LES/WOOD

VSEBINA / CONTENTS

Letnik 70, številka 2 / Volume 70, Number 2

Novice / News

Les/Wood

Založila/*Published by*
Založba Univerze v Ljubljani / *University of Ljubljana Press*

Za založbo/*For the Publisher*
Gregor Majdič, rektor Univerze v Ljubljani / *the Rector of the University of Ljubljana*

Izdala/*Issued by*
Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za lesarstvo /
University of Ljubljana, Biotehnical Faculty, Department of Wood Science and Technology

Za izdajatelja/*For the Issuer*
Nataša Poklar Ulrih, dekanja Biotehniške fakultete UL / *the Dean of the Biotehnical Faculty UL*

Naslov uredništva/*Editorial Office Address*
Univerza v Ljubljani, Biotehniška fakulteta, Revija Les/Wood, Jamnikarjeva ulica 101, 1000 Ljubljana, Slovenia

Jezikovni pregled/*Proofreading*
Darja Vranjek (slovensko besedilo/*Slovene text*)
Paul Steed (angleško besedilo/*English text*)

Prelom/*Layout*
DECOP, d.o.o., Železniki

Tisk/*Print*
Tiskarna Roboplast d. o. o., Ljubljana
Natisnjeno v decembru 2021 v 100 izvodih./*Printed in December 2021 in 100 copies.*

ISSN 0024-1067 (tiskana verzija/*printed version*)

ISSN 2590-9932 (spletna verzija/*on-line version*)

http://www.les-wood.si/

Periodičnost/*Frequency*
Dve številki letno/*Two issues per year*

Les/Wood je referiran v mednarodnih bibliografskih zbirkah
Les/Wood is indexed in the international bibliographic databases
AGRIS, CAB Abstract

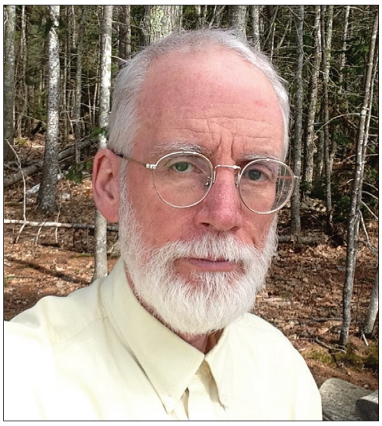
Izdajanje revije sofinancira Javna agencija za raziskovalno dejavnost Republike Slovenije (ARRS)
The journal is co-financed by Slovenian Research Agency (ARRS)

LES/WOOD

EDITORIAL / UVODNIK

Reflections by a member of the Editorial Board / Razmišljanje člana uredniškega odbora

Kevin T. Smith



I thank Co-Editors Ass. Prof. Dr. Jože Kropivšek and Prof. Dr. Katarina Čufar for the opportunity to serve as an Editorial Board member of *Les/Wood*, an international journal firmly grounded in the broad sweep of Slovene wood science and technology. The Editorial Board works to extend the relevance and impact of *Les/Wood* within and beyond Slovenia to the international community of wood science and technology in the broadest sense. We see the journal as a tool to support research and development of specific technologies, as well as to develop common terminology.

I would like to use this opportunity to sketch out how I came to be involved with wood science in Slovenia. In retrospect that involvement seems inevitable, but the path was not always clear at the time! After completing my postgraduate education in plant pathology and mycology in the USA in 1982, I accepted my current position as supervisory plant physiologist for the USDA Forest Service, a US federal land management agency with a strong commitment to research & development and to international forestry.

Throughout my career, my personal research has involved tree growth and wood decay in response to injury, infection, and environmental change. These tree responses affect forest health, the economic value of wood for art and industry, the tree-ring record of environmental conditions, and the performance of trees in urban and community environments.

My USDA FS mentor and colleague Dr. Walter Shortle met Prof. Dr. Niko Torelli and Prof. Dr. Katarina Čufar at the IAWA conference in Hamburg (1983) and at the IUFRO World Conference 1996 in Ljubljana, where the two of them were local organizers. Afterwards they obtained a joint Yugoslav American Project, "Possible alterations of wood in air polluted trees", which defined my earlier collaborations with Professor Torelli and Katarina Čufar on silver fir decline in Slovenia and Europe. Later, Katarina Čufar, Dr. Tom Levanič, and I identified changes in the climatic responses of silver fir in Slovenia and of red spruce in the northeastern US. I also worked with Dr. Primož Oven on special considerations for the health and safety of city trees. Later, Katarina Čufar and I both served on the Executive Council of the Tree Ring Society, an international association for dendrochronological research. We co-taught a tree biology section at the Dendro Fieldweek as part of the World Dendro conference 2010 in Finland. We found that our combination of research experience both intensified and broadened our understanding and presentation of wood structure and function. Since then, we have worked to provide Slovene students and scientists a platform to share techniques and experiences that both extend the science and community of scientists in the international research community.

As an active researcher, I see *Les/Wood* as noteworthy because of the potential breadth of articles reporting on topics from wood mechanical properties to technologies and industrial processing to underlying anatomy and the biological processes that result in wood formation and preservation. In addition to the high level of scholarship and technical expertise within *Les/Wood*, I find collegiality of spirit, openness of approach, and pride of history and context. These qualities lift up and support ongoing and future research for Slovenia, its geographic surroundings, and the broader world research community. I'm excited at the prospect of *Les/Wood* extending its traditional strengths to meet the critical need for wood science to optimize wood utilization, ecological understanding, and cultural patrimony.

Zahvaljujem se sourednikoma doc. dr. Jožetu Kropivšku in prof. dr. Katarini Čufar za priložnost, da sem postal član uredniškega odbora revije Les/Wood, ki je trdno zasidrana v širokem spektru znanosti o lesu v Sloveniji. Uredniški odbor si prizadeva razširiti pomen in vpliv revije Les/Wood na širšo geografsko regijo in širšo mednarodno skupnost. Revijo vidimo kot orodje za podporo raziskavam in razvoju znanosti in tehnologij ter strokovne terminologije.

Ob tej priložnosti bi rad orisal, kako sem prišel v stik z znanostjo o lesu v Sloveniji. Če se ozrem nazaj, se zdi, da je bila ta vključenost neizogibna, vendar pot na začetku ni bila tako jasna! Po končanem podiplomskem izobraževanju iz rastlinske patologije in mikologije v ZDA sem se leta 1982 zaposlil na sedanjem delovnem mestu nadzornega rastlinskega fiziologa pri USDA Forest Service, ameriški zvezni agenciji za upravljanje okolja, ki je močno zavezana raziskavam in razvoju ter mednarodnemu gozdarstvu v najširšem smislu.

V svoji karieri sem se posvečal raziskavam rasti dreves in razkroju lesa kot odzivu na poškodbe, okužbe in okoljske spremembe. Ti odzivi dreves vplivajo na zdravje gozdov, ekonomsko vrednost lesa za predelavo in rabo, informacije o okoljskih razmerah, zapisane v branikah ter obnašanje dreves v urbanem in skupnostnem okolju.

Moj mentor in kolega iz USDA FS dr. Walter Shortle je prof. dr. Nika Torellija in prof. dr. Katarino Čufar spoznal na konferenci IAWA v Hamburgu (1983) in na svetovni konferenci IUFRO 1996 v Ljubljani, kjer sta bila lokalna organizatorja. Po tem, ko so pridobili skupni jugoslovansko-ameriški projekt „Možne spremembe lesa pri drevesih iz območij z onesnaženim zrakom“, sem s profesorjem Torellijem in Katarino Čufar začel sodelovati pri raziskavah umiranja jelke v Sloveniji. Kasneje smo s Katarino Čufar, dr. Tomom Levaničem in sodelavci proučevali odzive jelke v Sloveniji in rdeče smreke na severovzhodu ZDA na podnebne spremembe. Z dr. Primožem Ovnom sem sodeloval tudi pri proučevanju različnih vidikov zdravja in varnosti mestnih dreves. Kasneje sva bila s Katarino Čufar člana izvršnega sveta mednarodnega združenja za dendrokronološke raziskave Tree Ring Society. Leta 2010 sva na dendrokronološkem terenskem tednu v okviru svetovne konference World Dendro na Finskem skupaj vodila sekcijo za biologijo lesa. Ugotovila sva, da je kombinacija najinih raziskovalnih izkušenj okrepila in razširila razumevanje in predstavitev strukture in funkcije lesa. Od takrat si prizadevamo, da bi slovenskim študentom in znanstvenikom zagotovili platformo za izmenjavo tehnik in izkušenj, ki širijo tako znanost kot tudi skupnost znanstvenikov v mednarodni raziskovalni prostor.

Kot aktivnemu raziskovalcu se mi zdi revija Les/Wood pomembna zaradi potencialne širine vprašanj, ki jih obravnavajo članki, od mehanskih lastnosti lesa do tehnologij, predelave in optimalne rabe lesa, ki temeljijo v anatomiji lesa in bioloških procesih, ki spremljajo nastajanje in razkroj lesa in so pomembni za zaščito in uporabno vrednost lesa. Poleg visoke znanstvene in strokovne ravni revija Les/Wood odraža tudi visoko stopnjo kolegialnosti in odprtosti ter ponos na zgodovino in tradicijo. Te kvalitete revije krepijo in podpirajo trenutne in bodoče raziskave v Sloveniji, njeni okolici in širši svetovni raziskovalni skupnosti. Navdušen sem, ker kaže, da bo revija Les/Wood v prihodnje še razširila svoje tradicionalne prednosti in tako zadostila naraščajočim potrebam po znanju o lesu, kar bo vplivalo na optimalno rabo lesa, njegovo razumevanje z vidika ekologije in njegov pomen za kulturno dediščino.

LES/WOOD Vol. 70, No. 2, 5-18
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a02

ANATOMICAL AND CHEMICAL CHARACTERIZATION OF *ALSTONIA BOONEI* FOR PULP AND PAPER PRODUCTION

ANATOMSKE IN KEMIJSKE LASTNOSTI LESA VRSTE *ALSTONIA BOONEI* ZA PROIZVODNJO CELULOZE IN PAPIRJA

Kojo Agyapong Afrifah[1*], Enoch Adjei-Mensah[1]

UDK: 630*811.1:813.1:176.1 Alstonia boonei
Original scientific article / Izvirni znanstveni članek

Received / Prispelo: 6. 7. 2021
Accepted / Sprejeto: 22. 9. 2021

Abstract / Izvleček

Abstract: *Alstonia boonei*, an abundant lesser utilized species within the West African Subregion, was evaluated as an alternative raw material for pulp and paper production. The basic density (BD), fibre characteristics [fibre length (FL), fibre diameter (FD), lumen diameter (LD) and wall thickness (WT)], derived anatomical indices [Flexibility Ratio (FR), Slenderness Ratio (SR), Rigidity Coefficient (RC), Luce's Shape Factor (LSF), Solids Factor (SF) and Runkel Ratio (RR)] and chemical composition (lignin, holocellulose, 1% NaOH solubility and ash contents) of *A. boonei* were studied to evaluate variation along the trunk (base, middle and top portions) and ascertain its suitability for pulp and paper production. Significant variations were observed in the density and fibre characteristics along the trunk of the tree. Although the FD was large, the observed adequate FL, thin-wall and large LD implied easy beating of fibres and manufacture of dense, smooth and strong papers. The favourable SF, RR, FR, RC, and LSF values obtained for the fibres would produce papers with suitable burst and tearing strengths and folding endurance. Chemically the lower lignin (< 30%), ash and 1% NaOH solubility and the high holocellulose contents of *A. boonei*, will generate a higher pulp yield. *A. boonei* although a low-density species, will be desirable for pulp and paper production.

Keywords: *Alstonia boonei,* fibre characteristics, lesser utilized species, pulp, paper

Izvleček: Predstavljamo oceno primernosti lesa vrste alstonija (*Alstonia boonei*) kot alternativnega vira za proizvodnjo celuloze in papirja. Vrsta je pogosta v zahodni Afriki, a je manj uporabljana. Proučili smo osnovno gostoto lesa (BD), značilnosti vlaken [dolžino vlaken (FL), premer vlaken (FD), premer lumna (LD) in debelino celične stene (WT)], anatomske indekse [prožnost (FR), vitkost (SR), koeficient togosti (RC), Luceov faktor oblike (LSF), stopnjo masivnosti (lesnatosti) vlaken (SF), Runklovo razmerje (RR)] in kemično sestavo ter lastnosti (vsebnost lignina in holoceluloze, topnost v 1 % NaOH in vsebnost pepela). Ocenili smo njihovo varibilnost vzdolž debla (spodnji, srednji in zgornji del) in ugotovili primernost lesa za proizvodnjo celuloze in papirja. Ugotovljene so bile znatne razlike v gostoti lesa in lastnostih vlaken vzdolž debla. Čeprav je bil premer vlaken velik, dolžina vlaken, tankost sten in veliki premeri lumnov omogočajo primerno formacijo vlaken ter izdelavo gostega, gladkega in močnega papirja. Ugodne vrednosti SF, RR, FR, RC in LSF vlaken bi omogočile izdelavo papirja z ustrezno odpornostjo proti trganju ter prepogibno stabilnostjo. Kemijsko gledano nižja vsebnost lignina (< 30 %), pepela in 1 % topnost v NaOH ter visoka vsebnost holoceluloze v vlaknih *A. boonei* omogočajo večji izkoristek pri izdelavi celulozne kaše (pulpe). Čeprav je *A. boonei* lesna vrsta z nizko gostoto, bi bila primerna za proizvodnjo celuloze in papirja.

Ključne besede: *Alstonia boonei*, značilnosti vlaken, manj uporabljana lesna vrsta, celuloza, papir

1 INTRODUCTION

1 UVOD

Paper is a versatile commodity that contributes to the growth and development of every country, and the level of development of a country can even be related to its paper consumption trends (Darkwa, 1996). The global consumption of paper has been estimated to be around 400 million tons per year and about 7.2 billion trees are harvested to satisfy this need for production of different types of paper (for writing, printing, wrapping, communication, education and packaging) (Tiseo, 2021). Continuous supply of paper to meet these increasing demands would require alternative suitable raw materials to supplement the dwindling traditional raw material sources.

[1] Department of Wood Science & Technology, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science & Technology, Kumasi, Ghana.
[*] e-mail: kagyapong@gmail.com

Fibre morphological and chemical compositions are essential in determining the level of efficiency of wood species in pulping and the quality of pulp produced. Therefore, these characteristics are taken into consideration in the deployment of any lignocellulosic material for pulp and papermaking (Omotoso & Ogunsile, 2009; Ajuziogu et al., 2019; Ajuziogu & Ojua, 2020). Fibre morphological characteristics such as fibre length, wall thickness, lumen diameter and fibre diameter have been shown to differ widely in species and exert diverse influences on the fibre strength, inter-fibre bonding, strength properties and bulk density of the produced papers (Larsson et al., 2018). Woods with long fibres produce papers with high tear strength and are desirable in the paper industry (Anthonio & Antwi-Boasiako, 2017). Fibre wall thickness also affects the tensile and burst strengths as well as folding endurance of paper, which is the durability of paper when repeatedly folded under constant load (Ofosu et al., 2020). In addition to the absolute fibre dimensions, fibre derived indices such as Runkel Ratio, Slenderness Ratio, Coefficient of Rigidity, Flexibility Coefficient, Luce's Shape Factor and Solids Factor help derive better judgement about the suitability of wood for pulp and papermaking (Ofosu et al., 2020). For instance, wood species with a high Runkel Ratio usually have stiff fibres, poor bonding ability and produce bulkier paper, and vice versa (Ajuziogu et al., 2019).

Analysis of the chemical components is also necessary for the selection of the right material for pulp and papermaking. The basic structure of all woody biomass consists of holocellulose (cellulose and hemicelluloses) and lignin. These constitute about 90% of dry matter in wood, with the remaining being extractives and ash. The proportion of these wood constituents varies among species (Dehkhoda, 2008). High holocellulose content is desirable for high quality and yield of pulp (Zhan et al., 2015; Afrifah et al., 2020). By contrast, lignin is undesirable for pulp and papermaking, and has to be removed due to its negative impact on fibre strength and pulp yield (Tran, 2006).

Wood properties and quality affect the quality of pulp and the paper made from it. A classic example is the preference for softwood pulping over hardwoods because softwoods mainly contain tracheids and reputedly produce stronger papers than hardwood fibres. However, some studies have shown that certain hardwood pulps have some strength properties (such as tear index, tensile resistance, folding endurance) equal to or even greater than those of softwood pulps (Shackford, 2003). Therefore, it would be beneficial to assess some hardwood species to augment softwood pulps, especially the lesser-utilized ones such as *Alstonia boonei*.

Alstonia boonei, from the family Apocynaceae, is a pioneer tree very common on old farms and also in the swampy forest from Senegal through Ethiopia to Congo (Hawthorne, 2006). This species provides a myriad of ecosystem services such as firewood and timber. Its sapwood, which cannot be differentiated from the heartwood, is very wide (up to 200 mm), soft, and light in weight when dried. The wood is nearly yellowish-white when freshly cut, but darkens on exposure. It has a low lustre and no characteristic odour or taste. The wood is also liable to staining. It works easily with hand and machine tools, but because of its softness it is essential to use tools with sharp cutting edges. The wood can be glued, stained and polished satisfactorily (Orwa et al., 2009).

The basic density, anatomical properties and chemical composition that determine the pulp yield, pulp and paper quality of the wood of *A. boonei* are not well documented, even though it is an abundant species. This study therefore analysed these pulping characteristics to ascertain the potential of *A. boonei* for pulp and papermaking.

2 MATERIALS AND METHODS
2 MATERIALI IN METODE
2.1 SAMPLE COLLECTION AND PREPARATION
2.1 IZBOR IN PRIPRAVA VZORCEV LESA

Three trees of *A. boonei* all about 12 m high and 50 cm girth were collected from the farm of the Faculty of Renewable Natural Resources (FRNR) of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana (6°39'53.66" N, 1°34'16.88" W). Disc samples (60 cm in height) were taken from the base (1 m from the ground up to 4 m), middle (4 m to 7 m) and top (7 m to 11 m) portions of the tree for processing, chemical and anatomical observations (Figure 1).

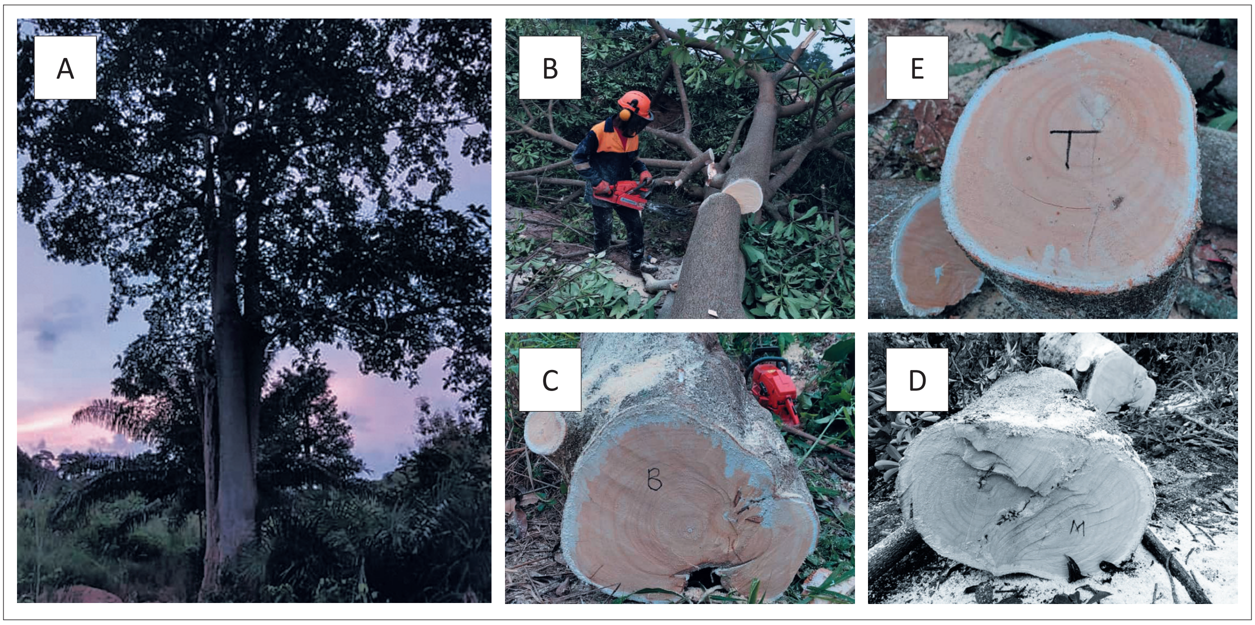


Figure 1. *Alstonia boonei*: living tree (A), harvested (B) and processed into base (C), middle (D) and top portions (E).

Slika 1. *Alstonia boonei*: rastoče drevo (A), posek drevesa (B) in krojenje debla na spodnji (C), srednji (D) in zgornji del (E).

2.2 BASIC DENSITY
2.2 OSNOVNA GOSTOTA

The test samples were processed into 20×20×20 mm sizes. A total of 54 samples were prepared from each tree. The dimensions of the 18 samples each from the base, middle and top portions of each tree were measured in all three principal directions (radial, tangential and longitudinal) and weighed before soaking in tap water for 24 hours.

The saturated volumes and wet weight of samples were determined after 24 hours. The samples were then oven-dried at 103±2 °C in a forced air oven to a constant weight after which dried weights and volumes of the samples were measured using a scale and electronic digital callipers, respectively. The basic density of *A. boonei* was determined according to TAPPI 258 om-11 (2011) using the relation (Equation 1);

2.3 MACERATION
2.3 MACERACIJA

Match-stick sized wood samples (5 each) were taken from the top, middle and base portions of the wood of each tree and placed into labelled test tubes. They were flooded with one-part Hydrogen Peroxide (6% w/v) to one-part Glacial Acetic Acid (1:1, v/v) and then incubated at 65 °C for six days. Wood samples were fully macerated at the end of the 6-day incubation period.

2.4 DETERMINATION OF FIBRE DIMENSIONS AND ANATOMICAL RATIOS
2.4 DIMENZIJE IN ANATOMSKA RAZMERJA VLAKEN

Images of fibres for fibre dimensions and anatomical ratios were captured from slides of macerated wood under an electronic microscope using Micron (USB2) (Figure 2). In all 75 straight fibres,

$$Basic\ Density = \frac{Oven - Dry\ Weight\ of\ Sample}{Saturated\ Volume}\ [kg/m^3] \quad (1)$$

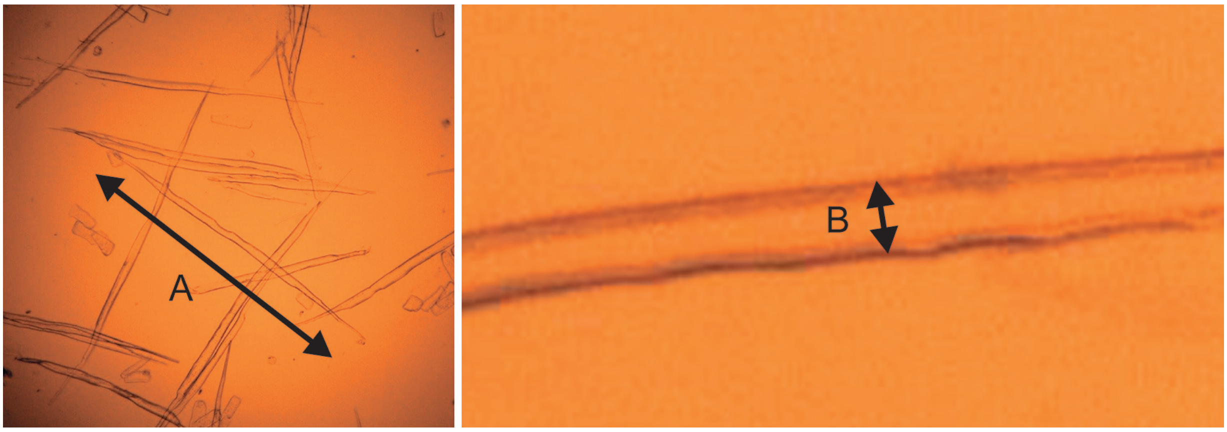


Figure 2. Micrographs of wood fibres of *Alstonia boonei* for measuring length (A) and diameter of fibres (B).
Slika 2. Mikrografije vlaken lesa vrste *Alstonia boonei* in merjenje dolžine (A) in premera vlakna (B).

25 from each portion (base, middle and top) were assessed per tree for fibre diameter, length, wall thickness, and lumen diameter using ImageJ software.

The determined fibre dimensions were incorporated in Equations 2 to 7 to calculate Slenderness, Runkel and Flexibility Ratios, Coefficient of Rigidity, Luce's Shape Factor and Solids Factor (Varghese et al., 2000; Hegde and Varghese, 2008; Rana et al., 2009; Afrifah et al., 2020).

2.5 CHEMICAL ANALYSIS
2.5 KEMIČNA ANALIZA
2.5.1 Preparation of Extractive-Free Wood
2.5.1 Priprava lesa brez ekstraktivov

Extractive-free wood was prepared for lignin and holocellulose determination according to ASTM D 1105 – 96 (2013). Air-dried samples of the base, middle and top portions of *A. boonei* were milled into powder with a Christy & Norris 8” Lab Mill. Extractive free samples of each portion were

$$Slenderness\ Ratio = \frac{Fibre\ Length}{Fibre\ Diameter} \quad (2)$$

$$Flexibility\ Ratio = \frac{Lumen\ Diameter}{Fibre\ Diameter} \quad (3)$$

$$Runkel\ Ratio = \frac{2 \times Cell\ Wall\ Thickness}{Lumen\ Diameter} \quad (4)$$

$$Coefficient\ of\ Rigidity = \frac{Fibre\ Wall\ Thickness}{Fibre\ Diameter} \quad (5)$$

$$Luce's\ Shape\ Factor = \frac{[(Fibre\ Diameter)^2 - (Fibre\ Lumen\ Diameter)^2]}{[(Fibre\ Diameter)^2 + (Fibre\ Lumen\ Diameter)^2]} \quad (6)$$

$$Solids\ Factor = \left[(Fibre\ Diameter)^2 - (Fibre\ Lumen\ Diameter)^2\right] \times Fibre\ Length\ [\mu m^3] \quad (7)$$

prepared by placing a suitable quantity (10 g) of the powder in a Soxhlet extraction apparatus ensuring that the samples did not extend above the top of the siphon tube. The sample was extracted for four hours with a ratio of 1:2 alcohol acetone mixture in the Soxhlet extraction apparatus, after which the sample was washed with alcohol and extracted with 95% of alcohol (ethanol) for another four hours or longer until the ethanol siphoned over colourless. The sample was removed from the thimble and allowed to dry in the air until it was free of alcohol. The sample, free of alcohol, was then placed in the thimble and this time extracted with distilled water for six hours. The air-dried material after hot water extraction is the extractive free material which was used for further chemical composition analysis.

