOI) tests according to ASTM D 3801 and ASTM D 2863 standards, respectively. The LOI test method is used to determine the minimum amount of oxygen needed to maintain a flammable condition under test conditions. According to the test, high-burning materials should have a low oxygen index, and low-burning materials should have a high oxygen index. 3 samples with dimension of 3.2 mm × 12.7 mm × 125 mm were prepared for each composition and the samples were placed vertically into the glass chamber. The oxygen and nitrogen gas mixture were adjusted to flow into the chamber. The specimen was ignited at the top by flame like a candle. The minimum oxygen concentrations required to sustain combustion were measured as a percentage. UL-94 is used to determine the V-0, V-1 and V-2 flammability ratings of the specimens. The self-extinguishing time of the vertically positioned specimens were measured by this test. Three replications were performed for each group, and the specimen dimensions were the same as in LOI test (3.2 mm × 12.7 mm × 125 mm). The specimen was clamped at the top and the flame was applied to the bottom. The flame was brought into contact with the test specimen for 10 seconds and then removed. The combustion time, dripping of sample and burning state at fixing determines the class of the sample. In the UL-94 rating system, the material will be rated V0 if burning time ≤10 seconds and no dripping after removal of the burner. The V1 and V2 rating requires the burning time of each specimen ≤ 30 seconds. The V2 rating allows the dripping of burning specimen, but for V1 rating specimen must not drip.

2.8 Scanning electron microscope (SEM)
2.8. Pretražni elektronski mikroskop (SEM)

The effect of the addition of PMDI to the composite composition on the morphology of WPCs was determined by scanning electron microscopy (SEM). SEM images of the surfaces and cross-sections of the samples were obtained by a Quanta 400F Field Emission SEM (FEI Company, The Netherlands). Samples were gold-coated and viewed at an acceleration voltage of 20 kV with different magnifications.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 BPO_4 Synthesis
3.1. Sinteza bor-fosfata (BPO_4)

Hydrothermal and microwave synthesis methods were used together to obtain pure BPO_4 and it was characterized by FTIR spectroscopy and XRD analysis, respectively (Figure 2). The unit cell parameters *a*=4.3414(2), *c*=6.6427(4) Å are in good agreement with the literature (*a* = *b* = 4.342 Å and *c* = 6.642 Å) (Wang *et al.*, 2012). In literature, the XRD analysis of synthesized boron phosphate indicated the tetragonal structure and crystallographic parameters of *a*=4.3425Å

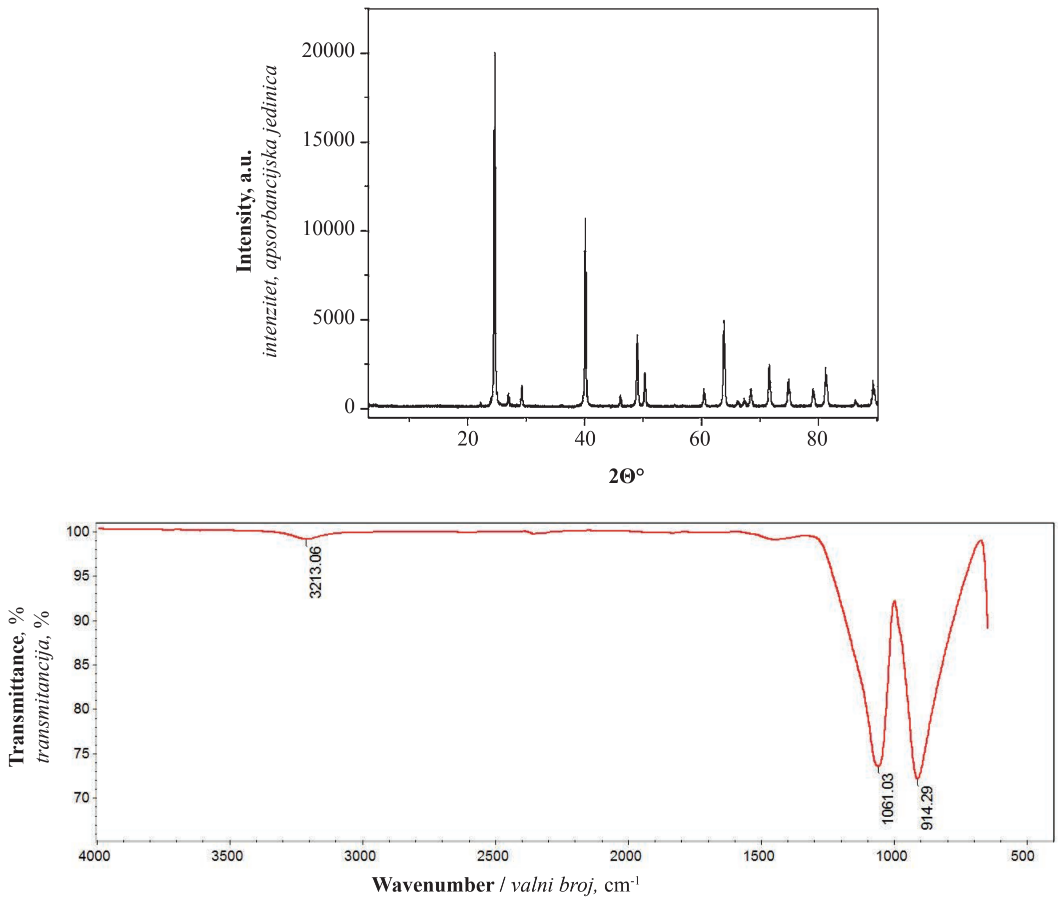

Figure 2 a) XRD pattern and b) FT-IR spectroscopy of BPO_4
Slika 2. a) Uzorak XRD, b) FT-IR spektroskopija spoja BPO_4

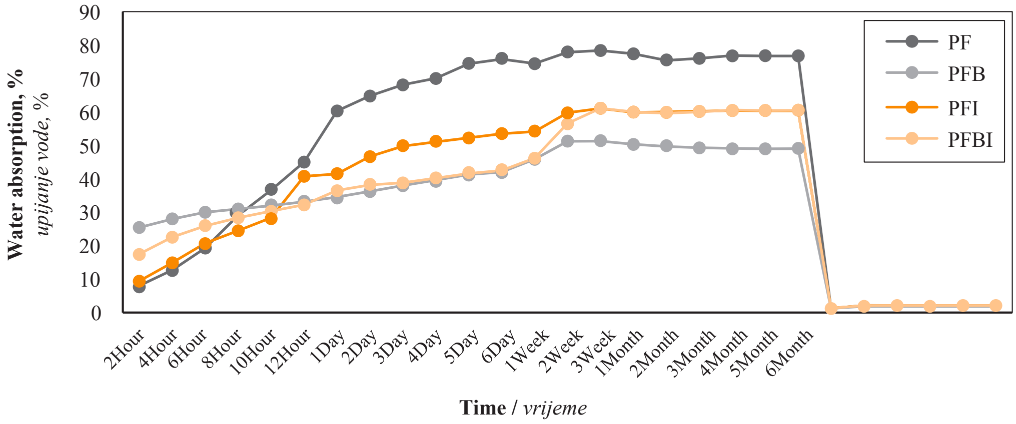

Figure 3 Water absorption (%) of WPCs in 6 months
Slika 3. Upijanje vode (%) WPC-a tijekom šest mjeseci

and *c*=6.6415Å (Mamlouk *et al.*, 2015). FTIR spectrum of BPO_4 also revealed the B-O stretching peak at 911 cm^{-1} and PO_4 asymmetric stretching peak at 1060 cm^{-1}. The peaks match with the previous studies in the literature, in which the broad band at 1100 cm^{-1} and the peak at 933 cm^{-1} was assigned to the asymmetric stretching vibrations of PO_4^{3-}, and B-O stretchings, respectively (Abd El-Ghaffar *et al.*, 2018). Accordingly, it has been proved that BPO_4 was successfully synthesized.

3.2 Physical properties
3.2. Fizička svojstva

The densities of boards were found in the range of 0.64-0.75 g/cm³ as shown in Table1. The PFB group (phenol-formaldehyde resin + wood flour + BPO_4) has the highest density within wood polymer composites. The introduction of BPO_4 flame-retardant additive has been found to increase density of composite. PMDI, which was introduced as a compatibilizer, showed the same effect. It was observed that the voids between the cells were filled with additive materials and the density was increased.

The rate of water uptake can vary depending on whether the materials forming the composites are water-attractive (hydrophilic) or water-repellent (hydrophobic). Figures 3 and 4 show the water absorption and thickness swelling tests results, respectively.

It was found that the control group (PF) was the group with the maximum absorption capacity of water, while the PFB group, which is a BPO_4 containing group, exhibited the minimum amount of water absorption. The PFB composite group showed about 50 % WA, while the PF group weight gained about 75 % within 6 months. The highest density can be seen in PFB (containing BPO_4) group, and the lowest density was found in control sample (PF) according to Table 1. Different densities led to different WA% of composites. The highest WA% was observed in the control group which has the lowest density. The presence of more empty pores in control sample made it easily accessible to water. As the other groups (PFI and PFBI) have close density values, the % WA values are close to each other. Baysal *et al*. (2007) investigated the water absorption rates of wood polymer composites impregnated with a mixture of boric acid and bo-

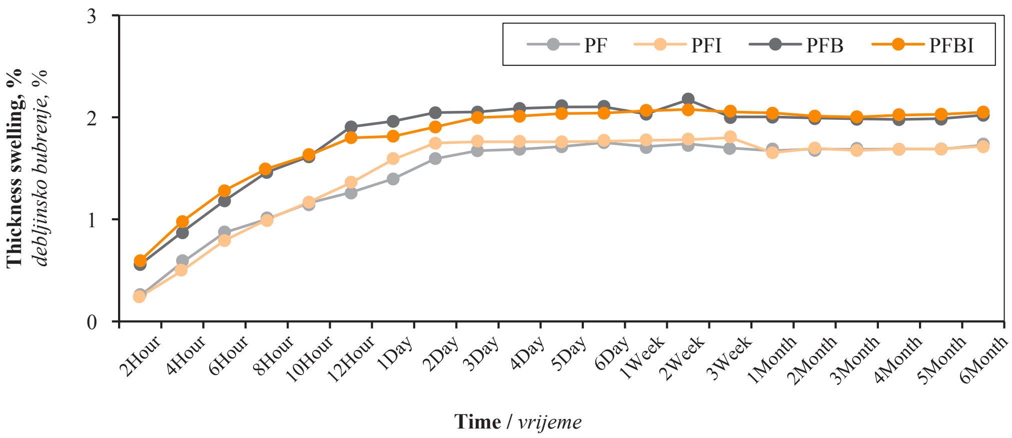

Figure 4 Thickness swelling (%) of WPCs in 6 months
Slika 4. Debljinsko bubrenje (%) WPC-a tijekom šest mjeseci

rax. They found that the boric acid and borax mixture impregnation resulted in less water absorption than the control groups.

The material can expand volumetrically as it receives water and, after a period of time, there may be deformation on the composite surfaces. The thickness swellings (*TS*) of the composite groups are given in Figure 4. The TS% of all groups increased over time and then remained almost fixed from the 3rd day. It can be seen that the composites having the highest *TS*% are groups containing BPO_4 and this group also showed the highest density values. The lowest *TS*% was found in the control group (PF) and this was expected because the control group has a low density and a more porous structure. While water diffuses into these empty spaces, there is no increment in volume. As the water filled the gaps in the composite structure, no volumetric expansion was seen.

3.3 Mechanical properties
3.3. Mehanička svojstva

Table 2 represents the flexural properties of WPCs with different formulations. The highest values of flexural modulus (*MOE*) were obtained from PMDI containing composites (PFI group). The lowest bending modulus was found in the control group (2.09 GPa). The *MOE* for PFI composite showed an increment of 37 % from 2.09 to 2.86 GPa. The modulus of rupture (MOR) of composites was also increased from 11.4 to 21.2 MPa by adding PMDI compatibilizer. Composites containing BPO_4 (PFB, PFBI) slightly decreased the *MOE* values when compared with PMDI added composites (PFI). The increase in bending strength and *MOE* of composites provided evidence of proper interfacial adhesion between wood flour and phenol formaldehyde resin in PMDI incorporated samples. The stress can be effectively transferred from resin to wood fibers by this strong adhesion and attraction. The significant improvements in both strength and modulus of PMDI compatibilizer added wood polymer composites were also reported by different research groups (Lu *et al*., 2000; Geng *et al*., 2005). Most polymers are hydrophobic and not compatible with hydrophilic wood. This structural difference resulted in a poor interfacial adhesion. The isocyanates functional groups of PMDI react with the hydroxyl groups of the wood and hydroxyl groups of phenol formaldehyde resin to form carbamate and urethane bonds. Hence, strong adhesion through covalent bonding between wood flour and polymer resin provides improved mechanical properties (Bodîrlău *et al*., 2012).

As seen in Table 3, according to the results of the statistical analysis applied for F_{max} loads, it was significant according to the $P = 0.000$ significance level for the ANOVA test. According to the LSD test results, it was found that the PFI composite group showed the best load carrying capacity compared to that of the other three composite groups. According to LSD test results, it can be seen that PFI test samples carried more load, such as 17.84 %, than PF test samples, 17.58 % more than PFB test samples and 17.58 % more than PFBI test samples. Additionally, PFBI samples were significant with a significance level of P = 0.048 and carried 1.23 % more load than PF test samples according to the LSD test (Table 4).

3.4 Morphology of WPCs
3.4. Morfologija WPC-a

The fracture surfaces of specimens tested in bending were characterized by SEM. Figures 5a and 5c show SEM images of control group (PF) and BPO_4 flame-retardant added WPCs group (PFB), respectively. There are voids and cracks around wood flour and these morphologies displayed a weak interfacial adhesion between wood particles and polymer resin. Besides, in the presence of PMDI compatibilizer the SEM images revealed fewer cavities (Figure 5b and 5d). It was also noticed that wood particles were surrounded by polymer and wood lumens were filled up with phe-

Table 2 Mechanical (flexural) properties of WPCs
Tablica 2. Mehanička (savojna) svojstva WPC-a

Sample codes *Oznake uzoraka*	***MOE***, **GPa**	***MOR***, **MPa**	F_{max}, **kg**	S_0, **mm²**
PF	2.09 ± 0.12	11.4 ± 1.5	0.93 ± 0.11	39.01 ± 1.33
PFI	2.86 ± 0.10	21.2 ± 1.9	1.65 ± 0.18	37.97 ± 0.53
PFB	2.28 ± 0.05	12.4 ± 0.5	0.94 ± 0.06	37.35 ± 1.37
PFBI	2.56 ± 0.09	14.6 ± 0.7	1.13 ± 0.02	38.00 ± 0.88

Table 3 Summary of ANOVA results for load carrying capacity (F_{max}) tests of experimental specimen
Tablica 3. Sažetak ANOVA rezultata za ispitivanje nosivosti (F_{max}) eksperimentalnog uzorka

Source *Izvor*	DOF	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	*F* value *F-vrijednost*	Level of sig. *Razina značajnosti*
Between groups / *između grupa*	1.035	3	0.345	28.676	0.000
Within groups / *unutar grupa*	0.096	8	0.012		
Total / *ukupno*	1.132	11			

Table 4 Comparison of averages of test samples for load carrying capacity (F_{max})
Tablica 4. Usporedba srednjih vrijednosti nosivosti (F_{max}) ispitnih uzoraka

	(I) Sample code *Oznaka uzorka*	**(J) Homogenous** group *Homogena grupa*	**(I-J) Mean difference** *Srednja razlika*	**Sig*.**	**95 % Confidence interval** 95 %-*tni interval pouzdanosti*	
					Lower bound *Donja granica*	**Upper bound** *Gornja granica*
LSD	PF = A	PFI B	-0.725000	0.000	-0.93157	-0.51843
		PFB C	-0.013333	0.885	-0.21990	0.19324
		PFBI D	-0.208333	0.048	-0.41490	-0.00176
	PFI = B	PF A	0.725000	0.000	0.51843	0.93157
		PFB C	0.711667	0.000	0.50510	0.91824
		PFBI D	0.516667	0.000	0.31010	0.72324
	PFB = C	PF A	0.013333	0.885	-0.19324	0.21990
		PFI B	-0.711667	0.000	-0.91824	-0.50510
		PFBI D	-0.195000	0.061	-0.40157	0.01157
	PFBI = D	PF A	0.208333	0.048	0.00176	0.41490
		PFI B	-0.516667	0.000	-0.72324	-0.31010
		PFB C	0.195000	0.061	-0.01157	0.40157

*The mean difference is significant at the 0.05 level. / *Srednja je razlika značajna na razini od 0,05.*

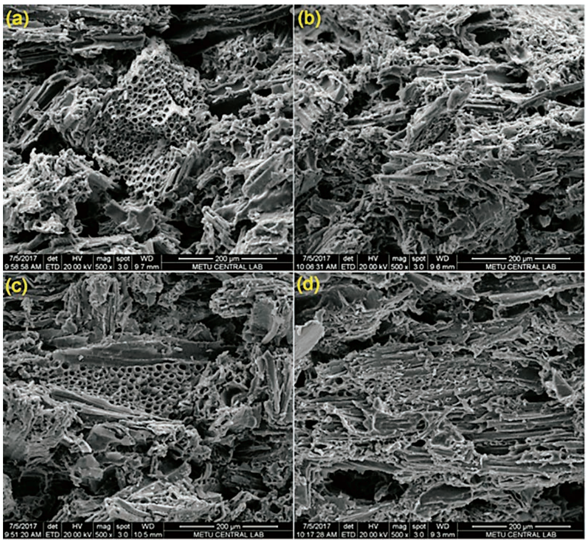

Figure 5 Morphology of fractured surfaces of WPCs: (a) PF (wood + polym), (b) PFI (wood + polym + compatibl), (c) PFB (wood + polym + BPO_4) and (d) PFBI (wood + polym + compatibl + BPO_4)
Slika 5. Morfologija lomnih površina WPC-a: (a) PF (drvo + polimer), (b) PFI (drvo + polimer + kompatibilizator), (c) PFB (drvo + polimer + BPO_4) i (d) PFBI (drvo + polimer + kompatibilizator + BPO_4)

nol formaldehyde resin (Figure 5d). The introduction of PMDI compatibilizer into the WPCs resulted in a good bonding between polymer matrix and wood flours. The well dispersed morphologies of PMDI added WPCs agreed well with the improved mechanical properties of PMDI added WPCs.

3.5 Thermogravimetric analysis
3.5. Termogravimetrijska analiza

Thermal degradation temperatures of the composite groups were compared by thermogravimetric analysis and the effects of BPO_4 addition to the composites on the thermal stabilities were investigated. The main decomposition temperatures and the char content at 750 °C of the composites are given in Table 5 and the TGA thermograms of composites is presented in Figure 6.

It is known that the wood components (hemicellulose, cellulose and lignin) start to degrade when they are subjected to heat. Initial degradation starts by hemicellulose hydrolysis at around 200 °C and the random cleavage of glycosidic linkages of cellulose, followed by the degradation of lignin at higher temperatures. To improve the thermal stability of wood, boron compounds were impregnated or added to the WPCs. Boron based compounds increased the degradation rate at lower temperatures, which causes the higher char yield. Boric acid, borax and their mixture were used with ammonium polyphosphate (APP) as a synergist for flame-retardants in WPCs (Kurt *et al*., 2012). APP and boron compounds retard flame by producing carbonaceous barrier which delays the heat transfer. Recently, five kinds of phosphorus-boron based transparent intumescent flame-retardants were synthesized by boric acid (BA) and cyclic phosphate ester acid (PEA). These flame-retardants were coated onto wood substrates and the results indicated that BA imparts excellent synergistic smoke suppression effect. Also, the residual masses of the coatings were noticeably increased with higher loading of BA. The reduction in the release of combustible gases resulted in less smoke production and heat release during burning (Xu *et al*., 2018). The effect of boron compounds on fire protection of epoxy system was studied by Unlu *et. al.* (2014) and three kinds of boron compounds namely boric acid (BA), zinc borate (ZB) and melamine borate (MB) were used with ammonium polyphosphate (APP). According to the fire test results, borates can promote ceramification and form strong residue among these additives (Unlu *et al*., 2017). Li *et*

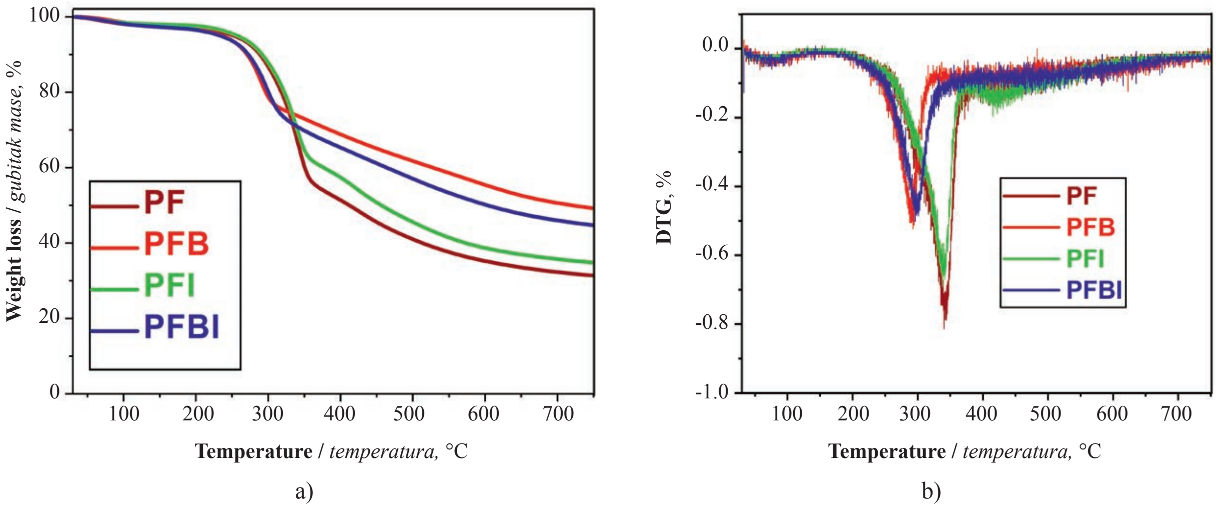

Figure 6 a) TGA, b) DTG curves of WPCs with different formulations
Slika 6. a) TGA, b) DTG krivulje WPC-a s različitim formulacijama

al. (2017) prepared boron phosphates through the reaction between boric acid and phosphoric acid for charring agent in epoxy resins. They increased the acid cites on the boron phosphate surface and it exerted a synergistic effect by catalyzing the carbonization of epoxy resin (Unlu *et al*., 2014).

TGA results revealed that the control (PF) group composite has the highest weight loss (69 %), while the BPO_4 containing (PFB) group composites has the lowest weight loss (51 %). The increase of residue is more obvious in the presence of $BPO_{4,}$ and it promoted the charring (Table 3). It was also noticed that BPO_4 and PMDI addition decreased the main decomposition temperatures but increased the char yield of WPCs. Tomak *et al*. (2012) reported similar TGA results. When boron compounds were added to the composites, they observed that the main decomposition temperatures were reduced by 15-50 °C, while the char content was increased. Mengeloğlu and Karakus (Mengeloglu and Karakus, 2008) examined thermal degradation temperatures of composites obtained from high density polyethylene (HDPE) and wheat straw flour. They observed that by adding boric acid and borax additives to composites, decomposition temperature shifted to the lower value and increased the char residue. As a result, they have indicated that the boron compounds increase the thermal stability of the composites.

3.6 LOI and UL-94 tests
3.6. LOI i UL-94 testovi

The flammability and flame retardancy of WPCs were investigated by LOI and vertical UL-94 tests and the results are presented in Table 5. The LOI values of composites were found in the range of 28.7 and 35.6. When the flame-retardant BPO_4 was added for 5wt% in WPCs, the LOI value increased from 28.7 to 35.6. The PMDI compatibilizer and BPO_4 containing composites (PFBI) also exhibited a higher LOI value than that of the control group (PF). It is well known that boron compounds form a protective barrier and promote charring (Unlu *et al*., 2014). Obviously, BPO_4 improved the thermal stabilities of WPCs, and LOI values correlated very well with the char yield data (Table 3) in TGA. The UL-94 test results revealed that the BPO_4 containing composites achieved V-0 rating and the BPO_4 incorporation into composite formulation improved the fire performance of WPCs. Stark *et al*. (2010). evaluated the effect of five additive-type commercial fire retardants (decabromodiphenyl oxide/ antimony trioxide mixture, magnesium hydroxide, zinc borate, melamine phosphate, ammonium polyphosphate) on fire performance of wood flour-polyethylene composites. All of these fire-retardant systems were incorporated into the composites for 10 wt%. They found that the most effective was ammonium polyphos-

Table 5 Results of TGA, LOI test and vertical flame (UL-94) test
Tablica 5. Rezultati TGA, LOI testa i testa okomitog plamena (UL-94)

Sample codes *Oznake uzoraka*	$T_{main,}$ °C	**Char yield at 750 °C, %** *Prinos ugljena pri 750 °C, %*	**UL-94 classification** *UL-94 klasifikacija*	**LOI**
PF	342.9	31.4	V2	28.7
PFI	339.4	34.8	V2	28.3
PFB	290.2	49.2	V0	35.6
PFBI	300.3	44.7	V0	33.8

phate with 29 LOI value. Comparing our LOI results of composites with those of Stark et. al, it can be concluded that even a lower amount of BPO_4 incorporation (wt 5%) into our composites resulted in a higher LOI value.

4 CONCLUSIONS
4. ZAKLJUČAK

This study focused on the use of boron phosphate (BPO4) flame-retardant in WPCs for the first time and the effect of BPO4 on physical, mechanical and thermal performances of WPCs. The earlier investigations reported several flame-retardant chemicals, and the boron compounds together with ammonium polyphosphates additives have shown a synergistic effect in enhancing the flame retardancy of polymers. Hence, in this study, BPO4 was added as a flame-retardant compound in WPCs made of phenol formaldehyde resin and Oriental beech wood (Fagus orientalis Lipsky) flour. TGA results revealed that the char yield of composite was 31.4 % in the absence of BPO4 and this value was increased to 49.2 % by incorporation of 5 wt% BPO4 to the formulation. The LOI values were increased from 28.7 to 35.6. The UL-94 test results also demonstrated that the BPO4 added composites have good flame retardancy. PMDI compatibilizer also played an important role in interfacial adhesion between wood particles and polymer matrix. The improved flexural strength and well dispersed SEM morphologies of composites proved that the PMDI was a good compatibilizer in WPCs.