2.5.2 Lignin Content Determination
2.5.2 Določanje vsebnosti lignina

Lignin contents for the three portions of *A. boonei* studied were determined in accordance with ASTM D 1106 – 96 (2007). The extractive free specimen of 1 g was placed in a 50 ml beaker. The sample was mixed with 15 ml of cold (15 °C) 72% H_2SO_4, stirred continuously for at least 1 minute and placed in a water bath at 20 °C for 2 hours. The contents of the beaker were diluted in a 1-litre Erlenmeyer flask to 3% H_2SO_4 by adding 560 ml of distilled water and boiling for 4 hours. The volume of the mixture was maintained nearly constant by occasionally adding hot water. This was followed by filtration of insoluble materials, washing with 500 ml of hot water and oven drying for 2 hours at 105 °C until constant weight. Simultaneously, 1 g of unextracted moisture free sample was oven dried at 105 °C until constant weight. The percentage lignin content was calculated as;

$$Lignin = \frac{Dry\,Weight\,of\,Lignin}{Oven\,Dry\,Weight\,of\,Sample} \times 100 [\,\%] \quad (8)$$

2.5.3 Holocellulose Content Determination
2.5.3 Vsebnost holoceluloze

Holocellulose contents in the three portions of the trees were determined in accordance with the methods presented in ASTM D 1104 – 56 (1978). For each material, a mixture of 8.6 g of sodium acetate, 5.7 ml of ethanoic acid, 6.6 g of sodium chlorite and 180 ml of distilled water was placed in a 250 ml conical flask and mixed with 2 g of its extractive free sample. The flask with its contents were covered and placed in a water bath in a fume chamber at a temperature of 60 °C for about 4 hours. The liquid in the flask turned yellowish while the sample turned whitish. The flask contents were filtered with weighed filter paper, washed with distilled water and oven-dried at 105 °C for 5 hours. Percentage holocellulose was calculated as follows (Equation 9);

$$Holocellulose = \frac{Oven\,Dry\,Weight\,of\,Residue}{Oven\,Dry\,Weight\,of\,Sample} \times 100\ [\,\%] \quad (9)$$

2.5.4 Ash Content Determination
2.5.4 Vsebnost pepela

Ash is the material remaining after the sample is ignited at a specified temperature. The percentage ash content of *A. boonei* was determined in accordance with ASTM D 1102 – 84 (2007). A weighed preheated crucible plus 2 g of specimen were dried in an oven at 100 to 105 °C to a constant weight. The crucible and contents were then ignited to 580 to 600 °C in a muffle furnace until all the carbon was eliminated. Heating and cooling were done until constant weight was recorded. The percentage of ash, based on the weight of the moisture-free wood, was calculated for the 3 replicates of each section of the tree with Equation 10;

$$Ash = \frac{w_1}{w_2} \times 100\ [\,\%] \quad (10)$$

where: W_1 = weight of ash;
W_2 = weight of oven-dry sample.

2.5.5 1% Caustic Soda (NaOH) Solubility Determination
2.5.5 Topnost v 1 % natrijevem hidroksidu (NaOH)

The 1% NaOH solubility determination was conducted on *A. boonei* in accordance with ASTM

D 1109 – 84 (2007). Two grams of moisture-free wood was mixed with 100 mL of 1% NaOH solution. The mixture was placed in a water bath boiling steadily and stirred at 10, 15, and 25 min intervals. It was then filtered and washed with 100 mL of hot water, then with 50 mL of acetic acid (10%) and thoroughly with hot water. The residue was dried at 103 ± 2 °C, cooled in a desiccator, and weighed. The weight percentage of matter soluble in 1% NaOH solution on moisture-free basis was then calculated for the 3 replicates of each section of the tree using Equation 11.

$$Matter\,soluble\,in\,1\,\%\,caustic\,soda = \frac{W_1 - W_2}{W_1} \times 100\ [\%] \tag{11}$$

where: W_1 = weight of moisture-free wood specimen prior to test;
W_2 = weight of dried specimen after treatment with 1% NaOH solution.

2.6 DATA ANALYSIS
2.6 ANALIZA PODATKOV

Data obtained from the study were set up in a completely randomized design and subjected to analysis of variance (ANOVA) using GenStat Release 10.3 (2011) and GraphPad Prism 5 (2007) analytical software. All post hoc mean separations were done using Fisher's protected least significant difference (LSD) at a maximum type I error rate (α) of 0.05.

3 RESULTS
3 REZULTATI

The basic densities for the base, middle and top portions of *A. boonei* are shown in Table 1. The mean basic density was 267.75 ± 36.01 kg/m^3 with the base portion recording the highest (314.95 ± 10.2 kg/m^3), followed by the middle portion (252.25 ± 14.7 kg/m^3) and the top portion (236.04 ± 6.6 kg/m^3) being the least (Table 1). Analysis of variance indicated significant differences ($p < 0.05$) between the three portions.

Table 1. Basic density and fibre characteristics of wood along the trunk of *Alstonia boonei*
Preglednica 1. Osnovna gostota in značilnosti vlaken vzdolž debla lesa vrste *Alstonia boonei*

Parameter	Portion		
	Base	Middle	Top
Basic Density (kg/m^3)	314.95 ± 10.2^a	252.25 ± 14.7^b	236.04 ± 6.6^c
Fibre Length (µm)	1421.38 ± 163.3^a	1338.89 ± 218.5^b	1184.99 ± 150.6^c
Fibre Diameter (µm)	48.97 ± 6.3^a	42.27 ± 7.9^b	37.77 ± 5.6^c
Lumen Diameter (µm)	33.18 ± 5.5^a	27.71 ± 5.5^b	23.00 ± 5.0^c
Wall Thickness (µm)	7.90 ± 3.7^a	7.28 ± 4.1^a	7.38 ± 2.9^a
Slenderness Ratio	29.51 ± 5.2^a	32.60 ± 7.2^a	31.92 ± 5.6^a
Runkel Ratio	0.51 ± 0.3^a	0.57 ± 0.4^a	0.70 ± 0.4^a
Flexibility Ratio	0.69 ± 0.1^a	0.67 ± 0.2^a	0.61 ± 0.1^a
Rigidity Coefficient	0.16 ± 0.1^a	0.16 ± 0.1^a	0.19 ± 0.1^a
Luce's Shape Factor	0.36 ± 0.2^a	0.384 ± 0.2^a	0.45 ± 0.2^a
Solids Factor (µm^3)	$1.83\times10^{-6} \pm 9.0\times10^{-5a}$	$1.42\times10^{-6} \pm 9.3\times10^{-5b}$	$1.08\times10^{-6} \pm 5.6\times10^{-5b}$

±: Standard deviation
Means with different superscripts denote significant differences and vice-versa at $p < 0.05$
±: Standardni odklon
Srednje vrednosti z različnimi nadnapisi pomenijo statistično značilne ali neznačilne razlike pri p < 0,05

An average fibre length (FL) of 1315 µm was observed for *A. boonei* with the base, middle and top portions of the tree recording 1421.38 ± 163.3 µm, 1338.89 ± 218.5 µm, and 1184.99 ± 150.6 µm, respectively. Highest values of fibre and lumen diameters were observed for the base portion (48.97 ± 6.3 µm, 33.18 ± 5.5 µm, respectively) of *A. boonei* (Table 1) with significant differences occurring between the three portions studied ($p < 0.05$). The fibre wall thickness ranged between 7.28 ± 4.1 to 7.90 ± 3.7 µm without significant differences between the three portions.

With the exception of the Solids Factor, there were no significant differences between the three studied portions of *A. boonei* for all the derived pulping properties or indices (Table 1). The base portion recorded the highest Solids Factor ($1.83\times10^{-6} \pm 9.0\times10^{-5}$ µm^3) with the middle and top portions recording equivalent values of $1.42\times10^{-6} \pm 9.3\times10^{-5}$ µm^3 and $1.08\times10^{-6} \pm 5.6\times10^{-5}$ µm^3, respectively (Table 1).

The results for the chemical compositions are presented in Table 2. The range of lignin, holocellulose, ash and 1% NaOH solubility contents for the base, middle and top portions of the trees were 25.48 – 25.95%, 66.47 – 67.58%, 1.08 – 1.35% and 10.55 – 13.29%, respectively. Statistical analysis indicated no significant differences in chemical contents at $p < 0.05$ for the portions of the trees studied (Table 2).

Table 2. Chemical compositions of wood along the trunk of *Alstonia boonei*
Preglednica 2. Kemijske lastnosti lesa vzdolž debla vrste *Alstonia boonei*

Chemical Properties	Portion		
	Base	Middle	Top
Lignin (%)	25.95 ± 0.1^a	25.48 ± 0.1^a	25.86 ± 0.12^a
Holocellulose (%)	67.51 ± 1.95^a	66.47 ± 1.85^a	67.58 ± 2.71^a
Ash (%)	1.35 ± 0.38^a	1.09 ± 0.01^a	1.08 ± 0.01^a
1% NaOH solubility (%)	11.95 ± 2.7^a	10.55 ± 2.8^a	13.29 ± 1.6^a

±: Standard deviation
Means with different superscripts denote significant differences and vice-versa at $p < 0.05$
±: Standardni odklon
Srednje vrednosti z različnimi nadnapisi pomenijo statistično značilne ali neznačilne razlike pri $p < 0,05$

4 DISCUSSION
4 DISKUSIJA
4.1 BASIC DENSITY
4.1 OSNOVNA GOSTOTA

Wood density is a complex physical property related to both the anatomical structure and the chemical composition of wood (Santos et al., 2012). The density of wood allows the prediction of a number of properties of wood, including the yield of pulp per unit volume (Adi et al., 2014). Generally, studies have shown that high density wood species give greater pulp yield (Bowyer et al., 2003). For instance, in a study of *Eucalyptus globulus* by Santos et al. (2008), "*E. globulus* with the highest wood basic density exhibited a much higher pulp yield (58.7%) than the *E. globulus* with the lowest wood basic density (49%)". Species of wood with less than 400 kg/m^3 basic density are classified as soft and low-density materials (Petro et al., 2016). Consequently, it is anticipated that pulp yield from *A. boonei* (mean basic density of 267.75 ± 36.01 kg/m^3) would be low, with the base portion which had the highest basic density (314.95 ± 10.2 kg/m^3) producing higher pulp yield.

4.2 FIBRE CHARACTERISTICS OF *A. BOONEI*
4.2 ZNAČILNOSTI VLAKEN LESA *A. BOONEI*
4.2.1 Fibre Length
4.2.1 Dolžina vlaken

Fibre characteristics and anatomical ratios can be used to predict the suitability of wood as raw material for pulp and papermaking (Adi et al., 2014).

The fibre lengths (1184.99 ± 150.6 to 1421.38 ± 163.3 µm) were within the range for hardwood fibres (700.0 to 1600 µm) and equivalent to those of industrial pulping species such as *Acacia mangium* Wild. (1,101 µm/1.101 mm) (Nugroho et al., 2012; Kiaei et al., 2014; Ofosu et al., 2020). Pulps with long fibres produce strong papers due to improved interlocking between the fibres (Ashraf et al., 2016; Ofosu et al., 2020). Consequently, the base portion with the longest fibres may produce stronger papers than the middle and top portions.

4.2.2 Fibre Diameter
4.2.2 Premer vlaken

Fibre diameters (FD) reported for hardwoods used for papermaking range between 20 – 40 µm (San et al., 2016). The observed mean FD for this study was higher (43.01 µm) with only the top portion (37.77 µm) falling within the range (Table 1). Fibres with a small diameter and thin wall are preferred for improved flexibility, high contact surfaces for fibres, good paper density and formation of stronger paper (Ashraf et al., 2016; Ofosu et al., 2020). In contrast, wood with large fibre diameters, as observed in the current study (37.77 - 48.97 µm), may produce papers with high void volume, and a bulky, coarse and poor printing surface (Kiaei et al., 2014).

4.2.3 Fibre Lumen Diameter and Wall Thickness
4.2.3 Premer lumnov in debelina celičnih sten vlaken

The papermaking properties of wood are also influenced by the relationship between fibre lumen diameter and wall thickness. Fibres with lumen size greater than the double wall thickness are classified as thin-walled and produce papers that are dense, smooth and have high tensile and bursting strengths (Ofosu et al., 2020). By contrast, fibres with lumen size less than the double wall thickness are classified as thick-walled, while those having intermediate characteristics are classified as thin-to-thick-walled (Ofosu et al., 2020). Thick-walled fibres produce bulky papers with poor printing surface and poor strength properties. The results of the current study indicate that fibres of *A. boonei* are thin-walled (Table 1) and suitable for the manufacture of dense, smooth and strong papers. Additionally, because of the large fibre lumen of *A. boonei,* it can be beaten easily due to improved liquid penetration into empty spaces and flattening of the fibres (Sharma et al., 2011; Ogunleye et al., 2017).

Differences were observed in the FL, FD, and LD morphological properties along the trunk of the *A. boonei*. Higher values were recorded in the base portion, and they decreased along the trunk to the top portion (Table 1). Similar results have been reported by several researchers who ascribed it to variations in the growth of the wood producing cells (e.g., variations in the length of the cambial initials as the cambium ages) along the trunk of the tree with the juvenile wood portions having lower fibre characteristics (Izekor & Fuwape, 2011; Anthonio & Antwi-Boasiako, 2017; Ofosu et al., 2020). Generally, the observed fibre characteristics of *A. boonei* indicate that it will be a suitable species for the manufacture of paper with good physical and mechanical properties.

4.3 MORPHOLOGICAL CHARACTERISTICS OF FIBRES
4.3 MORFOLOŠKE LASTNOSTI VLAKEN

4.3.1 Slenderness Ratio
4.3.1 Razmerje vitkosti

A fibrous material having an SR less than 33 has been reported as not suitable for quality pulp and paper production (Sharma et al., 2018; Ofosu et al., 2020). Low SR is indicative of short thick fibres which do not produce good surface contact for enhanced fibre-to-fibre bonding, thus reducing tearing resistance, bursting strength and double folding resistance of papers (Ogbonnaya et al., 1997; Sangumbe et al., 2018; Ofosu et al., 2020). The result for this study indicated low SR values for the wood of *A. boonei* (29.51 to 32.60) (Table 1), which were lower than the reported suitable range of 40 - 60 for hardwoods (Sangumbe et al., 2018). Based on the SR, *A. boonei* does not meet the desired requirement for a very good pulp and papermaking material.

4.3.2 Runkel Ratio
4.3.2 Runklovo razmerje

The Runkel ratio (RR) of a material is an important parameter for predicting the stiffness, flexibility and conformability of its paper (Ogunleye et al., 2017). RR also indicates the propensity for fibre-to-fibre bonding (Biermann, 1996; Bowyer et al., 2003). An RR of less than 1 is the best for quality paper, while greater than one results in papers of poor quality which are stiff, less flexible and bulky (Veveris et al., 2004; Ogunleye et al., 2017; Ofosu et al., 2020). Okoegwale et al. (2020) also claimed that when making paper with hardwood fibres an RR lower than 1 is desirable for good conformability and fibre-to-fibre contact for good bonding in paper.

Table 1 shows that the RR of the wood of *A. boonei* is less than 1, and thus can be used to produce quality paper. In line with the report of Ekhuemelo and Tor (2013) and Okoegwale et al. (2020), when RR is less than 1, it indicates that the cell wall is thin and the fibres are most suitable for paper production, while an RR of 1 indicates that the cell wall has medium thickness and is suitable for paper production, and an RR greater than 1 shows that the fibres have thick walls and are least suitable for paper production. The RR for *A. boonei* ranged between 0.51 to 0.71 (Table 1). These values were statistically not different for the three portions of the tree and fell within the range (0.4 to 0.7) that has been reported for hardwoods (Smook, 1997). This implies that *A. boonei* may produce paper with moderate burst and tensile indices.

4.3.3 Flexibility Ratio
4.3.3 Razmerje prožnosti

Flexibility Ratio (FR) has been reported to influence the burst, tearing and tensile strengths, as well as folding endurance of paper (Ververis et al., 2004; Sangumbe et al., 2018). Amidon (1981) also asserted that FR is the key to the development of the paper properties that affect printing. Fibres can be classified based on their FR into highly elastic (FR ≥ 0.75), elastic (FR = 0.50 – 0.75), rigid (FR = 0.3 to 0.5) and very rigid (FR = ≤ 0.3) (Ververis et al., 2004; Sharma et al., 2018; Ofosu et al., 2020). Elastic fibres produce writing and printing papers while rigid fibres are suitable for cardboards and packaging papers (Dutt & Tyagi, 2011).

Studies have shown that the flexibility index for hardwoods ranges between 0.55 to 0.7 and that for softwood averages around 0.75. According to Istas et al. (1954) and Takeuchi et al. (2016), fibres having an FR between 0.5 and 0.7 can easily collapse and be flattened during beating and paper drying, providing a large surface area for good bonding leading to the production of good paper with high strength properties. The FR obtained in this study fell within that for hardwoods and ranged from 0.61 for the top portion to 0.69 for the base section of the trees. The wood of *A. boonei* can therefore be classified as having elastic fibres which can be used for making papers with high burst and tearing strengths and folding endurance.

4.3.4 Rigidity Coefficient
4.3.4 Koeficient togosti

This fibre property is important for determining the tensile, bursting and tearing strength properties of paper (Afrifah et al., 2020). A low rigidity coefficient (RC) is preferable for fibres producing quality papers with high tensile and bursting strength properties (Takeuchi et al., 2016). Research has shown that the desired RC for softwood and hardwood pulp are 13 to 20 (0.13 – 0.2) and 15 to 35 (0.15 – 0.35), respectively (Istek et al., 2009; Tutus et al., 2015). The RC reported for the portions of *A. boonei* ranging from 0.16 ± 0.1 to 0.19 ± 0.1 (Table 1) fall in the range of both softwood and hardwood pulps, and hence may produce papers with better strength properties.

4.3.5 Luce's Shape Factor
4.3.5 Luceov faktor oblike

Luce's Shape Factor (LSF) is an index for the resistance of pulp to beating. Therefore, a low value for LSF indicates a decreased resistance to beating in papermaking (Luce, 1970). Pirralho (2014) reported that LSF ranged from 0.39 to 0.74 in several *Eucalyptus* species used in making paper. Ohshima et al. (2005) also reported mean values of LSF of 0.37 for *E. camaldulensis* and 0.42 for *E. globulus*. The values for LSF in *A. boonei* ranging from 0.36 ± 0.2 to 0.45 ± 0.2 (Table 1) are comparable to those of *Eucalyptus* species which is suitable for pulp and papermaking.

4.3.6 Solids Factor
4.3.6 Stopnja masivnosti (lesnatosti) vlaken

Ona et al. (2001) reported values for the Solids Factor (SF) of 46×10^3 µm^3 and 91.2×10^3 µm^3 for 14-year-old *E. camaldulensis* and *E. globulus*, respectively. In addition, they found a significant negative relationship between SF and sheet density. The mean values for the SF observed for *Alstonia* *boonei* (i.e. $1.08 \times 10^{-6} \pm 5.6 \times 10^{-5}$ µm^3 to $1.83 \times 10^{-6} \pm 9.0 \times 10^{-5}$ µm^3) were low (Table 1) and thus will positively influence the breaking length and sheet density of papers (Afrifah et al., 2020). Additionally, fibres of *Alstonia boonei* with these low SF will produce papers with good strength properties (Ofosu et al., 2020).

4.4 CHEMICAL ANALYSIS
4.4 KEMIČNA ANALIZA
4.4.1 Lignin Content
4.4.1 Vsebnost lignina

Lignin is undesirable in pulping and bleaching, and has to be removed. The removal of lignin requires high amounts of energy and chemicals (Zhan et al., 2015; Riki et al., 2019). High lignin content has greater bonding strength and creates difficulties in breaking fibre bonds and removing lignin during pulping (Tran, 2006). By contrast, lower lignin content implies greater fibre strength, higher yield of pulp, and the production of good quality paper (Enayati et al., 2009). The reported lignin contents of softwoods and hardwoods range between 21 – 37% and 14 – 34%, respectively (Kiaei et al., 2014; Zawawi et al., 2014). Table 2 presents the lignin contents at the base (25.95%), middle (25.48%) and top (25.86%) portions of the trunk of *A. boonei*. Although the results indicate a variation in lignin content from the base to the top of the trunk, there were no statistical differences ($p > 0.05$) between the various portions. Generally, the observed lignin contents for this study were lower (< 30%), and hence low amounts of energy and chemicals are required for its removal (Ververis et al., 2004).

4.4.2 Holocellulose Content
4.4.2 Vsebnost holoceluloze

Holocellulose is the combined composition of cellulose and hemicelluloses (Rowell, 2012). Wood with high holocellulose content is preferred for pulp and paper production, since it generates a higher pulp yield. Studies have shown that holocellulose content constitutes about 65 – 70% of the dry weight of plants (Zhan et al., 2015). The base (67.51 ± 1.95%), middle (66.47 ± 1.85%) and top (67.58 ± 2.71%) portions of *A. boonei* had relatively high holocellulose contents (Table 2). Analyses indicated no significant differences ($p = 0.4314$) in the holocellulose contents between the base, middle and top portions of the species. It can therefore be inferred that any portion of the wood of *A. boonei* would yield a high quantity of pulp for papermaking.

4.4.3 Ash Content
4.4.3 Vsebnost pepela

The inorganic constituent of lignocellulosic material is usually referred to as ash, and this is the residue remaining after combustion of organic matter at a temperature of 525 ± 25ºC. The ash content consists mainly of metal salts such as silicates, carbonates, oxalates and phosphate of potassium, magnesium, calcium, iron and manganese as well as silicon. High ash content is undesirable during refining and recovery of the cooking liquor (Rodríguez et al., 2008). High silica content, for instance, can complicate the recovery of chemicals during pulping. Nitrogen in the spent liquor can lead to generation of NOx in the chemical recovery furnace, while potassium in the fibre can combine with chlorine to form KCl, with a corrosive effect on metal parts in the furnace and boiler (Salmenoja & Makela, 2000). Low ash content, on the other hand, contributes to high pulp yield (López et al., 2004). The mean ash content (1.17%) observed in this study is low, consequently *A. boonei* is a suitable material for pulp and paper production and would result in high pulp yield.

4.4.4 1% Caustic Soda (NaOH) Solubility
4.4.4 Topnost v 1 % natrijevem hidroksidu (NaOH)

The solubility in 1% NaOH indicates the extent of fibre degradation from fungi during the pulping process. As the wood decays, the percentage of alkali-soluble material increases in proportion to the decrease in pulp yield. Hence high 1% NaOH solubility leads to low production of chemical pulp (Onggo & Astuti, 2005). The mean solubility observed for *A. boonei* is 11.93%, ranging between 10.55% to 13.29% for the base, middle and top portions of the trees studied (Table 2). This result is similar to those of *Pinus kesiya* (12.2%), *Eucalyptus cloeziana* (10.9%) and *Eucalyptus deglupta* (13.6%) (Tutus et al., 2015), but better than that of *Gmelina arborea* (15.1%) in terms of fibre degradation during pulping.

5 CONCLUSIONS
5 SKLEPI

Investigations on the morphological characteristics of fibres of the wood of *Alstonia boonei* revealed it as a potential species for pulp and paper production. Pulp yield is anticipated to be highest at the base portion due to its high basic density. Anatomically, the large fibre diameter implied the potential production of bulky paper with a high void volume and a coarse and poor printing surface. In contrast, the observed adequate fibre length, thin-wall and large lumen diameter would result in easy beating of fibres and manufacture of dense, smooth and strong papers. Derived anatomical indices showed low SR values indicating low tearing resistance, bursting strength, and double folding resistance of any papers produced. However, the obtained RR, FR, RC, SF and LSF values of the fibres classify it as elastic, which can produce papers with high burst and tearing strengths and folding endurance, with a quality printing surface. Chemically, the lower lignin content observed implies that less amounts of energy and chemicals will be required for its removal. The high holocellulose content, low ash content and adequate 1% NaOH solubility would result in high pulp yield, making *A. boonei* a suitable material for pulp and paper production.

6 SUMMARY
6 POVZETEK

Svetovna poraba papirja narašča zaradi povečevanja števila prebivalcev (Tiseo, 2021). Predvidevamo, da bo pomanjkanje lesa za pridobivanje celuloze ena od večjih težav, ki bo ovirala napredek papirne industrije (Ververis et al., 2004). Čeprav se trenutno za proizvodnjo celuloze izkoriščajo tudi drugi nelesni vlaknati materiali, je les zaradi ugodnih lastnosti še vedno glavna surovina za proizvodnjo celuloze in papirja (Pearson, 1998). Anthonio in Antwi-Boasiako (2017) navajata, da bi z raziskavami potenciala manj uporabljanih tropskih listavcev za proizvodnjo celuloze lahko razširili bazo virov za industrijo celuloze in papirja. Za stalno oskrbo s papirjem, ki bi zadovoljila naraščajoče potrebe, potrebujemo primerne alternativne in trajnostne materiale, ki bi dopolnili in nadomestili pomanjkanje tradicionalnih virov.

V tej študiji smo preučili primernost lesa alstonije (*Alstonia boonei*), ki je bila doslej malo znana za proizvodnjo papirja. Raziskali smo osnovno gostoto (BD), lastnosti vlaken [dolžina vlaken (FL), premer vlaken (FD), premeri lumnov (LD) in debeline celičnih sten (WT)], anatomske indekse [prožnost (FR), vitkost (SR), koeficient togosti (RC), Luceov faktor oblike (LSF), stopnjo masivnosti (lesnatosti) vlaken (SF), Runklovo razmerje (RR)] ter kemično sestavo in lastnosti (lignin, holoceluloza, topnost v 1 % NaOH in vsebnost pepela). Les *A. boonei* smo preučevali na različnih delih debla (spodnji, srednji in zgordnji del), da bi ocenili variabilnost proučenih parametrov vzdolž debla.

Vzorci lesa *A. boonei*, uporabljeni za študijo, so bili pridobljeni na farmi FRNR (Faculty of Renewable Natural Resources), KNUST (Kwame Nkrumah University of Science and Technology) v Gani.

Določitev osnovne gostote, karakterizacija vlaken in kemična analiza so bili opravljeni skladno s TAPPI 258 om-11 (2011), IAWA (1989), ASTM D 1105 - 96 (2013), ASTM D 1106 - 96 (2007), ASTM D 1104 - 56 (1978), ASTM D 1102 - 84 (2007) in ASTM D 1109 - 84 (2007). Pridobljene podatke smo analizirali z analizo variance (ANOVA) z analitičnima programoma GenStat Release 10.3 (2011) in GraphPad Prism 5 (2007). Post hoc analiza je bila opravljena z uporabo Fisherjeve najmanjše značilne razlike (LSD) pri stopnji napake tipa I (α) 0,05.

Povprečna osnovna gostota lesa je bila 267,75 ± 36,01 kg/m^3, pri čemer je bila največja gostota zabeležena v spodnjem delu (314,95 ± 10,2 kg/m^3), sledila je gostota v srednjem delu (252,25 ± 14,7 kg/m^3), najmanjša pa je bila v zgornjem delu debla (236,04 ± 6,6 kg/m^3) (preglednica 1). Rezultati morfoloških značilnosti vlaken so pokazali večjo povprečno dolžino (1421,38 ± 163,3 µm) in premer vlaken (48,97 ± 6,3 µm), premere lumnov (33,18 ± 5,5 µm) in debeline celičnih sten (7,90 ± 3,7 µm) v spodnjem delu debla *A. boonei*. Izračunani indeksi kažejo, da ima les *A. boonei* Runklovo razmerje od 0,51 ± 0,3 do 0,70 ± 0,4; razmerje prožnosti (0,61 ± 0,1 do 0,69 ± 0,1); koeficient togosti (0,16 ± 0,1 do 0,19 ± 0,1) in koeficient fleksibilnosti (0,19 ± 0,2). 1), koeficient vitkosti (29,51 ± 5,2 - 32,60 ± 7,2); Luceov koeficient oblike (0,36 ± 0,2 - 0,45 ± 0,2) in stopnjo masivnosti (lesnatosti) vlaken ($1,08 \times 10^{-6} \pm 5,6 \times 10^{-5}$ - $1,83 \times 10^{-6} \pm 9,0 \times 10^{-5}$ $µm^3$) vzdolž debla (preglednica 1). Analiza kemične sestave lesa *A. boonei* je pokazala želeno vsebnost lignina (<30 %), holoceluloze (65 do 70 %), nizko vsebnost pepela (1,17 %) in topnost v 1 % NaOH, ki je znašala 11,93 %.

Glede na navedene ugotovitve je *A. boonei* mogoče uvrstiti med lesne vrste z nizko gostoto, primerne za proizvodnjo celuloze. Poleg tega omogoča les iz spodnjega dela z višjo gostoto in daljšimi vlakni večji izkoristek celuloze in izdelavo močnejšega papirja v primerjavi z lesom srednjega in zgornjega dela debla. Zaradi velikega premera vlaken *A. boonei* bi lahko izdelali voluminozen grob papir s površino, ki je manj primerna za tiskanje. Vendar pa lahko zaradi tanjših sten in velikih premerov vlaken pride do kompenzacije za izdelavo gostih, gladkih in močnih papirjev. Poleg tega je mletje lažje zaradi velikih lumnov vlaken, boljšega prodiranja tekočine v prazne prostore in sploščitve vlaken.

Runklovo razmerje, razmerje prožnosti, koeficient togosti, Luceov faktor oblike in stopnja masivnosti (lesnatosti) vlaken imajo vrednosti v razponih, ki so zaželeni za proizvodnjo celuloze iz lesa, zato bi iz lesa alstonije lahko izdelali tudi papirje z boljšimi trdnostnimi lastnostmi.

Kemijsko gledano nižja vsebnost lignina nakazuje, da bi bilo za njegovo odstranitev potrebno manj energije in kemikalij. Visoka vsebnost holoceluloze, nizka vsebnost pepela in ustrezna topnost v 1 % NaOH bi omogočili visok izkoristek celuloze, zato se je les *A. boonei* izkazal kot primeren material za proizvodnjo celuloze in papirja.

REFERENCES
VIRI

Adi, D. S., Risanto, L., Damayanti, R., Rullyati, S., Dewi, L. M., Susanti, R., Dwianto, W., Hermiati, E., & Watanabe, T. (2014). Exploration of unutilized fast growing wood species from secondary forest in Central Kalimantan: Study on the fiber characteristic and wood density. Procedia Environmental Sciences, 20, 321-327.

Afrifah, K. A., Osei, L., & Ofosu, S. (2020). Suitability of Four Varieties of Cocos Nucifera Husk in Ghana for Pulp and Paper Production. Journal of Natural Fibers. DOI: https://doi.org/10.1080/15440478.2020.1870615

Ajuziogu, G. C., & Ojua, E. O. (2020). Comparative Anatomical Studies on the Wood and Bast Fibres of *Gmelina arborea*. Journal of Materials Science Research and Reviews, 40-46.

Ajuziogu, G. C., Ojua, E. O., & Aina, D. O. (2019). Comparative paper-making potentials of three species from the Verbenaceae and Lamiaceae family. Asian Journal of Research in Botany, 1-5.

American Society for Testing and Materials (ASTM) D 1102 – 84. (2007). Standard Test Method for Ash in Wood. Philadelphia, PA.

American Society for Testing and Materials (ASTM) D 1104 – 56, (1978). Standard Test Method for Holocellulose in Wood. Philadelphia, PA.

American Society for Testing and Materials (ASTM) D 1105 – 96. (2013). Standard Test Method for Preparation of Extractive-free Wood. West Conshohocken, PA, United States.

American Society for Testing and Materials (ASTM) D 1106 – 96. (2007). Standard Test Method for Acid-Insoluble Lignin in Wood. Philadelphia, PA.

American Society for Testing and Materials (ASTM) D 1107 – 96. (2007). Standard Test Method for Ethanol-Toluene Solubility of Wood. Philadelphia, PA.

American Society for Testing and Materials (ASTM) D 1109 – 84. (2007). Standard Test Method for 1% Sodium Hydroxide Solubility of Wood. Philadelphia, PA.

Amidon, T. S. (1981). Effect of the wood properties of hardwood on kraft paper properties. Tappi, 64(3), 123-126.

Anthonio, F., & Antwi-Boasiako, C. (2017). The Characteristics of Fibres Within Coppiced and Non-Coppiced Rosewood (Pterocarpus erinaceus Poir.) and their Aptness for Wood - and Paper - Based Products. Pro Ligno, 13(2), 27–39.

Ashraf, A., Ragab, M., Osama, G., & Ahmed, M. (2016). New raw material for paper pulp. Bsc Thesis, Minia University. Available at https://www.academia.edu/30668511/New_raw_material_for_paper_pulp

Biermann, C. J. (1996). Handbook of pulping and papermaking. Elsevier.

Bowyer, J. L., Haygreen, J. G., & Schmulsky, R. (2003). Forest Products and Wood Science: An Introduction. Fourth edition. Iowa State Press.

Darkwa, N. A. (1996). Paper imports and consumption patterns in Ghana. Ghana Journal of Forestry, 3, 55-60.

Dehkhoda, A. (2008). Concentrating lignocellulosic hydrolysate by evaporation and its fermentation by repeated fed batch using flocculating Saccharomyces cerevisiae. Master's thesis, University of Borås/School of Engineering. Available at http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-19095

Dutt, D., & Tyagi, C. H. (2011). Comparison of various eucalyptus species for their morphological, chemical, pulp and paper making characteristics. Indian Journal of Chemical Technology, 18, 145-151.

Ekhuemelo, D. O., & Tor, K. (2013). Assessment of fibre characteristics and suitability of maize husk and stalk for pulp and paper production. Journal of Research in Forestry, Wildlife and Environment, 5(1), 41-49.

Enayati, A. A., Hamzeh, Y., Mirshokraiei, S. A., & Molaii, M. (2009). Papermaking potential of canola stalks. BioResources, 4(1), 245-256.

Hawthorne, W. (2006). Photoguide for the forest trees of Ghana: a tree-spotter's field guide for identifying the largest trees. Oxford Forestry Institute, Department of Plant Sciences.

Hegde, R. K., & Varghese, M. (2008). Genetic analysis of wood traits in *Eucalyptus camaldulensis*. Journal of Tree Science, 27,1-13.

Iawa Committee (1989). IAWA list of microscopic features for hardwood identification. IAWA Bull. ns, 10(3), 219-332.

Istas, J. R., Heremans, R., & Roekelboom, E. L. (1954). General Characteristics of Wood, Hardwood of Congo Belge in relationship with their utilization in industry paper pulp: Detailed Study of Some species. Gembloux: INEAC, Technical Series, No. 43.

Istek, A., Tutus, A., & Gülsoy, S. K. (2009). The effect of tree age on fiber morphology of *Pinus pinaster* and paper properties. KSU Journal of Engineering Sciences, 12(1), 1-5.

Izekor, D. N., & Fuwape, J. A. (2011). Variations in the anatomical characteristics of plantation grown *Tectona grandis* wood in Edo State, Nigeria. Archives of Applied Science Research, 3(1), 83-90.

Kiaei, M., Tajik, M., & Vaysi, R. (2014). Chemical and biometrical properties of plum wood and its application in pulp and paper production. Maderas. Ciencia y tecnología, 16(3), 313-322.

Larsson, P. T., Lindström, T., Carlsson, L. A., & Fellers, C. (2018). Fiber length and bonding effects on tensile strength and toughness of kraft paper. Journal of Materials Science, 53(4), 3006-3015.

López, F., Alfaro, A., García, M. M., Díaz, M. J., Calero, A. M., & Ariza, J. (2004). Pulp and paper from tagasaste (*Chamaecytisus proliferus* LF ssp. palmensis). Chemical Engineering Research and Design, 82(8), 1029-1036.

Luce, G. E. (1970). The physics and chemistry of wood pulp fibers. STAP, 8, 278.

Nugroho, W. D., Marsoem, S. N., Yasue, K., Fujiwara, T., Nakajima, T., Hayakawa, M., Nakaba, S., Yamagishi, Y., Jin, H.O., Kubo, T., & Funada, R. (2012). Radial variations in the anatomical characteristics and density of the wood of *Acacia mangium* of five different provenances in Indonesia. Journal of Wood Science, 58(3), 185-194.

Ofosu, S., Boadu, K. B., & Afrifah, K. A. (2020). Suitability of *Chrysophyllum albidum* from moist semi-deciduous forest in Ghana as a raw material for manufacturing paper-based products. Journal of Sustainable Forestry, 39(2),153–66. DOI: https://doi.org/10.1080/10549811.2019.1623052

Ogbonnaya, C. I., Roy-Macauley, H., Nwalozie, M. C., & Annerose, D. J. M. (1997). Physical and histochemical properties of kenaf (*Hibiscus cannabinus* L.) grown under water deficit on a sandy soil. Industrial Crops and Products, 7(1), 9-18.

Ogunleye, B. M., Fuwape, J. A., Oluyege, A. O., Ajayi, B., & Fabiyi, J. S. (2017). Evaluation of fiber characteristics of *Ricinodedron Heudelotii* (Baill, Pierre Ex Pax) for pulp and paper making. International Journal of Science and Technology, 6(1), 634-641.

Ohshima, J., Yokota, S., Yoshizawa, N., & Ona, T. (2005). Examination of within-tree variations and the heights representing whole-tree values of derived wood properties for quasi-non-destructive breeding of *Eucalyptus camaldulensis* and *Eucalyptus globulus* as quality pulpwood. Journal of Wood Science, 51(2), 102-111.

Okoegwale, E. E., Idialu, J. E., Ehilen, O. E., & Ogie-Odia, E. A. (2020). Assessment of vessel and fiber characteristics of *Blighia sapida* Konig. and *Lecaniodiscus cupanoides* Planch ex Benth. growing in rainforest and derived savanna areas of Edo state, Nigeria. African Journal of Biological Sciences, 2(2), 58-69. DOI: https://doi.org/10.33472/AFJBS.2.2.2020.58-69

Omotoso, M. A., & Ogunsile, B. O. (2009). Fibre and chemical properties of some Nigerian grown Musa species for pulp production. Asian Journal of Materials Science, 1, 14-21.

Ona, T., Sonoda, T., Ito, K., Shibata, M., Tamai, Y., Kojima, K., Ohshima, J., Yokota, S., & Yoshizawa, N. (2001). Investigation of relationships between cell and pulp properties in Eucalyptus by examination of within-tree property variations. Wood Science and Technology, 35(3), 229-243.

Onggo, H., & Astuti, J. T. (2005). The effect of sodium hydroxide and hydrogen peroxide on the yield and color of pulp from pineapple leaf fiber. Journal of Tropical Wood Science and Technology, 3(1), 37-43.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Anthony, S. (2009). Agroforestree Database: a tree reference and selection guide version 4.0. World Agroforestry Centre, Kenya.

Pearson, G., & Richards, D. (Eds.) (1998). The ecology of industry: Sectors and linkages. National Academies Press.

Petro, R., Ndomba, O. A., Chidege, M. Y., Laswai, F., & Nyaradani, G. (2016). Basic density and its variation in *Olea capensis* established in matrix with *Grevillea robusta* grown in Meru-Usa Forest Plantation, Tanzania. International Journal of Agriculture and Forestry, 6(1), 8-11.

Pirralho, M., Flores, D., Sousa, V. B., Quilhó, T., Knapic, S., & Pereira, H. (2014). Evaluation on paper making potential of nine Eucalyptus species based on wood anatomical features. Industrial Crops and Products, 54, 327-334.

Rana, R., Langenfeld-Heyser, R., Finkeldey, R., & Polle, A. (2009). Functional anatomy of five endangered tropical timber wood species of the family Dipterocarpaceae. Trees, 23(3), 521-529.

Riki, J. T. B., Sotannde, O. A., & Oluwadare, A. O. (2019). Anatomical and chemical properties of wood and their practical implications in pulp and paper production: A review. Journal of Research in Forestry, Wildlife and Environment, 11(3), 358-368.

Rodríguez, A., Moral, A., Serrano, L., Labidi, J., & Jiménez, L. (2008). Rice straw pulp obtained by using various methods. Bioresource technology, 99(8), 2881-2886.

Rowell, R. M. (2012). Handbook of wood chemistry and wood composites. CRC press.

Salmenoja, K., & Makela, K. (2000). "Chlorine-induced superheater corrosion in boilers fired with biomass," In: Proceedings of the fifth European Conference on Industrial Furnaces and Boilers, April 2000, INFUB, Porto, Portugal.

San, H. P., Long, L. K., Zhang, C. Z., Hui, T. C., Seng, W. Y., Lin, F. S., Hun, A. T., & Fong, W. K. (2016). Anatomical features, fiber morphological, physical and mechanical properties of three years old new hybrid Paulownia: Green Paulownia. Research Journal of Forestry 10(1), 30–35. DOI: https://doi.org/10.3923/rjf.2016.30.35

Sangumbe, L. M. V., Pereira, M., Carrillo, I., & Mendonça, R. T. (2018). An exploratory evaluation of the pulpability of *Brachystegia* *spiciformis* and *Pericopsis angolensis* from the angolan miombo woodlands. Maderas. Ciencia y tecnología, 20(2), 183-198. DOI: https://doi.org/10.4067/S0718-221X201800500230

Santos, A., Amaral, M. E., Vaz, A., Anjos, O., & Rogério, S. (2008). Effect of *Eucalyptus globulus* wood density on papermaking potential. Tappi Journal, 25-32.

Santos, A., Anjos, O., Amaral, M. E., Gil, N., Pereira, H., & Simões, R. (2012). Influence on pulping yield and pulp properties of wood density of *Acacia melanoxylon*. Journal of wood science, 58(6), 479-486.

Shackford, L. D. (2003). A comparison of pulping and bleaching of kraft softwood and eucalyptus pulps. In 36th international pulp and paper congress and exhibition. Sao Paul Brazil.

Sharma, A. K., Dutt, D., Upadhaya, J. S., & Roy, T. K. (2011). Anatomical, morphological and chemical characterization of *Bambusa tulda*, *Dendrocalamus hamiltonii*, *Bambusa balcooa*, *Malocana baccifera*, *Bambusa arundinacea* and *Eucalyptus tereticornis*. BioResources 6(4), 5062–5073.

Sharma, M., Sharma, C. L., Bage, M., Gogoi, B. R., & Pangging, G. (2018). Anatomical Characteristics and Fibre Dimensions of Some Grass Species of Arunachal Pradesh and their Potential for Pulp and Paper. Journal of Bioresources 5(1), 41–48.

Smook, G. A. (1997). Handbook for Pulp & Paper Technologists. Vancouver, Angus Wilde Publications.

Takeuchi, R., Wahyudi, I., Aiso, H., Ishiguri, F., Istikowati, W. T., Ohkubo, T., Ohshima, J., Iizuka, K., & Yokota, S. (2016). Wood properties related to pulp and paper quality in two Macaranga species naturally regenerated in secondary forests, Central Kalimantan, Indonesia. Tropics, 25 (3), 107-115. DOI: https://doi.org/10.3759/tropics.MS15-23

Technical Association of the Pulp and Paper Industry (TAPPI) Test Method T258 om-11. (2011). Basic Density of Wood and Pulp. In: Tappi Test Methods. Atlanta, GA.

Tiseo, L. (2021). Global Paper Consumption 2020 – 2030. Statista. Available at https://www.statista.com/statistics/1089078/demand-paper-globally-until-2030/

Tran, A. V. (2006). Chemical analysis and pulping study of pineapple crown leaves. Industrial Crops and Product, 24(1), 66–74.

Tutuş, A., Kazaskeroğlu, Y., & Çiçekler, M. (2015). Evaluation of tea wastes in usage pulp and paper production. BioResources, 10(3), 5407-5416.

Varghese, M., Nicodemus, A., Ramteke, P. K., Anbazhagi, G., Bennet, S. S. R., & Subramanian, K. (2000). Variation in growth and wood traits among nine populations of teak in Peninsular India. Silvae Genetica, 49(4/5), 201-205.

Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P., & Santas, R. (2004). Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. Industrial crops and products, 19(3), 245-254.

Zawawi, D., Mohd, Z., Angzzas, S., & Ashuvila, M. A. (2014). Analysis of the chemical compositions and fiber morphology of pineapple (*Ananas comosus*) leaves in Malaysia. Journal of Applied Sciences, 14(12), 1355-1358. DOI: https://doi.org/10.3923/jas.2014.1355.1358

Zhan, H., Tang, G. J., Wang, C. M., & Wang, S. G. (2015). Chemical properties and fiber morphology of *Fargesia fungosa* at different culm ages and heights. BioResources, 10(3), 5666-5676. DOI: https://doi.org/10.15376/biores.10.3.5666-5676

LES/WOOD Vol. 70, No. 2, 19-29
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a03

ANALYSING THE EFFECT OF THERMAL MODIFICATION ON THE CALORIFIC VALUES OF *EUCALYPTUS NITENS* WOOD

ANALIZA VPLIVA TERMIČNE MODIFIKACIJE NA KALORIČNO VREDNOST LESA *EUCALYPTUS NITENS*

Saurav Nepal[1*], Rupert Wimmer[2], Volker Zelinski[3]

UDK: 630*813.4:543.572
Original scientific article / Izvirni znanstveni članek

Received / Prispelo: 28. 7. 2021
Accepted / Sprejeto: 16. 9. 2021

Abstract / Izvleček

Abstract: Gross and net calorific value of 13 samples of *Eucalyptus nitens* wood were determined at HAWK (Hochschule für Angewandte Wissenschaft und Kunst), Göttingen, Germany. Among 13 samples, 12 were thermally modified and one was unmodified. Calorific values of samples were determined by using a bomb calorimeter, and the wood components (cellulose, hemicellulose, lignin, and extractives) already analysed by Wentzel et al. (2019). After determination of the values, samples were statistically analysed by R studio to find the relations among the calorific value, temperature, and wood components. The gross calorific value and net calorific value of the untreated sample of *Eucalyptus nitens* were found to be 18.83 MJ/kg and 17.48 MJ/kg, and after thermal modification these increased up to 20.24 MJ/kg and 18.84 MJ/kg. Upon statistical analysis, the results for lignin showed a strong correlation with the temperature of thermal treatment and calorific value.

Keywords: *Eucalyptus nitens*, gross calorific value, net calorific value, thermal modification, cellulose, hemicellulose, lignin, extractives

Izvleček: Na 13 vzorcih lesa *Eucalyptus nitens* je bila izmerjena zgornja in spodnja kalorična vrednost. 12 vzorcev je bilo termično modificiranih, en vzorec pa je bil nemodificiran. Kalorične vrednosti vzorcev so bile določene z uporabo bombnega kalorimetra z upoštevanjem lesnih komponent (celuloza, hemiceluloza, lignin in ekstraktivi), ki so jih že določili Wentzel et al. (2019). S statističnim programom R studio smo statistično analizirali dobljene rezultate, da bi ugotovili povezavo med kalorično vrednostjo, temperaturo modifikacije in lesnimi komponentami. Ugotovljeno je bilo, da sta zgornja in spodnja kalorična vrednost neobdelanega lesa *Eucalyptus nitens* znašali 18,83 MJ/kg in 17,48 MJ/kg, po termični modifikaciji pa sta znašali 20,24 MJ/kg in 18,84 MJ/kg, kar pomeni, da termična modifikacija lesa povzroča višje kalorične vrednosti. Statistična analiza je prikazala tesno korelacijo med deležem lignina ter temperaturo in kalorično vrednostjo.

Ključne besede: *Eucalyptus nitens*, zgornja kalorična vrednost, spodnja kalorična vrednost, termična modifikacija, celuloza, hemiceluloza, lignin, ekstraktivi

1 UVOD
1 INTRODUCTION

Modification of wood through thermal heating is applied to enhance certain properties to make wood more suitable for various applications. Thermal modification is altering the chemical wood structure, i.e., cellulose, hemicellulose, lignin, and extractives, which ultimately improves the durability as well as the dimensional stability (Todaro et al., 2015). Biological decay and instability under a changing moisture regime are seen as a major drawback of wood, compared to competing materials (Homan & Jorissen, 2004). Properties that have been found to get altered by thermal modification include shrinking and swelling properties (Bak & Nemeth, 2012), losses in wood mass and strength, lower equilibrium moisture contents, a higher mechanical stiffness and modulus of elasticity (Kol et al., 2015) and improved durability (Rapp, 2001). Likewise, the calorific value of wood might also be altered after thermal treatments (Todaro et al., 2015).

[1] Department of Wood Biology and Wood Products, University of Göttingen, Faculty of Forest Science, Büsgenweg 4, 37077 Göttingen, Germany
* e-mail: sauravnepal94@yahoo.com, +49 15216713902
[2] Institute of Wood Technology and Renewable Materials, University of Natural Resources and Life Sciences, Vienna (BOKU), 3430 Tulln, Austria
[3] University of Applied Sciences and Arts Hildesheim / Holzminden / Göttingen, Büsgenweg 1a, 37077 Göttingen, Germany

The energy content of wood, also known as the calorific or heating value, is the amount of heat released during wood combustion. It is the energy units released when a unit of fuel undergoes complete combustion in presence of oxygen (Telmo & Lousada, 2011a). The calorific value of wood can be expressed as the higher heating value (gross calorific value), and the low heating value (net calorific value). The gross calorific value of a wood sample is referred to as the specified energy ignition of woody biofuel per unit mass, burned in the presence of oxygen in a bomb calorimeter under clear and definite conditions, and expressed in joules. The net calorific value refers to the value when the wood biofuel per unit mass is burned in the presence of oxygen in a bomb calorimeter under definite conditions, with the water remaining in the reaction as water vapour (ISO 18125). A higher heating value has water in a condensed state, but for a lower heating value the water remains gaseous (Acar et al., 2012). A lower heating value rather than a higher heating value is obtained when the moisture in a biofuel is reduced and the water vapour that forms during hydrogen ignition is excluded (Acar et al., 2012). The chemical nature of wood determines the calorific value, which is directly linked to the species, and to the between and within-variability of individual trees (Dhamodaran et al., 1989).

Wood is widely used as an energy source by people living in developing countries, who together account for some 77% of the world population (Trossero, 2002). Increasing demand for wood for energy purposes calls for the more efficient utilization of wood. Thermal modification has a vital role in using limited wood resources more efficiently. Previous studies depict the direct relation between thermal modification and calorific values in wood of several species (Todaro et al., 2015; Calonego et al., 2016). The calorific value of wood is dependent on the wood's chemical constituents (cellulose, hemicellulose, lignin and extractives) (Telmo & Lousada, 2011b; Ngangyo-Heya et al., 2016; White, 2007), which are affected by changes in temperature (Todaro et al., 2013; Yildiz et al., 2006).

This article aims to analyse the calorific value of thermally modified *Eucalyptus nitens* wood, analysing several chemical constituents of wood, finding the correlation between different wood constituents and heating values, and establishing the relationship between calorific values and wood components through linear modelling. *Eucalyptus nitens* is selected for this study because of its widespread nature and the fact that it is also a very wildly used plantation species.

2 MATERIALS AND METHODS
2 MATERIAL IN METODE

2.1 SAMPLE PREPARATION AND THERMAL MODIFICATION
2.1 PRIPRAVA VZORCEV IN TERMIČNA MODIFIKACIJA

Wood samples of *Eucalyptus nitens* (H. Deane & Maiden) were thermally modified at different temperatures in an earlier study, performed by Wentzel et al. (2019). Samples originated from a *Eucalyptus* plantation in the Región del Bío-Bío, Chile, with the plantation trees being 19 years old when sampled. Samples were sized 20*50*650 mm^3 (radial*tangential*longitudinal) and the average wood density was 663 kg/m^3. Samples were stored in a climate room having 20 °C / 65% RH, with the samples showing a moisture content of 12% (±0.85%). The samples were then dried in the simple kiln to avoid deformations and defects.