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Machinability of Kempili (*Lithocarpus Ewyckii* (Koth.) Rehd.) and Ubar (*Syzygium* Sp.) Wood from Borneo Forest

Obradivost drva kempili (*Lithocarpus Ewyckii* (Koth.) Rehd.) i drva ubar (*Syzygium* sp.) iz šume Borneo

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ABSTRACT • *This paper presents information on the machinability of Kempili (Lithocrapus ewyckii (Koth.) Rehd.) and Ubar (Syzygium sp.) for different machining operations at 14 % and 10 % moisture content. Both species are lesser-known species from the Borneo forest of Indonesia. The basic testing procedures followed ASTM D-1666-87. The machining operations applied were planing, shaping, boring, turning, and sanding. The surface quality for determining the machinability were defect percentage and defect-free value. Ten replications were used for each machining property and randomly collected from flat-sawn boards for each wood. The results showed that fuzzy grain defects were found for both species, resulting from all machining operations. Decreasing moisture content from 14 % to 10 % tended to increase the defect-free value of the wood. Wood species significantly affected the machinability of Kempili and Ubar wood in planing, shaping, boring, and sanding operations. Moisture content only significantly affected the machinability of both wood species in turning operation. Based on their defect-free values in all investigated machining operations, both Kempili and Ubar wood have good machining quality. Therefore, both species are recommended as raw materials for producing various wood-based products such as furniture, molding, leaf doors, dowels, or laminated wood.*

KEYWORDS: *wood surface quality; planing; shaping; boring; turning; sanding*

SAŽETAK • *U radu su prezentirane informacije o obradivosti drva kempili (Lithocrapus ewyckii (Koth.) Rehd.) i drva ubar (Syzygium sp.) različitim postupcima mehaničke obrade pri sadržaju vode 14 i 10 %. Obje vrste drva manje su poznate vrste iz šume Borneo u Indoneziji. Osnovni postupci ispitivanja slijedili su normu ASTM D-1666-87. Primijenjene operacije mehaničke obrade bile su blanjanje, profilno glodanje, bušenje, tokarenje i brušenje. Kvaliteta površine za određivanje obradivosti evaluirana je na temelju postotka površine drva s greškama i površine bez grešaka. Svakim mehaničkim postupkom obrađeno je po deset uzoraka. Uzorci su uzeti nasumično iz ravnih piljenica svake od dvije ispitivane vrste drva. Rezultati su pokazali da je nakon svake operacije mehaničke obrade na objema vrstama drva nastala čupava površina. Smanjenjem sadržaja vode s 14 na 10 % povećao se postotak površine drva bez grešaka. Vrsta drva znatno je utjecala na obradivost blanjanjem, profilnim glodanjem,*

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bušenjem i brušenjem. Sadržaj vode također je znatno utjecao na obradivost obiju vrsta drva samo tokarenjem. Na temelju postotka površine drva bez grešaka za sve se istraživane operacije mehaničke obrade može zaključiti da se na drvu kempili i drvu ubar postiže dobra kvaliteta mehaničke obrade. Stoga se obje vrste drva preporučuju kao sirovina za proizvodnju različitih proizvoda od drva kao što su namještaj, kalupi, vratna krila, moždanici ili lamelirano drvo.

KLJUČNE RIJEČI: *kvaliteta površine drva; blanjanje; profilno glodanje; bušenje; tokarenje; brušenje*

1 INTRODUCTION
1. UVOD

Wood is one of the raw materials from the forest that can be easily converted into various products. Wood is different from other materials as it is hygroscopic, can shrink and swell, and has a certain pattern, gloss, texture, and fiber arrangement. The community rarely uses wood in the form of logs and usually converts the logs into sawn timber before its use as raw material for building, furniture, or other needs.

Knowledge of the basic properties of a particular wood is required to optimize its utilization and economic value (Sandak *et al.*, 2017). Machining properties are one of basic properties of wood that need to be identified prior to further use of a particular wood. Any improper machining work during the conversion of logs into sawn timber could cause defects and reduce the quality of sawn timber and consequently of the final product (Sofuoglu and Kurtoglu, 2014). Even though wood is more easily machinable than metal and plastic products, it has a high characteristic variation within and between species, which significantly affects its machining process (Malkoçoğlu and Özdemir, 2006).

Indonesia's tropical forest has a high number of wood species, up to approximately 4000. However, many wood species remain lesser-known and lesser-used due to minimal information on their existence and properties. On the other hand, they are potentially an alternative material for construction and furniture purposes. Kempili (*Lithocarpus ewyckii Korth*.) and Ubar (*Syzygium sp*.) are two such species (Budiharta, 2010; Efiyanti *et al*., 2020; Kaul, 1987; Kusuma *et al*., 2018; Wyk *et al*., 2004). Both species grow naturally in Borneo Island and several other countries of South-East Asia (Soepadmo *et al*., 2000; Ismail and Ahmad, 2019; Efiyanti *et al*., 2020; Raharjo *et al*., 2021). Nevertheless, up to now, the information on Kempili and Ubar has been limited to their resistance to fungus attack and chemical components or the potency of Ubar plant as an antidiabetic agent (Efiyanti *et al*., 2020; Raharjo *et al*., 2021; Zulcafli *et al*., 2020). Their basic machining properties or machinability have not been reported elsewhere.

Many previous studies on the machinability of wood used samples with air-dry moisture content level of around 14-15 %, as instructed in ASTM D 1666-87 (Sutisna *et al*., 2004; Martawijaya *et al*., 2005; Malkoçoğlu and Özdemir, 2006; Muslich *et al*., 2013; Sofuoglu and Kurtoglu, 2014; Rianawati and Setyowati, 2015). However, moisture content (MC) and wood species are 2 of several intrinsic factors affecting the machinability of wood (Naylor *et al*., 2011; Lhate *et al*., 2017). Studies on the impact of both factors have rarely been carried out for tropical wood species from Indonesia's forests. This study aimed to investigate the effect of wood species and 2 MC levels (10 % and 14 %) on the machinability of Kempili and Ubar wood. The starting assumption was that decreasing wood MC from 14 % to 10 % would increase the defect-free value in both types of wood. Working with hard and dry wood will give better results than that with soft and wet wood, although it requires higher cutting forces and power (Wengert, 2006).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

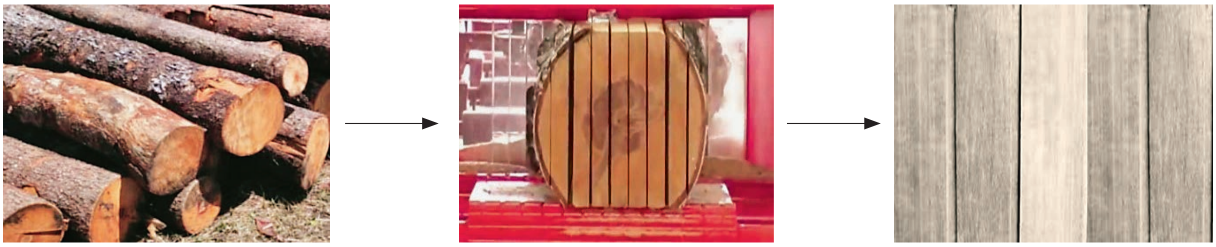
2.1 Material and equipment
2.1. Materijal i oprema

The main materials used for the research were the boards of Kempili (*Lithocrapus ewyckii* (Koth.) Rehd. and Ubar (*Syzygium sp*) wood. The location for collecting Kempili and Ubar logs was the natural forest region in Tanjung Asam, West Borneo, with coordinates of (S 01.09190°, E 111.23429°) and (S 01.09114°, E 111.23114°), respectively. Prior to the study, both wood species identities were synchronized with the existing wood collection at Xylarium Bogoriense, West Java, Indonesia. They were identical to the collection numbers of 34432 (Kempili) and 34433 (Ubar) from Xylarium Bogoriense.

2.2 Preparation of master samples and test specimens
2.2. Priprema glavnih i ispitnih uzoraka

The logs were all sawn to obtain flat-sawn large boards (further termed master samples) with less natural defects such as knots and surface crack/checks (Figure 1). Approximately 10 master samples were initially prepared for each species, each with a dimension of 30 mm (thickness) × 125 mm (width) × 1200 mm (length). The remaining boards produced during the sawing process were used for different studies.

The moisture content of each master sample was determined by using a moisture meter. The master samples were divided into 2 groups based on the targeted MC, 10 % and 14 %. All boards were further subdivided



Logs / *trupci* — **Sawing pattern** *način piljenja* — **Sawn board/master samples** *piljenice / glavni uzorci*

Figure 1 Master samples
Slika 1. Glavni uzorci

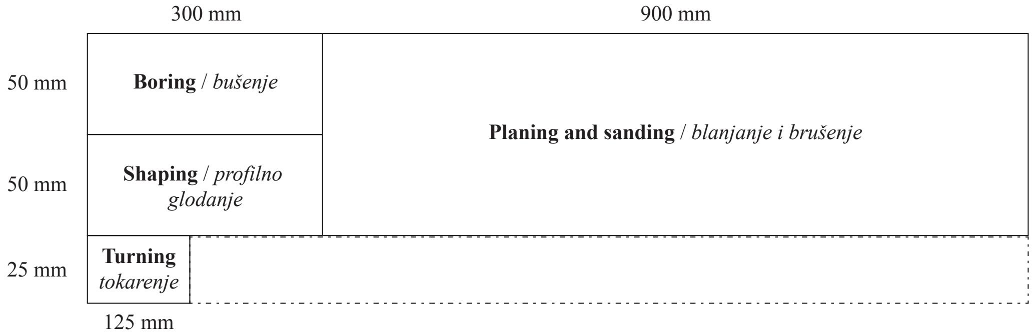


Figure 2 Preparation pattern for each machining property
Slika 2. Shema pripreme uzoraka za svaku vrstu mehaničke obrade

into several test specimens with various dimensions for different tests of machining properties. The pattern for preparing the test specimens from each master sample and their dimension is presented in Figure 2 and Table 1. The specimen dimensions were adjusted to the existing defect-free area space from each master sample. Boring and shaping specimens were separated, considering different machines used for these tests.

2.3 Machining properties test
2.3. Ispitivanje svojstava mehaničke obrade

The planing process was carried out with a planer (MB206D/AKS) at rotational frequency of 2200 rpm, tool diameter of 113 mm, cutting speed of 13.022 m/s, rake angle (γ_o) of 32° and feed per knife of 0.5 mm. The boring process was carried out with DTBM15/AEG at rotational frequency of 1200 rpm, tool diameter of 22 mm, cutting speed of 1.382 m/s, cutting angle of 45° and feed per cutting edge of 0.5 mm. The shaping process was carried out with BER/2 Wadkin machine at rotational frequency of 2800 rpm, rake angle of 45°, and cutting depth of 0.25 mm concave type knife surface. The sanding process was carried out with the T3EN/Sandmax machine at rotational frequency of 1200 rpm, feed speed of 6 m/s, and sanding grit of 120. The turning process was carried out with ML- 60/

Table 1 Various types of defects observed and specimen dimensions for each machining property
Tablica 1. Uočene različite vrste grešaka i dimenzije uzorka za svako svojstvo mehaničke obrade

Machining operations *Mehanička obrada*	**Types and characteristics of machining defects on wood surface** *Vrste i obilježja grešaka mehaničke obrade na površini drva*	**Dimension of specimens (width by length by thickness), mm** *Dimenzije uzoraka (širina × duljina × debljina),* mm
Planing / *blanjanje*	Raised grain, fuzzy grain, chip marks, torn grain *izdignuta vlakanca, čupava površina, tragovi oštrice alata, pokidana vlakanca*	100 × 900 × 20
Shaping / *profilno glodanje*	Raised grain, fuzzy grain, chip marks *izdignuta vlakanca, čupava površina, tragovi oštrice alata*	50 × 300 × 20
Boring / *bušenje*	Fuzzy grain, crushing, smoothness, tear cut *čupava površina, zdrobljena površina, zaglađena površina, resavost*	50 × 300 × 20
Turning / *tokarenje*	Fuzzy grain, torn grain, roughness *čupava površina, pokidana vlakanca, hrapava površina*	25 × 125 × 20
Sanding / *brušenje*	Fuzzy grain, scratching marks *čupava površina, ogrebotine*	100 × 900 × 20

a) b) c) d) e)

Figure 3 Post-test pictures of specimens for each machining operation: a) planing, b) shaping, c) boring, d) turning, e) sanding
Slika 3. Slike uzoraka nakon ispitivanja za svaku operaciju mehaničke obrade: a) blanjanje, b) profilno glodanje, c) bušenje, d) tokarenje, e) brušenje

Shengpeng at elevated rotational frequency of 1000 rpm, tool diameter of 22.9 mm, cutting speed of 1.198 m/s and rake angle of 32°. The number of specimens used for each test was 10 pieces (5 represented 10 % MC and 5 represented 14 % MC). This number was smaller than that recommended in ASTM D1666-87 due to the limited number of sawn boards that could be chosen as master samples. The specimen condition after each test is shown in Figure 3.

The presence or absence of defects on the specimens, such as raised grain, fuzzy grain, chip marks, torn grain, roughness, crushing, and scratching mark (Table 1), was examined during each planing, shaping, sanding, boring, and turning tests. The defects percentage for each specimen was calculated based on the area of the defective part on the cross-section of the specimen (Eq. 1). The defect-free values were obtained by subtracting the defects percentage from 100 % (Eq. 2) and used to classify the machining quality categories for the wood (Table 2).

$$Defects\ percentage(\%) = \frac{Defective\ area}{Total\ cross-section\ area} \cdot 100\ \% \quad (1)$$

$$Defects-free\ values = 100\ \% - defects\ percentage \quad (2)$$

2.4 Data analysis
2.4. Analiza podataka

A 2-way analysis of variance (ANOVA) was applied to investigate the significant effect of wood species and MC on the average defect-free values of each machining property. Tukey test was further carried out when ANOVA showed significant results. Minitab 16 software was used to perform all tests.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Planing
3.1. Blanjanje

Table 3 shows that the common defects that occurred during the planing of Kempili and Ubar wood were fuzzy grain and torn grain. Table 4 shows that Kempili wood had a good planing property (classified as grade II). The average defect-free values of Kempili wood were 62 % at MC of 14 % and 66 % at MC of 10 %. On the other hand, Ubar wood had an excellent planing property (classified as grade I) with its average defect-free values of 88 % at MC of 14 % and 94 % at MC of 10 %. Further statistical test results confirmed the significant effect of wood species on the planing property (Table 5). Reducing the moisture content of wood from 14 % to 10 % decreased the percentage of torn grain defect in Kempili wood by 50 % and the percentage of fuzzy grain defect in Ubar wood by 80 %.

The results revealed that the prevalent defects in Kempili wood were fuzzy grain (20 %) and torn grain (16 %), while Ubar wood exhibited fuzzy grain defects at 10 %. Kempili wood, with a moisture content of 14 % and 10 %, showed a lower average defect-free

Table 2 Relationship between defects-free values and machining properties grade classification (Abdurachman and Karnasudirdja, 1982)
Tablica 2. Odnos između postotka površine bez grešaka i klasifikacija svojstava mehaničke obrade (Abdurachman i Karnasudirdja, 1982.)

Defects-free values, % *Postotak površine bez grešaka, %*	Grade classification *Razred klasifikacije*	Categories *Kategorije*
0 – 20	V	Very poor / *vrlo loša kvaliteta*
21 – 40	IV	Poor / *loša kvaliteta*
41 – 60	III	Medium / *srednja kvaliteta*
61 – 80	II	Good / *dobra kvaliteta*
81 – 100	I	Excellent / *izvrsna kvaliteta*

value than Ubar wood. Consequently, the planing quality of Ubar wood is deemed excellent, while Kempili wood is considered good (as referred to Table 4). Moisture content, however, did not significantly impact planing properties. In conclusion, both wood species exhibit suitable characteristics as raw materials for wood products requiring a high-quality surface appearance, such as tables, chairs, and cupboards. The results of planing test for Kempili wood are similar to those of *Cinnamomum iners Reinw. Ex Blume*, *Erythrina fusca Lour*, *Pempis adiculata*, *Hymenaea sp*., and *Euretia acimunate R*. (Muslich *et al.*, 2013; Supriadi, 2017). In addition, the results of planing test for Ubar wood is similar to those of *Timonius sericeus* (Desf) K.Schum and *Acacia leucophloea* (Roxb.) Willd. from East Nusa Tenggara (Rianawati and Setyowati, 2015).

3.2 Shaping
3.2. Profilno glodanje

During the shaping process of both Kempili and Ubar wood, fuzzy grain and raised grain were the dominant defects (Table 3). Decreasing the moisture content of wood from 14 % to 10 % reduced the percentage of fuzzy grain in Kempili and Ubar wood (Table 3). This result is in line with several previous studies on the same topic (Sofuoğlu and Kurtoğlu, 2014; Sütçü, 2012).

Based on its defect-free values range (60 % - 80 %), Kempili wood has a good shaping property and can be classified into II grade (Table 4). On the other hand, Ubar wood can be classified as a wood species with excellent planing properties (grade I) (Table 4) due to its high defect-free values (89 % - 94 %). Further statistical test results confirmed the significant effect of wood species on the shaping property (Table 5). Due to their good shaping properties, both Kempili and Ubar wood can be used as molding materials or for crafting purposes

The results of the shaping test for Kempili wood are similar to those of *Sterculia cordata Blume*, *Sloane sigun* (*Blume*) *K. Schumann*, *Pouteria duclitan* (*Blanco*) *Baehni*., *Litsea angulate Blume*, *Melicope-ankenda* (*Gaertn*.) T.G. *Hartley*, *Mangliatia glauca Blume*, *Euretia acuminate* R., *Pempis adicula*, and *Tetra merista glabra* Miq. (Muslich *et al.*, 2013; Supriadi, 2017, 2019). On the other hand, the results of the shaping test for Ubar wood are similar to those of *Timonius sericeus* (Desf) K.Schum and *Acacia leucophloea* (Roxb.) Willd. from East Nusa Tenggara (Rianawati and Setyowati, 2015).

3.3 Boring
3.3. Bušenje

The fuzzy grain was the dominant defect during the boring process of Kempili and Ubar wood. Decreas-

Table 3 Types and percentages of defects observed in Kempili and Ubar wood at 2 MC levels for various machining operations (average values, %)
Tablica 3. Postotci i vrste grešaka za različite mehaničke obrade drva kempili i drva ubar s dva različita sadržaja vode (prosječne vrijednosti, %)

Machining operation / defects types and percentage *Mehanička obrada / vrste grešaka i postotci*	**Kempili**		**Ubar**	
	MC 10 %	**MC 14 %**	**MC 10 %**	**MC 14 %**
1. Planing / *Blanjanje*				
Fuzzy grain / *čupava površina*, %	20	11	2	10
Raised grain / *izdignuta vlakanca*, %	6	1	4	1
Torn grain / *pokidana vlakanca*, %	8	16	0	1
Chip marks / *tragovi oštrica alata*, %	0	10	0	0
2. Shaping / *Profilno glodanje*				
Fuzzy grain / *čupava površina*, %	20	20	6	11
Raised grain / *izdignuta vlakanca*, %	0	3	0	0
Chip marks / *tragovi oštrica alata*, %	1	0	0	0
3. Boring / *Bušenje*				
Fuzzy grain / *čupava površina*, %	20	26	9	4
Crushing / *pokidana vlakanca*, %	1	0	0	1
Smoothness / *zaglađena površina*, %	0	2	0	1
Tear-cut / *resavost*, %	1	1	0	0
4. Turning / *Tokarenje*				
Fuzzy grain / *čupava površina*, %	5	11	5	11
Torn grain / *potrgana vlakanca*, %	4	3	3.5	3
Roughness / *hrapava površina*, %	8	11	6.5	13
5. Sanding / *Brušenje*				
Fuzzy grain / *čupava površina*, %	11	14	7	8
Scratching mark / *ogrebotine*, %	0	0	0	0

Table 4 Machining-defect free values and machining quality classification of Kempili and Ubar wood at 2 MC levels (average values, %)
Tablica 4. Postotak površine drva bez grešaka i klasifikacija kvalitete mehaničke obrade drva kempili i drva ubar s dva različita sadržaja vode (prosječne vrijednosti, %)

Machining properties *Mehanička obrada*	**Machining-defect free values, %** *Postotak površine drva bez grešaka mehaničke obrade, %*							
	Kempili				**Ubar**			
	MC 10 %	**Class** *Klasa*	**MC 14 %**	**Class** *Klasa*	**MC 10 %**	**Class** *Klasa*	**MC 14 %**	**Class** *Klasa*
Planing / *blanjanje*	66[a*]	II	62[a]	II	94[b]	I	88[b]	I
Shaping / *profilno glodanje*	79[a]	II	77[a]	II	94[b]	I	89[b]	I
Boring / *bušenje*	78[ab]	II	71[a]	II	95[b]	I	91[b]	I
Tuning / *tokarenje*	83[b]	I	75[a]	II	85[b]	I	73[a]	II
Sanding / *brušenje*	89[a]	I	86[a]	I	93[b]	I	92[b]	I

*Figures with the same letter(s) indicate no significant difference(s) (based on Tukey's test). / *Brojke s istim slovom (slovima) pokazuju da nema značajne razlike (na temelju Tukeyjeva testa).*

ing the moisture content of wood from 14 % to 10 % reduced the percentage of fuzzy grain in Kempili and Ubar wood by approximately 23 % and 55 %, respectively (Table 3). Based on its defect-free values at both MC 10 % and 14 %, which was 60 % - 80 %, Kempili wood was classified as having a good boring property (grade II) (Table 4). On the other hand, Ubar wood could be classified as a wood species with excellent boring property (grade I) (Table 4) due to its high defect-free values (above 90 %). Further statistical test results confirmed the significant effect of wood species and their interaction with the moisture content on the planing properties of both Kempili and Ubar wood (Table 5).

The boring properties of Kempili and Ubar wood are similar to those of *Toona sinensis* (Adr.Juss) M.J. Roemer, *Pangium edule* Reinw, *Albizia lebbeck* (Linn.) Benth, *Cinnamomum iners* Reinw. Ex Blume, *Ficus nervosa* B. Heyne ex Roth, *Garcinia celebica* Linn, *Horsfieldia glabra* (Blume) Warb., *Dillenia sp.*, *Timonius sericeus* (Desf) K.Schum and *Acacia leucophloea* (Roxb.)Willd. (Asdar, 2010; Muslich *et al.*, 2013; Wahyudi, Makrus and Susilo, 2014; Rianawati and Setyowati, 2015). Further, considering their boring properties, both wood species could be combined or jointed together with dowels/rods/pins or with gluing for assembling composite wood or laminated wood products.

3.4 Turning
3.4. Tokarenje

Fuzzy grain appeared as the dominant defect during the turning process of Kempili and Ubar wood (Table 3). Reducing the moisture content of both wood species from 14 % to 10% tended to reduce the percentage of fuzzy grain. The turning process is categorized as orthogonal lathing (Supriadi, 2017). An orthogonal lathing process is characterized by a straight and continuous cutting blade movement over the wood surface. During the turning process, the cutting is carried out perpendicular to the fiber direction and affected by the MC distribution (Koch, 1964). Therefore, due to higher MC, boards with MC of 14 % had a higher fuzzy grain defect than those with MC of 10 %. On the other hand, the moisture content reduction tended to increase the percentage of torn grain of both Kempili and Ubar wood. However, only the surface roughness of Ubar wood increased as the moisture content decreased (Table 3).

The average defect-free values at MC of 14 % and 10 % for Kempili wood were 75 % and 83 %, respectively. Ubar wood had the average defect-free values of 73 % at MC of 14 % and 85 % at MC of 10 %, respectively. Therefore, reducing the moisture content of both wood species successfully increased their turn-

Table 5 ANOVA results for the effect of wood species and MC on each machining property
Tablica 5. ANOVA rezultati analize utjecaja vrste drva i sadržaja vode na obradivost drva svakim pojedinim mehaničkim postupkom

Machining property *Mehanička obrada*	**Main factor/P-values** *Glavni čimbenik / P-vrijednosti*		
	MC	**WS**	**MC × WS**
Planing / *blanjanje*	0.20	0.00*	0.52
Shaping / *profilno glodanje*	0.39	0.00*	0.04*
Boring / *bušenje*	0.33	0.00*	0.00*
Tuning / *tokarenje*	0.00*	1.00	0.09
Sanding / *brušenje*	0.09	0.00*	0.22

*indicates significant differences; MC – moisture content; WS – wood species / **označava značajne razlike; MC – sadržaj vlage; WS – vrsta drva* ing properties grade from II at MC of 14 % to I at MC of 10 %. Further statistical test results confirmed the significant effect of moisture content on the turning properties of both Kempili and Ubar wood. Both wood species with turning property grades I-II are considered suitable for parts of furniture and other turning-related processes. Furthermore, the results of the turning test for Kempili wood are similar to those of *Nauclea orientalis* (Linn.), *Litsea angulata* Blume, *Enonimus javanica*, *Hymenaea sp*. and *Tamamaus indica* (Muslich *et al.*, 2013; Supriadi, 2017).

3.5 Sanding
3.5. Brušenje

During the sanding process of Kempili and Ubar wood, the only defect developed was fuzzy grain (Table 3). The cause of fuzzy grain defect is torn wood fibers during the sanding process. Decreasing MC from 14 % to 10 % reduced the fuzzy grain by 21.4 % and 14.3 % in Kempili and Ubar wood, respectively.

Table 4 shows that the average defect-free value of Kempili wood after the sanding process was 89 % at MC of 10 %, higher than that for boards with MC of 14 % (which was 86 %). Ubar wood has the average defect-free values of 93 % and 92% at MC of 10 % and 14 %, respectively. Based on its defect-free value during the sanding process, the sanding quality of Kempili and Ubar wood at both MCs are categorized as excellent (grade I), making them suitable for doors, tables, panels, and wall coverings. The results of the sanding test for both wood species are similar to those of *Hostfieldia glabra* (Blume) Warb., *Litsea angulata* Blume, *Nauclea orientalis* (Linn.), *Cedrus libani* A. Rich, *Quercus petraea*, *Timonius sericeus* (Desf) K. Schum, *Acacia leucophloea* (Roxb.) Willd., *Tamarmaus indica*, and (*Hymenaea sp*.) (Muslich *et al.*, 2013; Rianawati and Setyowati, 2015; Sofuoğlu and Kurtoğlu, 2014; Supriadi, 2017). Further statistical tests showed that wood species, not moisture content in the examined range, significantly affected the sanding properties of Kempili and Ubar wood. This result supported a previous study showing the tendency of sanded aspen boards to have smoother surfaces, in both radial and tangential directions, than beech boards (Kilic *et al.*, 2006).

4 CONCLUSIONS
4. ZAKLJUČAK

The study reveals that fuzzy grain was the dominant defect during the planing, shaping, boring, turning, and sanding processes of both Kempili and Ubar wood. Decreasing the MC of both wood species from 14 % to 10 % tended to improve their defect-free values. Wood species significantly affected the planing, shaping, boring, and sanding properties of Kempili and Ubar wood. Moisture content, on the other hand, only significantly affected the turning properties of both wood species.