Modification was carried out in both an open and closed system. In the open system the temperature was increased at a rate of 12 °C per hour until 100 °C was reached inside the vessel. Afterwards, the pre-drying process was continued at heating rate of 2 °C per hour, until 130 °C was reached. The temperature was again raised at the rate of 12 °C per hour until the temperature required for the modification was reached, and the temperature was then kept constant for 3 hours and data on any modifications at that temperature was recorded. The temperatures for the open system of modification were 160 °C, 180 °C, 200 °C, 220 °C and 230 °C. For the closed system of modification, the WTT process by Willems (2009) was carried out. The modification temperatures used in the closed system of modification were 150 °C, 160 °C and 170 °C, with the relative humidity of 30% and 100% for each temperature.

2.2 DETERMINATION OF WOOD COMPONENTS
2.2 DOLOČANJE LESNIH KOMPONENT

Extractives, cellulose, hemicellulose and lignin contents were determined by Wentzel et al. (2019), who applied the wood and pulp test method T 204 cm-07 (TAPPI, 1997) to achieve this. Measurement of cellulose content was done by separation of lignin by sodium chloride from holocellulose, followed by using sodium hydroxide solution for separation of cellulose from the hemicellulose (Wentzel et al., 2019).

2.3 DETERMINATION OF GROSS AND NET CALORIFIC VALUE
2.3 DOLOČITEV ZGORNJE IN SPODNJE KALORIČNE VREDNOSTI

Determination of calorific value was done in the laboratory of HAWK, Göttingen. Thirteen wood samples modified at different temperatures were used for the determination of their calorific values. The fine dust particles of the different samples were subjected to a mechanical press to convert them into pellets that weighed less than 50 mg. Calorimeter C 7000 from the company IKA was used to obtain the energy liberated during the combustion of wood particles. One sample was put in a bomb calorimeter three times for the calculation of the calorific value. A bomb calorimeter was used since it is easy to operate at high efficiency.

2.3.1 Calculation Procedure
2.3.1 Postopek izračuna

The procedure and calculations for the gross calorific value were done based on ISO 18125. Calculations for the gross calorific value and the net calorific value were performed using software and the following equation:

$$Q_{p,net,d} = Q_{v,gr,d} - 212.2 \text{ x } w(H)_d - 0.8 \text{ x } [w(O)_d + w(N)_d]$$

Where,
$Q_{p,net,d}$ is the net calorific value.
$Q_{v,gr,d}$ is the gross calorific value.
$w(H)_d$ is the amount of hydrogen content in percent.
$w(O)_d$ is the amount of oxygen content in percent.
$w(N)_d$ is the amount of nitrogen content in percent.

2.4 STATISTICAL ANALYSIS
2.4 STATISTIČNA ANALIZA

Microsoft Excel was used to obtain various graphs. R statistics were used to find the relation

Table 1. Wood components and calorific values at different modification temperatures
Preglednica 1. Spodnje kalorične vrednosti (NCV), zgornje kalorične vrednosti (GCV) ter kemijska sestava lesa pri različnih temperaturah modifikacije; CS – zaprt sistem in OS – odprt sistem modifikacije.

Temperature [Celsius] and relative humidity [%]	NCV [MJ/kg]	GCV [MJ/kg]	Lignin** [%]	Extractives** [%]	Hemicellulose** [%]	Cellulose** [%]
Unmodified	17.48	18.83	22.5	4.7	27.4	48.3
150 and 30 (CS)	17.98	19.33	21.0	6.0	23.5	50.1
160 and 30 (CS)	17.7	19.05	23.1	7.6	17.6	51.3
170 and 30 (CS)	17.33	18.68	22.8	8.4	14.2	53.9
150 and 100 (CS)	17.19	18.54	25.4	12.7	5.9	55.7
160 and 100 (CS)	18.07	19.42	26.5	13.2	6.5	53.7
170 and 100 (CS)	18.73	20.08	31.8	10.1	10.3	49.7
160 (OS)	17.61	18.96	20.8	6.8	18.8	52.2
180 (OS)	17.62	18.97	23.5	9.0	18.7	48.6
200 (OS)	18.05	19.39	23.7	12.3	10.4	52.5
210 (OS)	18.89	20.24	27.4	12.7	10.8	49.3
220 (OS)	18.44	19.79	28.6	9.1	11.8	50.2
230 (OS)	18.72	20.07	36.9	7.4	12.2	45.8

GCV = Gross calorific value
NCV = Net calorific value
**Wentzel et al. 2019
CS = Closed system modification
OS = Open system modification

between different chemical components and calorific values. Simple linear regression analysis was applied for the estimation of the heating value. Linear regression was also used to build the model and predict the effects of the chemical components on the heating value.

3 RESULTS

3 REZULTATI

3.1 EFFECT OF THERMAL MODIFICATION

3.1 UČINEK TERMIČNE MODIFIKACIJE

The calorific values and wood components (cellulose, hemicellulose, lignin, and extractives) of unmodified and thermally modified wood samples of *Eucalyptus nitens* are presented in Table 1. The results show that the gross and net calorific values increased with thermal modification. The maximum values were observed when the samples were treated at 170 °C with a high relative humidity. Similarly, with an increase in temperature there was increase in lignin and extractive contents and decrease in cellulose and hemicellulose. In the open system of modification, as illustrated by Figure 2, the maximum rise in calorific value was seen between 210 °C and 230 °C. Overall, in both systems of modification an increase in the heating value was observed with the increase in temperature for *Eucalyptus nitens*.

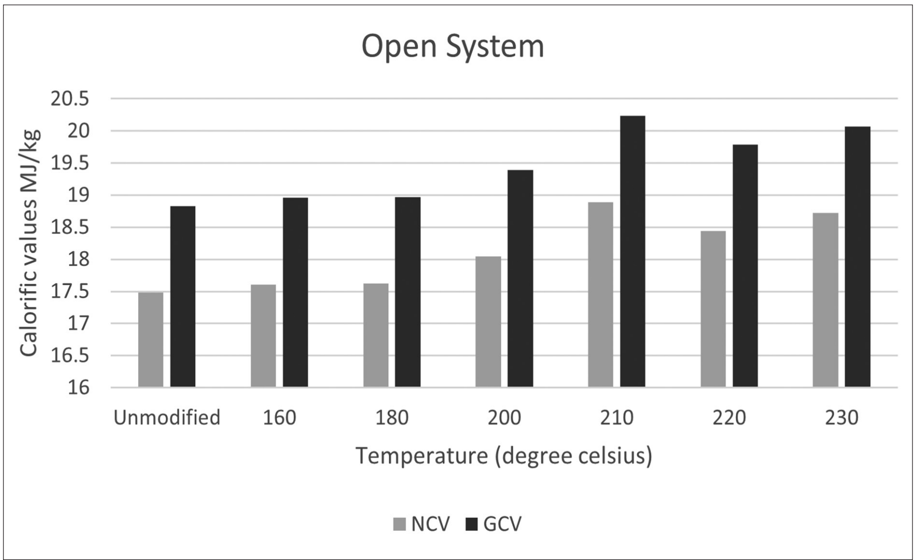


Figure 1. Open system of modification: Net (NCV) and gross (GCV) calorific values of untreated wood and wood modified at different temperature regimes

Slika 1. Odprt sistem modifikacije: Spodnje (NCV) in zgornje kalorične vrednosti (GCV) netretiranega lesa in lesa, modificiranega pri različnih temperaturnih režimih

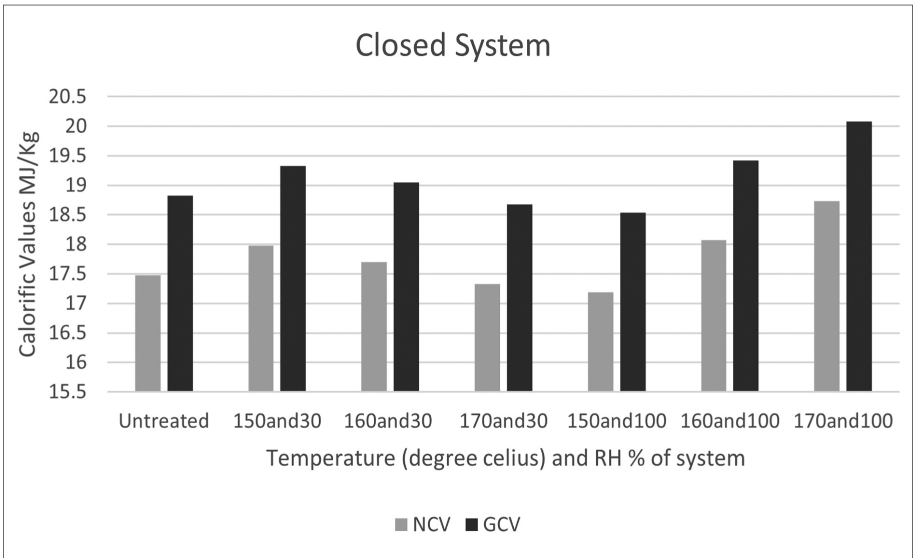


Figure 2. Closed system of modification: Net (NCV) and gross (GCV) calorific values of untreated wood and wood modified at different temperature regimes

Slika 2. Zaprt sistem modifikacije: Spodnje (NCV) in zgornje kalorične vrednosti (GCV) netretiranega lesa in lesa, modificiranega pri različnih temperaturnih režimih

3.2 STATISTICAL ANALYSIS
3.2 STATISTIČNA ANALIZA

3.2.1 Temperature of both modifications and calorific values
3.2.1 Temperatura modifikacije in kalorična vrednost

The relation between calorific value and temperature is illustrated in Figure 3. GCV (MJ/kg) and NCV (MJ/kg) were found to be positively corelated with temperature (°C), as seen in figures a and b.

3.2.2 Temperature and wood components
3.2.2 Temperatura in lesne komponente

Changes in wood constituents upon treating with different temperatures are depicted by Figure 4. Cellulose and hemicellulose were found to be negatively correlated with temperature (Figure 4 a and c) whereas lignin was positively corelated and extractives increased slightly with temperature (Figure 4 b and d). From the statistical analysis, the effects of temperature on cellulose and lignin were significant (shown in a and b), with p-values of 0.0268 and 0.0226 at a 5% level of significance.

3.2.3 Calorific value and wood components
3.2.3 Kalorična vrednost in osnovne sestavine lesa

The statistical relationship between calorific values (GCV and NCV) and wood components (cellulose, hemicellulose, lignin, and extractives) is elucidated by Figure 5. The calorific value was found to be negatively correlated with cellulose (Figure 5 a and b) and hemicellulose (Figure 5 c and d). However, the correlation was high in case of cellulose, with a coefficient of -0.695. There was a positive correlation of calorific value with lignin (Figure 5 e and f) and extractives (Figure 5 g and h). Calorific value was found to be positively and highly corelated with lignin, with a coefficient of 0.716 (lignin vs GCV) and 0.715 (lignin vs NCV).

3.2.4 Linear relationship
3.2.4 Linearno razmerje

The effects of temperature, lignin and cellulose were found to be significantly related to the calorific value of wood. Therefore, multiple regression analysis was carried out which includes these three as independent variables and energy content as a dependent variable. The results of the multiple regression analysis are shown in Table 3.

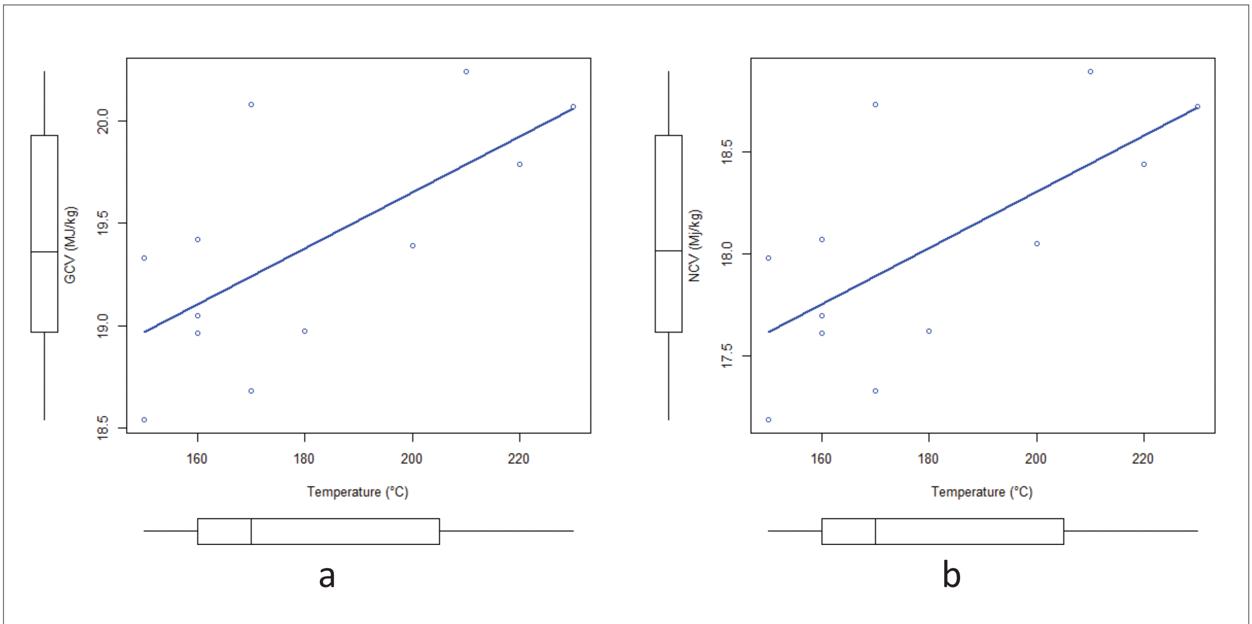


Figure 3. Relationship between temperature and calorific value; a (Temperature vs GCV) and b (Temperature vs NCV)

Slika 3. Razmerje med temperaturo in kalorično vrednostjo; a (temperatura v primerjavi z GCV) in b (temperatura v primerjavi z NCV)

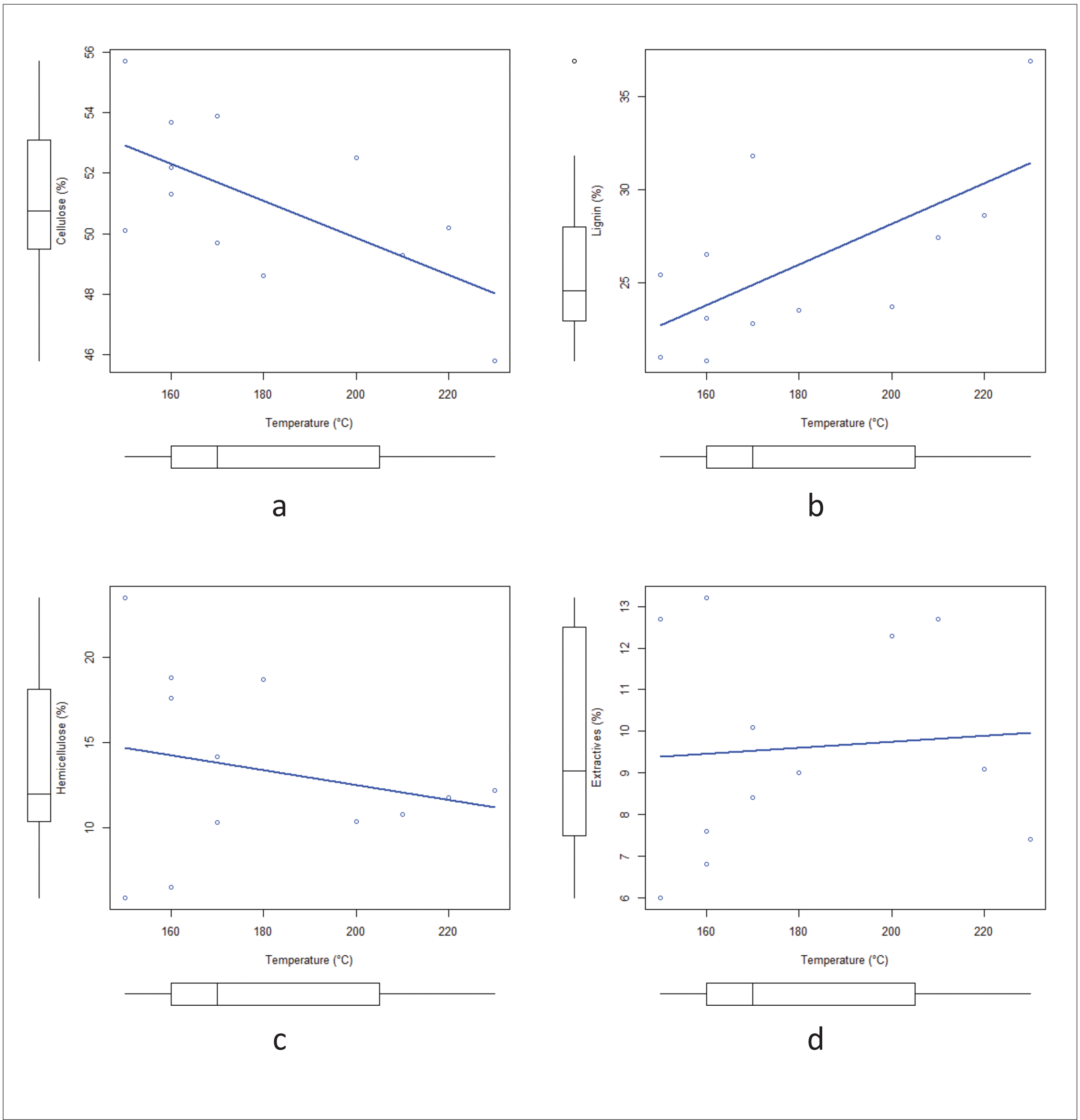


Figure 4. Percentages of wood components as affected by temperature: a (cellulose vs temperature), b (lignin vs temperature), c (hemicellulose vs temperature) and d (extractives vs temperature).
Slika 4. Deleži kemijskih komponent v odvisnosti od temperature: a (celuloze v odvisnosti od temperature), b (lignina v odvisnosti od temperature), c (hemiceluloze v odvisnosti od temperature) in d (ekstraktivov v odvisnosti od temperature).

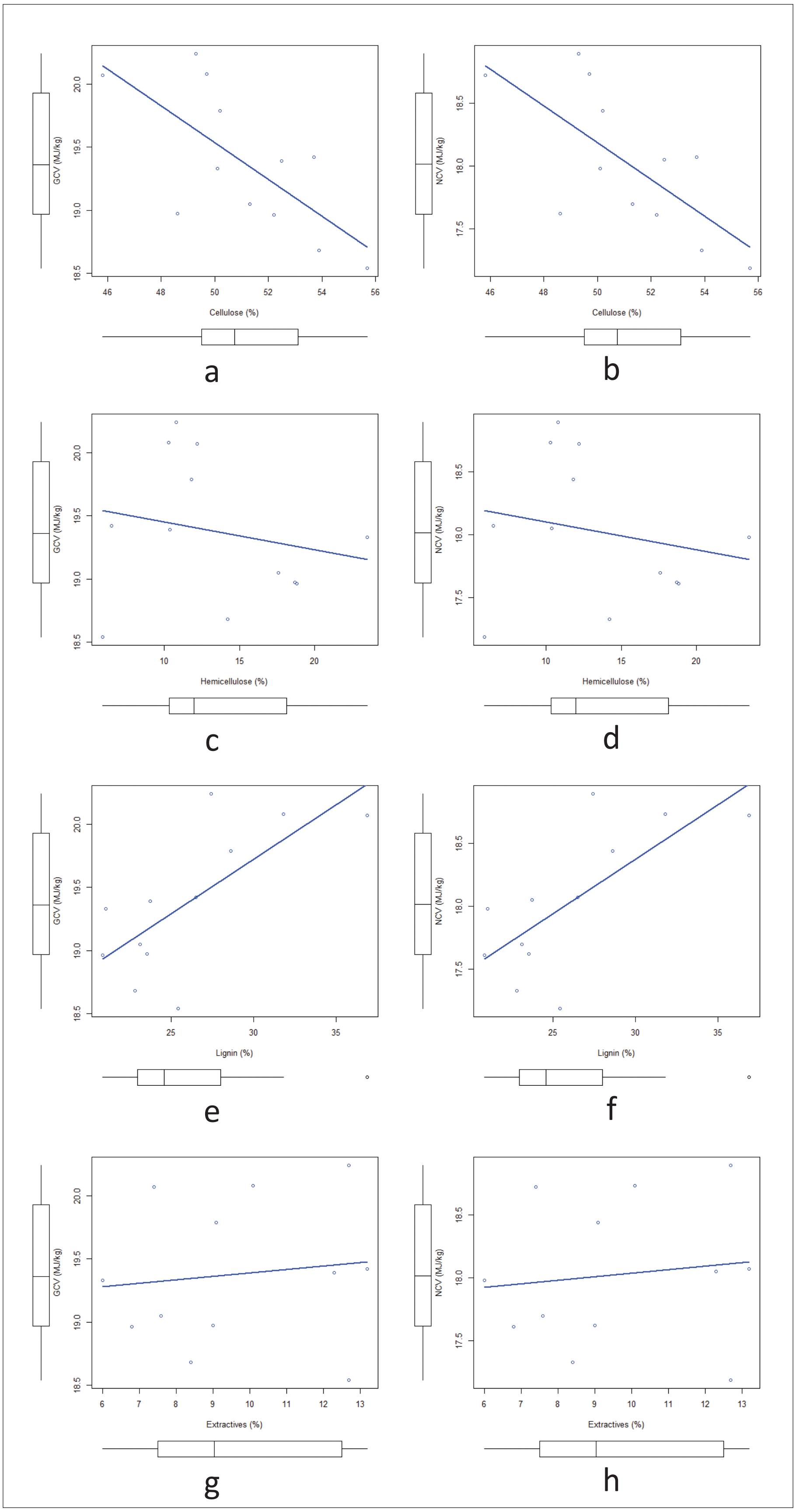


Figure 5. Relationship between calorific value and wood components: a (GCV vs cellulose), b (NCV vs cellulose), c (GCV vs hemicellulose), d (NCV vs hemicellulose), e (GCV vs lignin), f (NCV vs lignin), g (GCV vs extractives) and h (NCV vs extractives)

Slika 5. Razmerje med kalorično vrednostjo in sestavinami lesa: a (GCV v primerjavi s celulozo), b (NCV v primerjavi s celulozo), c (GCV v primerjavi s hemicelulozo), d (NCV v primerjavi s hemicelulozo), e (GCV v primerjavi z ligninom), f (NCV v primerjavi z ligninom), g (GCV v primerjavi z ekstraktivi) in h (NCV v primerjavi z ekstraktivi)

Table 2. Linear relationship between calorific value (dependent variable) and various independent variables

Preglednica 2. Linearna zveza med kalorično vrednostjo (odvisna spremenljivka) in različnimi neodvisnimi spremenljivkami

Relation	Model	Multiple R squared	Adjusted R squared	p-value
Calorific value and temperature (T)	GCV = 16.911+0.0137*T NCV = 15.557+0.0137*T	0.4575 0.4590	0.4033 0.4049	0.0157 0.0154
Calorific value and lignin (L)	GCV = 17.1418+0.0861*L NCV = 15.795+0.086*L	0.5128 0.5116	0.4641 0.4628	0.0088 0.0089
Calorific value and cellulose (C)	GCV = 26.8268-0.1458*C NCV = 25.4687-0.1457*C	0.4844 0.4832	0.4328 0.4315	0.0119 0.0121
Calorific value and hemicellulose (H)	GCV = 19.6692-0.02184*H NCV = 18.3213-0.0219*H	0.04204 0.04241	-0.0537 -0.0533	0.5226 0.5208

GCV: Gross calorific value; NCV: Net calorific value

Table 3. Multiple regression analysis

Preglednica 3. Analiza multiple regresije

Model	Multiple R squared	Adjusted R squared	P-value
GCV = 21.1194 +0.00419*T +0.04635*L- 0.07245*C	0.6569	0.5282	0.02903
NCV = 19.74042 +0.00427*T +0.046104*L- 0.072019*C	0.6561	0.5272	0.02927
GCV = 17.1101 +0.085762*L +0.004166*E	0.5131	0.4049	0.03920
NCV = 15.760314 +0.08536*L +0.004599*E	0.5121	0.4036	0.03960
GCV = 21.36830+0.06390*L-0.10565*C+0.03953*H+0.12669*E	0.7259	0.5692	0.03818
NCV = 20.16484+0.06259*L-0.10733*C+0.03821*H+0.12582*E	0.7254	0.5685	0.03839

T = Temperature, C = Cellulose, H = Hemicellulose, L = Lignin, E = Extractives

4 DISCUSSION
4 RAZPRAVA

Thermally modified samples of *Eucalyptus nitens* wood led to an increase in the calorific value of the wood in this experiment. As shown in Table 1, the gross calorific value and net calorific value recorded in the untreated samples of *Eucalyptus nitens* were found to be 18.83 MJ/kg and 17.48 MJ/kg, and after treatment the maximum values of 20.24 MJ/kg and 18.84 MJ/kg were recorded. The relationship between temperature and calorific value is also depicted by the high correlation between temperature and calorific value, as illustrated in Figure 3. When *Eucalyptus nitens* wood was thermally modified, there was an increase in both net and gross calorific values along with changes in lignin, holocellulose and extractive contents. These findings are similar to those found by Calonego et al. (2016) for mature *Eucalyptus grandis* wood when treated at 180 °C. Previous studies suggest the change in calorific value is a result of changes in the wood components (Telmo & Lausada, 2011b; Demribas, 2001). Furthermore, this relationship between calorific value, temperature and wood components is also elucidated by the results of the statistical analyses (Figures 3, 4 and 5) and multiple regression model (Tables 2 and 3).

The results of the experiment showed an increase in lignin content upon thermal treatment of *Eucalyptus nitens* wood, as shown in Figure 4b. This is also supported by the results of Esteves et al.'s (2008) experiment with *Eucalyptus globulus* wood, where the lignin content was found to be increased with autoclaving and oven drying of the sample. Previous studies suggest that the formation of insoluble by-products and humification results in an increase in lignin, which is the result of the hemicellulose degradation (Tjeerdsma et al., 1998; Wikberg & Mannu, 2004; Esteves & Pereira, 2009).

The higher correlation between lignin and calorific value demonstrated by this experiment, as indicated by the higher correlation coefficient of 0.716, suggests a direct relationship between lignin and calorific values, as the increase in the former causes an increase in the latter. A similar correlation was found by an experiment by Demribas (2001) that examined 14 lignocellulosic materials, where a higher correlation coefficient of 0.874 was found between lignin and a high heating value. Previous studies note that the heating value is mostly defined by the lignin content, as compared to holocellulose lignin has higher amounts of carbon and hydrogen, which are the main heat producing constituents in wood (Telmo & Lausada, 2011b; Demribas, 2001).

From the statistical analysis, cellulose was found to be negatively corelated with temperature and calorific value, as demonstrated by Figures 4a, 5a and 5b. Cellulose is the most stable compound due to its crystalline nature (Esteves & Pereira, 2009). The crystallinity of cellulose was found to be less affected by temperature in previous studies (Bourgois et al., 1989; Yildiz et al., 2006). When thermal modification is carried out, cellulose undergoes some temporary effects of temperature on its unstructured region (Bhuiyan & Hirai, 2005; Wirkberg & Mannu, 2004). Hemicellulose was also found to be negatively corelated with temperature and calorific value in this study. Hemicellulose degrades first even at a relatively low temperature, and the most common temperature for wood modification ranges from 180 °C to 250 °C (Esteves & Pereira, 2009). When hemicellulose starts degrading, it forms acetic acid which acts as a catalyst for the formation of furfural, formaldehyde and other aldehydes (Tjeerdsma et al., 1998). As a result, the percentage of the hemicellulose decreases even at low temperature treatment. The extractive contents in this experiment on *Eucalyptus nitens* were initially increased upon heating, but gradually started to degrade with a further increase in temperature beyond 220 °C. Similar results were reported by Esteves et al. (2008) for the extractives of *Eucalyptus globulus* upon heat treatment. Previous studies suggest that when wood is thermally treated the volatile substances vanish, but degradation of the cell walls leads to the creation of new compounds (Esteves & Pereira, 2009).

5 CONCLUSIONS
5 ZAKLJUČKI

The calorific value of *Eucalyptus nitens* wood was found to be increased upon thermal modification. The experiments showed that lignin was significantly and highly corelated with temperature and calorific value. Statistical analyses and comparisons with the results of previous studies indicate that changes in temperature favour alteration in wood's chemical constituents and changes the calorific value. Based on the results obtained in the current work, it is concluded that wood with high lignin content can result in high energy content. As an increase in the calorific value was observed with thermal treatment, *Eucalyptus nitens* wood can be used efficiently for energy production after thermal modification.

6 SUMMARY
6 POVZETEK

Les se zaradi svoje kurilne oziroma kalorične vrednosti v mnogih delih sveta uporablja kot pomemben vir energije. Povečanje povpraševanja po lesu za energetske namene zahteva učinkovito uporabo lesa. Ugotovljeno je bilo, da se s termično modifikacijo lesa spreminja delež lesnih komponent, kar je ključnega pomena za povečanje njegove kalorične vrednosti. V HAWK, Hochschule für Angewandte Wissenschaft und Kunst, Göttingen, je bila izvedena analiza vpliva termičnih sprememb na kalorično vrednost lesa *Eucalyptus nitens*. Glavni cilj raziskave je bil določiti kalorično vrednost termično modificiranega lesa in ugotoviti razmerje med ka-

lorično vrednostjo in temperaturo modifikacije ter deleži lesnih sestavin. Za to študijo smo uporabili termično modificirane vzorce lesa *Eucalyptus nitens* pri različnih temperaturah, ki so jih pripravili Wentzel et al. (2019). Po navedbah avtorjev je les izviral iz nasada evkalipta v regiji Regio del Bío-Bío v Čilu, vzorci pa so bili odvzeti pri starosti nasada 19 let. Zgornje in spodnje kalorične vrednosti so bile določene z bombnim kalorimetrom. Po določitvi kaloričnih vrednosti vzorcev, modificiranih pri različnih temperaturah in znanih podatkih o deležih posameznih komponent lesa (celuloze, hemiceluloze, lignina in ekstraktivov), določenih v predhodni študiji (Wentzel et al., 2019), je bila opravljena tudi statistična analiza za ugotavljanje zveze med kaloričnimi vrednostmi, temperaturo modifikacije in deleži lesnih komponent. Z uporabo statističnega programa R-studio je bilo statistično analiziranih 12 modificiranih in en nemodificiran vzorec.

Ugotovljeno je bilo, da sta bruto in neto kalorična vrednost neobdelanega vzorca *Eucalyptus nitents* 18,83 MJ/kg in 17,48 MJ/kg, po obdelavi pa sta bili izmerjeni vrednosti 20,24 MJ/kg in 18,84 MJ/kg, kar je pokazalo povečanje kalorične vrednosti zaradi termične modifikacije. Statistična analiza zgornje kalorične vrednosti in temperature je pokazala visoko korelacijo s korelacijskim koeficientom 0,676. Vrednost p pri linearni regresiji je bila 0,0152. Podobno smo opazili visoko korelacijo med neto kurilno vrednostjo in temperaturo s korelacijskim koeficientom 0,677 in p-vrednostjo 0,015.

Rezultati korelacij med temperaturo modifikacije, deležem celuloze, hemiceluloze, lignina in ekstraktivov ter kalorične vrednosti so pokazali negativno korelacijo vsebnosti celuloze in hemiceluloze s temperaturo in pozitivno korelacijo vsebnosti lignina in ekstraktivnih snovi s temperaturo. Analiza korelacije kalorične vrednosti z osnovnimi lesnimi sestavinami je pokazala negativen vpliv deleža celuloze in hemiceluloze na kalorično vrednost in pozitiven učinek lignina in ekstraktivnih snovi. V obeh primerih je bil vpliv lignina večji. Količina lignina je v tesni zvezi s kalorično vrednostjo. Korelacijski koeficient med deležem lignina in zgornjo kalorično vrednostjo je znašal 0,716, s spodnjo pa 0,715, kar potrjuje tudi p-vrednost 0,0088 pri 5-odstotni stopnji zaupanja. Pomemben vpliv deleža lignina so podprle tudi raziskave drugih avtorjev. Esteves et al. (2008) so izvedli raziskavo na lesu *Eucalyptus globulus* in ugotovili, da se delež lignina povečuje z avtoklaviranjem in sušenjem vzorca v peči. Predhodne študije so tudi pokazale, da nastajanje netopnih stranskih produktov in rezultati humifikacije povečajo delež lignina zaradi razgradnje hemiceluloze (Tjeerdsma et al., 1998; Wikberg & Mannu, 2004). Podobno je bila visoka korelacija lignina s kalorično vrednostjo prikazana tudi v poskusu, ki ga je opravil Demirbas (2001) na 14 lignoceluloznih materialih, kjer je bil ugotovljen višji korelacijski koeficient 0,874 med ligninom in temperaturo. Številne študije so pojasnile, da so višje temperature večinoma posledica višje vsebnosti lignina, saj ima lignin visok delež ogljika in vodika, kar prispeva k energetski vrednosti (Telmo & Lausada, 2011b; Demirbas, 2001).

Iz rezultatov statistične analize in primerjave rezultatov s predhodnimi študijami je mogoče sklepati, da termična modifikacija ugodno vpliva na spremembe deležev osnovnih kemičnih sestavin lesa in s tem na kalorično vrednost. Na podlagi rezultatov lahko ugotovimo, da ima les z visoko vsebnostjo lignina večjo kalorično vrednost. Ker je bilo med termično modifikacijo opaženo povečanje kalorične vrednosti, lahko les *Eucalyptus nitens* po toplotni modifikaciji učinkovito uporabimo tudi za energetske namene.

REFERENCES
VIRI

Acar, S., Ayanoglu, A., & Demirbas, A. (2012). Determination of higher heating values (HHVs) of biomass fuels. Energy Education Science and Technology Part A: Energy science and Research 28(2), 749-758.

Bak, M., & Nemeth, R. (2012). Modification of wood by oil heat treatment. International Scientific Development & Ecological Footprint.

Bhuiyan, T. R., & Hirai, N. (2005). Study of crystalline behavior of heat-treated wood cellulose during treatments in water. Journal of Wood Science, 51(1), 42-47.

Bourgois, J., Bartholin, M. C., & Guyonnet, R. (1989). Thermal treatment of wood: analysis of the obtained product. Wood Science and Technology, 23(4), 303-310.

Calonego, F. W., Severo, E. T. D., Sansígolo, C. A., de Rezende, M. A., Bruder, E. M., & Costa, V. E. (2016). Calorific Value and Chemical Properties in Juvenile and Mature Wood of Thermally-Modified *Eucalyptus Grandis*. Wood Industry/Drvna Industrija, 67(3), 207-214.

Demirbaş, A. (2001). Relationships between lignin contents and heating values of biomass. Energy conversion and management, 42(2), 183-188.

Dhamodaran, T. K., Gnanaharan, R., & Thulasidas, P. K. (1989). Calorific value variation in coconut stem wood. Wood Science and Technology, 23(1), 21-26.

Esteves, B., & Pereira, H. (2009). Wood modification by heat treatment: A review. BioResources, 4(1), 370-404.

Esteves, B., Graca, J., & Pereira, H. (2008). Extractive composition and summative chemical analysis of thermally treated eucalypt wood. Holzforschung, 62(3), 344-351.

Homan, W. J., & Jorissen, A. J. (2004). Wood modification developments. Heron, 49(4), 360-369.

ISO 18125 (2017) Solid biofuels – Determination of calorific value.

Kol, H. Ş., SefiL, Y., & Keskin, S. A. (2015). Effect of heat treatment on the mechanical properties, and dimensional stability of fir wood. In 27th İnternational Conference Research for the furniture industry (pp. 17-18).

Ngangyo-Heya, M., Foroughbahchk-Pournavab, R., Carrillo-Parra, A., Rutiaga-Quiñones, J. G., Zelinski, V., & Pintor-Ibarra, L. F. (2016). Calorific value and chemical composition of five semi-arid Mexican tree species. Forests, 7(3), 58.

Rapp, A. O. (2001). Review on heat treatments of wood. In Proceedings of special seminar, Antibes, France.

TAPPI (1997). Solvent extractives of wood and pulp. Test method T 204 cm-07.

Telmo, C., & Lousada, J. (2011a). Heating values of wood pellets from different species. Biomass and bioenergy, 35(7), 2634-2639.

Telmo, C., & Lousada, J. (2011b). The explained variation by lignin and extractive contents on higher heating value of wood. Biomass and bioenergy, 35(5), 1663-1667.

Tjeerdsma, B. F., Boonstra, M., Pizzi, A., Tekely, P., & Militz, H. (1998). Characterisation of thermally modified wood: molecular reasons for wood performance improvement. Holz als Roh-und Werkstoff, 56(3), 149.

Todaro, L., Dichicco, P., Moretti, N., & D'Auria, M. (2013). Effect of combined steam and heat treatments on extractives and lignin in sapwood and heartwood of Turkey oak (*Quercus cerris* L.) wood. BioResources, 8(2), 1718-1730.

Todaro, L., Rita, A., Cetera, P., & D'Auria, M. (2015). Thermal treatment modifies the calorific value and ash content in some wood species. Fuel, 140, 1-3.

Trossero, M. A. (2002). Wood energy: the way ahead. Unasylva, 53(4), 3-12.

Wentzel, M., Fleckenstein, M., Hofmann, T., & Militz, H. (2019). Relation of chemical and mechanical properties of *Eucalyptus nitens* wood thermally modified in open and closed systems. Wood Material Science & Engineering, 14(3), 165-173.

White, R. H. (2007). Effect of lignin content and extractives on the higher heating value of wood. Wood and fiber science, 19(4), 446-452.

Wikberg, H., & Maunu, S. L. (2004). Characterisation of thermally modified hard-and softwoods by 13C CPMAS NMR. Carbohydrate polymers, 58(4), 461-466.

Willems, W. (2009). A novel economic large-scale production technology for high-quality thermally modified wood. In Proceedings of the 4th European conference on wood modification, Stockholm, Sweden (pp. 31-35).

Yildiz, S., Gezer, E. D., & Yildiz, U. C. (2006). Mechanical and chemical behavior of spruce wood modified by heat. Building and environment, 41(12), 1762-1766.

LES/WOOD Vol. 70, No. 2, 31-40
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a01

PRIMERJAVA MEHANSKIH LASTNOSTI RECENTNEGA IN 400 LET STAREGA LESA EVROPSKEGA MACESNA

COMPARISON OF MECHANICAL PROPERTIES OF RECENT AND 400-YEAR-OLD EUROPEAN LARCH WOOD

Enej Lipovec Zupanc[1], Gorazd Fajdiga[1*], Miha Humar[1]

UDK: 630*814.7:630*812.7:630*174.7 Larix decidua
Izvirni znanstveni članek / Original scientific article

Prispelo / Received: 1. 9. 2021
Sprejeto / Accepted: 19. 9. 2021

Izvleček / Abstract

Izvleček: Les velja za vodilni gradbeni material v zgodovini človeštva. Pred drugimi inženirskimi materiali ima veliko prednosti, kar ga uvršča med vodilne materiale prihodnosti. Zelo pomembno je dejstvo, da les kot naraven material uvrščamo v skupino materialov, ki imajo majhen negativen vpliv na okolje. Poleg tega je njegova predelava energijsko nezahtevna. Zaradi ponovne široke uporabe v gradbeništvu je pomembno dobro poznati in tudi napovedati mehanske lastnosti ter ovrednotiti posledice delovanja biotskih in abiotskih dejavnikov na mehanske lastnosti skozi daljše časovno obdobje. Od tega je odvisna tudi varnost starejših zgradb. Tako smo ob priložnosti primerjali mehanske lastnosti svežega evropskega macesna *(Larix decidua)* in okoli 400 let starega macesna, odvzetega iz Ruardove graščine na Stari Savi na Jesenicah. V okviru tega prispevka smo ovrednotili statično upogibno trdnost in vpliv cikličnih obremenitev na obnašanje stare in sveže posekane macesnovine. Vpliva staranja na upogibno trdnost nismo potrdili. Rezultati utrujanja lesa kažejo, da je star les prenesel približno 18-krat manj obremenitvenih ciklov kot recentni les macesna.

Ključne besede: les, macesen, utrujanje, Ruardova graščina, star les

Abstract: Wood has been the leading building material throughout the history of mankind. Wood has several advantages over other construction materials, which also makes it one of the most promising materials of the future. The environmental aspect also plays a major role today, as wood is a natural, renewable resource whose processing is very energy-intensive. Due to its repeated and widespread use in construction, the prediction of mechanical properties and their change over time is also very well known, as the overall safety of all buildings also depends on it. Therefore, we compared the mechanical properties of fresh European larch (*Larix decidua*) and 400-year-old larch found in the Ruard manor house on the Stara Sava in Jesenice, where the renovation of the Upper Sava Museum is currently underway. In order to predict what will happen to the fresh wood over the long term, it is necessary to expose the wood to the same conditions, i.e. to change it with dynamic loads or material fatigue. The effect of aging on flexural strength has not been confirmed. Fatigue results show that old wood withstood about 18 times fewer load cycles than recent larch wood.

Keywords: wood, European larch (*Larix decidua*), fatigue, Ruard's Mansion, old wood.

1 UVOD
1 INTRODUCTION

Les velja za prevladujoč gradbeni material skozi celotno zgodovino človeštva. Začetki njegove rabe segajo v prazgodovino, kjer se je sprva uporabljal za gradnjo šotorov, kolib, že več tisočletij poznamo tudi hiše, grajene iz lesa (Kaplan et al., 2009; Čufar & Veluščck, 2002). V 20. stoletju se je uporaba lesa v gradbene namene zmanjšala, saj so v ospredje prihajali novi materiali z boljšimi mehanskimi lastnostmi. V zadnjem obdobju v vse več novogradnjah uporabljajo les kot osnovni gradbeni material v kombinaciji z drugimi materiali (beton, steklo, kovine …). V 21. stoletju lesena gradnja doživlja renesanso (Kitek Kuzman et al., 2018). Predvsem zaradi vedno večje okoljske zavesti se oziramo k obnovljivim virom, kamor sodi tudi les. Drugi pomemben razlog je povezan z razvojem novih kompozitov kot je križno lepljen les, lameliran les, slojnat furnirni les (LVL) … (Čufar et al., 2017). Pri rabi lesa v gradbeništvu so poleg

[1] Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za lesarstvo, Jamnikarjeva 101, 1000 Ljubljana, Slovenija
[*] e-mail: gorazd.fajdiga@bf.uni-lj.si; +386 1 3203 619

ustrezne naravne odpornosti pomembne predvsem mehanske lastnosti (Sotayo et al., 2020). Pri dimenzioniranju konstrukcij so to statične mehanske lastnosti (upogibna trdnost, natezna trdnost, tlačna trdnost …). Pri načrtovanju sodobnih konstrukcij v ospredje vedno bolj prihajajo tudi dinamične mehanske lastnosti materiala.

V gradbeništvu so leseni konstrukcijski elementi v glavnem podvrženi kvazistatični obremenitvi z majhno spremembo obremenitve skozi čas. V takšnih aplikacijah je nosilnost konstrukcije odvisna od statične trdnosti lesa. V primerih, kjer so konstrukcijski elementi pogosto izpostavljeni neugodnim okoljskim razmeram (npr. veter) ali dinamičnemu okolju (npr. vibracije ali ponavljajoče se mehanske obremenitve), lahko pride do porušitve konstrukcijskega elementa zaradi utrujanja materiala. Zaradi ponavljajočih se dinamičnih obremenitev se v gradivu pojavijo trajne deformacije, razpoke in lomi že pri nižjih nivojih napetosti kot bi se to zgodilo pri statični obremenitvi. Dinamična trdnost gradiva je zaradi pojava utrujenosti pri dinamičnih obremenitvah lahko tudi za 20 % do 60 % nižja v primerjavi s statično trdnostjo (Glodež et al., 2006). Eno prvih študij, povezanih z utrujanjem lesa, je izvedel Wood (Wood, 1951), ki je predstavil tako imenovano ''Madisonovo krivuljo'' kot razmerje med napetostjo in trajanjem obremenitve. V zadnjih letih je bilo opravljenih in objavljenih tudi veliko raziskav na temo utrujanja lesa.

Za razliko od kovin ali polimerov ima les zelo nehomogeno strukturo. Les je povsem naraven biološki material z značilnim priraščanjem, je anizotropen, zato na njegovo trdnost vpliva veliko parametrov kot so: smolni kanali, zavitost vlaken, reakcijski les, gostota, vlažnost lesa (Gorišek, 2009). Poleg tega je neodporen les ob neprimerni zaščiti ali pomanjkljivem vzdrževanju podvržen hitrejšemu propadanju zaradi delovanja gliv in insektov, v primerjavi s konkurenčnimi (netrajnostnimi) materiali kot sta na primer jeklo in beton. Zato je eden od predpogojev za uporabo lesa v trajnejših objektih poznavanje njegovega obnašanja v daljšem časovnem obdobju tudi v primeru delovanja biotskih in abiotskih dejavnikov razkroja. Upoštevati je treba, da se les kot biološki material s starostjo spreminja.

Za načrtovanje sodobnih varnih konstrukcij je tako nujno poznati statične in dinamične obremenitve ter predvsem odziv materiala na te obremenitve (napetosti in posledično deformacije). V praksi seveda ne želimo, da pride do zloma, saj ima lahko to katastrofalne posledice (porušitev zgradbe, izguba funkcije elementa, razpoke na stenah …).

V konstrukcijske namene se v srednji Evropi najpogosteje uporablja les navadne smreke (*Picea abies*), bele jelke (*Abies alba*), različnih borov (*Pinus* ssp.) in evropskega macesna (*Larix decidua*). Macesnovina se uporablja za fasadne in talne obloge, leseno kritino, okna in konstrukcijski les (Humar et al., 2020). Evropski macesen *(Larix decidua)* je razširjen v gorskem svetu v srednji Evropi, Alpah in tudi Karpatih. Macesen spada med iglavce, ima debelo skorjo in zraste tudi do 40 metrov visoko. Je ena izmed redkih vrst iglavcev, ki jim jeseni iglice odpadejo (Brus, 2012). Jedrovina macesna je rdečkaste barve in ima izrazit smolnat vonj (Čufar, 2006). Jedrovino macesna uvrščamo med srednje odporne lesne vrste. Standard SIST EN 350 (CEN, 2016) ga glede na odpornost lesa uvršča v 3. do 4. odpornostni razred na petstopenjski lestvici, kjer razred 1 predstavlja zelo odporne, razred 5 pa zelo občutljive lesne vrste (Lesar et al., 2008).

Predstavljen študij primera temelji na primerjavi mehanskih lastnosti konstrukcijskih elementov iz macesnovega lesa *(Larix decidua)*. V okviru raziskave smo primerjali statične in dinamične mehanske lastnosti okoli 400 let starega macesnovega lesa in nedavno posekanega in ustrezno osušenega (recentnega) lesa macesna. Star les smo pridobili iz Ruardove graščine na Jesenicah.

2 MATERIAL IN METODE

2 MATERIALS AND METHODS

2.1 ODVZEM MATERIALA

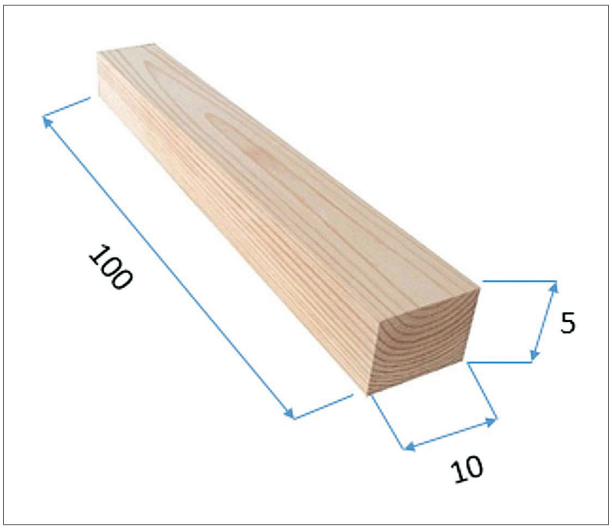
2.1 COLLECTION OF MATERIAL

V raziskavi smo uporabili vzorce jedrovine evropskega macesna (*Larix decidua*), pridobljene iz stropa Ruardove graščine, ki stoji na Stari Savi na Jesenicah. Po nekaterih virih mineva že skoraj pol tisočletja od samega začetka Ruardove graščine; natančneje se omenja letnica 1538, ko se je italijanska rodbina Bucelleni preselila in zgradila graščino ter fužino poleg nje. Z letom 1954 je le-ta postala muzej in do leta 1990 je v graščini deloval Tehniški muzej Železarne Jesenice, z letom 1991 je postala sedež medobčinskega Gornjesavskega muzeja Jesenice (Dnevnik.si). Na podlagi podatkov konzervatorskega načrta in literaturnih virov sklepamo, da je raziskani les star okoli 400 let (Mugerli, 2016). Zaradi premajhnega števila branik oziroma onesnaženosti z dimnimi plini organskega izvora dendrokronološka ali radiokarbonska datacija ni bila mogoča. Na graščini trenutno potekajo obnovitvena dela zaradi dotrajanosti zgradbe. Tako smo tudi mi dobili priložnost in poleg ostalih raziskav, ki potekajo, izvedli trenutno, v kateri primerjamo statične in dinamične mehanske lastnosti lesa macesna. Vzorce recentnega lesa macesna smo pridobili z območja Jezerskega. Širina branik obeh vzorcev je primerljiva. Za raziskavo smo uporabili le les jedrovine.

2.2 VZORCI IN POSTOPKI
2.2 SAMPLES AND PROCEDURES

S krožnim žagalnim strojem smo vzorce nažagali na okvirne dimenzije (100 × 10 × 5 mm^3) ter jih uravnovesili v laboratorijski klimi z relativno zračno vlažnostjo 65 % in temperaturo 23 °C.

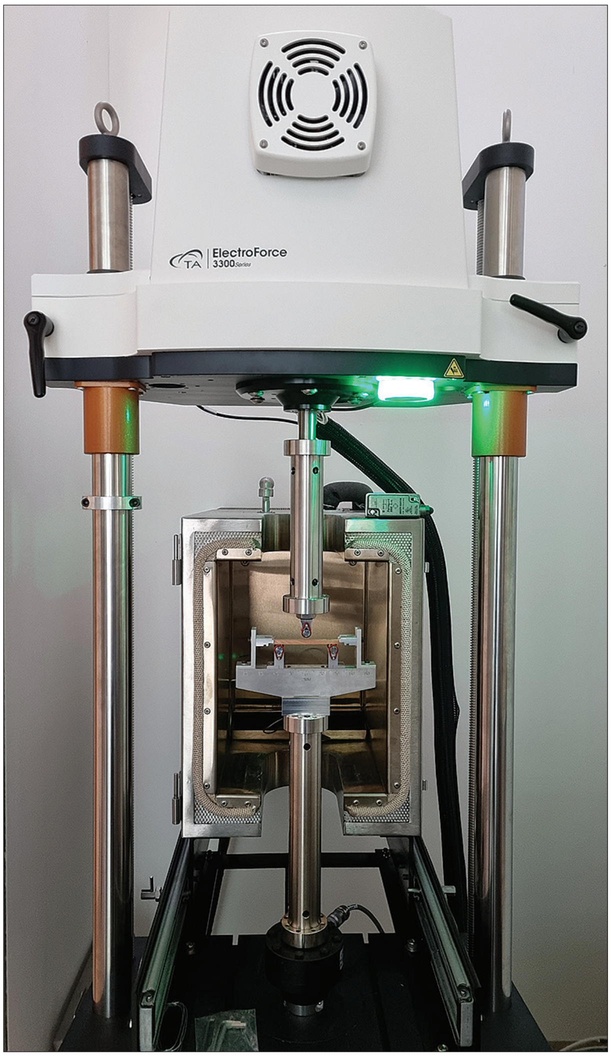
Po končanem procesu uravnovešenja smo vzorcem določili dimenzijo in maso ter izračunali gostoto zračno suhega lesa. Skupaj smo pripravili 60 čistih macesnovih vzorcev. 30 vzorcev je bilo izdelanih iz referenčne recentne macesnovine, drugih 30 pa je bilo izdelanih iz lesa macesna, ki je izviral iz Ruardove graščine. Iz vsake skupine smo izbrali 5 vzorcev in jim določili upogibno trdnost in pridobili podatek o sili, potrebni, da se vzorec poruši. Na podlagi petih meritev smo nato izračunali povprečje, ki smo ga uporabili za nadaljnje utrujanje materiala. Upogibno trdnost smo določili v skladu s standardom EN 310 (CEN, 1993).