Kempili wood at 14 % MC exhibited defect-free values of 62.5 %, 77 %, 71 %, 75 %, and 86 % for planing, shaping, boring, turning, and sanding, respectively. At 10 % MC, the defect-free values of Kempili wood were 66 %, 79 %, 78 %, 83 %, and 89 % for planing, shaping, boring, turning, and sanding, respectively. Meanwhile, the corresponding defect-free values for Ubar woods at 14 % MC were 88 %, 89 %, 91 %, 73 %, and 92 % for planing, shaping, boring, turning, and sanding, respectively. At 10 % MC, Ubar wood exhibited defect-free values of 97 %, 94 %, 95 %, 85 %, and 93 % for planing, shaping, boring, turning, and sanding, respectively. Based on their defect-free values, the grading classification of planing, shaping, and boring properties of Kempili and Ubar wood were grade II (good) and grade I (excellent), respectively. Both wood species had excellent sanding properties (grade I). Their turning properties classification increased from grade II to excellent (grade I) as their moisture content decreased. These two wood species are suitable raw materials for furniture molding, leaf doors, dowels, composite wood, and/or laminated wood.

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Optimization of Energy Consumption During Industrial Veneer Drying – A Preliminary Assessment

Optimizacija potrošnje energije tijekom industrijskog sušenja furnira – preliminarna procjena

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ABSTRACT • *The soaring energy prices and the increasing environmental issues have challenged many energy-intensive manufacturing processes, including wood veneer drying. This study aimed to explore how data-driven approaches could help optimize the industrial veneer drying process to minimize energy consumption and maintain quality. Four optimization scenarios were defined to determine optimal dryer temperature and drying speed. The results demonstrate the feasibility of using data-driven methods in veneer drying for process improvement. This approach could be used to optimize the veneer drying schedule or evaluate the potential of using alternative energy sources.*

KEYWORDS: *data-driven approach; minimize energy cost; maximize quality turnout; veneer drying case study; process improvement*

SAŽETAK • *Rastuće cijene energije i sve veći ekološki problemi postavili su izazov mnogim energetski intenzivnim proizvodnim procesima, uključujući sušenje furnira drva. Cilj ove studije bio je istražiti mogu li se na temelju podataka optimizirati industrijski procesi sušenja furnira kako bi se smanjila potrošnja energije i održala kvaliteta. Za određivanje optimalne temperature i brzine sušenja definirana su četiri optimizacijska scenarija. Rezultati pokazuju da primjena metoda vođenih podatcima pridonosi poboljšanju procesa sušenja furnira. Taj bi se pristup mogao primjenjivati za optimizaciju rasporeda sušenja furnira ili za procjenu potencijala korištenja alternativnih izvora energije.*

KLJUČNE RIJEČI: *pristup vođen podatcima; smanjenje troškova energije; maksimizacija kvalitete; studija slučaja sušenja furnira; poboljšanje procesa*

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1 INTRODUCTION
1. UVOD

Drying wood veneers from wet to their intended moisture content (MC) is a process that consumes a great amount of thermal and electric energy. Currently, wood veneer manufactures are encouraged to improve energy efficiency due to rising energy prices, increasing carbon taxes, and ongoing social-environmental concerns about energy usage. In addition, veneer drying is also known as a complicated and little-understood process to control. Achieving a consistent and uniform final MC could be challenging due to the anisotropy nature of wood itself. Modifications on the drying temperatures and time for less energy consumption might impact the quality turnout unfavourably. Therefore, the ultimate objective of this research was to optimize the veneer drying schedule to enhance overall energy performance and quality goals. In the literature, previous research has been found on estimating energy consumption of a drying process or predicting veneer drying quality but not in the combined field. Reports on drying process of grains (Bayati *et al*., 2023) or other energy intensive industrial processes (Matsunaga *et al*., 2022) were considered. However, their approaches did not apply to the current industrial context under study. As a preliminary assessment, the research examined four different optimization scenarios combining various requirements for energy consumption and veneer quality.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The raw data used in this study was collected by various sensors and recorded during production by a veneer manufacturing company located in British Columbia, Canada. The continuous jet dryer under study is fired with natural gas and contained four decks. Its longitudinal section was divided into three zones (i.e., Zone 1, Zone 2, and Zone 3), excluding the cooling area. There were multiple burners inside each zone to maintain the drying temperature so each zone could be further separated into subzones (e.g., Zone 1a and Zone 1b for Zone 1). Theoretically, the temperature of each subzone could be set to any valid value. However, in practice, the company primarily adjusted the temperature of the first subzone – Zone 1a – and ensured the temperatures of the sequential subzones decreased according to a gradient. Therefore, it may be possible to tailor the drying conditions by adjusting the temperature of Zone 1a and the drying speed.

2.1 Data collection and prediction models
2.1. Prikupljanje podataka i modeli predviđanja

The raw data obtained for this research can be classified into five categories: (1) energy consumption, (2) dryer parameters, (3) pre-drying veneer properties, (4) post-drying veneer properties, and (5) weather variables. The first four groups were collected by sensors positioned along the drying line and queried from the industry partner's internal servers, while the last group was collected on a daily basis and extracted from the Environment and Natural Resources of Canada database (http://climate.weather.gc.ca, accessed on July 1, 2020). As these five groups of raw data were recorded at various intervals, namely, per hour, per minute, per load, per veneer sheet, and per day, respectively, data transformation and compilation were necessary to harmonize raw data into a consistent and ready-for-analysis format. Details related to data description, transformation, and compilation can be found in Qiu (2022) and Qiu and Cool (2023a, b).

To achieve the ultimate goal of decreasing the energy consumed when drying Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) veneers while maintaining or improving the drying quality turnout, an easy-to-implement strategy is to determine the optimal drying schedule that fulfils these objectives. In this study, a preliminary assessment was conducted to examine how the generalized least square (GLS) models developed by Qiu and Cool (2023b) and the logistic regression (LR) models established by Qiu and Cool (2023a) could be employed in optimizing the Zone 1a temperature and drying time (i.e., drying speed) under different objectives and restrictions. As the dryer is expected to operate in a steady-state, the following assumptions were made:

- the hourly standard deviations of Zone 1a temperature and drying speed were approximated to be zero;
- the dryer only operates within the valid speed range;
- the variables from the energy prediction models have the same values as those from the quality classification models;
- the dryer only dries 3.175 mm thick light sapwood veneers in an hour;
- the weather was assumed to correspond to a temperature of 15 °C and precipitation of 0 mm;
- the batch ID, load weight, and the ambient temperature around the infeed conveyor were assumed to be 1, 1814.4 kg and 23.9 °C, respectively.

As a result, the models developed by Qiu and Cool (2023a, b) were simplified into Eqs. 1-4.

$$\widehat{UnitGasUsage} = -0.1161 + 0.0007 Zone1aTemp + 0.0277 DryingTime \quad (1)$$

$$\widehat{UnitGasUsage} = 1.9372 - 0.003 Zone1aTemp + 1.3604 DryingTime \quad (2)$$

$$logit(Quality{=}Overdry \mid x) = -4.5106 + 0.0041 Zone1aTemp + 0.3096 DryingTime \quad (3)$$

$$logit(Quality{=}Redry \mid x) = -0.0853 - 0.0033 Zone1aTemp - 0.1234 DryingTime \quad (4)$$

Where $\widehat{UnitGasUsage}$ is the unit gas usage (GJ), $Zone1aTemp$ is the average temperature of Zone 1a (°F), $DryingTime$ is the amount of time (minute) a veneer sheet spends in the dryer and corresponds to the drying speed, $\widehat{UnitGasUsage}$ is the unit electricity usage (KWh), $logit(Quality{=}Overdry \mid x)$ is the probability of a veneer sheet to be characterized as over-dry, and $logit(Quality{=}Redry \mid x)$ is the probability of a veneer sheet needing to be re-dried.

2.2 Optimization scenarios
2.2. Optimizacijski scenariji

Although better managing the energy use of a veneer dryer is an essential goal, this objective is often subjected to one or multiple quality requirements. This preliminary study explored four optimization scenarios including: 1) minimizing energy use, 2) minimizing energy cost, 3) minimizing energy cost while maintaining quality turnout, and 4) minimizing energy cost and maximizing quality turnout. The first two cases take only the energy aspect into consideration, while the last two include the quality of dried veneer sheets as well. The formulation of each optimization case and their preliminary results is presented below.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Minimizing energy use
3.1. Minimiziranje potrošnje energije

The first scenario consisted in simultaneously optimizing two types of energy consumption (i.e., gas and electricity usage). At the same time, the Zone 1a temperature and the drying time were limited by the partner company's operation specifications. The bi-objective optimization model is shown below (Eqs. 5-6) and was solved using the *mco* package in R (Mersmann *et al.*, 2020).

Objective 1: Minimize Unit gas usage, $\widehat{UnitGasUsage}$ (5)

Objective 2: Minimize Unit electricity usage, $\widehat{UnitGasUsage}$ (6)

Subject to: $176.7\ °C \le Zone1aTemp \le 210\ °C$ (7)

$3.8\ min/sheet \le Dryingtime \le 10\ min/sheet$ (8)

Figure 1 shows the Pareto front, on which solutions were non-dominated. According to the equations, both gas and electricity consumptions were in positive correlation with the drying time. It was therefore expected that all Pareto-optimum solutions held the same minimum drying time of 3.8 minutes per sheet. In contrast, the Zone1a temperature varied among Pareto-optimum solutions due to gas and electricity usage having opposite trends with Zone 1a temperature. Consequently, taking the prices of both energy types into consideration for the optimization of drying time, Zone 1a temperature may result in a different solution.

3.2 Minimizing energy cost
3.2. Minimiziranje troškova energije

The second scenario introduced energy prices to the optimization and reshaped the bi-objective problem into a single objective one – minimizing energy cost, with the constraints remaining the same. The electrical energy was charged at \$0.07527 per kWh (p_{elec}) for commercial service (FortisBC, n.d.-b), and the natural gas rate (p_{gas}) was billed at \$5.321 per GJ in terms of

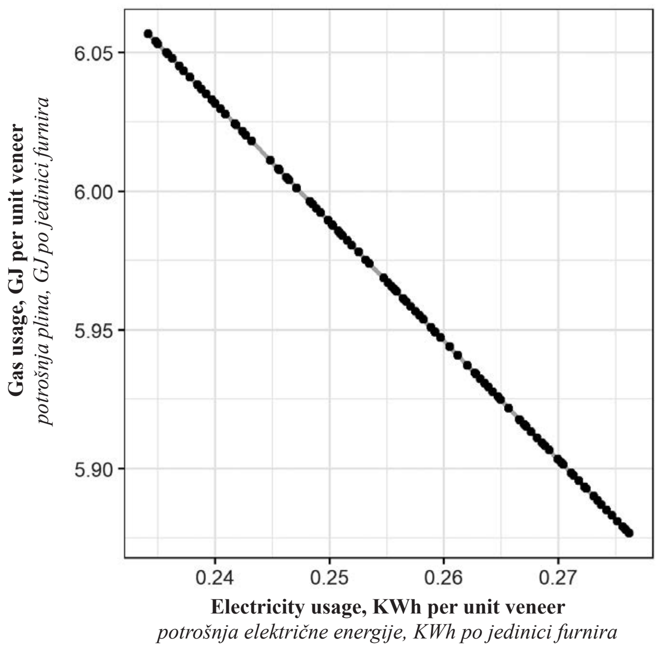

Figure 1 Pareto front of Scenario 1. The points are a set of non-dominated solutions
Slika 1. Pareto krivulja za 1. scenarij, točke su skup nedominiranih rješenja

commodity related charges for "a large-volume commercial, institutional, multi-family or other customer that uses about 5,000 GJ or more annually" (FortisBC, n.d.-a, para. 3). The model is presented below (Eq. 9).

Objective: Minimize Unit energy cost, Z_{cost}

$$Z_{cost} = p_{gas} \times Unit\widehat{GasUsage} + p_{elec} \times Unit\widehat{GasUsage} \tag{9}$$

Subject to: Eqs. 7-8

This second case was solved using a graphical method (Figure 2). When the dryer runs at a Zone 1a temperature of 350 °F (corresponding to 176.7 °C) and a drying time of 3.8 minutes per sheet, the energy cost per unit veneer could be minimized to $1.70. As explained previously, it was expected that the drying speed remained unchanged compared to that of the first scenario. However, in this second scenario, it was the cost of natural gas ($5.321 per GJ vs. $0.07527 per kWh for electricity) that was the main cause for limiting the dryer temperature. It is hypothesized that this optimization scenario would recommend a lower Zone 1a temperature as the cost of natural gas is steadily increasing (U.S. Energy Information Administration, 2022). However, this assumes the industry partner would be willing to lower their minimum Zone 1a temperature (Equation 7) and doing so would not impact the quality turnout of the veneer drying process, which will be discussed in the next two scenarios.

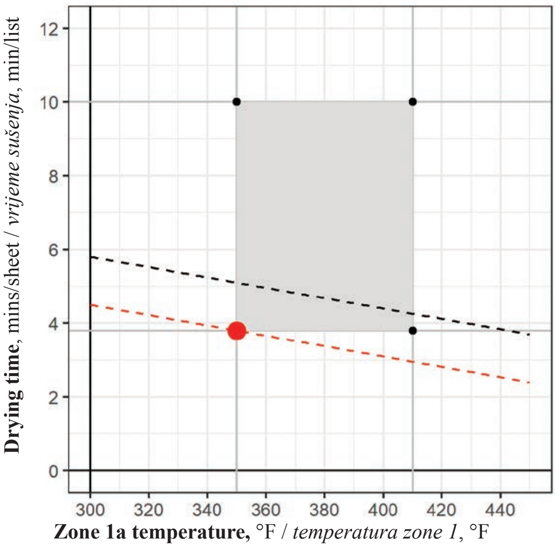

Figure 2 Graphical method to solve Scenario 2 (The grey represents the feasible solution region. The y-intercept of the black line indicates the objective function. As the goal is to minimize the objective function, the optimal solution (the red point) is achieved when the line of the objective function aligns with the left-bottom corner of the feasible region.)
Slika 2. Grafička metoda za rješavanje 2. scenarija (Sivi pravokutnik predočuje područje mogućeg rješenja. Y – odsječak crne linije označava istraživanu funkciju. Kako je cilj minimizirati istraživanu funkciju, optimalno rješenje – crvena točka, postiže se kada se linija istraživane funkcije poravna s donjim lijevim kutom područja mogućeg rješenja.)

3.3 Minimizing energy cost while maintaining quality turnout
3.3. Minimiziranje troškova energije uz održavanje kvalitete

When also considering the quality turnout, the third scenario maintained the single objective of minimizing energy cost, but upper specification limits were added to the probability of a veneer sheet being over-dried ($USL_{overdry}$) or needing to be re-dried (USL_{redry}), which can be calculated by Eqs. 10-11, respectively.

$$Prob(Quality = Overdry|x) = \frac{e^{logit(Quality=Overdry|x)}}{1+e^{logit(Quality=Overdry|x)}} \tag{10}$$

$$Prob(Quality = Redry|x) = \frac{e^{logit(Quality=Redry|x)}}{1+e^{logit(Quality=Redry|x)}} \tag{11}$$

The corresponding optimization model for minimizing energy cost while maintaining quality turnout is shown below.

Objective: Minimize Unit energy cost, Z_{cost}

Subject to: Eqs. 9-10

$$Prob(Quality{=}Overdry|x) \leq USL_{overdry} \tag{12}$$

$$Prob(Quality{=}Redry|x) \leq USL_{redry} \tag{13}$$

When assuming $USLoverdry{=}USLredry{=}0.15$, the optimal drying time remained 3.8 minutes per sheet, but the optimum Zone 1a temperature changed from 350 °F (corresponding to 176.7 °C and optimum in Scenario 2 (Figure 2)) to 357.8 °F (corresponding to 181 °C) to meet the quality requirements, and the minimum energy cost increased to $1.73 per unit veneer. This indicates that results from Scenario 2 would not create a profitable production yield for the industry partner, despite a reduction in energy cost. While the $0.03 increase in energy cost per unit veneer is a significant increase, the difference in value associated with higher quality veneers ($0.08 was the smallest difference between two grades sold by the company partner) offsets this rise in production costs.

3.4 Minimizing energy cost and maximizing quality turnout
3.4. Minimiziranje troškova energije uz povećanje kvalitete

Instead of having the drying quality requirements as constraints, the last scenario included them as objective functions to reduce the probabilities of a veneer sheet being over-dried and re-dried. These objectives formulated the multi-objective optimization model listed below along with the energy goal, and was solved using the mco package in R.

Objective 1: Minimize Unit energy cost, Z_{cost}

Objective 2: Minimize Probability of a veneer sheet being over-dried, *Prob(Quality=Overdry|x)*

Objective 3: Minimize Probability of a veneer sheet needs to be re-dried, *Prob(Quality=redry|x)*

Subject to: Eqs. 7-8

Figure 3 shows the Pareto front in pairs of objective functions. According to the figure, unit energy cost and the over-dry probability changed in the same direction as decision variables varied, but the re-dry probability demonstrated an opposite trend. A subset of Pareto-optimum solutions where the probability of over-dry or re-dry was not greater than 0.15 can be found in Table 1. The minimum unit energy cost of $1.70 was again achieved when the Zone 1a temperature was maintained at 350 °F (corresponding to 176.7 °C), and the drying speed was 3.8 minutes per sheet, with the over-dry and re-dry probability equal to 0.13 and 0.15, respectively. However, the unit energy cost could climb to $1.84 when the re-dry probability was down to 0.14 (with over-dry probability still equal to 0.15). Thus, eclipsing the benefits associated with a better-quality product ($0.14 increased unit energy cost vs. $0.08 increase product value). Although the data from the start-up hours were not included in this study, the knowledge gained while analyzing the dataset and discussing with the partner company suggests that using the time when dryers warm up to re-dry veneers may be a good strategy not to increase energy consumption costs.

Based on the results obtained in the four scenarios considered in this preliminary assessment, optimizing the veneer drying schedule to reduce energy costs could be a relatively simple and valuable approach to implement. However, the benefit associated with such an approach will depend on the scenario, the energy costs and the potential increase in product value. Optimizing the drying schedule could be a short-term solution that could be implemented, while exploration on alternative (and cost-saving) energy sources to natural gas are underway.

In this preliminary assessment, single, bi- or multi-objective functions were used to effectively optimize veneer drying schedules based on a series of assumption. This type of optimization was referred to as machine parameter optimization by Matsunaga *et al*. (2022), and has the potential to optimize different sub-processes (Bayati *et al*., 2023) as well as assist in process control systems. In a future phase of this project, it would be interesting to maintain the complexity of the industrial dataset to evaluate the benefits of using cyber-physical systems and deep learning algorithms to both maintain or improve product quality and minimize energy consumption in real-time. The approach described by El Mazgualdi *et al*. (2022) could serve as a framework to develop an optimization model involving big data.

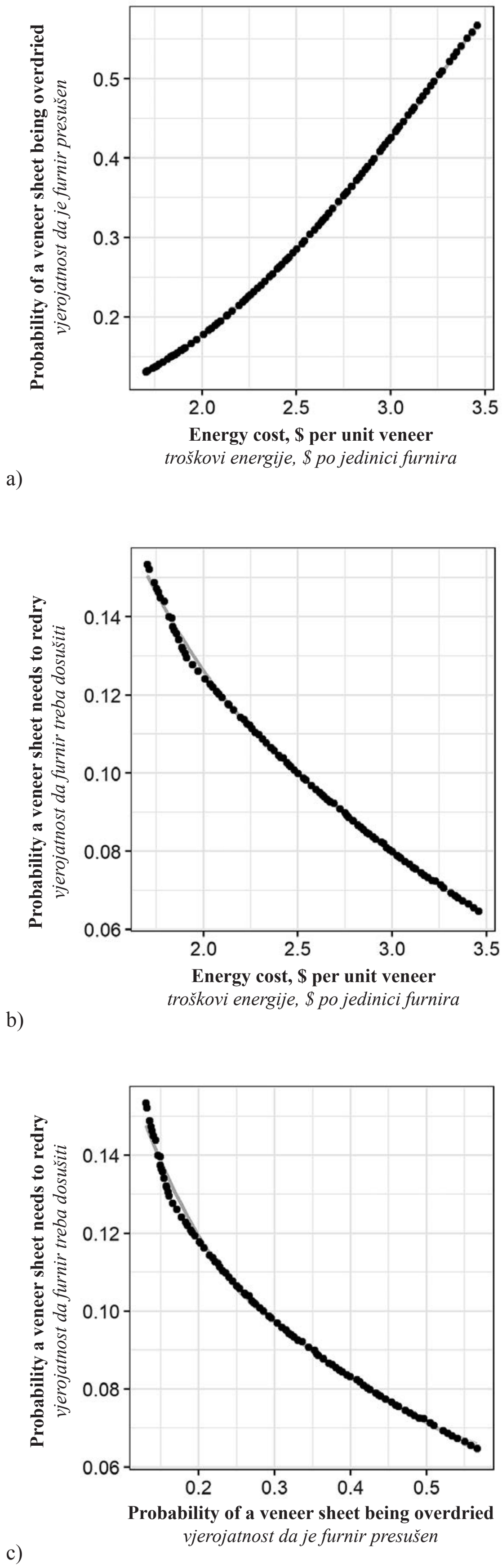

Figure 3 Pareto front of Scenario 4
Slika 3. Pareto krivulja za 4. scenarij

4 CONCLUSIONS
4. ZAKLJUČAK

In summary, this study explored how previously developed prediction models could be implemented in

Table 1 A subset of the Pareto-optimum solutions obtained from the optimization model to minimize unit energy cost and maximize the quality turnout (i.e., minimizing the probabilities of a veneer sheet being over-dried or needing to be re-dried) with Zone 1a temperature and drying time being the decision variables
Tablica 1. Podskup Pareto optimalnih rješenja dobivenih iz optimizacijskog modela za minimiziranje jediničnih troškova energije i maksimiziranje kvalitete (tj. minimiziranje vjerojatnosti da će list furnira biti previše osušen ili da se treba dosušiti) u zoni 1, u kojoj su temperatura i vrijeme sušenja varijable odluke

Zone 1 temperature, °F *Temperatura u zoni 1, °F*	**Drying time, mins/sheet** *Vrijeme sušenja,* min/list	**Unit energy cost, $ per unit veneer** *Jedinični trošak energije, $ po jedinici furnira*	**Probability of a veneer sheet being over-dried** *Vjerojatnost da je furnir presušen*	**Probability of a veneer sheet needing to be re-dried** *Vjerojatnost da furnir treba dosušiti*
350.02	3.8	1.70	0.13	0.15
352.69	3.8	1.71	0.13	0.15
360.66	3.8	1.74	0.14	0.15
364.36	3.8	1.75	0.14	0.15
366.77	3.8	1.76	0.14	0.15
369.13	3.9	1.79	0.14	0.14
369.13	3.9	1.79	0.14	0.14
370.08	3.8	1.77	0.14	0.14
378.32	3.9	1.83	0.15	0.14
381.66	3.8	1.82	0.15	0.14
388.86	3.8	1.84	0.15	0.14

operation research, assisting the quality control of industrial veneer drying processes. The preliminary results obtained from four different optimization scenarios provided insights on improving the veneer drying schedule in terms of Zone 1a temperature and drying speed. While this preliminary optimization study only focused on 3.175 mm thick light sapwood veneers, it is anticipated that a similar approach could be applicable to other types of veneer products.

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Empowering Advancement of Wood and Furniture Sector Through Key Digital and Sustainability Competencies

Osnaživanje napretka drvoprerađivačkog sektora putem ključnih digitalnih kompetencija i kompetencija održivosti

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ABSTRACT • *In the context of the growing importance of sustainable development and digitalization, our study examines which are the most important digital and sustainability competencies for wood science and technology graduates. This enabled us to map the development of competencies at the different levels of education across the entire vertical and determine the scope and type of competencies that graduates should have. To achieve this, we conducted surveys among experts and companies within the wood sector. The results underline that expectations placed on the digital and sustainability competencies of graduates for the transition of the sector are very high, which 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 immediate and future needs. In addition, we found differences in stakeholder expectations that indicate a disparate adoption of digital technologies by companies and prioritization of sustainability. We can conclude that lower levels of education should focus primarily on general digital and sustainability competencies to provide a foundation for the subsequent levels of education where students are expected to have more profession-specific competencies.*

KEYWORDS: *key competencies; DigComp, GreenComp; digitalization and sustainability; wood and furniture sector*

SAŽETAK • *U kontekstu sve veće važnosti održivog razvoja i digitalizacije, ovo je istraživanje posvećeno određivanju najvažnijih digitalnih kompetencija i kompetencija održivosti za diplomante studija drvne znanosti i tehnologije. To nam je omogućilo da mapiramo razvoj kompetencija na različitim razinama obrazovanja po cijeloj vertikali te da odredimo opseg i vrstu kompetencija koje diplomanti trebaju usvojiti. Kako bismo to postigli, proveli smo ankete među stručnjacima i tvrtkama iz drvoprerađivačkog sektora. Rezultati pokazuju da su očekivanja vezana za digitalne kompetencije i kompetencije održivosti diplomanata za tranziciju sektora vrlo visoka, što naglašava potrebu da diplomanti budu dobro podučeni za snalaženje u tehnološkome i održivom krajoliku koji se razvija, te ističe važnost osmišljavanja obrazovnog programa za zadovoljenje trenutačnih i budućih potreba. Osim*

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toga, otkrili smo razlike u očekivanjima sudionika anketa koje upućuju na različito prihvaćanje digitalnih tehnologija u tvrtkama i davanje prioriteta održivosti. Stoga možemo zaključiti da bi se niže razine obrazovanja trebale ponajprije usredotočiti na opće digitalne kompetencije i kompetencije održivosti kako bi se osigurao temelj za sljedeće razine obrazovanja, na kojima se od studenata očekuje da imaju više kompetencija specifičnih za struku.

KLJUČNE RIJEČI: *ključne kompetencije; DigComp; GreenComp; digitalizacija i održivost; drvoprerađivački sektor*

1 INTRODUCTION
1. UVOD

Climate change and environmental degradation present unprecedented challenges to our planet. In an alarming "code red" warning, the International Panel on Climate Change has highlighted the accelerating pace of global warming due to human activities, threatening our ecosystems (UN, 2021). In light of these, as well as other pertinent challenges, the European Commission (EC) has outlined key objectives for the period 2019-2024 (von der Leyen, 2019), with a clear emphasis on facilitating the transition to a sustainable, circular, and climate-neutral economy, which is expected to bring about profound social, economic, and employment changes. Simultaneously, the EU's updated Industrial Strategy aims to cement Europe's status as a leading global industrial powerhouse, particularly with digital and green practices, acknowledging the crucial role of digitalization in advancing a sustainable circular economy (EC, 2020). Today's businesses face a paradigm shift as societal challenges necessitate a balance between public welfare and private interests (Dyllick and Muff, 2016). This balance often requires navigating through stricter regulatory measures, investing in innovation, realigning strategies to prioritize environmental stewardship, and potentially undergoing restructuring to adhere to emerging policies. To address these evolving challenges, many industries are turning to renewable materials like wood, which offers numerous environmental advantages. Wood is recognized for its biodegradability, its ability to sequester carbon, its lower energy consumption during processing, its durability, its versatility, etc., making it an invaluable resource. In Slovenia, wood plays an important role as a strategic and industrial material (MGRT, 2021); it is natural, renewable and currently underutilized. That is why wood-based industry, which is one of the conventional bioeconomy industries, can help address many environmental challenges and is identified as a sector of strategic importance at both national and EU levels, contributing also to rural preservation and offering extensive employment opportunities. Although the wood industry utilizes wood - an inherently eco-friendly material - the ecological impact of its technological processes, the materials used alongside wood, the lifecycle of the products, and their disposal present significant environmental challenges (Oblak and Jošt, 2011) that require careful consideration and sustainable practices.