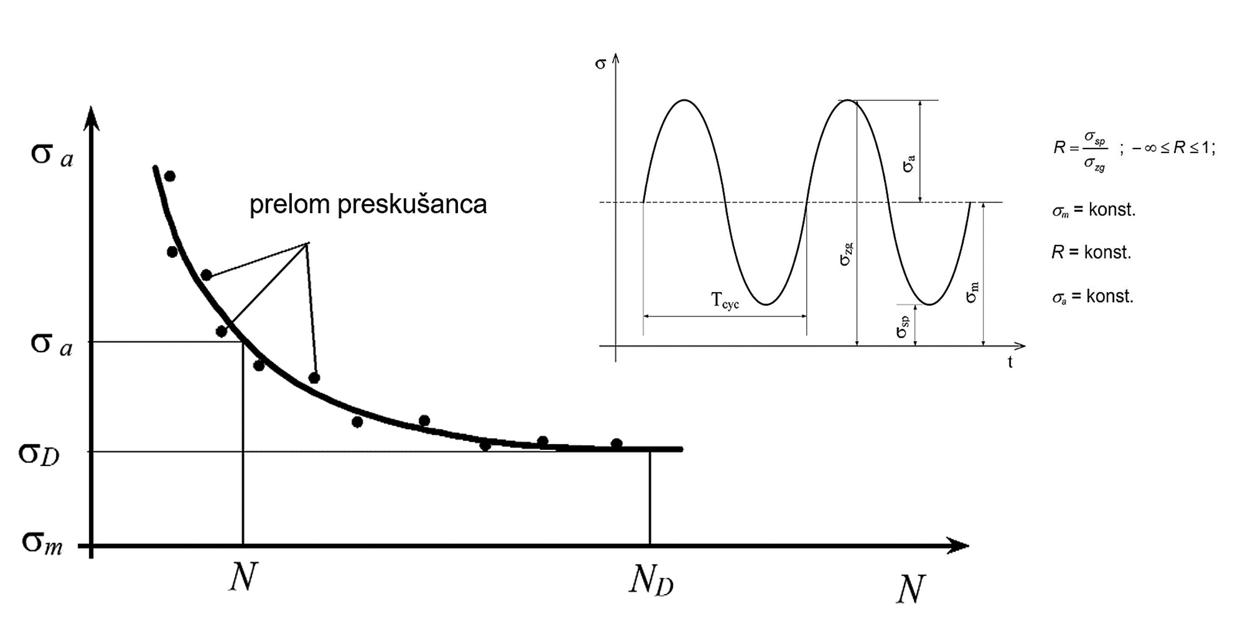
Slika 1. Dimenzije preskušanca
Figure 1. Dimensions of the test piece

2.3 PROCES UTRUJANJA
2.3 MATERIAL FATIGUE PROCESS

Krivulje zdržljivosti gradiv dobimo kot rezultat testiranj na preskuševališčih za utrujanje materiala. Takšni preizkusi zahtevajo izredno natančna preskuševališča, ki so odvisna tako od razreda natančnosti uporabljenih merilnih naprav kot tudi od togosti in kakovosti izdelave konstrukcije preskuševališča z vsemi sestavnimi deli. Preskuševališča so lahko namenska, zgrajena za določen tip preskušancev (Fajdiga et al., 2020), ali pa so komercialna. V tej raziskavi so bili statični in dinamični preskusi



Slika 2. Preskuševališče DMA Electroforce 3310 Series III
Figure 2. Test site DMA Electroforce 3310 Series III



Slika 3. Wöhlerjeva krivulja dinamične trdnosti
Figure 3. Wöhler dynamic strength curve

izvedeni na komercialnem preskuševališču DMA Electroforce 3310 Series III.

Dinamična trdnost gradiva je odvisna od vrste vplivnih parametrov (Glodež, 2006). V tej študiji so bili izvedeni tritočkovni upogibni preskusi s faktorjem dinamičnosti obremenitve *R*=0 (razmerje med spodnjo σ_{sp} in zgornjo napetostjo σ_{zg}, slika 3) in frekvenco utrujanja 10 Hz. Velikost obremenitve je bila določena glede na statično porušno silo in je navedena v poglavju z rezultati.

Rezultate preskusov v obliki števila obremenitvenih ciklov *N* do nastanka razpoke oziroma preloma preskušanca lahko prikažemo v diagramih σ–*N*, v tako imenovani *Wöhlerjevi krivulji* oziroma *krivulji dinamične trdnosti gradiva*. V tej raziskavi nas je zanimala primerjava rezultatov (število nihajev *N* do porušitve) med recentnim in starim macesnom in krivulje zdržljivosti niso bile kreirane.

Porušne preskušance smo preiskali z digitalnim mikroskopom Olympus DSX1000. Analizirali smo reprezentativne vzorce iz referenčne in stare macesnovine. Pregled smo izvedli s kombinirano osvetlitvijo s kombinacijo svetlega in temnega polja.

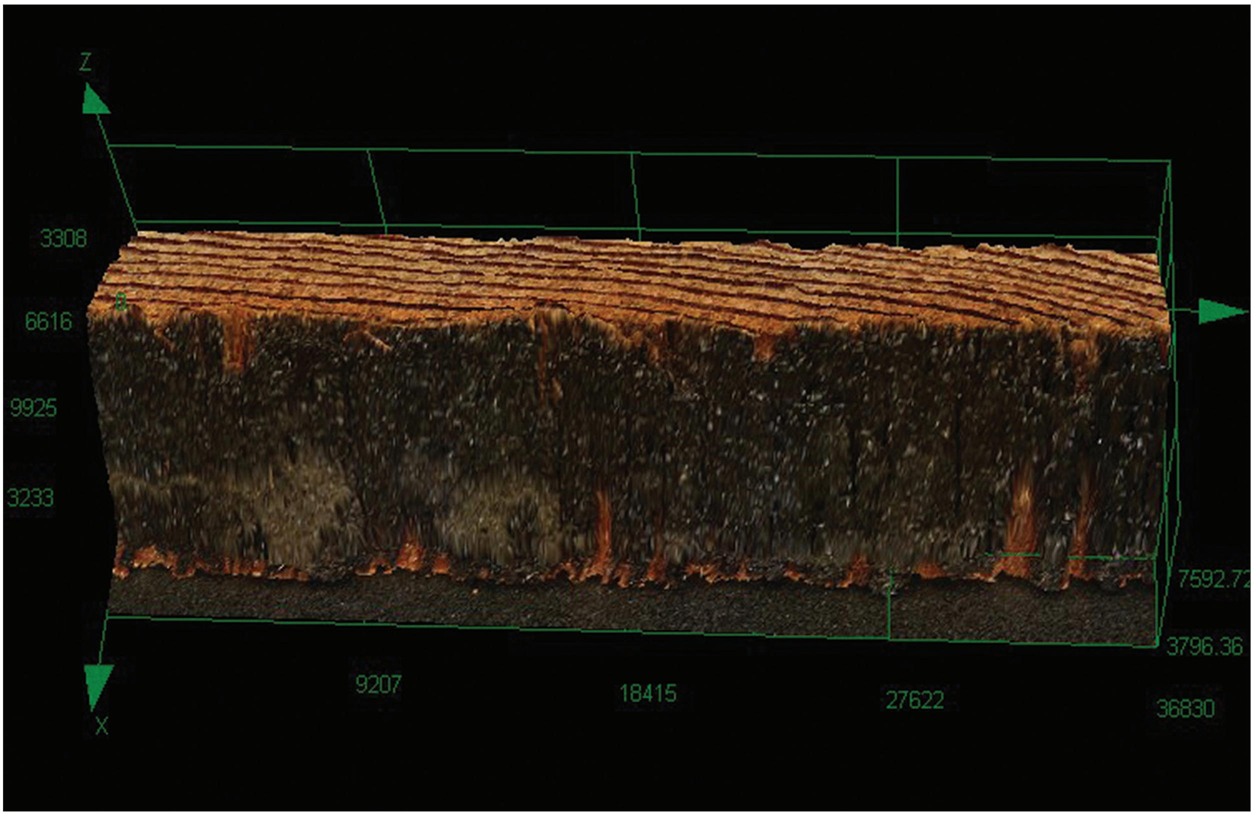
3 REZULTATI IN RAZPRAVA
3 RESULTS AND DISCUSSION

Beljava macesna iz Ruardove graščine je bila močno poškodovana zaradi delovanja insektov (slika 4). Beljavo so poškodovali hišni kozliček (*Hylotrupes bajulus*) in navadni trdoglavec (*Anobium punctatum*). Ta dva lesna škodljivca sodita med terciarne škodljivce, ki poškodujejo suh les. Insekta se prehranjujeta s škrobom v beljavi, jedrovina pa je za te lesne insekte praviloma strupena (Kervina-Hamović, 1990). Do okužbe je prišlo v preteklosti. V času analize insekti niso bili več aktivni.

Površina lesa je bila ožgana (slika 5). Po vsej verjetnosti je ožiganje posledica kurjenja v pritličnih prostorih. Ker so bile deske ožgane le s spodnje strani, menimo, da ožiganje ni bilo namerno. Ožiganje in dimljenje sodi med tradicionalne postopke zaščite lesa, ki do določene mere preprečujejo glivni razkroj in napade insektov (Unger et al., 2001). Glede na to, da je bila beljava močno razkrojena zaradi insektov, smo mnenja, da je v splošnem zadovoljiva ohranjenost lesa predvsem posledica dobre naravne odpornosti macesnove jedrovine.

Primerjali smo rezultate mehanskih testiranj na preskuševališču DMA Electroforce 3310 Series III preskušancev iz 400 let starega lesa macesna iz Ruardove graščine in referenčno macesnovino.

Slika 4. Prečni prerez vzorca macesna iz Ruardove graščine z beljavo, ki so jo poškodovali insekti
Figure 4. Cross-section of a larch sample from Ruard’s mansion with the sapwood damaged by insects



Slika 5. Obžgana površina vzorca iz Ruardove graščine
Figure 5. Burnt surface of a sample from Ruard's mansion

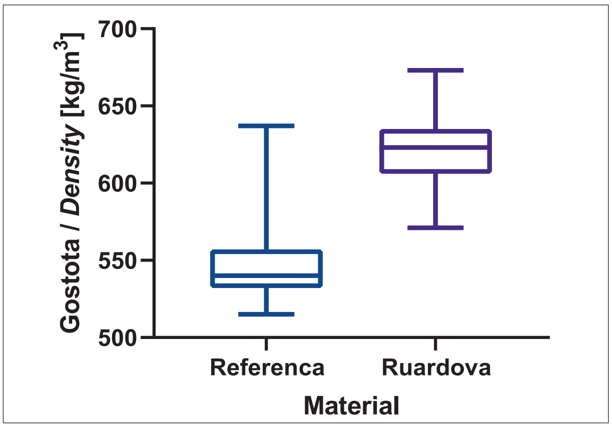
Povprečna gostota zračno suhega lesa preskušancev z Ruardove graščine je 620 kg/m^3, gostota referenčne macesnovine pa 550 kg/m^3 (slika 6). Ugotovljene gostote lesa so znotraj razpona vrednosti za mecesnovino iz literature (Wagenführ, 2007). Visoka gostota zračno suhega lesa je posledica visokega deleža kasnega lesa. Za les naših domačih komercialnih iglavcev je v splošnem značilno, da je gostota lesa obratno sorazmerna s širino branik. Les z ožjimi branikami ima v splošnem večji delež kasnega lesa, višjo gostoto in boljše mehanske lastnosti kot les s širšimi branikami.

Na odpornost lesa širina branik nima statistično značilnega vpliva (Humar, 2013). Višja gostota zračno suhe stare macesnovine se tako odraža tudi v višjem modulu elastičnosti (slika 7) in upogibni trdnosti (slika 8), v primerjavi z referenčno macesnovino. Razlika v gostoti in upogibni trdnosti je statistično značilna (p<0.0001).

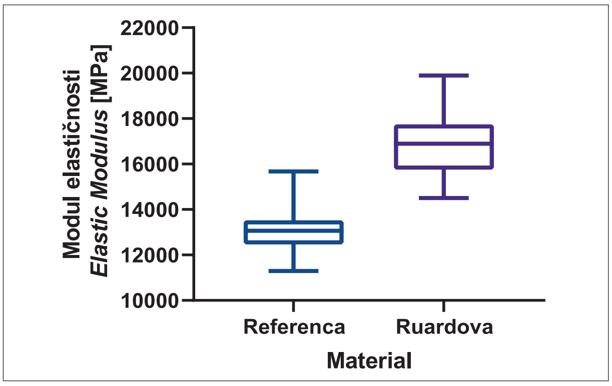
Preskušance za test utrujanja smo razdelili v več podskupin glede na silo, s katero smo vzorce utrujali. Faktor dinamičnosti obremenitve je bil za vse preskuse enak *R*=0, prav tako je bila enaka za vse preskuse tudi frekvenca utrujanja in sicer 10 Hz. Prvo skupino smo obremenili s 75 % statične porušne sile, sledili sta še skupini z 80 % in 85 % statične porušne sile, dobljene s statičnimi preskusi (poglavje 2.2.).

Vsak vzorec smo utrujali do porušitve (slika 9) oziroma do 2.000.000 obremenitvenih ciklov. Utrujali smo 25 vzorcev svežega macesna in 25 vzorcev macesna, pridobljenega z Ruardove graščine. Podatki so se med procesom utrujanja shranjevali v računalniku.

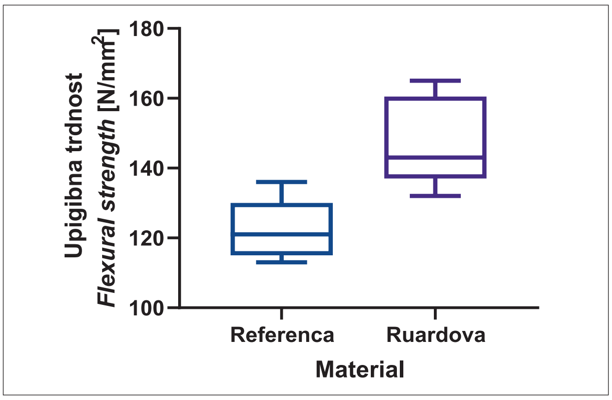
Na sliki 10 so prikazani rezultati utrujanja kontrolnih preskušancev, izdelanih iz lesa recentnega macesna. V prvi skupini petih kontrolnih preskušancev iz recentnega lesa pri 75 % statične porušne sile (225 N) sta dva preskušanca prestala preizkus do 2.000.000 obremenitvenih ciklov. Preskušanec, ki se je najhitreje porušil, je dosegel 254.725 obremenitvenih ciklov. V povprečju so vzorci prestali 1.142.049 obremenitvenih ciklov. Pri obremenjevanju z 80 % porušne sile (240 N) so kontrolni vzorci prestali v povprečju 278.495 obremenitvenih ciklov. Tretjo skupino preskušancev smo obremenjevali s 85 % statične porušne sile, ta je za kontrolne preskušance znašala 255 N. Kontrolni vzorci so v povprečju dosegli 112.324 ciklov.



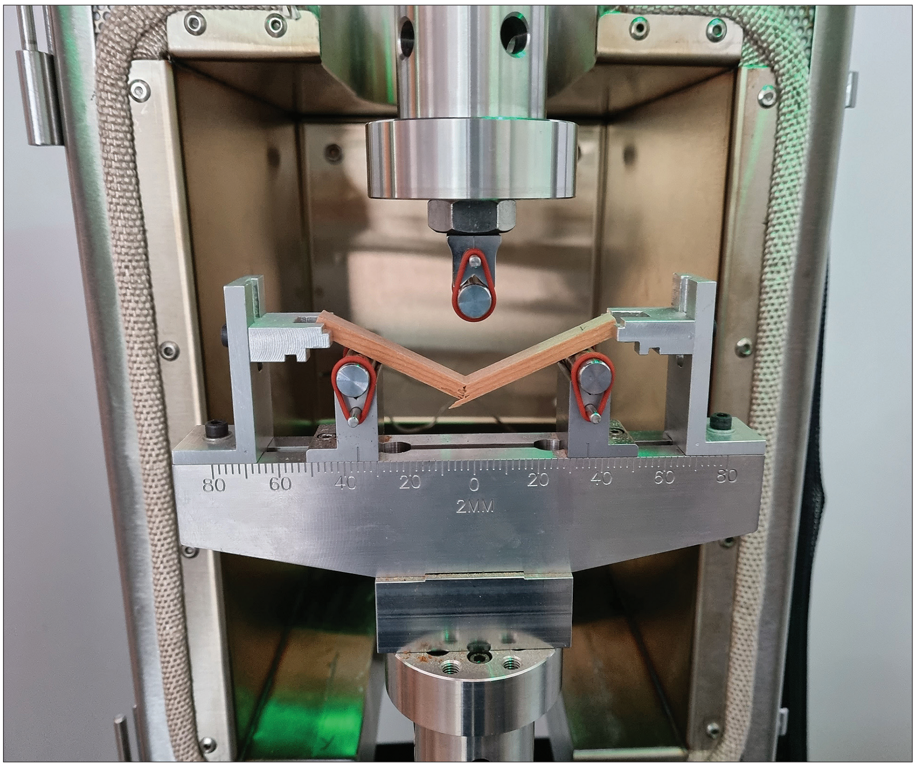
Slika 6. Gostota zračno suhe referenčne in stare macesnovine iz Ruardove graščine
Figure 6. Density of air dried reference and historical larch wood from the Ruard mansion



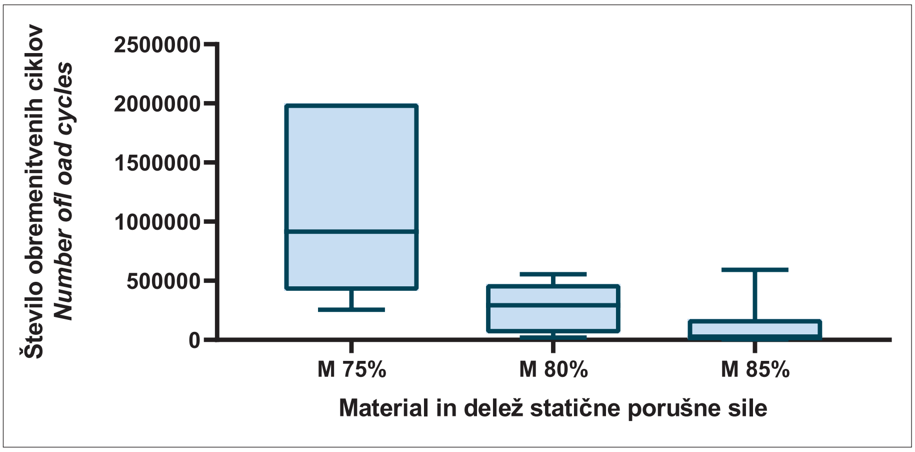
Slika 7. Modul elastičnosti referenčne in stare macesnovine iz Ruardove graščine
Figure 7. Modulus of elasticity of reference and historical larch wood from the Ruard mansion



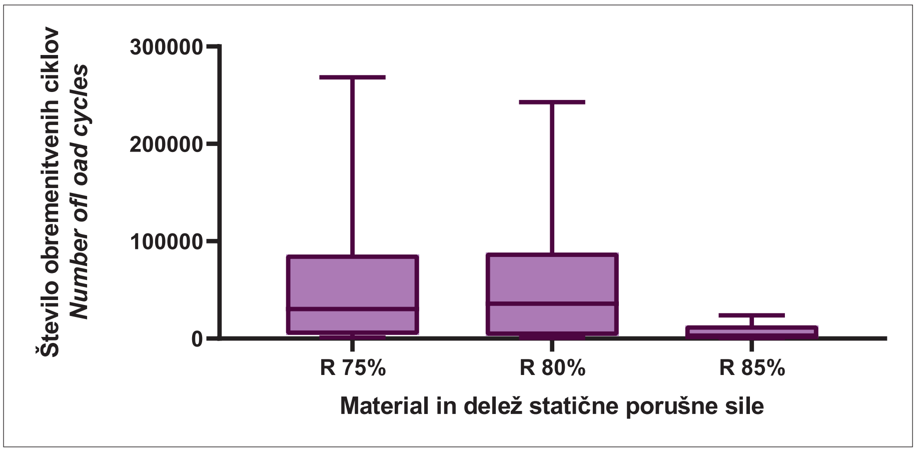
Slika 8. Upogibna trdnost referenčne in stare macesnovine iz Ruardove graščine
Figure 8. Flexural strength of reference larch and historical larch wood from the Ruard mansion



Slika 9. Porušitev preskušanca pri testu utrujanja
Figure 9. Breakdown of the specimen at fatigue testing



Slika 10. Število obremenitvenih ciklov do porušitve (kontrolni preskušanci iz recentnega lesa macesna)
Figure 10. Number of load cycles to failure (reference larch wood specimens)



Slika 11. Število obremenitvenih ciklov do porušitve (preskušanci macesna iz Ruardove graščine)
Figure 11. Number of load cycles to failure (Ruard manor larch test specimens)

Slika 12. Prikaz žilavega loma med določanjem upogibne trdnosti (levo) in krhkega loma stare macesnovine po utrujanju (desno).

Figure 12. Demonstration of ductile fracture during determination of flexural strength (left) and brittle fracture of old larch after fatigue (right).

Na sliki 11 so prikazani rezultati utrujanja preskušancev, izdelanih iz lesa macesna iz Ruardove graščine. Povprečno število obremenitvenih ciklov pri utrujanju s 75 % porušne sile (255 N) je znašalo 58.150 obremenitvenih ciklov. Pri obremenjevanju z 80 % porušne sile (272 N) so preskušanci iz Ruardove graščine prestali v povprečju 60.924 ciklov. Tretjo skupino preskušancev smo obremenjevali s 85 % statične porušne sile in sicer je ta znašala 289 N. Število obremenitvenih ciklov do porušitve je v povprečju znašalo 6.266 ciklov. Rezultati kažejo približno 18-krat manj obremenitvenih ciklov, potrebnih za porušitev preskušancev iz starega lesa macesna glede na preskušance iz recentnega lesa.

Iz pridobljenih rezultatov preskusov je razvidno, da so preskušanci iz macesna iz Ruardove graščine bolj odporni na statično obremenitev, saj prenesejo v povprečju za 40 N oziroma za približno 13 % višjo obremenitev kot kontrolni macesnovi preskušanci. Pri dinamičnem obremenjevanju so se veliko bolje izkazali preskušanci iz recentnega macesnovega lesa. Razlika v številu obremenitvenih ciklov, potrebnih za porušitev preskušanca, se je z večanjem obremenitve (glede na upogibno trdnost) med preskušanci iz svežega macesna in preskušanci iz starega macesna še povečevala. Tudi Schultz et al. (1984) so testirali 300 let star les, vgrajen v strešno konstrukcijo in prišli do podobnih rezultatov.

4 ZAKLJUČKI
4 CONCLUSIONS

Na podlagi meritev lahko potrdimo, da les velja za kakovosten in odporen gradbeni material. Statične mehanske lastnosti starega in referenčnega recentnega lesa so primerljive. Po drugi strani se lesu močno poslabšajo dinamične lastnosti. Star les je bolj dovzeten na dinamične obremenitve kot recentni les. Rezultati utrujanja kažejo, da je star les prenesel približno 18-krat manj obremenitvenih ciklov kot recentni les macesna.

5 POVZETEK
5 SUMMARY

Wood is considered the most promising building material as its mechanical properties along with the environmental aspect are by far the best compared to other competing materials. Ageing has considerable influence on natural and synthetic pol-

ymers, including wood. In wooden constructions it is therefore important to consider the performance of the material over time. Through a case study, we want to approximate the behaviour of wood used for construction over time. At Ruard's mansion, on the Stara Sava in Jesenice, Slovenia, we were given a unique opportunity to compare the mechanical properties of around 400-year-old larch and recently cut European larch (*Larix decidua*). Ceiling samples were taken from the mansion and compared with samples of recent wood with regard to the three-point bending strength and dynamic sample fatigue. The results showed the old larch wood, which had a higher density than the recent wood, withstood the flexural strength testing better than recent larch (the difference was on average 40N). In the fatigue process, we achieved an average of 1,142,049 cycles at the 75% maximum force of the control larch samples, 278,495 cycles at the 85% maximum force, and 112,324 cycles at the 85% maximum force of the control samples. We repeated the procedure on samples from Ruard's mansion and found that the samples withstood an average of 58,150 load cycles at 75% force, 60,924 cycles at 80% failure, and only 6,266 cycles at 85%. The average number of load cycles for recent wood is as much as 18 times higher compared to old larch from Ruard's mansion.

We can therefore conclude that the static mechanical properties of old and recent larch wood are comparable, while dynamic properties of old larch wood deteriorated strongly, which we have demonstrated with fatigue tests

ZAHVALA
ACKNOWLEDGEMENTS

Prispevek je rezultat več med seboj povezanih projektov, ki jih je sofinancirala Agencija za raziskovalno dejavnost RS: P2-0182-Programska skupina razvojna vrednotenja; P4-0015 - Programska skupina les in lignocelulozni kompoziti, 0481-09 - Infrastrukturni center za pripravo, staranje in terensko testiranje lesa ter lignoceluloznih materialov (IC LES PST 0481-09) in Projekta Woolf-OP20.03520, ki poteka v okviru programa Razvoj verig vrednosti v okviru razpisov Strategije pametne specializacije. Za tehnično pomoč pri pripravi in analizi vzorcev se najlepše zahvaljujemo Blažu Jemcu.

VIRI
REFERENCES

Brus, R. (2012). Drevesne vrste na Slovenskem. 2. izdaja. Ljubljana: Mladinska knjiga.

CEN. (1993). EN 310 – Wood Based Panels - Determination of modulus of elasticity in bending and of bending strength. European Committee for Standardisation, Brussels, Belgium, 8.

CEN. (2016). European Standard EN 350 - Durability of wood and wood-based products. Testing and classification of the durability to biological agents of wood and wood-based materials.