Looking towards the future of work, it is crucial to adapt our mindset and skillset to meet the changing job demands. (Murawski and Bick, 2017). The EU's Green Deal Industrial Plan underscores the need for new skills and competencies across all occupations, both new and existing, as part of the green transition. The European Skills Agenda echoes this sentiment, indicating that quality education can equip young people for success in a greener economy (EC and DG EMPL, 2023). Organizational success hinges on competencies aligned with strategic goals – without them, even the most well-crafted strategies may fail in execution (Cardy and Selvarajan, 2006). Workforce's limited expertise or insufficient skills is acutely felt in the wood industry, where the level of education of employees is often low, which can hinder adaptability and innovation (Kropivšek *et al.*, 2009). That is why education and training of employees as a part of organizational learning is the key to ensuring their competency for the job, which in turn leads to their increased motivation and greater efficiency and quality of work (Kropivšek and Zupančič, 2016), also in the face of sustainable and digital transformation. Fostering organizational learning processes also leads to the development of firm-specific competencies.

To effectively navigate the intricacies of today's globalized societies, individuals require a robust and lifelong educational foundation. Therefore, high-quality and comprehensive knowledge, which is defined through goals and knowledge standards by the curriculum at various levels of the educational system, will also have to remain closely connected with a complex and pervasive system of objectives, standards, and content in the future (Krek and Metljak, 2011). This alignment is critical as the European Green Deal sets a policy framework that has sparked educational reform, placing a pronounced emphasis on digitalization and environmental sustainability. The National Environment Protection Program with programs of measures until 2030 (ReNPVO20-30, 2020) reflects the impact of European policies on national education, advocating for education for sustainable development and the transition to a low-carbon society at all educational levels in Slovenia. The ReNPVO20-30, alongside other national and international directives, focused on a green and digital transition, also underpin initiatives aimed at the renewal of professional standards (Institute for Vocational Education and Training, 2022a, 2022b). The latter serves as the foundation for the design and implementation of vocational education and training programs and post-secondary study programs. The Resolution on National program of higher education 2030 (ReZrIS30, 2022) is the key document that defines the strategy and guidelines of higher education in Slovenia and encourages the inclusion of higher education in priority strategic areas of social development. A similar situation can be observed within national strategies for the wood sector, as one of the main measures of the implementation document for the development of the wood industry in Slovenia until 2030, which pursues the goals and directions of the Slovenian Industrial Strategy 2021-2023, is equipping graduates and employees with modern knowledge and skills (MGRT, 2022).

Complementing these efforts, in 2022 the European Commission's Joint Research Centre (JRC) updated the Digital Competence Framework for Citizens (DigComp), which has been defining the digital competencies of individuals for more than a decade (EC *et al.*, 2022). In addition to the updated DigComp framework in 2022, a competence framework for sustainability (GreenComp) was developed, as part of the European Green Deal (Bianchi *et al.*, 2022), which defines a set of sustainable competencies for their inclusion in educational programs and training in order for learners to develop competencies that encourage thinking, planning and acting with empathy, responsibility and concern for our planet and public health. These frameworks serve as references for various applications, including competency assessments and curriculum design, synergizing with competency-based education aims.

The concept of competencies has long been underway, its roots tracing back to when David McClelland, a notable psychology professor, introduced the notion of 'competency' in 1953, acknowledging a distinct human attribute (Chouhan and Srivastava, 2014). This concept has since evolved, accruing as many interpretations as there are scholars pondering its nuances (Muršak, 2008a; Wong, 2020). According to the European Centre for the Development of Vocational Training (CEDEFOP, 2011) competency is the ability to apply learning outcomes effectively across various settings, including education, work, and personal or professional development. It encompasses not just cognitive aspects like theory and knowledge but also practical skills, social or organizational abilities, and ethical values. Professional competencies can be divided into generic competencies, common across similar professions, and profession-specific competencies, which are characteristic of individual professions or fields of work. In the European context, the push to embed competencies into education gained significant traction in the 1990s. Initially, it permeated vocational and professional training, further crystallizing in higher education with the advent of the Bologna Process (Makovec *et al.*, 2013).

This study was undertaken to identify the key competencies essential for graduates from various educational levels within formal wood science and technology programs, aimed at bolstering a smooth digital and sustainable transition of the Slovenian wood and furniture sector. Recognizing that the labor market's expectations regarding graduate qualifications (Petanjek, 2021; Sabina, 2012) and the alignment between the labor market's needs and the educational system's output stands as a critical indicator of the system's quality (Muršak, 2008b), our research focused to encompass the needs of the industry.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Based on the European framework for digital competencies (DigComp) (EC *et al*., 2022) and the framework for sustainability competencies (GreenComp) (Bianchi *et al.*, 2022), as well as considering the implementation document for the development of the Slovenian wood industry until 2030 (MGRT, 2022), we have developed a set of competencies that include both digitalization and sustainability. We have used DigComp and GreenComp for generic digital and sustainability competencies, while the formulation of profession-specific competencies was guided by the experts' suggestions that closely followed the key areas mentioned in the document for the development of the wood industry. To identify which competencies are crucial for the digital and sustainable transformation of the wood and furniture industry in Slovenia, we conducted surveys during July and August 2023, among experts and companies in the wood sector classified under NACE codes C16 (wood processing – except furniture) and C31 (manufacture of furniture).

The competencies were assessed by directors/human resources managers (n=16) in companies, and by experts (n=12), who were individuals from all levels of wood science and technology educational institutions, representatives of the wood and furniture industry and expert consultants in the wood sector (from the Institute of the Republic of Slovenia for Vocational Education and Training). This careful selection of stakeholders showcases a diversity that provides a comprehensive mix of practical in-field experiences and broader perspectives, covering all aspects of the sector.

The competencies were assessed based on "8" proficiency levels (Table 1) defined within DigComp 2.1 (EC *et al.*, 2017), where we have omitted the cognitive domain as it was not relevant for our study. In addition

Table 1 Rating scale for the expected proficiency level of competencies (EC *et al*., 2017)
Tablica 1. Ljestvica ocjenjivanja očekivane razine posjedovanja kompetencija (EC *et al*., 2017.)

Competencies levels *Razine kompetencija*	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Complexity of tasks *složenost zadataka*	No task *nema zadatka*	Simple tasks *jednostavni zadatci*	Simple tasks *jednostavni zadatci*	Well-defined and routine tasks, and straightforward problems *dobro definirani i rutinski zadatci, a jednostavni problemi*	Tasks, and well-defined and non-routine problems *zadatci te dobro definirani i nerutinski problemi*	Different tasks and problems *razni zadatci i problemi*	Guiding others *vođenje drugih*	Resolve complex problems with limited solutions *rješavanje složenih problema ograničenim rješenjima*	Resolve complex problems with many interacting factors *rješavanje složenih problema s mnogo međusobno povezanih čimbenika*
Autonomy *autonomija*	/	With guidance *uz vođenje*	Autonomy and with guidance where needed *autonomija, i uz vođenje gdje je potrebno*	On my own *na svom području*	Independent and according to my needs *samostalan i prema mojim potrebama*	Most appropriate tasks *najprikladniji zadatci*	Able to adapt to others in a complex context *sposobnost prilagođivanja drugima u složenom kontekstu*	Integrate to contribute to the professional practice and to guide others *integrirati se kako biste pridonijeli profesionalnoj praksi i vodili druge*	Propose new ideas and processes to the field *predložiti nove ideje i procese na terenu*

to the 8 levels, respondents could also choose “0” if they thought that the competencies were not needed for graduates of a certain level of education, or they could withhold an answer if they felt unable to assess.

They assessed the level of individual competencies that vocational and higher education graduates with different qualifications need for a smoother digital and sustainable transition of the wood sector. The qualifications were part of the entire vertical of formal education in wood science and technology in Slovenia, with the exception of short vocational education (EQF 3) and doctoral studies (EQF 8): 3 years of vocational education for “Carpenters” (EQF 4), 4 years of technical vocational education for “Technicians” (EQF 4), 2 years of higher vocational education for “Engineers” (EQF 5), 3 years of vocational/academic bachelor’s degree program for “Bachelors of Wood Engineering” (EQF 6) and 2 years of master’s degree program for “Masters of Wood Engineering” (EQF 7). A “box and whiskers plot”, a graphical method for visualizing the distribution of data, was used to present the results. It consists of a rectangular box representing the interquartile range and the median. The whiskers, which represent the range of data without outliers or extreme values, extend from the box. Outliers are shown as individual data points.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Figures 1, 2 and 3 show a series of box-and-whisker plots, each illustrating the expected proficiency levels for different digital and sustainability competencies for wood science and technology graduates.

The results show that the higher the level of education, the higher the expected level of competencies, which is reflected in the increasingly higher medians that extend from lower to higher education. One notable observation is the wider variability of data for carpenters and technicians compared to their more highly educated counterparts, highlighting a considerable divergence in respondents’ requirements regarding the importance of specific digital and sustainability competencies at these foundational levels. At the higher levels of education, the variability is present but less pronounced, suggesting greater consistency of respondents for the competencies required. Nonetheless, the variability observed at all levels could be a sign that the stakeholder’s requirements are not homogenous, possibly due to a spectrum of digital adoption of wood and furniture companies (Kropivšek and Grošelj, 2020) and different prioritization of sustainable development.

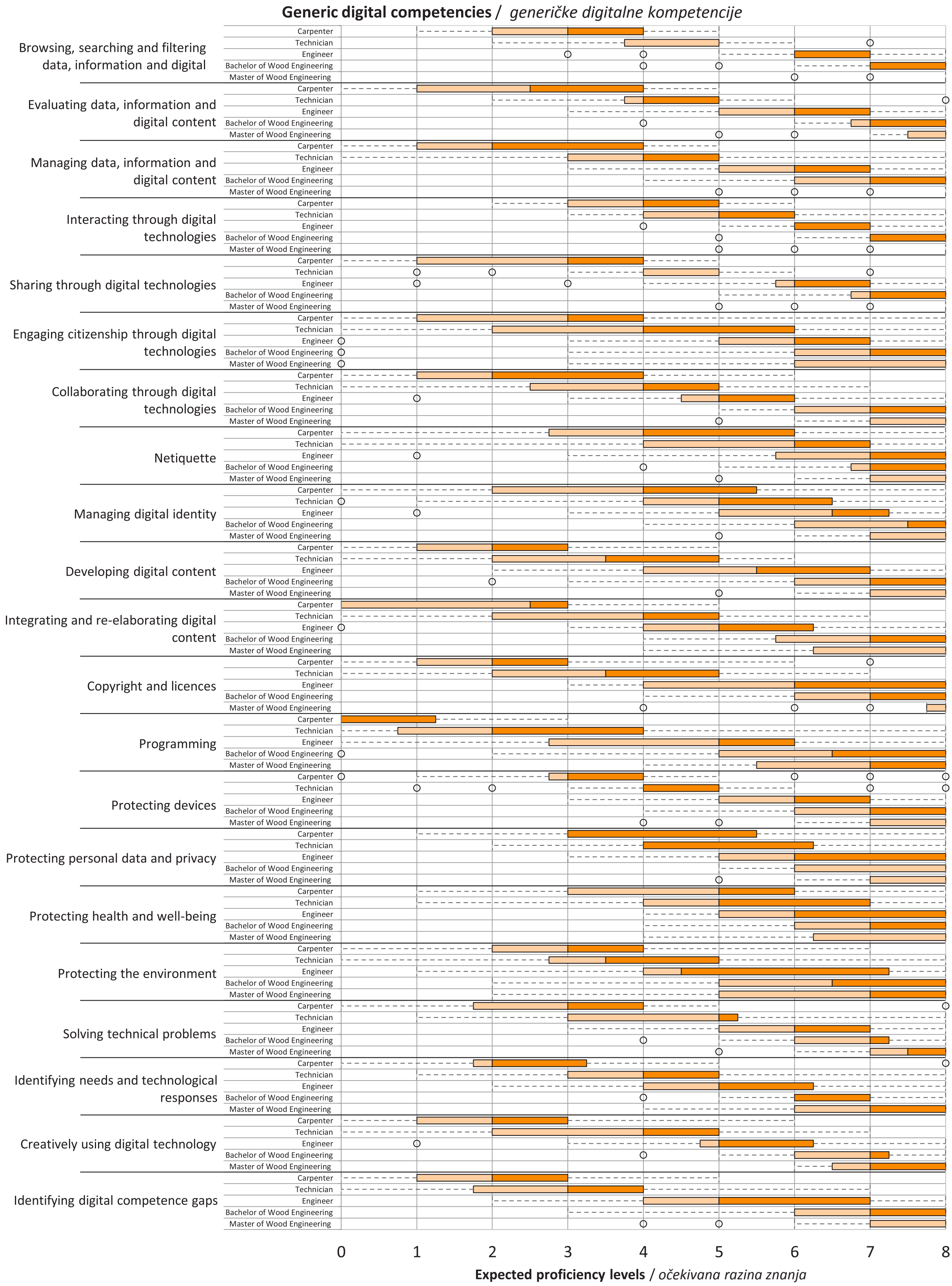

Figure 1 Box-and-whisker distribution of generic digital competencies for wood science and technology graduates in Slovenia: Carpenters (EQF 4), Technicians (EQF 4), Engineers (EQF 5), Bachelors of Wood Engineering (EQF 6), and Masters of Wood Engineering (EQF 7). Legend in Table 1

Slika 1. Distribucija generičkih digitalnih kompetencija za diplomante u području drvne znanosti i tehnologije u Sloveniji: stolari (EQF 4), tehničari (EQF 4), inženjeri (EQF 5), prvostupnici inženjeri drvne tehnologije (EQF 6) i magistri inženjeri drvne tehnologije (EQF 7); legenda u tablici 1.

In the following analysis of the results, the specific educational qualifications are discussed in detail, with the focus on the median values. This reflects the central point of the data and provides a revealing balance between the minimum and maximum values without outliers.

When analyzing the average of the generic digital competencies, shown by median line in Figure 1, it becomes clear that "protecting health and well-being" is the most important competency for carpenters, with a targeted proficiency of level 5. Not far behind, with a proficiency expectation of level 4, are competencies such as "interacting through digital technologies", "netiquette" and "managing digital identity". Half of the respondents believe that graduates at this level of education should achieve proficiency levels 2 to 3 in all other general digital competencies. The notable exception is "programming", which is considered non-essential for carpenters by 75 % of the surveyed experts and companies in the wood and furniture sector in Slovenia.

For wood technicians, "netiquette" is the highest rated competency, with an expected proficiency of level 6, surpassing that of carpenters by two levels. Competencies rated relatively high, at level 5, include "interacting through digital technologies", "managing digital identity" and "solving technical problems". Less critical competencies for technicians are in the level 3 to 4 range, with "programming' again being the least important.

Regarding wood engineers, half of the experts and companies surveyed agree that these professionals should have most general digital competencies at a level above 6. "Netiquette" is again at the top of the list, requiring a proficiency level of 7. Technicians completing their engineering degree face the challenge of increasing their "programming" skills by three levels in just two years, representing the biggest jump in proficiency expectations for this level of education.

In contrast to their peers with less advanced education, bachelor's graduates in wood engineering are expected to achieve the highest level of general digital competencies in "protection of personal data and privacy". With a few exceptions, namely "programming," "protecting the environment" and "identifying needs and technological responses", they should master all competencies at level 7 or higher. Technicians studying engineering at bachelor level must increase their competencies in the areas of "programming", "protecting personal data and privacy" and "identifying digital competence gaps" by up to four levels during their three-year academic journey, which creates an enormous gap.

Master's graduates in wood engineering are expected to reach level 8 in most general digital competencies, which is the highest point on the proficiency scale used in this study. At this proficiency level, graduates should demonstrate the ability to deal with complex, multi-layered problems. For the competencies "browsing, searching, and filtering data, information, and digital content", "managing data, information, and digital content", "interacting through digital technologies", and "sharing through digital technologies" all respondents, apart from a few outliers, agree that proficiency level 8 should be achieved. In contrast to bachelor's level, where a significant improvement in general digital competencies is required, progression to master's level requires only a modest increase in competency levels, no more than one level.

When analyzing the median values of the general sustainability competencies shown by box-and-whisker plots in Figure 2, it becomes clear that "supporting fairness", "promoting nature" and "individual initiative" are identified as the most important competencies for carpenters, from this set of competencies. These are expected to be at proficiency level 4 or more, by 75 % of respondents. The secondary competencies in this area are generally between proficiency levels 2 and 3, with "political agency" being seen as the least important competency.

Wood technicians are expected to demonstrate a relatively high level of proficiency, level 5 or higher, in key competencies such as "supporting fairness", "promoting nature", "collective action" and "individual initiative". The expectations for proficiency in other general sustainability competencies for technicians are moderate and target levels 2 to 3, with "political agency" again being classified as the least relevant competency.

For wood engineers, in addition to the competencies required by carpenters and technicians, a heightened emphasis is placed on "critical thinking", where they must improve their proficiency by more than two levels within a two-year study program. The minimum requirements for graduates at this level relate to "collective action" and "political agency".

It is expected that bachelor's graduates specializing in wood engineering achieve the highest level of proficiency in general sustainability competencies such as "promoting nature", "critical thinking", "collective action", "individual initiative" and "problem framing". Since "problem framing" appears to be less important at lower levels of education, technicians pursuing a bachelor's degree need to improve their proficiency by four levels by the time they graduate, which represents a considerable leap. A similar increase is expected for "political agency", as a proficiency level of 6 is required at this level.

Finally, graduates with a master's degree are expected to achieve the highest proficiency level 8 in some of the general sustainability competencies, which includes "critical thinking", "problem framing", "col-

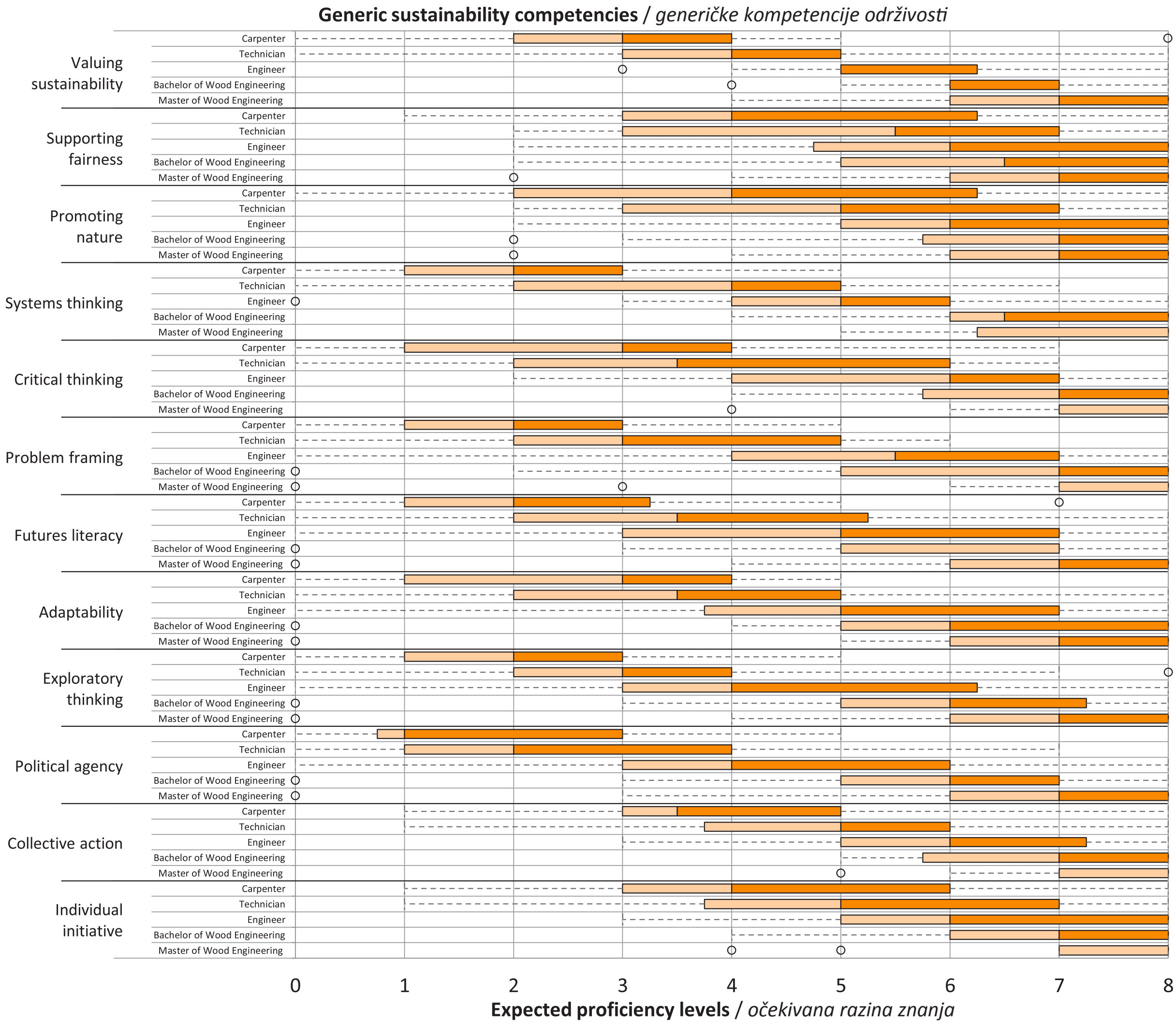

Figure 2 Box-and-whisker distribution of generic sustainability competencies for wood science and technology graduates in Slovenia: Carpenters (EQF 4), Technicians (EQF 4), Engineers (EQF 5), Bachelors of Wood Engineering (EQF 6), and Masters of Wood Engineering (EQF 7). Legend in Table 1

Slika 2. Distribucija generičkih kompetencija održivosti za diplomante u području drvne znanosti i tehnologije u Sloveniji: stolari (EQF 4), tehničari (EQF 4), inženjeri (EQF 5), prvostupnici inženjeri drvne tehnologije (EQF 6) i magistri inženjeri drvne tehnologije (EQF 7); legenda u tablici 1.

lective action", "individual initiative" and "systems thinking".

If we look at Figure 3, which represents the profession-specific digital and sustainability competencies, we can see that the highest proficiency required for carpenters in our list is for "wooden constructions", at proficiency level 4. The proficiency levels of the other competencies from this group, based on the opinions of most respondents, are between 1 and 3, apart from "digitalization of consumer behaviour monitoring", which is the least required competency for carpenters, as 75 % of experts and companies believe that they do not need it.

For wood technicians, in addition to "wooden constructions", "renewable resources and sustainable energy" is the highest rated competency, with a level 5. A competency that also stands out at this level is "digital technology and operations", as technicians must acquire 3 levels higher proficiency compared to carpenters, namely level 4. Graduates studying to become carpenters, who decide to continue their studies for technicians, must therefore acquire 3 additional proficiency levels in "digital technology and operations" in two years. The proficiency of the other competencies lies between level 2 and 4.

The requirements for wood engineers seem to be highest for "wooden constructions", at proficiency level of 7, closely followed by "computer-aided design". Most respondents believe that these graduates should have the lowest proficiency levels of 4 from the areas of "human-robot interactions" "industry symbiosis", "digitalization of consumer behaviour monitoring" and "pyramid of social responsibility". The highest jump in proficiency from technician to engineer seems to be in "energy-efficient and smart houses" as engineering graduates need to acquire 4 levels of proficiency in 2 years.

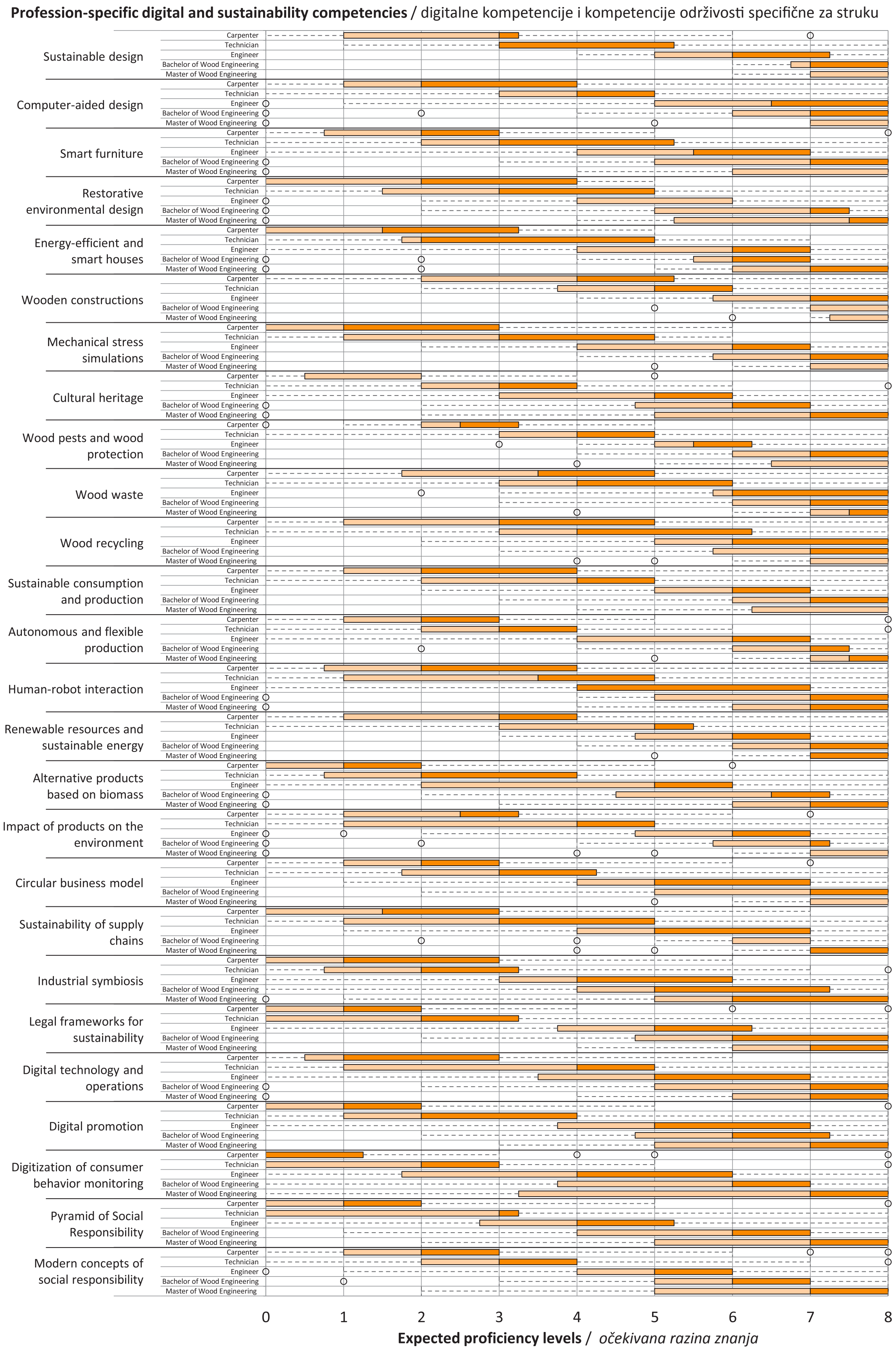

Figure 3 Box-and-whisker distribution of profession-specific digital and sustainability competencies for wood science and technology graduates in Slovenia: Carpenters (EQF 4), Technicians (EQF 4), Engineers (EQF 5), Bachelors of Wood Engineering (EQF 6), and Masters of Wood Engineering (EQF 7). Legend in Table 1

Slika 3. Distribucija generičkih digitalnih kompetencija i kompetencija održivosti specifičnih za struku za diplomante u području drvne znanosti i tehnologije u Sloveniji: stolari (EQF 4), tehničari (EQF 4), inženjeri (EQF 5), prvostupnici inženjeri drvne tehnologije (EQF 6) i magistri inženjeri drvne tehnologije (EQF 7); legenda u tablici 1.

As can also be seen in Figure 3, bachelor's graduates of the wood engineering are expected to achieve the highest level of proficiency in the field of "wooden constructions", for which they must achieve the highest level (8) on the scale used in our research. At this level, graduates must improve their competencies by 4 levels within 3 years, which also accounts for almost half of all competencies in this group of competencies. The least important seems to be "industrial symbiosis", for which they still need to improve their competencies by 3 levels from technician to bachelor graduate.

Graduates with a master's degree are expected to achieve the highest proficiency level, which is 8, in 10 out of the 26 profession-specific competencies from our list. For some competencies such as "wooden constructions", "human-robot interaction", "renewable resources and sustainable energy", "sustainability of supply chains" and "digital technology and operations", the required levels are the same as for engineers with a bachelor's degree. The least required competency appears to be "industrial symbiosis", at level 6.

It should be noted that in this research we have focused exclusively on digital and sustainability competencies, and it is possible that not all competencies have been considered. In addition, it is important to recognize that the development of digital and sustainability competences can also be indirectly supported by other knowledge, skills and attitudes that students acquire throughout their education, which at first glance may not be directly related to digitalization and sustainability, but they facilitate the acquisition of logical thinking, literacy, critical analysis, teamwork, adaptability, etc. Other competencies were also mentioned in some studies, but in a general context and not in relation to a specific level of education or a specific sector. Suciu *et al*. (2023), for example, highlighted the key competencies for a sustainable, resilient, and inclusive Industry 5.0, which are: "abilities of using, monitoring and controlling technological devices", "analytical and innovative thinking", "lifelong learning", "development of technological and programming solutions", "creativity, originality and initiative", "emotional intelligence", "leadership", "ability to solve complex problems". In an article highlighting the importance of soft skills in the labour market in the context of Industry 5.0 (Poláková *et al*., 2023), it was stated that even in technology-oriented fields such as "information technologies and engineering" or "production" and "logistics", employers place great emphasis on soft skills such as "critical and analytical thinking", "problem solving", "communication skills" and "creativity with flexibility" and that applicants are expected to have a good balance between soft skills and digital skills.

Nevertheless, the expectations placed on the digital and sustainability competencies of graduates of wood science and technology degree programs are growing as education increases. Lower levels of education should emphasize on general (digital and sustainability) competencies, while higher levels require a balanced mix of general and profession-specific competencies. This aligns with the diction of the White Paper on Education in the Republic of Slovenia, where it is noted that upper secondary education places a greater emphasis on general competencies, which ensures a foundation for further integration into education and enables more effective functioning in knowledge societies (Krek and Metljak, 2011).

Overall, for carpenters, "protecting health and well-being" is most important, while "programming" and "digitization of consumer behaviour monitoring" are considered least important. For technicians, "netiquette" is the most important competency, while "programming", "political agency" and 6 competencies from the list of profession-specific competencies are less important. Engineers must achieve a high level in the "netiquette" and "wooden constructions", while "exploratory thinking", "political agency" and some profession-specific competencies are least emphasized.

Bachelor graduates are expected to reach the highest level in "protecting personal data and privacy" and "wooden constructions", while "industrial symbiosis" is less prioritized. At this level of education, graduates must make the greatest leap in proficiency in many competencies. Master's engineers are expected to achieve the highest level in most competencies, while "industrial symbiosis" is at the bottom of the importance list.

4 CONCLUSIONS
4. ZAKLJUČAK

The principle of sustainable development, which focuses on people, their mutual relationships, and their relationship with the planet, must come to the fore, as the consequences of global warming are no longer just projections, but actual realities we are facing today. Against this backdrop, the potential of digitalization should also be harnessed and strategically aligned with these goals. By equipping individuals with key competencies and cultivating new professions, we have the opportunity to make a far-reaching and lasting impact (Meyer, 1977).

With this research, we have gained an insight into the scope and type of digital and sustainability competencies that are essential for graduates at different educational levels in the field of wood science and technology. It shows a clear progression of expected competencies depending on the level of education;

the further we move up the educational vertical, the more profession-specific competencies come to the fore. Carpenters are mostly expected to perform routine tasks and solve independently basic problems. The bar is much higher for university graduates, as they are expected to reach highest level of digital and sustainability competencies and tackle complex, multi-layered problems. The study also shows a clear gap in proficiency expectations between technicians and bachelor's graduates, with the latter facing the daunting task of bridging this gap within three years, which is a challenge, as the scaling of proficiency levels is not a simple linear progression, but rather a hierarchical model, following Bloom's Taxonomy (Table 1). In addition, this study found considerable variation in responses for all levels of education, suggesting that stakeholder's requirements are not homogenous, possibly due to a spectrum of digital adoption of industry and different prioritization of sustainable development.

It should be noted that we have focused exclusively on digital and sustainability competences and that we may not have included all of them, but the importance that companies and experts in the wood sector attach to digital and sustainability expertise underlines their central role in enabling continuous progress in this area. Our next goal is to assess the current competence level of graduates to determine whether they meet the needs of the sector. In addition, it is important for future research to investigate the adoption of digitalization and sustainability practices in the wood and furniture sector. A limitation of this research is that it is difficult to determine whether respondents' opinions are genuinely their own or whether they are simply behaving like 'mockingbirds', merely echoing the prevailing sentiments in this extensive discourse, currently dominated by the principles of digitalization and sustainability. Nonetheless, as Brečko (2001) points out, the competency needs of the sector should be continuously monitored to ensure the alignment of educational programs and thus equip students with the necessary competencies to cope with the future developments and challenges.

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Evaluation of Some Physico-Mechanical Properties and Formaldehyde Emission of Ecological Chipboards Produced from Annual Residue Plant Stems

Procjena nekih fizičko-mehaničkih svojstava i emisije formaldehida ekoloških ploča iverica proizvedenih od ostataka stabljika jednogodišnjih biljaka

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ABSTRACT • *Urea formaldehyde glue is one of the most preferred glues in the production of wood composite panels. It has many advantages such as economy, effective adhesive power and easy use. However, due to formaldehyde emission, it negatively affects the environment and human health. Formaldehyde emission can cause diseases in the respiratory system depending on the concentration and duration of exposure. In recent years, with legal regulations and increasing consumer awareness, low emission plate production has become inevitable. Therefore, low-emission adhesives, formaldehyde-scavenging chemicals and alternative binders are used to reduce formaldehyde emissions. Many studies have been made on the use of urea formaldehide glue and this topic is still actual. In this study, varying proportions (0, 25, 50, 75 and 100 %) of annual residue plant (ARP) were added to the wood chips used in the production of chipboards to solve these problems. The results showed that in physical properties, with the increase of ARP ratio, water absorption (WA) and thickness swelling (TS) values deteriorated for 2 and 24 hours. In mechanical measurements, the highest figures were obtained from the bending strength (SBS), modulus of elasticity (MOE) and tensile strength perpendicular to the surface (TSP) measurements of the boards produced from 25 % WAP added mixtures. TS EN 120 perforator method was applied to measure the formaldehyde emission in the boards. The test boards can be considered "ecological" since most results of formaldehyde emission (FE) measured on value-added products (WAP) were below the upper limit (8 mg/100g) specified in the E1 (EN 120) standard.*

KEYWORDS: *annual residue plants; physico-mechanical properties; formaldehyde emission; ecological chipboards*

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SAŽETAK • *Urea formaldehidno ljepilo jedno je od najpoželjnijih ljepila u proizvodnji kompozitnih ploča od drva. Ima mnoge prednosti kao što su ekonomičnost, učinkovita moć lijepljenja i jednostavna uporaba. Međutim, zbog emisije formaldehida negativno utječe na okoliš i zdravlje ljudi. Udisanje formaldehida može prouzročiti bolesti dišnog sustava, ovisno o njegovoj koncentraciji i trajanju izloženosti. Posljednjih se godina zbog zakonskih regulativa i sve razvijenije svijesti potrošača teži proizvodnji ploča s niskim emisijama tog plina. Za smanjenje emisije formaldehida upotrebljavaju se ljepila s niskom emisijom, kemikalije za hvatanje formaldehida i alternativna veziva. Objavljene su mnoge studije o upotrebi urea formaldehidnog ljepila, ali tema je i dalje aktualna. Za rješavanje tih problema u ovom su istraživanju drvnoj sječki rabljenoj za proizvodnju iverica dodani različiti udjeli ostataka jednogodišnjih biljaka (ARP): 0, 25, 50, 75 i 100 % Rezultati ispitivanja fizičkih svojstava pokazali su da se s povećanjem omjera ARP-a vrijednosti upijanja vode (WA) i debljinskog bubrenja (TS) tijekom 2 i 24 sata pogoršavaju. Glede mehaničkih svojstava, najveće vrijednosti čvrstoće na savijanje (SBS), modula elastičnosti (MOE) i vlačne čvrstoće okomito na površinu (TSP) dobivene su za ploče proizvedene od smjese s dodatkom 25 % WAP-a. Za mjerenje emisije formaldehida u pločama primijenjena je perforatorska metoda TS EN 120. Ispitane se ploče mogu smatrati "ekološkim" proizvodom jer je većina rezultata emisije formaldehida (FE) izmjerenih na proizvodima s dodatkom WAP-a bila niža od gornje granične vrijednosti (8 mg/100 g) za emisijski razred E1 (EN 120).*

KLJUČNE RIJEČI: *ostatci jednogodišnjih biljaka; fizičko-mehanička svojstva; emisija formaldehida; ekološka ploča iverica*

1 INTRODUCTION
1. UVOD

The inability of renewable natural resources such as forests to meet the increasing demand due to worldwide economic growth and development has created unprecedented needs for recycled forest products from lignocellulosic residues (Bektas *et al.*, 2005; Youngquist *et al.*, 1993). Producing high value-added products (WAP) such as furniture, interior design, and various construction and building materials from WAP, which is not used properly today, is an important activity in terms of economic and environmental awareness. At the same time, the increase in costs, because of the contraction in the supply of wood raw materials, makes the need for alternative raw material sources such as WAP and the research to be carried out even more important. So far, numerous researchers have studied the main properties of particleboard, fiberboard and other lignocellulosic based composite boards produced from different annual plant wastes; some of the studies dealing with waste chestnut bur (Liang *et al.*, 2021), lignocellulosic agro-industrial waste (Martins *et al.*, 2020), agricultural residues (Ferraz *et al.*, 2020), canola straws (Kord *et al.*, 2016), cotton stalks (Nazerian *et al.*, 2016), eggplant stalks (Guntekin and Karakus, 2008), pepper stalks (Guntekin *et al.*, 2008), sunflower stalks (Bektas *et al.*, 2005; Youngquist *et al.*, 1993), wheat straws and corn pith (Wang and Sun, 1998) waste of tea leaves (Yalinkilic *et al.*, 1998) crops residues (Kalaycioglu, 1992) and cob and maize husk (Sampathrajan *et al.*, 1992).

On the other hand, the available annual plant waste in Turkey is estimated to be 142.4 m ton/year (Saka and Yilmaz, 2017). The total amount of annual plants harvested and produced as agricultural waste in Turkey is 37 million tonnes (Guler, 2015). Wheat stalk accounts for the largest part of these annual plant wastes (18 m tonnes), followed by barley stalk (8 m tonnes), cotton stalk (3.5 m tonnes), sunflower stalk (3 m tonnes), corn stalk (2.5 m tonnes), rice stalk (200 tonnes), tobacco stalk (300 tonnes) and lake cane stalk (200 tonnes).

As a result, formaldehyde emission limit (Wang *et al.*, 2017), which is one of the factors that connect this study to the environment, is one of the important health indicators that connects wood-based boards and products to the environment. However, the first study that systematically examined the relationships between wood main chemical components and *FE* was carried out by Schafer and Roffael, (2000) at the beginnings of the 21st century. The results of this research revealed that the *FE* of the main components of wood is very different. As it is known, the two main chemical components of wood are lignin (18-35 %) and holocellulose (65-75 %), which consists of cellulose (40-50 %) and hemicellulose (25-35 %) (Bozkurt and Goker, 1996; Pettersen, 1984).

The starting point of this study is to search for alternative raw material sources that can substitute or add to wood, which is not sufficiently available from worldwide scarce forest resources. While focusing on this point, it was also aimed that the physico-mechanical properties (PMP) and FE values of the materials, to be manufactured from the new raw materials to be tested, would meet the criteria stipulated by the relevant standards. Investigating the FE within the scope of the study and comparing it with the requirements of the relevant standard is particularly important in terms of showing the "environmental sensitivity" of the study.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Preparation of test boards
2.1. Priprema ispitnih ploča

In this study, cotton (*Gossypium hirsitum* L.) stalks (CS), sunflower (*Helianthus annuus* L.) stalks

(SS), wheat (*Triticum aestivum* L.) stalks (WS) and wood chips were used from the annual plant wastes as test materials. The test materials used were provided from the Eastern Mediterranean region. The raw material collected from the field was prepared for flaking after a rough preliminary grading. In this process, particles were screened using a horizontal moving sieve. In the production of single-layer particleboards, chips with average sizes between 3 mm and 1.5 mm were used. After chipping, the chips were dried at 110 °C until they reached an average humidity of 3 %. Urea formaldehyde (UF) glue and 1 % hardener (NH4CL) were added at the rate of 10 % of its dry weight to the dry sawdust prepared in the proportions given in Table 1. For the pressing process, first, the mixing matrix was prepared in 55 cm × 55 cm dimensions and pressed to provide a density of 650 kg/m^3.

Then, the boards which were pressed in the hot press by keeping them at 185 °C under 120 atm pressure for 7 minutes, were taken to the air-conditioning process until they were ready for the tests (Bektas *et al.*, 2005; Ayrilmis, 2010; Guler and Sancar, 2017). During pressing, the press temperature is 185 °C, the press time is 7 minutes after the press is closed, and the press pressure is 4 N/mm^2. Following this, the test boards were subjected to conditioning until they were ready for tests (Bektas *et al.*, 2005; Ayrilmis, 2010; Guler and Sancar, 2017). These conditions were ensured for all the test samples, and a randomly selected sample from the production stages is shown in Figure 1.

2.2 Test procedure
2.2. Provedba ispitivanja

Within the scope of the tests, the *WA* and *TS* values were measured from physical properties according to EN 317 (1993). As for the mechanical properties, static bending strength (*SBS*) EN 310 (1993), modulus of elasticity (*MOE*) EN 310 (1993) and tensile strength perpendicular to the surface (*TSP*) EN 319 (1993) tests were determined in accordance with the relevant standards. Similarly, the formaldehyde emission (*FE*) values of the test boards were determined based on the EN 120 (1996) perforator method included in the BS EN 13986 (2005) standard. As is known, this method measures the formaldehyde content of wood-based panels, which can potentially diffuse under harsh conditions (Costa, 2013). The *FE* values of the samples were briefly measured as follows.

Table 1 Experimental design
Tablica 1. Postavke eksperimenta

Board type *Vrsta ploče*	**Raw materials and mixing ratios, %** *Sirovine i omjeri miješanja, %*			
	WC(*)	CS	SS	WS
A00	100	0	0	0
B25	75	25	0	0
C50	50	50	0	0
D75	25	75	0	0
E00	0	100	0	0
F25	75	0	25	0
G50	50	0	50	0
H75	25	0	75	0
K00	0	0	100	0
L25	75	0	0	25
M50	50	0	0	50
N75	25	0	0	75
P00	0	0	0	100

*Control groups / *kontrolne grupe*

First, completely dry weights of the samples cut in 25×25 mm dimensions from each produced test board were adjusted to be 100 g Myers, (1985). Then, 600 ml of pure toluene was added to them in a 1-liter glass balloon and boiled for 2 hours. After that, the formaldehyde that decomposed after boiling for 2 hours was transferred to distilled water (250 ml) and the solution was completed with pure water to 2 liters. Finally, the formaldehyde in the solution was determined photometrically with the help of a spectrophotometer.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In this section, the physico-mechanical properties (PMP) and formaldehyde emission (*FE*) in the study are evaluated and discussed based on tables and

a) b) c) d)

Figure 1 Production stages of test samples: a) in the field, b) chipping, c) pressing, d) sample
Slika 1. Faze proizvodnje ispitnih uzoraka: a) na terenu, b) usitnjavanje, c) prešanje, d) uzorak

figures formed from the results of ANOVA and DUNCAN's mean separation tests applied to the data obtained in the laboratory. Board density distributions are shown in Figure 2.

As seen in Figure 2, although the density distribution curves of the boards are non-linear, the density values are within certain limits. Since the amount of fiber per unit area in the board varies, the density distribution graphs also vary accordingly. As known, the type of wood used, the production conditions and the amount of chemicals affect the density. When the obtained values were compared with the targeted 650 kg/m^3 density, it was determined that they were in accordance with the 7 % tolerance specified in the TS EN 622-5 (2011) standard.

Likewise, the statistical analysis results of the WA and TS averages of the test boards made from wood chips and annual plant mixtures during the water absorption periods of 2 and 24 hours are presented in Table 2.

Table 2 shows that there was no significant difference between the two-hour *WA* values of the control samples and the board samples produced from cotton and sunflower stalks. However, a significant difference was detected between the 2 hours *WA* values of the wheat stalks and control samples. Compared to the control samples, the best 2-hour *WA* values were measured in cotton stalks, sunflower stalks and wheat stalks, respectively. The highest values in 24-hour *WA* were calculated as 129.6 % and 134.6 % in M50 and N75 group samples with high wheat stalk additives, respectively. These results show that in parallel with the increase in annual plant rate in the board, the 2– and 24-hour water absorption values also deteriorated. Similarly, Kozlowski and Piotrowski (1987) reached TS values of 20 % and 25 % for composite boards made from flax and hemp, respectively. In a study conducted with similar material Bektas *et al.* (2005) noted that the *WA* values of particle boards increased with the increase of sunflower ratio in the board matrix. Buyuksari *et al.* (2010) also proved that the addition of stone pinecone particles positively affected the dimensional stability of the boards. Kalaycioglu (1992), Arslan *et al.* (2007) and Copur *et al.* (2007) confirmed that the use of non-wood lignocellulosic materials in particle board production increases the water absorption values of the produced boards compared to wood.

Analysis of the data in Table 2 revealed the existence of significant differences at the $\rho<0.001$ confidence level between the water absorption values of control group specimens and the water absorption values of group E00, M50, N75 and P00 samples.

Guler *et al.* (2008), Yasar and Icel (2016) revealed that adding annual plants to composite boards increased the thickness increase values of the produced boards compared to wood. At the same time, Bektas *et al.* (2005) determined that in composites produced from sunflower stalks, the TS values of the samples varied depending on the sunflower concentration in the board.

However, the results of water absorption and thickness swelling increment results, including control samples, did not exceed the minimum threshold required by the EN standard EN 312 (2005) for general purpose use and interior equipment. In order to eliminate this negativity regarding water absorption values in composite boards, the use of paraffin is recommended by Ugur (2021).

Table 3 shows the results of ANOVA and Duncan's mean separation analysis applied to the measured data for mechanical properties and formaldehyde emission. It can be seen in the same table that all ANOVA analysis results applied to mechanical properties show significant differences at the ($P<0.05$) level. Also, the test results on the mechanical properties of the test boards produced from annual plants and their mixtures were lower than the control group samples. Again, it was observed that the mechanical properties of the test

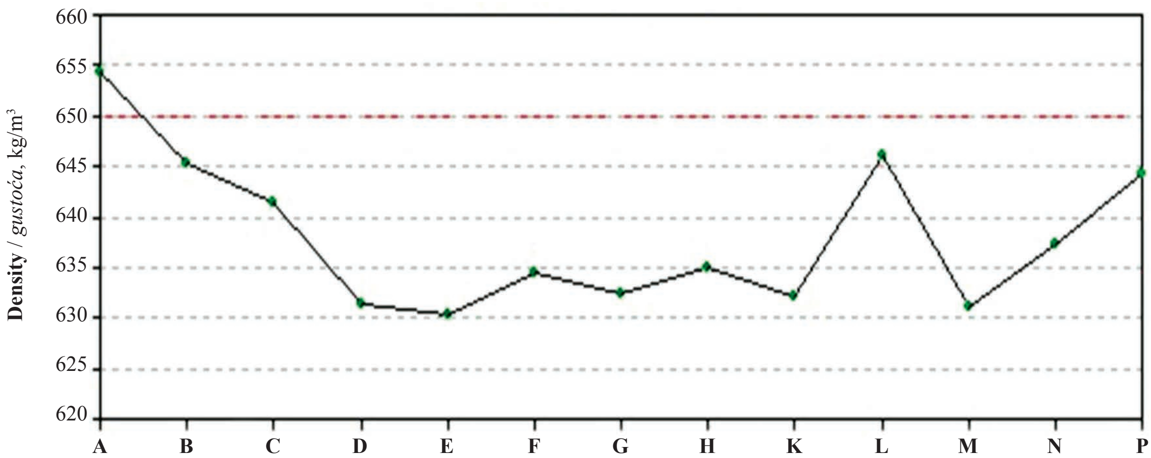

Figure 2 Boards density distribution
Slika 2. Prikaz gustoće ploča

Table 2 Statistical analysis results of water absorption and thickness swelling tests*
Tablica 2. Statistička analiza rezultata ispitivanja apsorpcije vode i debljinskog bubrenja*

Board type *Vrsta ploče*	***ST*, h**	**Water absorption** / *Upijanje vode*			**Thickness swelling** / *Debljinsko bubrenje*		
		Mean, %** *Srednja vrijednost, %***	**Standard deviation** *Standardna devijacija*	***COV*, %**	**Mean, %**** *Srednja vrijednost, %***	**Standard deviation** *Standardna devijacija*	***COV*, %**
A00	2	68.0a	16.10	23.67	19.6a	15.28	72.03
B25	2	71.6a	60.49	84.46	23.5ab	19.42	82.5
C50		72.3a	81.50	112.76	25.1ab	7.7	30.64
D75		76.6ab	64.28	83.94	26.1ab	6.6	25.25
E00		79.0abc	58.88	74.56	27.1abc	4	14.72
F25	2	76.0ab	8.34	10.97	22.5a	14.07	62.43
G50		78.8abc	12.76	16.20	24.1ab	36.98	52.96
H75		83.3abc	38.13	45.76	25.5ab	9.55	37.45
K00		84.2abc	23.52	27.93	26.7abc	21.42	79.93
L25	2	100.6bcd	29.05	28.88	32.0abcd	21.74	67.93
M50		105.1cd	30.56	29.08	34.3abcd	18.28	53.27
N75		115.8d	53.48	46.17	37.7cd	22.23	58.98
P00		116.4d	41.57	35.73	40.3d	20.94	51.91
A00	24	81.9a	26.67	32.53	23.2a	0.98	4.23
B25	24	84.6a	54.97	64.94	28.1ab	0.54	1.93
C50		87.0a	89.12	60.12	29.1ab	2.38	8.16
D75		89.6a	53.87	60.15	31.2abc	2.69	8.61
E00		93.3ab	70.92	75.98	33.9bc	18.89	55.72
F25	24	86.9a	10.86	12.5	27.9ab	9.06	32.45
G50		91.7ab	27.64	30.12	28.1ab	12.16	43.17
H75		93.1ab	50.1	53.78	30.4ab	16.56	62.74
K00		95.6abc	27.01	28.14	32.1abc	16.64	51.84
L25	24	118.9bcd	26.47	22.26	34.7ab	22.44	72.95
M50		120.7cd	30.18	24.99	38.9bc	18.89	55.72
N75		129.6d	44.81	34.56	42.9bc	24.8	68.96
P00		134.6d	36.76	27.3	46.0c	24.69	61.65
P_{SL}		*P<0.001*	-	-	*P<0.09*	-	-

*The number of samples is 30, *ST* – Soaking time, *SL*– Significance level, *COV*– Coefficient of variation, **According to the Duncan Test, there is no significant difference between the mean values represented by the same letters. / **Broj uzoraka je 30, ST – vrijeme potapanja, SL – razina značajnosti, COV – koeficijent varijacije; **prema Duncanovu testu, nema značajne razlike između srednjih vrijednosti označenih istim slovima.*

specimens decreased with the increase of annual plant rate in the panel matrix.

The total group averages of the strength values of the test samples in Table 3 can be listed as follows, from the largest to the smallest: cotton stalks (B25, C50, D75, E00), sunflower stalks (F25, G50, H75, K00) and wheat stalks (L25, M50, N75, P00). In addition, from the results of Duncan's mean separation test in Table 3, it can be said that annual plant properties in general. In terms of the mechanical properties of particle boards, Martins *et al.* (2020) recorded that annual plant waste is lower than eucalyptus wood-based control. Results of some studies on the subject (Ferraz *et al.*, 2020; Onuaguluchi and Banthia, 2016; Hejna *et al.*, 2020; Kashparow *et al.*, 2019; Pickering *et al.*, 2016; Saba *et al.*, 2016; Stokke *et al.*, 2013) indicate that the ratio of chemical components strongly influences the mechanical properties, since cellulose, hemicellulose and lignin in the structure of lignocellulosic material are primarily responsible for the bonding behavior and degradation of natural fibers in composites. According to the findings of Salem and Böhm (2013), the effect of the chemical composition of wood on formaldehyde release is much more important than its physical or anatomical structure. Based on these assumptions, it is stated in the relevant literature that especially cellulose is more effective on the tensile and elastic properties of lignocellulosic materials (Genet *et al.*, 2005; Commandeur and Pyles, 1991; Turmanina, 1965), while the effect of lignin concentrates on compressive and hardness properties (Zhang *et al.*, 2013; Aili *et al.*, 2012; Hathaway and Penny, 1975; Ouyang *et al.*, 2011).