Čufar, K., & Veluščék, A. (2012). Les s koliščarskih naselbin na Ljubljanskem barju in njegov raziskovalni potencial. Les, 64 (3-4), 49-56. https://repozitorij.uni-lj.si/IzpisGradiva.php?id=68586&lang=slv&prip=dkum:1742412:d1

Čufar, K., Gorišek, Ž., Merela, M., Kropivšek, J., Gornik Bučar, D., & Straže, A. (2017). Lastnosti bukovine in njena raba. Les/Wood, 66 (1), 27-39. DOI: https://doi.org/10.26614/les-wood.2017.v66n01a03

Dourado, N., de Moura, M. F. S. F., & de Jesus, A. (2019). Fatigue-fracture characterization of wood under mode I loading. International Journal of Fatigue, 121, 265–271.

Čufar, K. (2006). Anatomija lesa. Univerzitetni učbenik. Ljubljana: Biotehniška fakulteta, Oddelek za lesarstvo.

Fajdiga, G., Rajh, D., Vidic, D., & Gospodarič, B. (2020). The development of Pneumatic fatigue test rig for wood-based specimens. Forests, 11(11),1187. DOI: https://doi.org/10.3390/f11111187

Glodež, S., & Flašker, J. (2006). Dimenzioniranje na življenjsko dobo. Maribor: Pedagoška fakulteta: Fakulteta za strojništvo.

Gorišek, Ž. (2009). Les: zgradba in lastnosti: njegova variabilnost in heterogenost. Ljubljana: Biotehniška fakulteta, Oddelek za lesarstvo.

Humar, M. (2013). Influence of Norway spruce and European larch heartwood ring-width oextractive content and durability. Drvna Industrija, 64, 2.

Humar, M., Lesar, B., & Kržišnik, D. (2020). Tehnična in estetska življenjska doba lesa. Acta Silvae et Ligni, 121, 33–48.

Ifko, B. (2016). Vpliv staranja na fizikalno-mehanske lastnosti lesa stropne konstrukcije. Diplomsko delo. Ljubljana: Biotehniška fakulteta, Oddelek za lesarstvo

Kaplan, J. O., Krumhardt, K. M., & Zimmermann, N. (2009). The prehistoric and preindustrial deforestation of Europe. Quaternary Science Reviews, 28 (27–28), 3016–3034.

Kervina-Hamović, L. (1990). Zaščita lesa. Ljubljana: Biotehniška fakulteta, VTOZD za lesarstvu.

Kitek Kuzman, M., Klarić, S., Pirc Barčić, A., Vlosky, R. P., Janakieska, M. M., & Grošelj, P. (2018). Architect perceptions of engineered wood products: An exploratory study of selected countries in Central and Southeast Europe. Construction and Building Materials, 179, 360–370.

Lesar, B., Humar, M., & Oven, P. (2008). Dejavniki naravne odpornosti lesa in njegova trajnost. Les, 11/12 (60), 408–414.

Mugerli, M. (2016). Vloga družin Bucelleni in Ruard v gornjesavskem fužinarstvu. Kronika, 463–476.

Sotayo, A., Bradley, D., Bather, M., Sareh, P., Oudjene, M., El-Houjeyri, I., … Guan, Z. (2020). Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. Developments in the Built Environment, 1, 100004.

Smith, I., Landis, E., & Gong, M. (2003). Fatigue and fracture in Wood. New York: Wiley.

Unger, A., Schniewind, A. P., & Unger, W. (2001). Conservation of wood artifacts : a handbook. Berlin: London: Springer.

Wagenführ, R. (2007). Holzatlas. Leipzig: Fachbuchverlag.

Wood, L. (1951). Relation of Strength of Wood to Duration of Laods. Madison: United States Department of Agriculture.

LES/WOOD Vol. 70, No. 2, 41-51
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a04

ODPORNOST PREMAZOV PROTI OBARVANJU ZARADI GRČ V LESU

KNOT STAINING RESISTANCE OF WOOD COATINGS

Matjaž Pavlič[1*], Jure Vrbec[1], Jure Žigon[1], Marko Petrič[1]

UDK 630*829.18
Izvirni znanstveni članek / Original scientific article

Prispelo / Received: 30. 9. 2021
Sprejeto / Accepted: 15. 11. 2021

Izvleček / Abstract

Izvleček: Po premazovanju lesa in izpostavitvi zunanjim klimatskim pogojem in/ali višjim temperaturam lahko na mestih, kjer so prisotne grče, pride do obarvanja utrjenega filma, ki ga povzročajo hidrofilni in lipofilni ekstraktivi. Zaradi tega je odpornost premaznega sistema proti obarvanju zaradi grč v lesu zelo pomembna. V naši raziskavi smo preizkusili nekaj osnovnih tipov belo pigmentiranih sistemov. Pri tem smo metodo SIST EN 927-7:2020 ustrezno prilagodili našim zmogljivostim, jo optimizirali in kritično presodili, ali so kje možne izboljšave standardizirane metode. Rezultati naše raziskave so pokazali, da je odpornost premaznih sistemov proti obarvanju zaradi grč v lesu povezana z vrsto topila v premazih, s prekrivnostjo sistema in njegovo slojnostjo oz. debelino suhega filma. Premazi na osnovi organskih topil so se izkazali za boljše, prav tako tisti, ki so vsebovali več pigmentov, in tisti z večjo debelino suhega filma. Prav tako smo dokazali, da lahko z vrednotenjem barvnih razlik na mestih z grčami in brez njih že pred izpostavitvijo in upoštevanjem te izhodiščne barvne razlike pri vrednotenju razlik po izpostavitvi premazne sisteme veliko bolj objektivno razvrstimo po njihovi učinkovitosti proti obarvanju zaradi grč v lesu. Na podlagi te ugotovitve menimo, da je standardizirano metodo potrebno ustrezno korigirati.

Ključne besede: les, grča, premaz, obarvanje

Abstract: After wood has been coated and exposed to external climatic conditions and/or elevated temperatures, staining of the coating film by hydrophilic and lipophilic extractives may occur where knots are located. For this reason, the knot staining resistance of the coating system is very important. In our study, we tested some basic types of white pigmented systems. In doing so, we adapted the method SIST EN 927-7:2020 according to our capabilities, optimized it and critically evaluated whether there is room for improvement of the standardized method. The results of our research showed that the knot staining resistance of coating systems is related to the type of solvent in the coatings, the hiding power of the system and its build-up or dry film thickness. Accordingly, solvent-borne coatings were found to be better, as were those containing more pigments and those with a higher dry film thickness. We have also found that by evaluating the colour difference on the regions with and without knots before exposure and accounting for this in evaluation of colour differences after exposure, we can make a much more objective classification of coating systems according to their effectiveness against knot staining. Based on this finding, we believe that the standardized method needs to be corrected accordingly.

Keywords: wood, knot, coating, staining

1 UVOD

1 INTRODUCTION

Zaščita površin lesa s premaznim sredstvom za zunanjo uporabo ima dekorativni in zaščitni pomen. Premazno sredstvo lesu lahko zagotavlja daljšo trajnost in obstojnost barve, hkrati pa ga ščiti pred negativnimi učinki sončnega sevanja ter pred okužbami z glivami in napadi insektov. Zaradi zaščitne vloge mora biti premaz trpežen in čim dalj časa ohranjati svoje fizikalne lastnosti, s čimer se tudi podaljšujejo intervali med potrebnim obnavljanjem (Ekstedt, 2002).

Ena izmed pomembnih lastnosti premaznega sistema je, da mora biti odporen proti obarvanju zaradi grč v lesu. Grča je povezana z anatomsko strukturo lesnega materiala, in sicer je del veje, vklopljene v deblu. Prisotnost grč v lesu zmanjšuje njegovo uporabnost in s tem tudi njegovo ceno. Grča ima sama po sebi drugačno gostoto (običajno višjo) in njena orientacija je običajno pravokotna na okoliški les (Williams et al., 2000). Oprijem premazov na grčah je lahko zaradi njihove običajno

[1] Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za lesarstvo, Jamnikarjeva 101, 1000 Ljubljana, SLO
[*] e-mail: matjaz.pavlic@bf.uni-lj.si; +386 1 320 3621

višje gostote otežen. Po premazovanju in izpostavitvi zunanjim pogojem in/ali višjim temperaturam lahko na mestih v lesu, kjer so prisotne grče, pride do obarvanj, ki jih povzročajo hidrofilni in lipofilni ekstraktivi. Te v lesu prisotne spojine se prebijejo v in skozi film premaza in se na površini pokažejo kot rumena ali rjava območja. Ta pojav imenujemo ''rumenenje grč'' (Nussbaum, 2004).

Nussbaum (2004) omenja, da je v Skandinaviji rumenenje grč problem predvsem v mizarstvu. Najpogosteje se pojavlja pri bukovini, pobarvani v belo (najpogostejša kombinacija podlage in površinske obdelave), lahko se pojavi tudi na smrekovini. Še en dejavnik, ki domnevno vpliva na porumenelost grč, je zaščitna obdelava lesa z impregnacijo ali z namakanjem v sredstvih za zaščito lesa pred površinsko obdelavo. Nussbaum (2004) je še raziskoval vplive parametrov površinske obdelave stavbnega pohištva na obarvanje filma premaza zaradi izločanja smole iz grč. Ugotovil je, da na rumenenje grč sicer vpliva več dejavnikov, vendar je največji učinek proti zaustavitvi obarvanja dosegla obdelava s premaznimi sredstvi, ki vsebujejo organska topila.

V industriji lesnih premazov je prišlo do zmanjšanja uporabe premazov na osnovi topil, ki imajo visoko vsebnost hlapnih organskih spojin (HOS, angleško *VOC,* razna topila in redčila). Raba premazov na vodni osnovi se je povečala, zaradi česar je rumenenje grč postalo še toliko bolj problematično. Kimerling et al. (2004) so ugotovili, da se tako imenovanemu rumenenju grč pri vodnih sistemih lahko delno izognemo oz. ga zmanjšamo, če pred nanašanjem vodnih premaznih sistemov uporabimo temeljne impregnacije, ki vsebujejo amfifilne stirenske blok-kopolimere, s katerimi se ustvari manj prepustna bariera.

Obarvanje premaza na smrekovini in borovini je najpogosteje povezano z grčami. Ekstraktivi kot nestrukturne komponente lahko migrirajo iz lesa v premaze in tako povzročijo njihovo obarvanje. Lastnosti premaznih sistemov (vrsta topila in veziva, slojnost, pigmentiranost …) igrajo pomembno vlogo pri zmanjševanju tovrstnega obarvanja (Ekstedt, 2002), vendar se avtor te raziskave v svojem obširnem doktorskem delu ni toliko posvetil lastnostim premazov kot pa vplivu različnih režimov sušenja lesa na rumenenje grč pri premazanem lesu.

Z optimizacijo metode za določanje odpornosti premazov proti obarvanju zaradi grč v lesu sta se že leta 2004 ukvarjala Suttie in Ekstedt. Takrat sta jo poimenovala metoda za določanje obarvanja premazov na lesu zaradi taninov iz grč. Rezultat njune raziskave je bila priprava osnutka metode za pripravo standardne metode, ki jo poznamo danes (SIST EN 927-7:2020). Ravno to metodo smo uporabili v naši raziskavi, v kateri smo preizkusili nekaj osnovnih tipov belo pigmentiranih sistemov. Pri tem smo metodo SIST EN 927-7:2020 ustrezno prilagodili našim zmogljivostim, jo optimizirali in kritično presodili, ali so kje možne izboljšave standardizirane metode.

2 MATERIAL IN METODE
2 MATERIAL AND METHODS
2.1 PREMAZNI SISTEMI
2.1 COATING SYSTEMS

V raziskavi smo uporabili 6 osnovnih tipov belo pigmentiranih premaznih sistemov, ki smo jih tvorili s tremi nanosi. Med sabo so se razlikovali po vrsti topila, vrsti veziva, slojnosti in prekrivnosti podlage:

- sistem 1 (TLV) - tankoslojni poltransparentni lazurni sistem na vodni osnovi
- sistem 2 (DLV) - debeloslojni poltransparentni lazurni sistem na vodni osnovi
- sistem 3 (DEV) - debeloslojni prekrivni emajl sistem na vodni osnovi
- sistem 4 (TLO) - tankoslojni poltransparentni lazurni sistem na organski osnovi
- sistem 5 (DLO) - debeloslojni poltransparentni lazurni sistem na organski osnovi
- sistem 6 (DEO) - debeloslojni prekrivni emajl sistem na organski osnovi

Podrobnejši podatki o premaznih sredstvih in tvorbi sistemov so navedeni v diplomskem delu Vrbec (2021).

2.2 PRIPRAVA VZORCEV
2.2 SAMPLE PREPARATION

Za pripravo vzorcev smo uporabili radialno do polradialno orientiran grčav les rdečega bora (*Pinus sylvestris* L.), brez vidnih razpok, modrenja in ostalih poškodb. Letve so bile klimatizirane pri (20 ± 2) °C in relativni zračni vlažnosti (65 ± 5) %, do ravnovesne lesne vlažnosti (13 ± 2) %.

Po klimatiziranju smo letve razžagali na 24 preizkušancev dimenzij 280 mm × 70 mm × 20 mm. Standard SIST EN 927-7:2020 sicer predvideva dimenzije 150 mm × 74 mm × min. 10 mm, a smo se kljub temu odločili za večje dimenzije, saj je bilo tako lažje kontrolirati nanos premaznih sredstev. Vsak vzorec lesa je vseboval vsaj eno grčo, ki je bila večjega premera od premera odprtine merilne naprave (14 mm) za določanje barve.

Ker smo ustrezno grčav les težko pridobili, smo za vsak premazni sistem naključno izbrali po 4 vzorce lesa in ne 20, kot to predvideva standard SIST EN 927-7:2020. Premazne sisteme smo nanesli po metodah in zahtevah, določenih s strani proizvajalca. Količino nanosa smo predhodno preračunali za vsak premaz posebej in jo nadzorovali gravimetrično.

2.3 IZPOSTAVITEV VZORCEV
2.3 SAMPLE EXPOSURE

Preizkušanci so bili 72 ur izpostavljeni v UV komori za umetno pospešeno staranje brez kondenzacije ali vodnega pršenja. Po izpostavljenosti smo preizkušance odstranili iz komore in jih pred merjenjem barve 24 ur klimatizirali pri sobni temperaturi (20 ± 2) °C.

Po standardu EN ISO 11507:2007 in SIST-TS CEN/TS 16359:2012 bi morali vzorce izpostaviti v komori za umetno pospešeno staranje z nizkotlačnimi živosrebrovimi ultra-vijoličnimi (UV) sijalkami tipa 2, ki imajo največjo intenziteto sevanja pri valovni dolžini 340 nm. V novejši različici metode (SIST EN 927-7:2020) je 72-urna izpostavitev vzorcev predvidena v komori s ksenonskimi sijalkami s sestavo ponavljajočega se cikla: 102 min suhe izpostavitve, 18 min škropljenja z vodo. Ker tovrstne opreme v laboratoriju nismo imeli na voljo, smo izpostavitev izvedli v prirejeni komori s klasično UV žarnico z žarilno nitko OSRAM ULTRA VITALUX 300 W (Osram, 2021), ki poleg vidne svetlobe seva tudi z UV svetlobo valovne dolžine od 315 nm do 400 nm (UVA; 13,6 W) in od 280 nm do 315 nm (UVB; 3,0 W) (Slika 1).

Bolj kot valovna dolžina in moč sevanja se nam je zdela pomembna temperatura, ki jo svetloba žarnice s svojo emisijo ustvarja na površini vzorca. Le-ta naj bi znašala (60 ± 3) °C („black-standard temperature"). To temperaturo, ki smo jo izmerili s termometrom na črni površini, smo dosegli z ustrezno razdaljo vzorca od žarnice, ki je znašala 300 mm.

2.4 MERJENJE BARVE IN IZRAČUN BARVNIH RAZLIK
2.4 COLOUR MEASUREMENT AND CALCULATION OF COLOUR DIFFERENCES

Za numerično vrednotenje barve smo uporabili spektrofotometer SP62, proizvajalca X-Rite GmbH - OPTRONIK (Planegg, Nemčija, Slika 2), ki vsebuje standardizirano svetlobo D65. Spektrofotometer ali laično kolorimeter smo pred izvedbo meritev kali-

Slika 1. Komora (levo odprta, desno zaprta) za izpostavitev UV svetlobi.
Figure 1. Chamber (left – open, right – closed) for UV light exposure.

Slika 2. Spektrofotometer SP62 (X-Rite).
Figure 2. Spectrophotometer SP62 (X-Rite).

brirali s pomočjo priloženega pripomočka, ki vsebuje bel in črn standard. Spektrofotometer deluje na principu zaznave barve oz. barvnega odtenka, glede na raven odbitih svetlobnih žarkov, kar mu omogoča vgrajena spektrofotometrična krogla, z usmerjeno osvetlitvijo (Pavlič, 2009).

Za merjenje barve smo izbrali CIELAB sistem (Slika 3), ki je najpogosteje uporabljen in izpopolnjen sistem za numerično vrednotenje barve. Predstavlja matematično kombinacijo kartezijskega in cilindričnega koordinatnega sistema (Golob & Golob, 2001), barva pa je opredeljena s tremi osnovnimi vrednostmi:

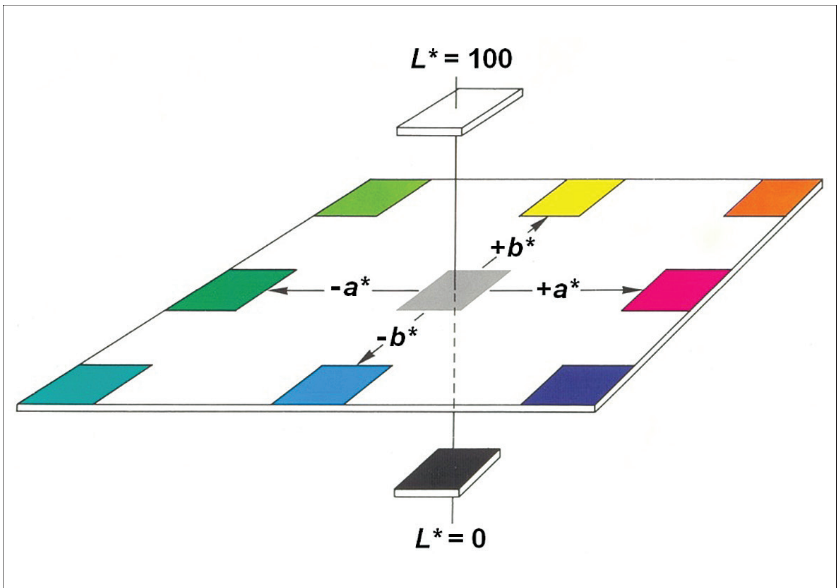
- L^* – določa svetlost barve in zavzema vrednost od 0 (absolutno črno) do 100 (absolutno belo),
- a^* – določa lego barve na rdeče (+) - zeleni (-) osi,
- b^* – določa lego barve na rumeno (+) - modri (-) osi.

Po CIELAB sistemu barvne razlike izrazimo z vrednostjo ΔE^*, ki jo izračunamo po naslednji enačbi:

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

ΔE^*... sprememba barve po CIELAB sistemu
ΔL^*... razlika med barvno komponento svetlosti barve L^* pred izpostavljenostjo in po njej
Δa^*... razlika med barvno komponento a^* pred izpostavljenostjo in po njej
Δb^*... razlika med barvno komponento b^* pred izpostavljenostjo in po njej

Na vsakem premazanem vzorcu smo izvedli po 5 meritev na lesu normalne rasti in mestih, kjer je pod premaznim sistemom bila prisotna grča. Standard SIST EN 927-7:2020 predpisuje, da meritve



Slika 3. CIELAB sistem (Golob & Golob, 2001).
Figure 3. CIELAB system (Golob & Golob, 2001).

opravimo samo po izpostavitvi preizkušancev, saj predvideva, da so premazi prekrivni in površine po premazovanju popolnoma bele. Večina naših premaznih sistemov (4) je bila poltransparentnih in tako so se že pred izpostavitvijo pojavile večje razlike v barvi premazane površine na grči in poleg nje. Zaradi tega je bilo smiselno, da opravimo meritve pri vseh sistemih že pred izpostavitvijo in ne samo po njej.

Za lažjo vizualno predstavo površin vzorcev smo le-te dodatno še optično prebrali, za kar smo uporabili Mustek S 2400 Plus A3 High Speed Flatbed Scanner (Mustek Europe B.V., Nizozemska) (ločljivost 600 pik na palec, barvna globina 24 bit).

2.5 MERJENJE DEBELINE SUHEGA FILMA PREMAZA
2.5 COATING DRY FILM MEASUREMENT

Da bi proučili še eventualno povezavo med slojnostjo premaznega sistema in njegovo odpornostjo proti obarvanju zaradi grč v lesu, smo z ultrazvočno metodo po SIST EN ISO 2808:2019 izmerili še debelino suhega filma premaza. Za to smo uporabili ultrazvočni merilec PosiTector 200, proizvajalca DeFelsko Corporation (Ogdensburg, ZDA) (Slika 4). Na vsakem vzorcu smo opravili po 5 meritev, kot rezultat smo navedli povprečno vrednost in standardni odklon meritev na vseh štirih vzorcih skupaj.

3 REZULTATI IN RAZPRAVA
3 RESULTS AND DISCUSSION

V Preglednici 1 so predstavljene povprečne barvne razlike (*ΔE**) premazanih površin premaznih sistemov na mestih z grčami in brez njih, in sicer pred izpostavitvijo UV svetlobi in po njej. Iz vrednosti barvnih razlik pred izpostavitvijo (po premazovanju) vidimo, da so le-te že v začetku pri večini sistemov bile kar velike (do 8,74), kar je pričakova-

Slika 4. Ultrazvočni merilec debeline suhega filma premaza PosiTector 200.
Figure 4. Dry coating film ultrasonic gage PosiTector 200.

no, saj smo v naši raziskavi uporabili 4 poltransparentne premazne sisteme (sistemi 1, 2, 4 in 5). Transparentnost utrjenega filma premaznega sistema je seveda močno povezana s količinami pigmenta, ki so jo premazi vsebovali. Manj kot je bilo pigmenta, bolj transparenten je bil film, ki smo ga s takim premazom ustvarili. Tako se tudi iz Slik 5 in 6 lepo vidi, da je transparentnost utrjenega filma premaznega sistema 2 največja in posledično je zaradi vpliva barvne nehomogenosti podlage tudi barvna razlika premazanih površin premaznih sistemov na mestih z grčami in brez njih največja (8,74). Pri prekrivnih sistemih (sistema 3 in 6) pa so bile barvne razlike po premazovanju presenetljivo tudi prisotne, a dovolj majhne, da jih naše oko ni zaznalo. Namreč, vrednosti barvne razlike ΔE^* sta bili pod 0,50, ki velja za spodnjo mejo vizualne zaznavnosti (Buchelt & Wagenführ, 2012).

Po izpostavitvi so se barvne razlike premazanih površin premaznih sistemov na mestih z grčami in brez njih pričakovano še povečale (Preglednica 1), saj je na mestih z grčami prišlo do obarvanja utrjenega filma, ki ga povzroča smola (razne kisline in terpenoidi) in/ali lipofilni in hidrofilni ekstraktivi (Nussbaum, 2004). Zanimivo je, da to povečanje barvnih razlik po izpostavljenosti ni bilo sorazmerno. Namreč, če pogledamo barvne razlike pred premazovanjem, so bile le-te največje pri sistemu 2, sledili so sistemi 4, 1, 5, 3 in 6. Po premazovanju pa je največja barvna razlika bila prav tako ugotovljena pri sistemu 2, sledili so sistemi 1, 4, 5, 3 in 6 (Slika 5). Na podlagi te ugotovitve smo sklenili, da je za objektivno razvrstitev premaznih sistemov glede njihove odpornosti proti obarvanju zaradi grč v lesu nujno upoštevati izhodiščne barvne razlike po premazovanju (Slika 6). V preglednici 1 smo to upoštevali tako, da smo od barvne razlike po izpostavitvi (ΔE^*_{po}) odšteli izhodiščno razliko po premazovanju oz. pred izpostavitvijo (ΔE^*_{pred}), da smo dobili podatek o povečanju barvne razlike ($\Delta E^*_{razlika}$), ki jo je povzročila izpostavitev. Ob upoštevanju te barvne razlike je tako bil najmanj odporen proti obarvanju sistem 1, sledili so sistemi 2, 5, 4, 3 in 6. Ta razvrstitev je tudi bolj skladna z našo vizualno zaznavo, saj je npr. rumenenje grč na bolj belkasti površini pri sistemu 1 veliko bolj moteče kot je rumenenje grč pri sistemu 2, pri katerem je zaradi večje transparentnosti utrjenega filma barvna raznolikost podlage (lesa) sicer bolj vidna (sistem 2) (Slika 6).

Ob upoštevanju izhodiščnih barvnih razlik po premazovanju (Preglednica 1, $\Delta E^*_{razlika}$) lahko vidimo, da so prekrivni sistemi (3 in 6) bolj odporni proti obarvanju zaradi grč v lesu kot poltransparentni premazni sistemi (1, 2, 4 in 5). Več kot ima premazni sistem pigmentov, bolj odporen je proti obarvanju zaradi grč v lesu, vendar ob tem zelo pomembno vlogo igra tudi slojnost oz. debelina suhega filma premaznega sistema. Npr. premazni sistem 1 vsebuje večjo količino pigmenta in je bolj prekriven kot premazni sistem 2, a je kljub temu manj odporen proti obarvanju ($\Delta E^*_{razlika}$ = 22,27) kot sistem 2 ($\Delta E^*_{razlika}$ = 18,01), saj je njegova debelina suhega filma

Preglednica 1. Debeline suhega filma sistemov (*d*) in barvne razlike pred (ΔE^*_{pred}) in po izpostavitvi (ΔE^*_{po}) ter izračunana barvna razlika ($\Delta E^*_{razlika}$), ki jo je povzročila izpostavitev ($\bar{x}$ - povprečna vrednost, *SD* - standardni odklon).

Table 1. Dry film thicknesses (*d*) of the systems and colour differences before (ΔE^*_{pred}) and after exposure (ΔE^*_{po}) as well as calculated colour differences due to exposure ($\Delta E^*_{razlika}$) ($\bar{x}$ - average value, *SD* - standard deviation).