On the other hand, the comparison of the *FE* values measured according to the mixture percentages of the test samples obtained from the composite boards produced from WC-CS, WC-SS and WC-WS mixtures with the relevant standard EN 120 (1996) can be seen in Figure 3. Considering the results of WC-CS mixtures in Fig.3a, it can be seen that the FE values of the A00, B25 and C50 group samples, except for D75 and

Table 3 Test and analysis data of mechanical properties *
Tablica 3. Podatci ispitivanja mehaničkih svojstava i njihova analiza *

Board type *Vrsta ploče*	***SBS*, N/mm²**	***COV*, %**	***MOE*, N/mm²**	***COV*, %**	***TSP*, N/mm²**	***COV*, %**
Means (Standard divisions) / *Srednje vrijednosti (standardne devijacije)***						
A00	18.0 (1.79)a	9.94	4620.8(449.8)a	9.72	0.97(0.20)a	20.70
B25	17.4 (2.36)a	13.53	3773.1(435.8)b	11.56	0.91(0.21)bc	23.69
C50	15.3(0.75)cd	11.95	3757.3(542.3)b	14.44	0.80(0.15)de	19.18
D75	14.4(1.99)d	13.75	3282.2(605.9)c	18.85	0.77(0.18)e	23.41
E00	13.1(1.78)e	13.60	2819.0(418.6)d	14.86	0.55(0.14)f	24.75
F25	17.0(2.14)ab	9.55	3173.2(697.7)c	20.71	0.80(0.11)cd	14.08
G50	16.2(2.46)bc	11.55	2312.7(802.9)e	20.10	0.83(0.13)de	14.86
H75	16.1(2.85)bc	14.23	2023.1(210.4)ef	24.72	0.75(0.14)e	17.25
K00	15.6(1.35)bc	15.70	1800.3(493.3)fg	22.40	0.47(0.10)g	19.32
L25	11.7(1.70)f	15.10	3114.2(909.1)c	25.19	0.35(0.05)h	13.55
M50	7.2(1.06)g	12.50	2265.4(424.8)e	17.75	0.33(0.05)h	12.17
N75	6.6(0.59)h	14.60	1555.41(416.4)g	25.41	0.30(0.02)h	11.16
P00	5.4(0.32)h	7.95	1085.8(406.9)h	29.33	0.29(0.04)h	15.02
P_{SL}	*P<0.000*	-	*P<0.000*	-	*P<0.000*	-
V_{EN}	11.5		1600		0.24	

*The number of samples is 30, BT – Board type, *SBS* – Static bending strength, *MOE* – Modulus of elasticity, *TSP* – Tensile strength perpendicular to the surface, *SL* – Significance level, *COV*– Coefficient of variation (%), EN – Standard value for EN, **According to the Duncan's mean separation test, there is no significant difference between the mean values represented by the same letters.
**Broj uzoraka je 30, BT – vrsta ploče, SBS – statička* čvrstoća *na savijanje, MOE – modul elastičnosti, TSP – vlačna* čvrstoća *okomito na površinu, SL – razina značajnosti, COV – koeficijent varijacije (%), EN – standardna vrijednost za EN; ** prema Duncanovu testu, nema značajne razlike između srednjih vrijednosti označenih istim slovima.*

E00, are below the upper limit specified in EN 120 (1996) (8 mg/100 g). Again, the *FE* values of D75 (75 %) and E00 (100 %) group specimens, which have high CS content, were determined to be higher than other mixture samples. In a study on the subject, Liang *et al.* (2021) remarked that chestnut bark chips effectively reduced *FE* values. Similar results were reported in previous studies (Nemli *et al.*, 2004; Buyuksari *et al.*, 2010). This research stressed that the decrease in *FE* values in the panels may be due to the high amounts of polyphenolic extractives in bark, especially tannins. Similarly, Nemli and Colakoglu (2005) found that the incorporation of mimosa bark particles greatly reduces *FE* values of particleboards.

As for the WC-SS matrixes in Figure 3b, the best result in terms of *FE* was obtained from these mixture samples. All the *FE* values calculated for the samples belonging to F25, G50, H75 and K00 groups were within the limits specified in the EN 120 (1996) standard. Here, it is a remarkable result that the *FE* values (7.2 mg/100 g) of the K00 group samples produced from 100 % SS were below the standard value (8 mg/100 g). For this reason, in areas of use, where environmental sensitivity comes to the fore, composite materials produced from pure SS or WC-SS mixtures in varying proportions may be preferred. Similarly, Martins *et al.* (2020) state that increasing the tannin extract in urea-formaldehyde adhesive reduces free formaldehyde emission in particleboards by 22.5 %. As seen in Figure 3c, *FE* analysis performed for board groups consisting of WC-WS mixtures yielded results similar to the values obtained from WC-CS mixture samples. While the *FE* values of the L25 and M50 group samples (5.1 and 6.0 mg/100 g, respectively) remained below the upper limit required by the relevant standard, the *FE* values of the N75 and P00 groups (8.5 and 9.3 mg/100 g, respectively) exceeded the relevant ultimate value.

It can be thought that this negative result regarding the *FE* value, which occurred in the N75 and P00 groups related to *FE* value, was due to the components of *WS* (Table 2) and their known sensitivity to glue. Shi *et al*. (2006) state that raw materials with lower *FE* values, such as WC, SS and tea leaves, can be added to composite panels to reduce the *FE* values exceeding the standard emissions emitted from high proportions of WS mixtures in the board matrix.

Similar to these findings, Buyuksari *et al*. (2010) determined that formaldehyde emissions were significantly reduced by adding cone particles to composite panels. Besides, the addition of poppy husks into particleboards significantly decreased formaldehyde emission (Keskin *et al*., 2015). Processing conditions of wood-based panels have an important role in reducing board formaldehyde emission, therefore Ismail *et al*. (2006) stated that board formaldehyde emission will decrease with increasing press cycle time.

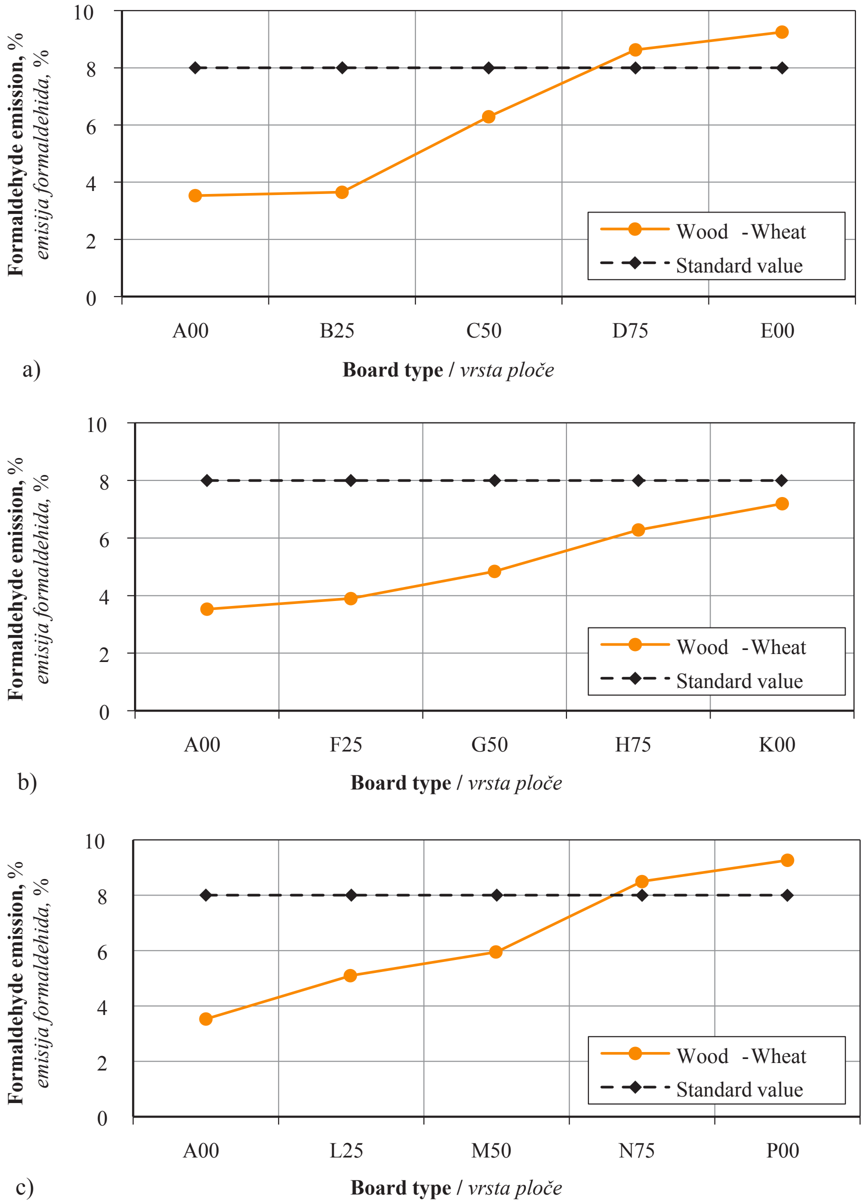

Figure 3 Comparison of formaldehyde emission percentages with the standard value: a) Cotton stalks, b) Sunflower stalks, c) Wheat stalks
Slika 3. Usporedba postotaka emisije formaldehida sa standardnom vrijednošću: a) stabljikâ pamuka, b) stabljikâ suncokreta, c) stabljikâ pšenice

4 CONCLUSIONS
4. ZAKLJUČAK

The main outcomes obtained as a result of the tests and analyses carried out within the scope of this research are summarized below.

In the study, parallel with the increase in the annual plant ratio in the board, 2– and 24-hour water absorption and thickness swelling values worsened and the results could not meet the requirements of the EN 312 (2005).

In mechanical properties, it was also found that the strength values decreased as the WAP ratio in the board matrix increased. Except for the control group (K00: 0.68 N/mm^2), the best mechanical properties in WAP-mixed samples were obtained from B25 group samples with 25 % CS added. Most of the mechanical properties, except tensile strength, met the requirements of the relevant standards.

In terms of ecology, the *FE* values of the test specimens met the requirements of EN 120 (1996), except for the D75 (8.63 %), E00 (9.26 %), N75 (8.50 %) and P00 (9.25 %) groups.

In the light of the data obtained, it can be suggested that the test panels can be used in environmentally sensitive areas where low relative humidity and moderate mechanical strength are required, such as interior design, wooden building partition panels and furniture.

Furthermore, in case annual residue plants (ARP) stalks are not used in industrial areas, the prevention of their inappropriate disposal and destruction, such as incineration and burial, should also be considered an important environmental benefit.

Finally, this study can be an important step for those who want to conduct more advanced level research on this subject and who will produce low-cost ecological building materials.

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Analysis of Primary Value Chains in Slovenian Forest and Wood Bioeconomy

Analiza primarnih lanaca vrijednosti u slovenskome šumskom i drvnom biogospodarstvu

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ABSTRACT • *Green value chains are becoming increasingly important due to the current European and global strategic orientation. Wood and wood-related value chains are one of them. There are many challenges to overcome in the Slovenian forest-wood bioeconomy in order to strengthen it and make it more efficient. One of the biggest challenges is the increasing share of deciduous trees in Slovenian forests. This raises the question of how to build or strengthen forest-wood value chains with hardwood of different qualities as a basic raw material. The most important thing for the entire forest-wood bioeconomy is to have effective and functioning primary value chains in order to have a strong basis for multiplying the impact and value in the entire forest-wood value chain. The aim of this study was to analyze the primary value chains in the Slovenian forest-wood bioeconomy, with a focus on the processing of hardwood. The main research question was whether the primary value chains are equivalent for the efficient functioning of the forest wood chain, whose main raw material is hardwood. Based on an in-depth qualitative multi-criteria decision-making analysis, we can conclude that all analyzed primary value chains are very important for creating the conditions for the maximum utilization of the potential of hardwood raw materials of different quality. From the point of view of providing basic and advanced materials for further value chains in the wood sector (and related industries), these are mainly the chains P1 Sawlogs, P2 Veneer logs and P3 Wood for pulp and composites, and for other industries also the most advanced materials from the chain P4 Other industrial wood, which still require a lot of investment in research and development to reach the level of their wider (industrial) implementation. In terms of ensuring circular economy and sustainability, connecting chains C6 Residues and C7 Reclaimed wood are particularly important.*

KEYWORDS: *value chains; forest-wood chain; primary production; bioeconomy; hardwood*

SAŽETAK • *Zeleni vrijednosni lanci postaju sve važniji zbog trenutačne europske i globalne strateške orijentacije. Drvo i lanci vrijednosti vezani za drvo jedni su od njih. U slovenskome šumsko-drvnom biogospodarstvu mnogo je izazova koje treba prevladati kako bismo ga ojačali i učinili učinkovitijim. Jedan od najvećih izazova jest*

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sve veći udio listopadnog drveća u slovenskim šumama. Postavlja se pitanje kako izgraditi ili ojačati vrijednosne lance šuma – drvo listačama različite kvalitete kao osnovnom sirovinom. Za cjelokupno šumsko-drvno biogospodarstvo najvažnije je imati učinkovite i funkcionalne primarne vrijednosne lance kako bismo imali čvrstu osnovu za multipliciranje utjecaja i vrijednosti u cijelom lancu vrijednosti šuma – drvo. Cilj ove studije bio je analizirati primarne lance vrijednosti u slovenskome šumsko-drvnom biogospodarstvu, s fokusom na preradi listača. Glavno istraživačko pitanje bilo je jesu li primarni vrijednosni lanci ekvivalentni za učinkovito funkcioniranje lanca šuma – drvo, čija su glavna sirovina listače. Na temelju dubinske kvalitativne analize višekriterijskog odlučivanja možemo zaključiti da su svi analizirani primarni lanci vrijednosti vrlo važni za stvaranje uvjeta za maksimalno iskorištenje potencijala sirovinâ listača različite kvalitete. Sa stajališta opskrbe osnovnim i naprednim materijalima daljnjih lanaca vrijednosti u drvnom sektoru (i u srodnim industrijama), to su uglavnom lanci P1 – pilanski trupci, P2 – furnirski trupci i P3 – drvo za celulozu i kompozite, a za ostale su industrije također najnapredniji materijali iz lanca P4 – ostalo industrijsko drvo, za koje je još potrebno mnogo ulaganja u istraživanje i razvoj da bi dosegnuli razinu svoje šire (industrijske) primjene. U smislu osiguranja kružnoga gospodarstva i održivosti posebice su važni povezani lanci C6 – ostatci i C7 – regenerirano drvo.

KLJUČNE RIJEČI: *lanci vrijednosti; lanac šuma – drvo; primarna proizvodnja; biogospodarstvo; listače*

1 INTRODUCTION
1. UVOD

Green value chains are becoming very important due to the current European and global strategic orientations. One of the most important strategic documents supporting the transition to a green society is the "Green Deal" from 2019 (Evropski zeleni dogovor: Postati prva podnebno nevtralna celina, no date; Evropska komisija, 2019). This is a unique opportunity to strengthen green value chains, the forest-wood value chain being one of the most important. (European Organization of the Sawmill Industry (EOS), n.d.). In EU policies, there is a special emphasis on the use of wood for construction purposes, although wood currently accounts for only 3 % of all materials used. (The international wood industry in one information service, 2020).

On this basis, there are many opportunities for the development of the entire Slovenian forest-wood value chain. However, the forest-wood value chain has faced several challenges in recent decades. Increasing competition, especially in the supply of raw materials, including those based on wood and/or wood biomass, and the past loss of production infrastructure, especially in the production of veneer, wood composites and pulp, entails a high degree of dependence on international markets and uncertainty about the possible breakdown of supply chains. The functioning and ability of competitive production of primary forest-wood value chains ensures stability for more advanced wood value chains (e.g. wood construction, furniture, vehicles and ships, etc.) and other value chains (e.g. construction, chemical and textile industries, etc.). On the other hand, these chains face a variety of challenges. One of the long-term challenges of the domestic forest-wood value chain is the expected change in the structure of the domestic supply chain of forest-wood assortments, in which the share of hardwood trees will increase due to climate change, as well as the share of lower-quality assortments.

According to the Slovenian Forest Administration (ZGS), the hardwood stock in Slovenian forests is increasing and accounted for 55.7 % of the total wood stock in 2021 (in 2000 it was 51.7 %). The most frequently represented tree species in Slovenian forests is European beech (*Fagus sylvatica*) with a share of 33 % (Breznikar and Poljanec, 2023; Ščap and Triplat, 2023), which continues to increase (the share of Norway spruce (*Picea abies*) is 30 % and declining). In 2021, the volume of harvested trees in Slovenia amounted to 4.075 million m^3 (Statistični urad RS, 2023) with a 47 % share of hardwood. According to the study on the material flows of hardwood logs and sawn wood in Slovenia (Ščap and Triplat, 2023), the estimated total volume of processed hardwood sawlogs in Slovenian sawmills in 2021 was 27,000 m^3, the veneer mills processed 34,000 m^3 of hardwood logs, of which about 90 % were imported. In the reference year, 223,000 m^3 of low-grade industrial hardwood was processed by companies in the wood-based panels, mechanical pulp and chemical industries. For energy purposes, 0.997 million m^3 of total hardwood production was used in Slovenia (year 2021). Projections of hardwood potential show that in 2025 there will be similar quantities of wood on the market as in the reference year (Ščap and Triplat, 2023).

Climate change will cause a redistribution of existing forest types and a change in their tree species composition, which will also have consequences for the entire forest-wood chain (Arnič *et al.*, 2023; Breznikar and Poljanec, 2023; Gričar *et al.*, 2023). Model predictions about tree composition in the future are rather vague, but despite everything, experts agree that the ratio between conifers and deciduous trees is changing quite strongly in favor of the latter (Breznikar and Poljanec, 2023). The decline in the share of spruce in the wood stock of forests has already been observed in the last decade and is primarily the result of pronounced fluctuations in growing conditions, natural damage and bark beetle infestation. According to current forecasts on the development of climate indicators, forest production and wood properties, the following tree species have the greatest potential in Slovenia in the future: European beech (*Fagus sylvatica*), Sycamore maple (*Acer pseudoplatanus*), silver fir (*Abies alba*), European oak (*Quercus robur*, *Quercus petraea*), black locust (*Robinia pseudoaccacia*), black poplar (*Populus nigra*), black pine (*Pinus nigra*), Scots pine (*Pinus sylvetris*), Douglas fir (*Pseudotsuga menziesii*) and sweet chestnut (*Castanea sativa*) (Gričar *et al.*, 2023). In the long term, climate change is also expected to result in a higher proportion of low-grade wood, as thermophilic forest communities, which are generally less economically interesting (Breznikar and Poljanec, 2023). However, this represents a (currently still) untapped potential and is an opportunity for the development of new (innovative) ways of using such raw materials (Kropivšek and Čufar, 2015; Gornik Bučar *et al.*, 2017; Zule *et al.*, 2017).

According to the United Nations Economic Commission for Europe (UNECE) (UNECE, 2023), the consumption of hardwood in Europe is increasing, which could represent an opportunity for the activation of new and different uses of hardwood in Slovenian bioeconomy. The term bioeconomy is used to describe the broad spectrum of forest and wood products in the utilization of renewable natural resources. Bioeconomy can be defined as an economy in which the basic building blocks for materials, chemicals and energy are derived from renewable biological resources (McCormic and Niina, 2013). Another definition states that "bioeconomy is the production of renewable biological resources and the conversion of these resources and waste streams into value-added products such as food, feed, bio-based products and bioenergy" (Stegmann *et al*., 2020). In our case, we understand the bioeconomy as the integration of the sustainable production of renewable biological resources and the transformation of these resources and waste streams into value-added products. It should form an integrated, sustainable and robust bioeconomy system that connects different bioeconomy sectors, including forestry and wood processing (Juvančič *et al*., 2023).

One of the most important reasons for the inefficient utilization of hardwood is a poorly functioning forest-wood chain, which is interrupted at certain points and so the great potential of (mainly) high-quality raw materials is lost. That results in a higher consumption of other, non-environmentally friendly materials.

The insufficiently efficient functioning of the forest-wood chain, in which the main raw material is hardwood, is also confirmed by the data on the structure of hardwood production by purpose, as fuelwood traditionally dominates with more than 50 % (Ščap and Triplat, 2023; Arnič *et al.*, 2023; Kropivšek *et al.*, 2023). Research results (Marenče *et al.*, 2017; Marenče *et al.*, 2020) show that more than 60 % of the wood mass of beech trees is often not or only partially used for energy, as a large part of the wood volume often remains in the forest.

Arnič (2023) states in the latest detailed analysis, in which five scenarios for the restructuring of the forest-wood chain in Slovenia were created, that the available quantities of roundwood in Slovenia are between 1.6 and 2.4 times the current processing capacities, whereby the currently available processing capacities of veneer and saw logs from hardwood are even 3.8 to 5.4 times lower than the projected availability of roundwood. Ščap and Triplat (2023) also state that in the Slovenian market in 2021 only 30 % of the estimated available amount of low-grade hardwood was processed in the particleboard, mechanical pulp, and chemical pulp industries. We can conclude that a large part of the hardwood of different quality in Slovenia remains unused or underutilized, which also indicates inefficient functioning of the forest-wood chain.

This is also reflected in the poor performance of the individual connections in the chain, low profits and inadequate implementation of the concepts of sustainability and circular economy. The solution lies in the search for innovative products, which can be achieved through the development and introduction of modern technologies and digitalization, but above all through the development of new, even more complex value chains.

All of this requires certain investments, the introduction of a modern organization and an increase in employee skills in all forest-wood chains. By introducing digitalization (anautomation) of processes in these chains, greater efficiency and flexibility of these chains can be achieved on the one hand, and on the other a lower carbon footprint and a more people-friendly operation of the entire forest and wood chain (including social sciences and humanities (SSH) as an essential element of the activities needed to address each of the social challenges in order to increase their impact) (Directorate-General for Research and Innovation, 2020). With this aim in mind, value chains in the Slovenian forest and wood bioeconomy were analyzed, paying attention both to existing chains and to the concept of new value chains; value chains are interlinked and interdependent and do not end with the forest and wood industry, but also extend to other sectors and can have major multiplier effects on the economy (Straže *et al.*, 2023). There are differences between the individual chains, both in terms of the (current) level of development and the potential for further development. This is influenced by many factors. In previous research, a SWOT analysis (Benzaghta *et al.*, 2021) was used to strategically analyze the value chains in the Slovenian forest and wood bioeconomy, which makes it possible to formulate a strategy to build on strengths, eliminate weaknesses, exploit opportunities and avoid threats (Kropivšek *et al.*, 2023). The optimal functioning of value chains requires investments in (certain) technologies (e.g. structural timber, veneer production, wood-based composites, etc.), increasing the competencies of employees and introducing digital transformation throughout the organization. By taking advantage of the benefits in the value chains, we can very effectively exploit opportunities or reduce risks. Among the most important measures are certainly those that strengthen the functioning of the individual chains, creating effective connections between them (and outwards to other sectors). These results support key measures for the development of the wood processing industry in Slovenia (MGRT, 2022).

The aim of this study was to analyze the primary value chains in the Slovenian forest-wood bioeconomy, with a focus on the processing of hardwood. The primary value chains were analyzed and evaluated with regard to the technological, environmental, market and innovation potential as well as the social aspect. The main research question was whether the primary value chains are equivalent for the efficient operation of the forest wood chain, whose main raw material is hardwood.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

For decision-makers at the national level, it is extremely important to analyze and evaluate the individual chains in more detail from a national and economic perspective. The starting point for the assessment of value chains is the concept of value chains, which enables a systemic approach to their assessment (Wang, 2015), as well as the concept of marginal quality of the input raw material (marginal log), which determines the intended use of the wood according to its quality (Ringe and Hoover, 1987). In this way, available logs can be used to manufacture products with the highest possible added value. In previous research, SWOT analysis of value chains in the Slovenian forest and wood bioeconomy were used (Kropivšek *et al.*, 2023). One of the main limitations of the SWOT method is its inability to rank criteria and prioritization strategies (Shakoor Shahabi *et al.*, 2018), which is why it is often extended/supplemented by other methods (Kurttila *et al.*, 2000; Abdel-Basset *et al.*, 2018; Taghavifard *et al.*, 2018). A more detailed assessment requires an in-depth analysis that helps to identify the most strategic value chains and predict (propose) the actions needed to improve them. A deeper and more detailed analysis usually requires the consideration of a different (usually larger) number of criteria, not all of which are equally important. It is therefore a typical case of multi-criteria decision making (MCDM), where alternatives are evaluated against multiple, possibly conflicting, criteria (Trdin and Bohanec, 2018).The MCDM problems can generally be solved using different methods, such as the Analytic Hierarchy Process (AHP) (Saaty, 2008; Saaty and Vargas, 2012), the French acronym for Elimination and Choice Expressing Reality (ELECTRE) (Roy, 1990), the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and so on. Each of the MCDM methods has its own advantages and disadvantages or is familiar or unfamiliar to different decision makers (Omer Saracoglu, 2016). MCDM methods are widely used in the assessment of various cases (Taherdoost and Madanchian, 2023), including for agri-food supply chain performance evaluation (Bhattacharya *et al.*, 2014; Uygun and Dede, 2016; Kumar *et al.*, 2022). The essential element of these methods is to break down the decision problem into smaller sub-problems, which are later treated individually (Bohanec and Rajkovic, 1995). The evaluation/ranking process is then a process that can differ between the methods, while behind the process there are different procedures. One of the MCDM methods is also DEX, which was used in this analysis.

2.1 Qualitative value chain evaluation with DEX method
2.1. Kvalitativno vrednovanje lanca vrijednosti DEX metodom

DEX is a qualitative multi-attribute decision modeling method that integrates multi-criteria decision modeling with rule-based expert systems (Bohanec *et al.*, 2013). The main advantage of this method is that it can also be used for attributes that cannot be quantified. The evaluation is (often) based on the comparison of different alternatives at the level of a specific attribute and not on a precise evaluation of the attribute.

Like all other MCDM methods, DEX aims to evaluate and analyze a set of decision alternatives $A=\{a_1, a_2, \ldots, a_m\}$ described with a set of variables $X=\{x_1, x_2, \ldots, x_n\}$, called attributes, which represent all observed or evaluated properties of the alternatives (Bohanec *et al.*, 2017). In DEX, each attribute $x_i \in X$ has an associated qualitative value scale $D(x_i)=D_i=\{v_{i1}, v_{i2}, \ldots, v_{iki}\}$, where each v_{ij} represents some ordinary word, such as "low", "high", "acceptable", "excellent". The hierarchical topology allows decomposition of the decision problem into simpler sub-problems. In DEX, the alternatives are described with qualitative values that are taken from the scales of the corresponding input attributes in the hierarchy. The evaluation of alternatives is performed in a bottom-up way, utilizing aggregation functions defined for each aggregated attribute in the form of decision rules (Trdin and Bohanec, 2018). The bottom-up aggregation of the values of alternatives is defined in the form of decision rules, which are specified by the decision maker and are usually represented in the form of decision tables. Each aggregated attribute in the model has an associated decision table that defines how the value of that attribute is determined (aggregated) from the values of its immediate descendants in the hierarchy. Within the decision tables for the purpose of aggregation, the decision maker has to define an aggregation function (f_y):

$$f_y: D_1 \times D_2 \times \cdots \times D_r \rightarrow D_y$$

In DEX, the aggregation function $y=f_y(x_1, x_2, \ldots, x_r)$ is defined with a set of decision rules of the form

$$if\ x_1=v_1\ and\ x_2=v_2\ and\ \ldots\ and\ x_r=v_r\ then\ y=v_y.$$

Here, $v_i \in D_i$ and $v_y \in D_y$.

In principle, any number of decision rules can be defined by the decision maker for each aggregate attribute. However, the decision maker is encouraged to define as many rules so that the decision space $D_1 \times D_2 \times \cdots \times D_r$ is covered as completely as possible (Bohanec *et al.*, 2017). The evaluation of alternatives is then as a straightforward bottom-up aggregation procedure. The method DEX is implemented as a computer program called DEXi that supports both the development of DEX models and their application for the evaluation and advanced analysis of decision alternatives (Bohanec *et al.*, 2013, 2017).

In our research, for the evaluation of value chains in the bioeconomy, first the value chains were listed as alternatives and a list of evaluation variables with measurement scale and description was created; then, utility functions were defined for each aggregate attribute in the form of decision rules; and finally, each value chain was evaluated bottom-up as an alternative in the decision-making process. The assessment was carried out by a group of three experts from different fields (economics, material science and technology, all related to wood), each of whom gave an individual assessment. The assessments were then compared by calculating the average value and standard deviation to identify the attributes within a single value chain with the greatest differences between the assessors. These attributes were then discussed in a joint meeting of evaluators to determine the final score. After calculating each individual value chain using the DEXi software, the final score was determined. Based on the final "what-if" analysis of the alternatives, where different scenarios were considered, the final discussion was held.

2.2 Value chains
2.2. Lanci vrijednosti

In the Slovenian forest and wood bioeconomy, five primary (P1...P5) and two connecting (C6...C7) value chains were identified based on the quality classes of hardwood as input material (Straže *et al.*, 2023): P1 *Sawlogs*, P2 *Veneer logs*, P3 *Wood for pulp and composites*, P4 *Other industrial roundwood* (for chemical processing – biorefinery), P5 *Fuelwood* (for energy use), C6 *Residues* and C7 *Reclaimed wood*. The chains are intertwined, and the (semi-)products and residues that arise within the chains can be the beginning of other chains or be included in one of the phases. The results of the primary value chains are outputs that are destined for further processing into higher value-added products, mainly in the wood industry, but also in other sectors (e.g. construction, chemical and food industries, paper production, etc.). The connecting chains (C6 *Residues* and C7 *Reclaimed wood*) ensure the circular economy, as they do not obtain their resources directly from nature. Instead, they are based on the residues from other chains and supply the primary chains with their outputs.

2.3 List of evaluation variables
2.3. Popis varijabli za evaluaciju

When evaluating chains, various criteria can and have to be considered (Hurm*ekoski et al.*, 2018): the technology readiness level (TRL), feasibility, quantitative potential, availability of resources, market interest, cost efficiency and sustainability. Based on the literature and the SWOT analysis of value chains in the Slovenian bioeconomy (Kropivšek *et al.*, 2023), a comprehensive tree of evaluation variables was created (Figure 1) with 19 different variables. According to the DEX method, the variables were divided into five groups to assess the technological, environmental, market and innovation potentials as well as the social aspects.

Each of the evaluation variables for this tree was then aligned with the measurement scale and a short description (Table 1).

Using measurement scales related to a specific attribute, utility functions were first defined for each aggregated attribute in the form of decision rules. In the next phase, each value chain was evaluated bottom-up as an alternative in the decision-making process.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The final evaluation of the value chain is summarized in Figure 2 and is fully in line with previous research (see: Kropivšek *et al.*, 2023), as it identifies chains P1 *Sawlogs* and P3 *Wood for pulp and composites* as excellent and very perspective chains, while others received lower final grades.

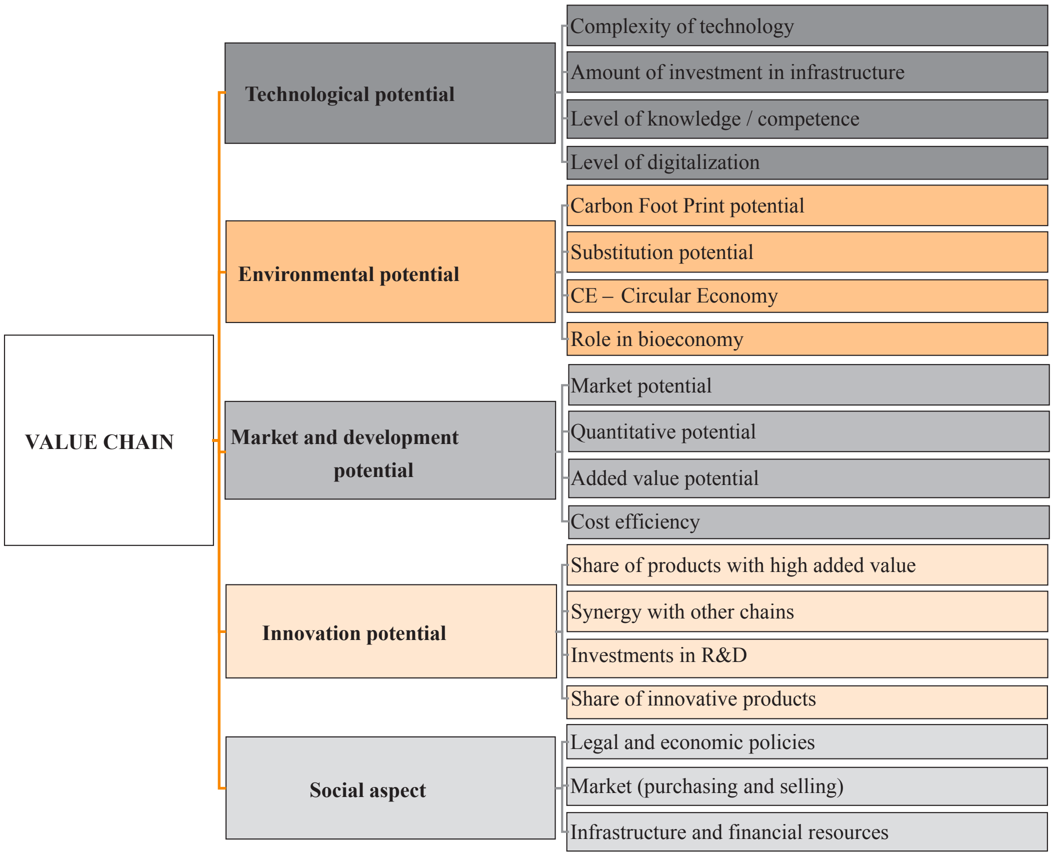

Figure 1 Tree of evaluation variables (attributes)
Slika 1. Stablo varijabli (značajki) za evaluaciju

The detailed results of the DEX analysis (Table 2) show a great environmental and development potential of the chain P1 *Sawlogs*, which currently operates in Slovenia mainly at a basic level and in some cases at a more technologically sophisticated level. Currently, the use of hardwood in timber construction is associated with some challenges (e.g. standardization of structural hardwood, use of different tree species for certain products, etc.), but the same (similar) challenges also exist abroad. Knowing these challenges and, above all, solving them as quickly as possible, can also give this chain a competitive advantage on an international level.

In the case of sufficient investment in technology, infrastructure and improving the skills of employees, the chain P2 *Veneer logs*, which is currently (almost completely) non-functioning in Slovenia, is recognized as a very perspective chain (Kropivšek *et al.*, 2023), which could produce innovative products with very high added value (Gornik Bučar *et al.*, 2017). If this chain fails, the marginal log quality criterion, which is the fundamental criterion in the design of value chains, will not be met, as the raw material for this chain is of the highest quality.

The operation of the chain P3 *Wood for pulp and composites*, which is very limited in the current situation, requires large investments in infrastructure and in the competence of employees, while the chain has an extremely great potential for the production of innovative products. These products supply other forest-wood and related chains (e.g. timber construction, furniture manufacturing, ship and vehicle manufacturing, etc.), have great potential to replace other materials (Gornik Bučar *et al.*, 2017) and show great synergy effects.

The chain P4 *Other industrial wood* is supplied with raw material that is suitable for chemical processing or biorefineries. It has great potential for innovative products and for the substitution of other materials, but requires high investment in technology, additional expertise and investment in research and development. We assume that with appropriate social aspects (which we currently do not consider to be supportive), reasonable cost efficiency could be achieved in a relatively short time, which would have a positive impact on the entire chain. The chain P5 *Fuelwood* is a chain where the raw material is of the poorest quality and the end products are intended for energy use (mainly as firewood and/or pellets). Even though wood is a natural material, and the energy use of wood is recognized as CO_2 neutral, it should be emphasized that the use of wood as raw material for energy purposes means the shortest possible cycle, so the chain is also the shortest,

Table 1 List of evaluation variables with measurement scale and description
Tablica 1. Popis varijabli za procjenu s ocjenama i opisom

Aggregate attributes / *Zbirne značajke* — Input attributes (1st level) / *Ulazne značajke (1. razina)*	Measurement scale / *Ocjene*	Description / *Opis*
Value chain	Poor; Good; Very good; Excellent	Final evaluation of a value chain
Technological potential	1…limited; 2…medium; 3…great	What is the status of technological potential?
Complexity of technology	1…low; 2…medium; 3…high	What complexity of (production) technology is required to operate the chain?
Amount of investment in infrastructure	3… medium; 2... high; 1… very high	What is the level of investment in the technology at national level given the current situation?
Level of knowledge / competence	3...same; 2...a little higher; 1... much higher	What level of knowledge is required to operate the chain given the current state of the industry/economy?
Level of digitalization	1…low; 2…medium; 3…high	What is the potential/reasonable level of digitalization of the chain (smart chain, smart factory, etc.)?
Environmental potential	1…limited; 2…medium; 3…great	What is the status of environmental potential?
Carbon Footprint potential	1…limited; 2…medium; 3…great	What is the potential for environmental protection?
Substitution potential	1…limited; 2…medium; 3…great	What is the potential to replace other materials?
CE – Circular Economy	1…small; 2…medium; 3…great	To what extent does the chain/product comply with modern EU and global guidelines (development of rural areas, settlements, cities, etc.)?
Role in bioeconomy	1…small; 2…medium; 3…large	What significance does the chain have for the bioeconomy in the broader sense (incl. SSH)?
Market and development potential	1…limited; 2…medium; 3…great	What is the status of market and development potential?
Market potential	1…limited; 2…medium; 3…great	Global and local potential of the chain/products in terms of market size, market attractiveness, opportunities for market expansion, competition, and trends.
Quantitative potential	1…limited; 2…medium; 3…great	What is the potential given the availability of the raw material in suitable quality – marginal roundwood?
Added value potential	1…limited; 2…medium; 3…great	How high is the value creation potential for the products depending on the raw material used?
Cost efficiency	1…low; 2…medium; 3…high	What is the level of cost efficiency?
Innovation potential	1…limited; 2…medium; 3…great	What is the current situation regarding innovation potential?
Share of products with high added value	1…low; 2…medium; 3…high	How high is the proportion of products with higher added value due to investments in the chain?
Synergy with other chains	1…low; 2…medium; 3…high	What synergies or linkages are there with other chains, industries, products?
Investments in R&D	3…low; 2…medium; 1…high	What investments in R&D can be expected in order to achieve the chain development potential?
Share of innovative products	1…low; 2…medium; 3…high	How high is the proportion of innovative products in the next 5 years (current level: TRL 4 and higher)?
Social aspect	1…not supportive; 2…neither-nor; 3…supportive	What influence do external and social factors have on the chain?
Legal and economic policies	1…not supportive; 2…neither-nor; 3…supportive	Industrial strategy; digital society development; current and future economic growth; legal opportunities
Market (purchasing and selling)	1…not supportive; 2…neither-nor; 3…supportive	Purchasing power in the market; environmental awareness of the market and customers; competition for products with high added value
Infrastructure and financial resources	1…not supportive; 2…neither-nor; 3…supportive	Infrastructure development, supportive environment; government incentives (e.g. Green Deal...); availability of finance and investments; state aid for investment in R&D

as CO_2 is released much faster than when it is embedded in wood products. The chain has no great technological and innovative potential (except in the case of advanced biofuel production) and the added value of the products (especially pellets) is very sensitive to social aspects. The chain P5 *Fuelwood* has a very limited

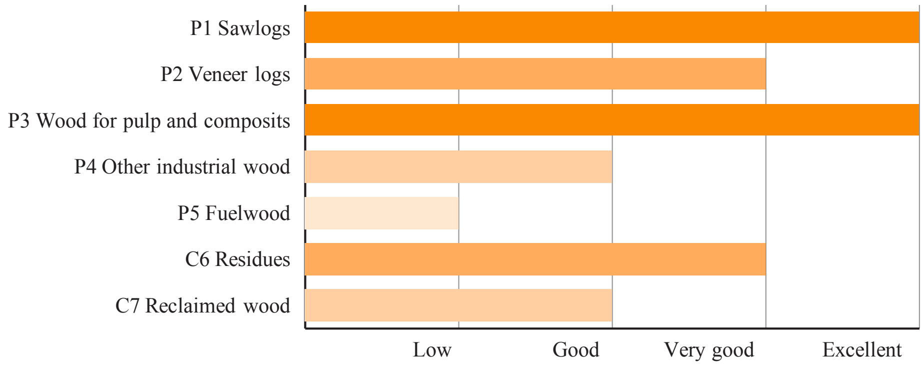

Figure 2 Final evaluation of alternatives (primary value chains)
Slika 2. Konačna ocjena alternativâ (primarni lanci vrijednosti)

potential for the introduction of the Industry 4.0 concept. There is currently a quantitative potential that can or will be fully exploited in the near future. From a sustainability perspective, chain P5 *Fuelwood* has no scope for expansion without interfering with the concept of marginal log quality. Furthermore, if the chains P4 *Other industrial wood* and P3 *Wood for pulp and composites* were to operate efficiently, the scope for the chain P5 *Fuelwood* would even be reduced in the future.

The connecting chains C6 *Residues* and C7 *Reclaimed wood* are not primary chains, but they are extremely important chains in the concept of the circular economy and sustainability. If the outputs of these chains are inputs for the chains P3 *Wood for pulp and composites* and P4 *Other industrial wood*, we also follow the concept of cascading use, so both chains are very promising and important for the forest-wood bioeconomy. However, if the outputs of the connecting chains are (mostly) inputs for chain P5 *Fuelwood*, the perspective and circularity of these chains is severely limited. The chains C6 *Residues* and C7 *Reclaimed wood* can otherwise be operated as fully separated chains, partially or fully connected, as they face (at least on a simple technological level) similar challenges (e.g. dispersion of input, collection and sorting logistics, etc.); on a more technologically demanding level, the chain C7 *Reclaimed wood* requires relatively large investments and new skills, while at the same time showing potential for innovation and substitution (Mehr *et al.*, 2018) and positive environmental impact. The operation of the chain C7 *Reclaimed wood* is also very sensitive to social aspects.

4 CONCLUSIONS
4. ZAKLJUČAK

It can be concluded that all primary value chains in the Slovenian forest and wood bioeconomy are very important for creating conditions for the maximum utilization of the potential of hardwood raw materials. From the point of view of providing basic and advanced materials for further value chains in the wood sector (and related industries), these are mainly the chains P1 *Sawlogs*, P2 *Veneer logs* and P3 *Wood for pulp and composites*, and for other industries also the most advanced materials from the chain P4 *Other industrial wood*, which still require a lot of investment in research and development to reach the level of their wider (industrial) implementation. In terms of ensuring circularity and sustainability, connecting chains C6 *Residues* and C7 *Reclaimed wood* are particularly important. To exploit their innovation and substitution potential, it is necessary to invest in development, research and employee knowledge.

However, due to the complexity of the forest-wood chain, we cannot choose the chain according to the "best option" principle, because for an optimal functioning of the entire forest-wood value chain, whose main raw material is hardwood, all primary chains are crucial (by analogy with (Falcone *et al.*, 2020), but they are not equivalent for the efficient functioning of the forest wood chain, which is the answer to our main research question.

For further research, we suggest extending the focus to the entire forest-wood chain, i.e. including the production of finished wood products (timber construction, furniture, vessels and other groups). When analyzing the chain, it would be useful to include all tree species, i.e. also conifers, which would provide a comprehensive picture of the functioning of the entire forest wood chain. In any case, it would be necessary to carry out an even more thorough analysis of the other chains linked to the wood chain and to investigate how they influence each other. We specifically refer to wood in construction, which is also recognized at the European level as a very perspective industry. Therefore, it is thoroughly researched, resulting in many ideas for improving the state of traditional wood chains (e.g. the European Basajaun project, which explores the possibilities of increasing the use of wood in construction (Cordis, 2023; Romih and Kropivšek, 2023). It is also necessary to network and collaborate with other forest

Table 2 Final evaluation of alternatives – detailed results
Tablica 2. Konačna ocjena alternativa – detaljni rezultati

Attributes *Značajke*	***P1*** Sawlogs *Pilanski trupci*	***P2*** Veneer logs *Furnirski trupci*	***P3*** Wood for pulp and composites *Drvo za celulozu i kompozite*	***P4*** Other industrial roundwood *Ostala industrijska oblovina*	***P5*** Fuelwood *Ogrjevno drvo*	***C6*** Residues *Ostatci*	***C7*** Reclaimed wood *Regener-irano drvo*
Value chain	**Excellent**	**Very Good**	**Excellent**	**Good**	**Poor**	**Very Good**	**Good**
Technological potential	**Medium**	**Medium**	**Medium**	**Medium**	**Limited**	**Great**	**Medium**
Complexity of technology	Medium	High	High	High	Low	Medium	Medium
Amount of investment in infrastructure	High	High	Very High	Very High	Medium	Medium	High
Level of knowledge / competence	Same	A little Higher	A little Higher	Much Higher	Much Higher	Same	A little Higher
Level of digitaliza-tion	Medium	High	High	High	Low	High	Medium
Environmental potential	**Great**	**Medium**	**Great**	**Great**	**Limited**	**Great**	**Great**
Carbon Footprint potential	Medium	Medium	Medium	Medium	**Limited**	**Great**	Medium
Substitution potential	**Great**	**Great**	**Great**	**Great**	Medium	Medium	Medium
CE – Circular Economy	**Great**	Medium	**Great**	Medium	**Small**	Medium	**Great**
Role in bioecono-my	Medium	Medium	Large	Large	**Small**	Large	Large
Market and development potential	**Great**	**Great**	**Great**	**Medium**	**Limited**	**Medium**	**Medium**
Market potential	**Great**	**Great**	**Great**	**Great**	Medium	Medium	Medium
Quantitative potential	**Great**	Medium	**Great**	**Great**	**Great**	**Great**	Medium
Added value potential	Medium	**Great**	**Great**	**Great**	**Limited**	Medium	Great
Cost efficiency	High	Medium	Medium	Low	Medium	High	Medium
Innovation potential	Medium	Medium	Medium	**Great**	**Limited**	Medium	**Limited**
Share of products with high added value	Medium	Medium	High	High	Low	Low	Low
Synergy with other chains	Medium	High	High	High	Low	High	High
Investments in R&D	Low	Medium	High	Medium	Low	Low	High
Share of innovative products	Medium	High	High	High	Low	Medium	Low
Social aspect	**Supportive**	**Supportive**	**Supportive**	**Not Supportive**	Neither-nor Supportive	Neither-nor Supportive	Neither-nor Supportive
Legal and econom-ic policies	Supportive	Supportive	Supportive	Neither-nor Supportive	Neither-nor Supportive	Supportive	Neither-nor Supportive
Market (purchasing and selling)	Supportive	Supportive	Supportive	Neither-nor Supportive	Neither-nor Supportive	Neither-nor Supportive	Not Supportive
Infrastructure and financial resources	Not Supportive	Not Supportive	Neither-nor Supportive	Not Supportive	Neither-nor Supportive	Not Supportive	Neither-nor Supportive

and wood chains in the region that are facing similar climatic (environmental) challenges and are looking for optimal solutions (following the example of the sustainable Mediterranean agri-food value chain (PRIMA, 2023).

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Possibilities of Using Artificial Intelligence in Furniture/Woodworking Industry

Mogućnosti primjene umjetne inteligencije u drvoprerađivačkoj industriji i proizvodnji namještaja

REVIEW PAPER

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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 also has great potential in various areas of the woodworking industry. In the design phase, AI-supported design software can facilitate the development of new ideas and shorten 3D modelling processes. In the construction phase, AI plays a crucial role in optimising construction details using techniques such as topology optimisation, numerical simulations and generative design. The use of AI can also be applied in the production process, where it automates the creation of CNC machining programs and optimises machining methods. Quality control is improved through AI monitoring of machines and surface quality using advanced image analysis and machine vision systems. In addition, AI contributes to predicting production needs and facilitates the maintenance of production machines. AI can be used in market analysis and enables companies to make informed decisions. It helps in the strategic planning of marketing activities and the sales process by providing insights derived from comprehensive market analyses. AI could help in creating marketing materials, communicating with customers, managing social networks and websites, analysing competitors, predicting demand, etc. The use of AI could enable major technological improvements with efficiency gains and innovation in various operational areas, but also causes some concerns about trust in these new systems and fear of being replaced by machines. AI should be seen as a tool to improve our productivity and performance, automate certain tasks and transform existing jobs. There is a need for ethical oversight, policy decisions and regulations to ensure fair treatment of all humans. An overview of currently available solutions was given to discover new opportunities for the use of AI in the wood industry, as a pivotal aspect of the ongoing digital transformation.*

KEYWORDS: *artificial intelligence; digital transformation; furniture design; woodworking industry*

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SAŽETAK • Primjena umjetne inteligencije (AI) u raznim područjima privuklo je veliku pozornost u protekloj godini, posebice nakon izlaska ChatGPT-a, besplatno dostupnoga inteligentnog online sustava. Nekoliko naprednih softverskih rješenja koja uključuju AI postaju sve dostupnija i mogu pomoći u poboljšanju svake sastavnice naših života. Korištenje AI-a također ima veliki potencijal u raznim područjima drvoprerađivačke industrije. Dizajnerski softver podržan AI-em u fazi projektiranja može olakšati razvoj novih ideja i skratiti procese 3D modeliranja. U fazi konstruiranja AI ima ključnu ulogu pri optimizaciji konstrukcijskih detalja zahvaljujući primjeni tehnika kao što su optimizacija topologije, numeričke simulacije i generativni dizajn. Korištenje AI-a također se proširuje na proizvodni proces putem automatizacije stvaranja CNC programa za obradu i optimizaciju metoda obrade. Kontrola kvalitete poboljšana je primjenom AI-a za praćenje rada strojeva i kvalitete površine uz pomoć napredne analize slike i sustava strojnog vida. Osim toga, AI pridonosi predviđanju proizvodnih potreba i olakšava održavanje proizvodnih strojeva. AI se može upotrijebiti i u analizi tržišta te tvrtkama omogućiti donošenje informiranih poslovnih odluka. Pomaže u strateškom planiranju marketinških aktivnosti i procesa prodaje dajući uvide proizašle iz sveobuhvatnih analiza tržišta. AI bi mogao pomoći i u kreiranju marketinških materijala, komunikaciji s kupcima, upravljanju društvenim mrežama i web stranicama, u analizi konkurenata, predviđanju potražnje itd. Primjena AI-a mogla bi omogućiti velika tehnološka poboljšanja, uz povećanje učinkovitosti i postizanje inovacija u raznim operativnim područjima, ali ipak donosi i dozu zabrinutosti glede povjerenja u te nove sustave, kao i strah da će sve ljude zamijeniti strojevi. No AI treba promatrati kao alat za poboljšanje naše produktivnosti i performansi, za automatizaciju određenih zadataka i transformaciju postojećih poslova. Definitivno postoji potreba za etičkim nadzorom, političkim odlukama i propisima kako bi se osiguralo pošteno postupanje prema svim ljudima. Dan je pregled trenutačno dostupnih rješenja da bi se otkrile nove prilike za primjenu umjetne inteligencije u drvnoj industriji kao ključnom aspektu digitalne transformacije koja je u tijeku.

KLJUČNE RIJEČI: *umjetna inteligencija; digitalna transformacija; dizajn namještaja; drvna industrija*

1 INTRODUCTION
1. UVOD

Artificial intelligence (AI) refers to the simulation of human intelligence in machines, especially computer systems, that are programmed to think, learn and solve problems like humans (National Science and Technology Council, 2016; Russell and Norvig, 2010). There are various definitions of AI that emphasise the behaviour that requires intelligence or the rational management of complex problems or the taking of appropriate actions to achieve goals under changing conditions.

AI, which includes technologies such as machine learning and deep learning algorithms, enables computers to analyse large amounts of data, recognise patterns and make decisions. These systems mimic human intelligence by performing tasks such as understanding natural language, recognising speech or images and making predictions. The aim of artificial intelligence is to develop machines that can adapt and continuously improve on their own, so that over time they can better deal with complicated problems and tasks (National Science and Technology Council, 2016). As a transformative technology, AI is revolutionising various industries, from healthcare and finance to manufacturing and entertainment, fundamentally changing the way we live, work and interact with the world.

The fundamental ideas of artificial intelligence were formulated by Alan Turing in his famous 1950 paper, "Computing Machinery and Intelligence", with the question: "Can machines think?". Milestones in the development of AI were the victory of IBM's chess computer Deep Blue over the world champion Garry Kasparov in 1997, DARPA's Cognitive Agent that Learns and Organises (CALO), from which Siri from Apple Inc. emerged, the victory of IBM's question-and-answer computer Watson in the TV game show "Jeopardy!" and the success of self-driving cars in the DARPA Grand Challenge competitions in the 2000s (National Science and Technology Council, 2016; Stone *et al.*, 2022).

With the availability of big data from multiple sources, improved machine learning approaches and algorithms, more powerful computers and increasing investment, AI has really evolved over the last decade. In current AI practises, machines predominantly plan, manage, control and optimise work without adequately considering human input and preferences (Rafsanjani and Hossein Nabizadeh, 2023). While AI tools are advanced, they are not omnipotent and require intelligent input from users. Users must carefully consider their input to optimise idea, prototype and solution generation. The syntax of the questions is of great importance.

The use of AI in the economy is closely linked to digitalisation and can be intertwined with it in various ways. Digitalisation is changing the way companies do business and is closely linked to investing in, developing and using modern (digital) technologies. It involves the use of digital technologies to change a technology-based business model to generate new revenue and value by creating new opportunities; it is the process of transitioning to a digital enterprise (Rachinger *et al.*, 2019).

Despite the great importance of the digital transformation of companies and despite the economic growth in Slovenia in recent years, as many as 82 % of Slovenian companies have a low digital index in 2019, and the situation is even worse among manufacturing companies (Kmet Zupančič, 2019; Zupan, 2017). In 2022, the proportion of larger companies with a low digitalisation index was still 73 %, while the situation is even worse for small companies (81 % with a low index) ("Digital entrepreneurship, detailed data, 2022," n.d.).

Companies must decide how and where to invest in new technologies and which ones best meet their needs. Within the technological pillars and trends of the concept of digital transformation within the fourth industrial revolution, blockchain, digital twins, quantum computing, augmented analytics and artificial intelligence are expected to drive disruption and new business models (Panetta, 2018). We are approaching the concept of the 'smart factory', also referred to as the U-factory, factory of things and smart factory of the future (Hozdić, 2015; Movrin, 2017), arguing that a smart factory combines the human, the product, the process and the organisation into a holistic system and includes the following components: smart products, smart equipment, smart people, smart conceptual processes and smart management.

Smart factories are a key feature of Industry 4.0 and they focus on the creation of intelligent products, processes and procedures with an emphasis on sustainable development (Červený *et al.*, 2022). Globalisation and networking will be crucial for the future nature of production – in the post-Internet of Things or so-called Industry 4.0 era (Matt and Rauch, 2020). The new direction, Industry 5.0, is already emerging, aimimg to highlight the role of humans in Cyber–Physical Systems (CPS) and promote the symbiosis of humans with new technologies. This new model for creating the factories of the future is known as the Human–Cyber–Physical System (HCPS) (Saniuk *et al.*, 2022). It is about the penetration of artificial intelligence into people's everyday lives, their "collaboration" to strengthen human capabilities and the return of humans to the "centre of the universe". In this context, the term Industry 5.0 Society 5.0 is more appropriate (Červený *et al.*, 2022; Saniuk *et al.*, 2022).

Industry 4.0 is a great opportunity for woodworking processes. Wood is a material of biological origin that is subject to fluctuations during the manufacturing process. Today, robust sensors, computing capacity, communication and intelligent algorithms make it possible to control the variability of wood. By learning from data, actions can be taken in real time (Ramos-Maldonado *et al.*, 2021). Based on the results of the study of the level of digitalisation in the Slovenian wood industry (Kropivšek and Grošelj, 2020), which found that digitalisation is still at a relatively low level, awareness of the importance of digitalisation and previous experience with digitalisation appear to be the main reasons for the further development of such technologies and approaches in companies. In the context of investment in ICT, companies rate investment in cloud computing and conversational platforms, the development of smart apps and smart things, and the implementation of some elements of the smart factory (i.e. advanced materials, sensor technologies, smart guidance systems and smart mechatronic tools) as most important.

The aim of this review article was to provide an overview of the currently available solutions that are based on the use of AI to support processes in the wood industry as an important aspect of the digital transformation of wood processing companies. We wanted to show how AI can support various processes and be an important part of the digitalisation of wood processing companies in line with New European Bauhaus values. The aim was also to help woodworking companies understand the practical ways in which AI can shape their operations and make them more efficient and competitive.

2 AI IN MANUFACTURING – POSSIBLE USES OF AI IN WOODWORKING INDUSTRY

2. AI U PROIZVODNJI – MOGUĆNOSTI KORIŠTENJA AI-a U DRVNOJ INDUSTRIJI

The woodworking industry today faces various challenges and opportunities that emphasise the need for innovation and dominance in the furniture market during the transition from the traditional furniture industry to smart upgrading (Xiong *et al.*, 2017). Sustainable furniture design has emerged as an important area of research that focuses on the interactions between people, furniture and the environment (Ashraf and Johar Town, 2023; Zhu *et al.*, 2023). In the past, furniture factories relied on manual labour and craftsmanship to produce furniture. With technological advancements, furniture factories are now integrating AI into their production processes to improve efficiency, quality and customer satisfaction (Ahmadli, 2023).

AI can be used in various ways in the wood processing industry to increase productivity, quality and efficiency. Here are some selected promising (in our opinion) applications of AI technologies in the wood industry:

- Generative design and customisation
- Optimisation of the supply chain
- Quality control and inspection
- Predictive maintenance
- Virtual shopping and augmented reality (AR)

These technologies offer numerous opportunities to increase efficiency, personalise products and improve the customer experience. Their application is constantly evolving as technology advances and companies find new ways to utilise them. Each of these technologies is briefly described. In addition, the tenets of the New European Bauhaus, focusing on sustainability, aesthetics, and cross-disciplinary collaboration, also exhibit potential synergy with the integration of Artificial Intelligence (AI) in the woodworking industry.

2.1 Generative design and customisation
2.1. Generativni dizajn i prilagodba

AI-powered generative design algorithms can create a variety of unique furniture designs based on specific parameters and constraints. This allows designers and customers to quickly explore a variety of creative options (Kocaman and Toğay, 2023). AI can also facilitate real-time personalisation, allowing customers to personalise furniture pieces according to their preferences, resulting in bespoke designs. Various platforms have been developed in recent years, some of which are already available to the public. Various versions are used, such as the creation of 3D models from existing images, text-to-image and 3D model generators, applications that modify or optimise existing models.

Spline AI, Masterpiece Studio, MirageML or 3DFY, for example, are AI-supported text-to-3D generators that can create photorealistic 3D models in response to text instructions ("Spline AI – 3D Design faster with AI.," n.d.). Only a few lines of text are required from users to generate fully functional 3D models and animations (Figure 1) (Caires *et al*., 2024). The AI text-to-3D generator turns a user's descriptive speech into a 3D model using sophisticated natural language processing (NLP) technology ("Generate – Masterpiece X," n.d.). In these cases, the exact product description is needed, and a correct prompt is important (usually at least 3-7 words long, including subject and descriptors, avoid abstract description, with added aesthetic and stylistic keywords). The text can also be created using AI-assisted generators, or even brainstorming using various platforms such as www. NUclino.com.

Sometimes it is easier to start modelling from an existing sketch or photo of a product. Make3D and Kaedim3D are web applications that allow you to convert a 2D image into a high-resolution, production-ready 3D model without the need for prior modelling experience. This process is fully automated and simply requires you to upload your image to the website and wait for the model to be generated (Figure 1, right). Even images for 3D model generators can be created based on some initial sketches using the Midjourney platform.

AI also offers great support in the creation of realistic photos of existing 3D models. The NeROIC (Neural Rendering of Objects from Online Image Collections) app, for example, suggests different lighting and style settings and generates several different rendered views of the model so that the users only have to select the photo they like best (Figure 2).

AI in design can create new shapes and forms and optimise product structures. Traditional furniture design is based on experience, calculations or finite element analyses. Generative design software improves this process by optimising the design based on constraints such as load, material properties and product lifespan, considering the environmental impact in terms of sustainability (Papallo *et al*., 2023).

Generative design, a subfield of artificial intelligence, addresses technical issues with defined constraints and offers a range of solutions. It can be used in various industries such as consumer goods, automotive, aerospace, industrial machinery and building products. The main application is the automatic generation of pre-tested design options that fulfil specific requirements (Miles, 2022). The fundamental goals of

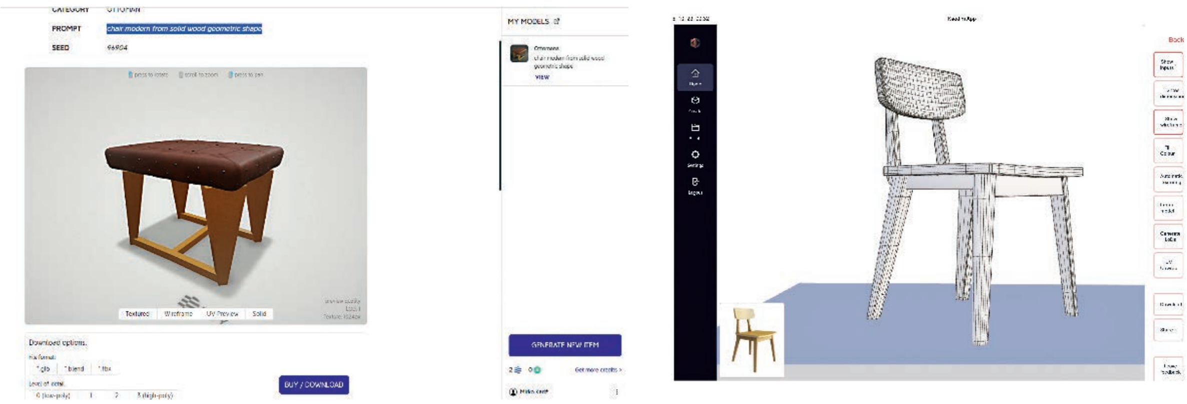

Figure 1 Left: Suggested model of chair from text prompt: "*chair modern from solid wood geometric shape*"("3DFY Prompt – Download Model," n.d.); right: 3D model from image generator – Kaedim3d (https://www.app.kaedim3d.com/dashboard)
Slika 1. Lijevo: predloženi model stolice iz tekstualnog upitnika opisan kao: "moderna stolica od punog drva geometrijskog oblika" ("3DFY Prompt – Download Model", n.d.); desno: 3D model iz generatora slika – Kaedim3d (https://www.app.kaedim3d.com/dashboard)

Figure 2 Example of AI supported rendering app NeROIC (Kuang *et al.*, 2022)
Slika 2. Primjer aplikacije za renderiranje NeROIC podržane umjetnom inteligencijom (Kuang *et al.*, 2022.)

Figure 3 Left: Generative design of construction joint concept (Han *et al*., 2022); right: AI Chair made with support of generative design tools ("A.I. chair Starck Kartel," 2020)
Slika 3. Lijevo: generativni dizajn koncepta konstrukcijskog spoja (Han *et al*., 2022); desno: AI stolica izrađena uz podršku alata za generativni dizajn ("AI chair Starck Kartel", 2020.)

generative design are to improve product performance (e.g. lightweight construction for logistics and sustainability), reduce costs and promote innovation. In contrast to traditional design methods or optimisation methods such as topology optimisation, generative design starts earlier and presents ideas based on functional constraints rather than incrementally improving an existing solution.

Topology optimisation refines an engineer's original solution, while generative design explores the entire design space to propose solutions without relying on an existing design (Miles, 2022). With the rapid development of AI, generative design introduces more automatic and efficient methods for collaborative designs (Figure 3) and provides a modern approach to comprehensive design plans (Han *et al*., 2022; Tyflopoulos *et al*., 2018).

One of the first famous commercial furniture products to be produced using AI was the "AI chair", designed by "Philippe Starck" in collaboration with the Italian furniture manufacturer Kartell using Autodesk's generative design tools ("A.I. chair Starck Kartel," 2020; Buonamici *et al*., 2021) (Figure 3).

AI, especially machine learning algorithms, has the potential to revolutionise the modern furniture industry. By analysing consumer data from sources such as social media, online searches and purchase history, AI can predict design trends and preferences (Haleem *et al*., 2022). This information enables designers to create furniture that is customised to consumer needs and desires (Ai in the Furniture Industry: Business Better with or without Ai?, n.d.). Furthermore, the influence of AI extends to both the creative and scientific aspects of furniture design by providing innovative ideas and assisting with stress calculations, design constraints and statistical analyses (Zahra, 2023), thereby reducing material waste and manufacturing costs (Ahmadli, 2023). In the manufacturing of complex products, AI can be used as a decision support system by analysing big data and product lifecycles to identify industry differences and select optimal production methods (Luo *et al*., 2021).

Traditionally, designers invest a lot of time in tasks such as data research, sketching, material selection and structural testing to achieve a few design results. However, AI can quickly generate thousands of results and help designers analyse complex data, simulate thought processes and solve problems intelligently. AI results can even present unique shapes not conceived by humans, with the final selection left to the designer's discretion (Zahra, 2023).

While many open-source AI tools such as TensorFlow and PyTorch are available for free, some platforms offer limited free access with possible usage restrictions. For example, Kaedim3d.com, a photo-to-3D model creation service, offers various pricing plans (for 50 models, the price is $300 per month), which emphasises the importance of checking costs on official websites or documentation, being aware of product development costs.

2.2 Supply chain optimisation
2.2. Optimizacija lanca opskrbe

AI algorithms can analyse historical data, market trends (Bharadiya, 2023) and customer preferences using machine learning algorithms to optimise the furniture supply chain. This includes demand forecasting, inventory management and efficient logistics, resulting in lower costs and less waste. By analysing data from social media, online searches and purchase history, the AI can identify the most popular styles, colours and materials. This information can then be used by designers to create furniture that meets the needs and desires of consumers.

Inventory management is another area where AI can improve efficiency and reduce costs. By analysing demand patterns, AI algorithms can optimise stock levels, reducing the risk of over or under stocking. This can help to reduce inventory costs, improve production planning and increase customer satisfaction (Ahmadli, 2023).

However, there is also great potential in using AI to manage waste or used furniture and all types of wood materials in the supply chain to promote sustainability and efficiency in forest-based supply chains (Feng and Audy, 2020; Onyeaka *et al.*, 2023). Many wood wastes remain unutilised or are used for low value-added products or even for heating purposes, which could be better utilised with better decision support systems (Garcia and Hora, 2017). Advanced planning systems can help support the decisions of the different actors in the supply chain, e.g. forest owners, harvesters, transporters, wood processing industry, traders and users. Such tools can help manage the complex interdependencies between different companies that often have conflicting goals and actions, which can increase the efficiency of forest-based supply chains (Scholz *et al.*, 2018).

In the sawmill industry, for example, many efforts have already been made to use resources effectively, plan optimally and maximise productivity, but there are still many challenges ahead. AI-based approaches are the most popular techniques for solving optimisation problems, especially in the transport and logistics sector. The combination of AI techniques such as neural networks, multi-agent simulation, genetic algorithm, ant colony algorithm, simulated annealing, discrete event simulation and mathematical programming, etc. with simulation models significantly enriches the flexibility of problem solving (Hosseini and Peer, 2022; Rahman *et al.*, 2014).

Inventory management, including inventory analysis with systems that read images in real time to count boards, identifies sizes and minimises waste. Traditionally, these operations rely on manual processes and outdated systems, leading to inefficiencies, errors and increased costs (Albayrak Ünal *et al.*, 2023, Singh and Adhikari, 2023). Sales forecasting and delivery logistics will all utilise AI and machine learning. This technology will permeate the entire timber supply chain. AI can analyse historical data and current market trends to predict demand and help sellers optimise their stock levels and reduce waste.

2.3 Quality control and inspection
2.3. Kontrola kvalitete i nadzor

AI-based computer vision systems can inspect furniture components and finished products for defects to ensure compliance with quality standards. AI algorithms can analyse images, videos and sensor data to detect defects, deviations from specifications and inconsistencies (Ren *et al.*, 2021). This can lead to early detection of defects, reduce rework and increase customer satisfaction. Advanced robotics and AI-driven machines are used to produce customised furniture with incredible precision and speed. These machines can cut, mould and assemble furniture with an accuracy that would be impossible for humans to achieve. Current problems in the furniture industry such as low production efficiency, low accuracy and lack of product innovation can be addressed by introducing AI management systems to improve product quality and production efficiency in furniture companies (Jin Long *et al.*, 2020).

AI with augmented reality (AR) equipment can help improve the quality and efficiency of wood processing and assembly. For example, AR can provide workers with advanced work instructions, real-time feedback and quality control (Deshpande *et al.*, 2021). AR can also help workers detect and repair defects and damage to wood products ("AI in Manufacturing: Solutions & Stories | Microsoft AI," n.d.).

AI can facilitate the automation of tasks by enabling machines (including robots) to take over or facilitate repetitive, routine and dangerous tasks that would otherwise be performed by humans (Deshpande *et al.*, 2021). The machines are not affected by repetitive tasks, and the quality of the products thus manufactured is more consistent and with less degradation.

AI-assisted quality control of the wood surfaces of CLT panels could be combined with autonomous material handling and thus incorporate Industry 4.0 concepts such as the Industrial Internet of Things (IoT), the smart factory, flexible automation and cyber-physical systems to create modern automated production (Ericsson *et al.*, 2021). In sawmills, AI can be used to sort logs based on their quality, texture and other characteristics. This data could then be used to optimise the allocation of logs and wood parts to conserve resources, reduce waste and increase the value of incoming material ("AI for the wood processing industry | Bid Group," n.d.). Defect detection is another area where AI can recognise knots and other defects to cut out bad sections using connected tools and machines (Lopes *et al.*, 2020).

Artificial intelligence (AI) is revolutionising the field of computer-aided numerical control (CNC) and manufacturing by optimising various steps in the production process. AI-powered computer-aided manufacturing (CAM) software can automatically generate CNC programmes from CAD models and optimise machining parameters, workflows, toolpaths and speeds, leading to shorter cycle times, improved tool life and higher quality results (Hashmi *et al.*, 2022; Park and Kim, 1998; Soori *et al.*, 2023). During the production process, the machines and the product could be monitored by various methods such as image processing or various sensors (vibrations, acoustic emissions, power consumption, temperature, etc.) and the processes could be optimally adapted (Soori *et al.*, 2023). By combining 3D scanning, image analysis, AI-supported machine vision and other measuring instruments, the final product can be compared with the original CAD model, deviations or errors can be recognised and the production process can be adjusted to improve efficiency and quality (Rojek *et al.*, 2022).

2.4 Predictive maintenance
2.4. Prediktivno održavanje

AI-powered sensors in furniture manufacturing monitor the condition of machines and analyse data patterns to predict maintenance needs, prevent breakdowns and ensure smooth production. Together with cameras, these sensors can detect faults, alert maintenance teams and self-correct errors to minimise downtime and improve plant utilisation (Ahmadli, 2023).

Artificial intelligence is also extending its influence on CNC machine tools by predicting maintenance periods and equipment structures. By analysing production data, AI provides insights into machine performance and tool life and helps with production planning by indicating maintenance intervals. This predictive data results in fewer tool failures, longer tool life, reduced downtime and machining times, ultimately leading to cost savings in part production (Soori *et al*., 2023).

2.5 Virtual shopping and augmented reality (AR)
2.5. Virtualna kupnja i proširena stvarnost (AR)

AI could be involved in customer service on several levels. AI-driven chatbots can instantly help customers with personalised support, product recommendations and purchase assistance (Zimmermann *et al.*, 2023). This can improve customer satisfaction and reduce the workload of customer service agents, allowing them to focus on more complex issues (Ahmadli, 2023). One example is the Alibaba chatbot, which handled 95 % of customer enquiries in 2017, allowing human employees to focus on complex cases and challenging interactions with customers (Deshpande *et al.*, 2021). AI can be used as a content generator for marketing materials, such as product descriptions and social media posts (Anantrasirichai and Bull, 2021).

By analysing big data about consumer preferences, AI can create personalised furniture designs based on individual preferences and needs. The right product could be suggested and presented to customers with its advantages and disadvantages. On the other hand, the analysis of buyer behaviour, products and future trends could be suggested to the production departments.

AI-driven virtual shopping platforms can offer customers immersive experiences that allow them to visualise pieces of furniture in their living spaces through augmented reality. This improves the online shopping experience, reduces the risk of returns and gives customers the opportunity to make informed decisions. With virtual reality (VR) and AR tools, furniture selection is now even more immersive. Designers traditionally provide complex sketches that are often difficult for customers to understand. With augmented reality, customers can view and even change interior designs in real time (Carvalho *et al.*, 2011).

Augmented reality could also be used to support complex engineering tasks, including for ready-to-assemble furniture, especially for first-time users of such furniture (Deshpande & Kim, 2018), ultimately increasing user satisfaction and reducing the risk of frustration, poor usability, product damage and user injury.

An AI-powered camera and non-invasive technologies could be used to detect and analyse users' biometric reactions in order to recognise their emotions and changes in behaviour. Based on big data analysis, decisions could be made to change the interior design to simulate a change in user behaviour and increase the efficiency of the space ("AMBIT Cluster – Interiors Living Lab," 2022).

3 CONCERNS ABOUT USING AI TECHNOLOGIES
3. ZABRINUTOST U VEZI S PRIMJENOM AI TEHNOLOGIJA

The use of AI enables such technological improvement in terms of scientific advances, human welfare, economic value and the potential to solve important social and environmental problems that are certain to become more prevalent in our daily lives (Omrani *et al.*, 2022; Russo-Spena *et al.*, 2019). The success of the integration of AI in companies depends crucially on employees' trust in AI technology. Trust is a central component of the interaction between humans and AI, as the wrong level of trust can lead to incorrect use, misuse or non-use of the technology (Omrani *et al.*, 2022).

Current AI models can approximate the cognitive abilities of humans in many areas and are even better than humans in some of them. This opens the possibility of fully automating some tasks, including those that require sophisticated skills and decision-making. However, this has raised concerns about the risk of unemployment for skilled workers (Kwilinski *et al.*, 2020; Omrani *et al.*, 2022) and questions about trust in new systems. The fear of being replaced by artificial intelligence and automation is a widespread concern, especially as these technologies are advancing rapidly (Brower, 2023; Cox, 2023). According to a recent study that analysed 300 fictional and non-fictional works about AI, people's fears about intelligent machines can be divided into four main categories (Cave and Dihal, 2019): fear of loss of identity (also known as 'inhumanity"); fear of 'obsolescence' or obsolescence; concern that humans will no longer need each other (also known as 'alienation"); and concern that AI will rebel against humans. The most discussed concern is the first, and it is generally agreed that increasing automation will increase the AI fear factor (Khogali and Mekid, 2023).

However, AI should be seen as a tool to improve our productivity and performance, to automate certain tasks and to transform existing jobs. While certain jobs can be automated, the development, implementation and maintenance of AI systems also creates jobs in areas such as AI research, software engineering, data analytics and cybersecurity. With the increasing integration of AI into the workplace, there will be a need for ethical oversight, policy decisions and regulations to ensure fair treatment of workers. Addressing concerns related to job displacement will require careful consideration of the social and economic impact of these technologies.

The costs of AI-supported systems are also significant as the tools are not equally available to all people. This is all the more true for education systems. The concept of equality in the context of the use of paid AI raises several issues that need to be considered: availability of technology or internet connection, opportunities limited by financial constraints, ethical considerations on equal access to AI services, etc.

4 CONCLUSIONS
4. ZAKLJUČAK

AI is transforming the modern furniture industry by driving innovation, improving design processes, optimising supply chains and enhancing quality control. It also offers exciting opportunities for customer engagement and augmented reality applications that ultimately improve the overall customer experience. Accessibility and cost considerations remain key factors for the widespread adoption of these technologies in the industry. In addition, experts predict that AI will continue to evolve at a rapid pace and become even more powerful over the next few years at least, while computing power will continue to increase as companies spend more money and the underlying technology becomes cheaper (Henshall, 2023).

Companies continue to see profits in the business areas where they use AI and plan to increase their investments in the coming years (McKinsey & Company, 2023). Consequently, the integration of AI into the modern furniture industry is crucial and has great potential to transform various aspects of the sector and drive the industrial transition to digitalisation and circular economy practises.

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Upute

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Primjer

Kärki, T., 2001: Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz als Roh- und Werkstoff, 59: 79-84. http://dx.doi.org/10.1007/s001070050479.

Knjige: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. (ev. izdavač/editor): izdanje (ev. svezak). Mjesto izdanja, izdavač (ev. stranice od – do).

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Ostale publikacije (brošure, studije itd.)

Müller, D., 1977: Beitrag zür Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forstund Holzvvirt schaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

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Kärki, T., 2001: Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz als Roh- und Werkstoff, 59: 79-84. http://dx.doi.org/10.1007/s001070050479.

Books:
Author's second name, initial(s) of the first name, year: Title. (ev. Publisher/editor): edition, (ev. volume). Place of publishing, publisher (ev. pages from - to).

Examples:
Krpan, J. 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb: Tehnička knjiga.
Wilson, J.W.; Wellwood, R.W. 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551-559.

Other publications (brochures, studies, etc.):
Müller, D. 1977: Beitrag zur Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanslalt für Forst- und Holzwirtschaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Websites:
***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node 00.html. First published 1997 (Accessed Jan. 27, 2010).

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HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE

Osnovana je na temelju Zakona o Hrvatskoj komori inženjera šumarstva i drvne tehnologije.

Komora je samostalna i neovisna strukovna organizacija koja obavlja povjerene joj javne ovlasti, čuva ugled, čast i prava svojih članova, skrbi da ovlašteni inženjeri obavljaju svoje poslove savjesno i u skladu sa zakonom, promiče, zastupa i usklađuje njihove interese pred državnim i drugim tijelima u zemlji i inozemstvu.

Članovi komore:

inženjeri šumarstva i drvne tehnologije koji obavljaju stručne poslove iz područja šumarstva, lovstva i drvne tehnologije.

Stručni poslovi:

projektiranje, izrada, procjena, izvođenje i nadzor radova iz područja uzgajanja, uređivanja, iskorištavanja i otvaranja šuma, lovstva, zaštite šuma, hortikulture, rasadničarske proizvodnje, savjetovanja, ispitivanja kvalitete proizvoda, sudskoga vještačenja, izrade i revizije stručnih studija i planova, kontrola projekata i stručne dokumentacije, izgradnja uređaja, izbor opreme, objekata, procesa i sustava, stručno osposobljavanje i licenciranje radova u šumarstvu, lovstvu i preradi drva.

Zadaci Komore:

- promicanje razvoja struke i skrb o stručnom usavršavanju članova,
- poticanje donošenja propisa kojima se utvrđuju javne ovlasti Komore,
- reagiranje struke na pripremu propisa iz područja šumarstva, lovstva i drvne tehnologije,
- suradnja s nadležnim institucijama i zastupanje struke u odnosu prema njima,
- organizacija stručnoga usavršavanja,
- zastupanje interesa svojih članova,
- izdavanje pečata i iskaznice ovlaštenim inženjerima,
- briga i nadzor poštivanja kodeksa strukovne etike,
- osiguravanje članova Komore za štetu koja bi mogla nastati investitorima i trećim osobama i sl.

Članovima Komore izdaje se rješenje, pečat i iskaznica ovlaštenoga inženjera.
Za uspješno obavljanje zadataka te za postizanje ciljeva ravnopravnoga i jednakovrijednoga zastupanja struka udruženih u Komoru, članovi Komore organizirani su u razrede:

- Razred inženjera šumarstva
- Razred inženjera drvne tehnologije

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