Prem. sistem / Coating system	*d* (µm)		ΔE^*_{pred}		ΔE^*_{po}		$\Delta E^*_{razlika}$	
	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*
1 – TLV	**58,6**	2,3	**3,92**	1,29	**26,19**	14,55	**22,27**	13,39
2 – DLV	**87,0**	11,6	**8,74**	1,68	**26,75**	8,58	**18,01**	7,91
3 – DEV	**106,6**	5,6	**0,36**	0,17	**13,66**	5,33	**13,30**	5,47
4 – TLO	**53,1**	9,4	**6,98**	1,61	**21,11**	6,09	**14,13**	6,95
5 – DLO	**76,8**	12,2	**3,34**	0,62	**21,02**	4,97	**17,68**	5,09
6 – DEO	**142,5**	17,7	**0,38**	0,26	**7,05**	4,85	**6,67**	5,08

Slika 5. Razvrstitev premaznih sistemov (od 1 do 6) po njihovi odpornosti proti obarvanju (od najslabše zgoraj do najboljše spodaj) glede na barvno razliko po izpostavitvi (levo vzorci pred in v sredini po premazovanju ter desno po UV obsevanju).

Figure 5. Classification of coating systems (from 1 to 6) according to their resistance (from the worst to the best) according to the colour difference after exposure (left samples before and in the middle after coating and right after UV light exposure).

Slika 6. Razvrstitev premaznih sistemov (od 1 do 6) po njihovi odpornosti proti obarvanju (od najslabše zgoraj do najboljše spodaj) glede na barvno razliko pred izpostavitvijo in po njej (levo vzorci pred in v sredini po premazovanju ter desno po UV obsevanju).
Figure 6. Classification of coating systems (from 1 to 6) according to their resistance (from the worst to the best) according to the colour difference before and after exposure (left samples before and in the middle after coating and right after UV light exposure).

Slika 7. Preboj lesne smole (sistem 4).
Figure 7. Wood resin breakthrough (system 4).

Slika 8. Obarvanje filma premaznega sistema brez preboja lesne smole (sistem 6).
Figure 8. Discoloration of coating system film without wood resin breakthrough (system 6).

(*d* = 58,6 μm) dosti manjša kot je le-ta pri sistemu 2 (*d* = 87,0 μm) (Preglednica 1, Slika 6).

Bolj učinkoviti proti obarvanju so tudi premazni sistemi na osnovi organskih topil v primerjavi s primerljivimi sistemi na vodni osnovi (sistem 4 – sistem 1, sistem 5 – sistem 2, sistem 6 – sistem 3). Podobno ugotavljajo tudi Kimerling et al. (2004), ki navajajo, da se rumenenju grč pri vodnih sistemih skoraj ne da izogniti, če se pred njihovim nanosom ne uporabi ustreznih temeljnih premazov oz. tako imenovanih „blockerjev".

Odpornost premaznega sistema proti obarvanju zaradi grč v lesu je očitno povezana s prepustnostjo utrjenega filma, ki je prav tako odvisna od podobnih dejavnikov, kot npr. števila nanosov in njihove količine, stopnje in vrste pigmentacije ter drugih dodatkov, tipa veziva in topila (De Meijer, 1999; Van der Wel & Adan, 1999). Splošno je znano, da imajo akrilni premazi večjo prepustnost kot alkidni; prav tako imajo premazi na vodni osnovi večjo prepustnost kot premazi istega veziva na osnovi organskih topil (Ahola et al., 1999; De Meijer, 2000; Wegen & Hellwig, 2000; Ekstedt & Östberg, 2001). Permeabilnost premaza se lahko zaradi staranja zmanjša ali poveča (Derbyshire & Miller, 1996; Mihevc et al., 1995). Tako lahko sklepamo, da so manj prepustni filmi utrjenih premaznih sistemov tudi bolj odporni proti obarvanju zaradi grč v lesu.

Poleg neupoštevanja barvnih razlik (*ΔE**) premazanih površin pred izpostavitvijo smo pri standardizirani metodi SIST EN 927-7:2000 našli še eno pomanjkljivost. Namreč, vrednotenje premaznega sistema po njegovi učinkovitosti proti obarvanju zaradi grč v lesu temelji samo na merjenju barvnih razlik po izpostavitvi na mestih z grčami in brez njih, nikjer pa ni omenjeno spremljanje preboja smole skozi utrjen film premaznega sistema, ki je seveda tudi estetsko moteče, obenem pa nakazuje na večjo permeabilnost utrjenega filma premaznega sistema. V naši raziskavi je do preboja smole prišlo pri sistemih 1, 2, 4 in 5 (Slika 7). Preboj se je pojavil predvsem na robu in okoli grč, kar je tudi oteževalo merjenje barve na tem mestu. Preboj smole sta preprečila le debeloslojna prekrivna sistema (sistema 3 in 6) (Slika 8).

4 ZAKLJUČEK
4 CONCLUSION

V naši raziskavi smo pokazali, da z vrednotenjem barve pred izpostavitvijo in po njej in upoštevanjem te barvne razlike veliko bolj objektivno razvrstimo premazne sisteme po njihovi učinkovitosti proti obarvanju zaradi grč v lesu. Poltransparentni premazni sistemi že v samem začetku niso popolnoma prekrili površine. Razlog za to je v njihovi manjši količini pigmentov, ki prekrivajo podlago. Prav tako smo pri prekrivnih sistemih dokazali, da barvne razlike med premazanimi površinami z grčami in brez njih obstajajo, čeprav jih naše oko lahko ne opazi. Zaradi tega menimo, da je to izhodiščno barvno razliko pri vseh sistemih, ne glede na njihovo prekrivnost, pri vrednotenju njihove učinkovitosti proti obarvanju zaradi grč v lesu nujno upoštevati.

Rezultati naše raziskave so še pokazali, da je odpornost premaznih sistemov proti obarvanju zaradi grč v lesu povezana z vrsto topila v premazih, s prekrivnostjo sistema in njegovo slojnostjo oz. debelino suhega filma. Premazi na osnovi organskih topil so se tako izkazali za boljše, prav tako tisti, ki so vsebovali več pigmentov, in tisti z večjo debelino suhega filma.

Z izsledki naše raziskave smo že seznanili tehnični odbor Evropskega komiteja za standardizacijo (CEN TC 139 WG2 – *Coating materials and coating systems for exterior wood*), ki se ukvarja z razvojem metode za določanje odpornosti premazov proti obarvanju zaradi grč v lesu SIST EN 927-7. Izsledke naše raziskave bodo tako do naslednje predvidene revizije standarda uporabili za pripravo nove verzije.

5 POVZETEK

5 SUMMARY

The ability of coating systems on wood to maintain their decorative function during use is especially important in exterior applications. The elevated temperature on the surface of exposed wood can cause water-soluble substances, resins, tannins, and other wood extracts to migrate to the surface and discolour the coating system. Staining can occur in both soft- and hardwoods and is particularly problematic on wood surfaces coated with white pigmented coatings. In addition to environmental conditions and the characteristics of the coated wood, the extent of staining also depends on the type of coating system (water- or solvent-borne), its composition and the thickness of the coating. In softwoods, staining may occur particularly in areas where knots are present in the wood substrate.

The aim of the present study was to evaluate the staining of six different white pigmented wood coatings according to the method described in the standard SIST EN 927-7:2020. Red pine (*Pinus sylvestris* L.) wood with knots was used as substrate. The colour of the coated samples was measured before and after exposure to ultraviolet (UV) light (OSRAM ULTRA VITALUX 300 W, surface exposure temperature (60 ± 3) °C) for 72 hours, and the colour differences between coated surfaces with the knots and without them were calculated. In addition, the thickness of the dry coating films was measured using the ultrasonic coating thickness gauge.

After application of the coating systems, the greatest colour differences between coated surfaces with the knots and without them were observed at the samples coated with the system 2, followed by the systems 4, 1, 5, 3, and 6. As expected, these colour differences (ΔE^* from 0.36 to 8.74) were obviously related to the pigment concentration in the coatings. Greater transparency of coating system film offered higher colour difference.

After irradiation with UV light, the discoloration was particularly pronounced in the areas where knots were present in the wood substrate. Again, the colour differences between coated surfaces with the knots and without them were most pronounced in the samples coated with the coating system 2, followed by the systems 1, 4, 5, 3 and 6. But when also considering the initial colour differences due to the application of the coating systems, the coating system 1 (ΔE^* = 22.27) was the least resistant to knot staining, followed by the systems 2 (ΔE^* = 18.01), 5 (ΔE^* = 17.68), 4 (ΔE^* = 14.13), 3 (ΔE^* = 13.30), and 6 (ΔE^* = 6.67). These results show that the colour differences after the application of the coating systems must be considered in this context. It was found that the greater colour differences caused by exposure to UV light were related to the thickness of the coating film rather than the amount of pigment. Thus, the film of coating system 1 was able to hinder the texture of the underlying wood more than coating system 2. However, the film of coating system 1 was notably thinner (58.6 µm) than that of coating system 2 (87.0 µm), and consequently the colour differences were greater on the samples coated with coating system 1 (ΔE^* = 22.27 vs. ΔE^* = 18.01). In addition, similar to the usual studies, the solvent-borne coating systems were found to be more resistant to staining than water-borne ones. The other properties of the coating systems, such as the number of coating layers, the type of binder (alkyd or acrylic), the additives in the coating formulation, and the permeability of the coating film could significantly affect the staining resistance of the coating systems. Finally, the present study has shown that resin breakthrough occurs in the tested samples coated with low-build coating systems. However, the phenomenon of resin breakthrough is not considered in the methodology of the standard SIST EN 927-7:2000.

ZAHVALA
ACKNOWLEDGEMENT

Neimenovanemu podjetju se najlepše zahvaljujemo za donacijo premaznih sistemov in Blažu Jemcu za dobavo lesa. Prav tako se za financiranje raziskave zahvaljujemo Javni agenciji za raziskovalno dejavnost (ARRS) in programski skupini P4-0015.

LITERATURA
REFERENCES

Ahola, P., Derbyshire, H., Hora, G., & De Meijer, M. (1999). Water protection of wooden window joinery painted with low organic solvent paints with known composition. Part 1. Results of inter-laboratory tests. Holz als Roh- und Werklstoff, 57, 45–50.

Buchelt, B., & Wagenführ, A. (2012). Evaluation of color differences on wood surfaces. European Journal of Wood and Wood Products, 70 (1-3), 389–39.

De Meijer, M. (1999). Interactions between wood and coatings with low organic solvent content. PhD thesis, Wageningen University, Wageningen.

De Meijer, M. (2000). Comparison between laboratory water permeability test and wood moisture content in full scale window frames. V: Second Woodcoatings Congress. Woodcoatings. Challenges and Solutions in the 21st Century. October 2000 Hague, Netherlands, Congress papers. Hague; Teddington: Paint research association, 23–25.

Derbyshire, H., & Miller, E. R. (1996). Moisture conditions in coated exterior wood. Part 1: An investigation on the moisture transmission characteristics of exterior wood coatings and the effect of weathering on coating permeability. Journal of the Institute of Wood Science, 14 (1), 40–47.

Ekstedt, J. (2002). Studies on the barrier properties of exterior wood coatings. PhD thesis. Stockholm, KTH- Royal Institute of Technology, Department of Civil and Architectural Engineering, Division of Building Materials.

Ekstedt, J., & Östberg, G. (2001). Liquid Water Permeability of Exterior Wood Coatings – Testing According to a Proposed European Standard Method. Journal of Coating Technology, 73 (914), 53–59.

Golob, V., & Golob, D. (2001). Teorija barvne metrike. V: Interdisciplinarnost barve. 1. del. V znanosti, Maribor, 2001. Jeler, S., Kumar, M. (ur.). Ljubljana, Tiskarna Pleško, 199–230.

Kimerling, A. S., & Bhatia, S. R. (2004). Block copolymers as low-VOC coatings for wood: characterization and tannin bleed resistance. Progress in Organic Coatings, 51, 15–26.

Mihevc, V., Knehtl, B., & Žepič, R. (1995). Water-vapour permeability of the wood-coating system of different surface coating systems. Zbornik gozdarstva in lesarstva, 46, 177–190.

Nussbaum, R. N. (2004). The effect of processing and treatment parameters on the discoloration of painted joinery due to resin exudation from knots. Surface Coatings International Part B: Coatings Transactions, 87, 4, 181–186.

Osram (2021). Ultra vitalux 300 W 230 V E27: Data sheet. https://www.osram.com/ecat/ULTRA-VITALU UV-A-UV-A-Ultraviolet lamps-Industry-Specialty Lighting/com/en/GPS01_1028569/ZMP_60829/ (27. 7. 2021).

Pavlič, M. (2009). Lastnosti površinskih premazov v odvisnosti od njihovih interakcij s termično modificiranim lesom. Doktorska disertacija. Ljubljana, Univerza v Ljubljani, Biotehniška fakulteta, 3–59.

SIST EN 927-7 (2020). Barve in laki - Premazi in premazni sistemi za zaščito lesa za zunanjo uporabo - 7. del: Ocenjevanje odpornosti premazov proti obarvanju zaradi grč v lesu. *Paints and varnishes - Coating materials and coating systems for exterior wood - Part 7: Assessment of knot staining resistance of wood coatings (EN 927-7: 2020).*

SIST EN ISO 11507 (2007). Barve in laki - Izpostavitev premazov umetnemu vremenskemu staranju - Izpostavitev fluorescentnemu UV sevanju in vodi. *Paints and varnishes - Exposure of coatings to artificial weathering - Exposure to fluorescent UV lamps and water (EN ISO 11507: 2007).*

SIST EN ISO 2808 (2019). Barve in laki - Ugotavljanje debeline plasti (ISO 2808:2019). *Paints and varnishes - Determination of film thickness (ISO 2808: 2019)*.

SIST-TS CEN/TS 16359 (2012). Barve in laki - Premazi in premazni sistemi za zaščito lesa v zunanji uporabi - Ocenjevanje odpornosti premazov proti obarvanju zaradi lesnih grč. *Paints and varnishes - Coating materials and coating systems for exterior wood - Assessment of knot staining resistance of wood coatings (CEN/TS 16359: 2012).*

Suttie, E., & Ekstedt, J. (2004). Evaluation of a method to determine discoloration of paints on wood due to tannin staining from knots. Surface Coatings International Part B: Coatings Transactions, 87 (1), 57–61.

Van der Wel, G. K., & Adan, O. C. G. (1999). Moisture in organic coatings – a review. Progress in Organic Coatings, 37, 1–14.

Vrbec, J. (2021). Optimizacija metode določanja odpornosti premazov proti obarvanju zaradi grč v lesu. Diplomsko delo. Ljubljana, Univerza v Ljubljani, Biotehniška fakulteta: 8–13.

Wegen, W. H., & Hellwig, V. 2000. Artificial weathering of coatings including blue stain infection under laboratory conditions. V: Second Woodcoatings Congress. Woodcoatings. Challenges and Solutions in the 21st Century. October 2000 Hague, Netherlands, Congress papers. Hague; Teddington: Paint research association, 23–25.

Williams, R. S., Jourdain, C., Daisey, G. I., & Springate, R. W. (2000). Wood Properties Affecting Finish Service Life. Journal of Coatings Technology, 72 (902) 35–42.

LES/WOOD Vol. 70, No. 2, 53-69
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a05

UPORABA LESNO-PLASTIČNIH KOMPOZITOV V TEHNOLOGIJI 4D TISKA

USE OF WOOD-PLASTIC COMPOSITES IN 4D PRINTING TECHNOLOGY

Daša Krapež Tomec[1*], Aleš Straže[1], Matevž Kokot, Manja Kitek Kuzman[1], Mirko Kariž[1]

UDK 630*862:004
Izvirni znanstveni članek / Original scientific article

Prispelo / Received: 29. 9. 2021
Sprejeto / Accepted: 22. 11. 2021

Izvleček / Abstract

Izvleček: Tridimenzionalni tisk (3D) z uporabo lesno-plastičnih filamentov je že dobro poznan, vse bolj pa se raziskuje tudi uporaba lesa v štiridimenzionalnem (4D) tisku. 4D tisk je razvijajoče se področje dodajalnih tehnologij, kjer s primerno zasnovo 3D tiskanja in uporabo ustreznih materialov naredimo izdelke, ki ob ustreznih zunanjih sprožilcih spreminjajo obliko in tvorijo dinamične strukture. Pri 4D tisku lahko higroskopnost lesa - običajno pojmovano kot njegovo pomanjkljivost - izkoristimo in zasnujemo izdelke, ki spremenijo obliko glede na spremembo klimatskih pogojev, predvsem vlažnost okolice.

V raziskavi smo s FDM tehnologijo (modeliranje s spajanjem slojev) 3D tiska iz PLA (polimlečna kislina) in lesno-plastičnih filamentov (les-PLA) izdelali preizkušance z različnimi razmerji materialov, pri katerih smo spremljali odziv v spreminjajočih klimatskih pogojih. Za spremljanje spremembe oblike, kot je ukrivljanje, smo izdelali sestavljene preizkušance po principu bimetala (aktuatorje), kjer smo za pasivno plast (ob spremembi vlažnosti okolice ne spreminja svojih dimenzij) uporabili PLA, za aktivno plast (spreminja dimenzije ob spremembi vlažnosti okolice) pa les-PLA v različnih razmerjih debelin ter jih izpostavili laboratorijskim ter zunanjim pogojem.

Rezultati so pokazali, da dodatek lesa pri lesno-plastičnih kompozitih v spreminjajoči se klimi povzroča dimenzijske spremembe in s tem spremembe oblike načrtovanih aktuatorjev. Sprememba oblike je odvisna od razmerja debelin slojev materialov v dvoslojnem aktuatorju, od sorpcije vodne pare ter od vsebnosti lesa v uporabljenem lesno-plastičnem kompozitu.

Ključne besede: 3D tisk, 4D tisk, lesno-plastični kompoziti, materiali z oblikovnim spominom

Abstract: Three-dimensional (3D) printing with wood-plastic composites is already well known, and the use of wood in four-dimensional (4D) printing is being increasingly explored. 4D printing is an evolving area of additive technologies where, with the appropriate design of 3D printing and use of appropriate materials, we can create products that change shape and form dynamic structures when triggered externally. In 4D printing, the hygroscopicity of wood – usually considered a disadvantage – can be used as a positive property to design products that change their shape according to climatic conditions, especially humidity.

In this research, we used the FDM (fused deposition modelling) technology of 3D printing PLA (polylactic acid) and wood-plastic composites (wood-PLA) to produce specimens with different material proportions, whose response to changing climatic conditions we monitored. To monitor the change in shape, or curvature, we fabricated composite test specimens using the bimetal principle (actuators), in which we used PLA for the passive layer and wood-PLA for the active layer in different thickness ratios and exposed them to laboratory and external conditions.

The results showed that the wood content of the wood-plastic composites leads to dimensional changes in a changing climate, resulting in changes in the shape of the designed actuators. The change in shape depends on the thickness ratio of the layers in the two-layer actuator, the sorption of water vapor, and the wood content in the wood-plastic composite used.

Keywords: 3D printing, 4D printing, wood-plastic composites, shape memory materials

1 UVOD

2 INTRODUCTION

4D tisk je razvijajoče se področje znotraj dodajalnih tehnologij (3D tiska), kjer z uporabo materialov, ki pod določenimi pogoji spremenijo svoje lastnosti, oblikujemo izdelke, ki lahko spreminjajo

[1] Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za lesarstvo, Jamnikarjeva 101, 1000 Ljubljana, SLO
[*] e-mail: dasa.krapez.tomec@bf.uni-lj.si

svojo obliko (Ryan et al., 2021). Četrto dimenzijo predstavlja čas, potreben za aktivacijo in doseganje želene spremembe. To odpira nove možnosti izdelave dinamičnih struktur, ki se odzivajo na umetne sprožilce (magnetno, električno polje) ali samodejno na spremembe pogojev okolice npr. temperature ali vlažnosti.

4D tisk je mogoč z običajnimi materiali, ki jim med tiskanjem z vnaprej premišljeno zasnovo (uporabljenimi materiali na ustreznih mestih v ustrezni količini/razmerju) vgradimo notranje napetosti, ki se potem sprostijo (npr. deli, ki se ob ustreznem sprožilcu sestavijo/deformirajo v ustrezno obliko). Druga možnost izvedbe 4D tiska je s »pametnimi« materiali, ki se ob ustrezni spremembi v okolici spremenijo (npr. sprememba vlage, temperature, pH, UV sevanja, električnih in magnetnih polj …) (Erb et al., 2013; Manen et al., 2017; Rayate & Jain, 2018; Ryan et al., 2021). 4D tiskanje oziroma tiskanje spreminjajočih se struktur je mogoče tudi s cenovno dostopnimi FDM 3D tiskalniki, saj se večino dejavnikov, ki vplivajo na odziv izdelka, določi z izbiro materiala in zasnovo izdelka med določitvijo parametrov tiskanja (debelina slojev, razporeditev in delež materialov, usmerjenost ekstrudiranih linij) (Manen et al., 2017).

4D tisk je zanimiv za uporabo na različnih področjih, od mehke robotike, samosestavljive embalaže, biomedicinskih aplikacij, pametnih tekstilov, začasnih objektov, senzorskih in vesoljskih tehnologij (Ryan et al., 2021), v arhitekturi in oblikovanju (Correa et al., 2015; Reichert et al., 2015)

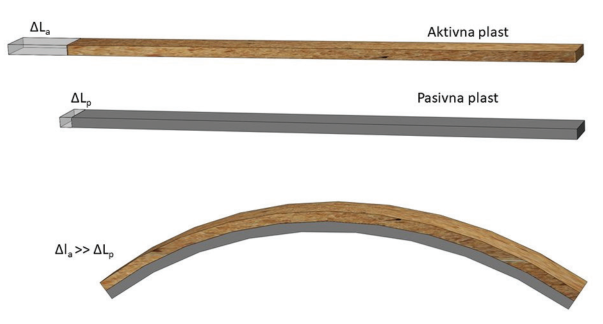
Na področju arhitekture bi posebej izpostavili dve zanimivi aplikaciji; – možnost odpiranja/zapiranja streh za objekte, kot so športni stadioni, in prilagodljive fasade, ki poskušajo doseči odzivnost z bolj lokaliziranim nadzorom prepustnosti, medtem ko večina raztegljivih/konvertibilnih streh/fasad/sten uporablja gibanje večjih gradbenih komponent. Za obe aplikaciji so značilne kompleksne procesne in mehanske zahteve, ki poleg tega zahtevajo vsaj en zunanji vir energije, številne pogone in senzorje ter logično krmilno enoto (Reichert et al., 2015). Izkoriščanje higroskopskega vedenja materiala je še posebej obetavno za uporabo v arhitekturni in gradbeni praksi, saj za svoje delovanje ne zahteva nobenega umetnega zunanjega, električnega ali kakršnega koli drugega aktiviranja.

V naravi najdemo številne organizme, ki delujejo na podoben način kot pametni materiali, zato raziskovalci pogosto posnemajo njihovo delovanje pri snovanju novih izdelkov (Cheng et al., 2021a; Correa et al., 2020; Le Duigou et al., 2016; Le Duigou et al., 2017; Manen et al., 2017). Npr. storži iglavcev se odpirajo in zapirajo v odvisnosti od zračne vlažnosti, to zmožnost ohranijo tudi, ko niso več del žive rastline. Načelo higroskopskega aktiviranja temelji na hierarhični, dvoslojni mikrostrukturi, ki jo sestavljajo sklerenhim in sklereide. Vsako od teh tkiv je organizirano kot snop posameznih vlaken, pri čemer je vsako vlakno koncentrični sestavljeni valj, sestavljen iz različnih celičnih sten. Sekundarno celično steno, ki je v glavnem odgovorna za higromehanske lastnosti posameznega vlakna, sestavljajo usmerjene toge celulozne mikrofibrile, vdelane v higroskopski hemicelulozni/pektinski matriks. Dvoplastna struktura povzroči diferencialno nabrekanje med dvema plastema, povezanima s prehodno medfazo (Le Duigou et al., 2020).

Številni naravni materiali lahko spremenijo obliko pod vplivom okoljskih stimulatorjev, kot sta toplota ali vlažnost (Cheng et al., 2021). Higromorfni materiali ali materiali, ki spreminjajo obliko z navzemanjem ali oddajanjem vlage, delujejo drugače, ker je zunanji dražljaj tisti, ki sproži preoblikovanje iz prvotne oblike; transformacija je obrnjena, ko dražljaj odstranimo – predmet se vrne v prvotno obliko. Tako material niha med dvema ravnotežnima stanjema brez potrebe po zunanji sili, kar omogoča več ciklov preoblikovanja. Smer in amplituda gibanja sta vnaprej določeni v strukturi materiala (Zhou & Sheiko, 2016).

Novi pametni materiali predstavljajo enega najbolj ključnih izzivov za razvoj in nadaljnjo širitev 4D tiskanja. Odzivi na dražljaje pri 4D tiskanju za različne vrste materialov, vključno z materiali z oblikovnim spominom in hidrogeli, so uspešno raziskovani, vendar počasen odziv in nizka učinkovitost zaenkrat ovirajo nadaljnji razvoj. Kljub temu so Chen in sodelavci zasnovali visoko zmogljiv integriran aktuator z zaznavanjem deformacij in samozaznavanjem temperature, katerega povprečni odzivni čas je približno 20 sekund (Chen et al., 2020). Večina obstoječih materialov reagira le na en dražljaj in ta ne deluje v primeru okvare opreme za ustvarjanje dražljajev. Zato imajo materiali, odzivni na različne dražljaje, strateško prednost.

Les lahko v 3D tiskanju vključimo v filament, sestavljen iz lesa in plastike oz. polimera. V kompozitih les obdrži del svojih prvotnih lastnosti - higroskopnost in dimenzijsko nestabilnost (Ayrilmis et al., 2019; Kariž et al., 2018a; Kariž et al., 2018b), saj so naravna vlakna anizotropna in občutljiva na vlago, kar je ena izmed njihovih pomanjkljivosti, kadar se uporabljajo za konstrukcijske namene (Faruk et al., 2012). Anizotropno nabrekanje naravnih vlaken pa lahko uporabimo kot gonilo za aktivacijo pri razvoju higromorfnih biokompozitov s 3D tiskanjem. Vsebnost vlaken, nadzor usmerjenosti vlaken in neprekinjenost vlaken so opisani v povezavi z (znanimi) izzivi učinkovitosti proženja/aktiviranja (Le Duigou et al., 2020). Razlike v prostorninskem raztezanju, upogibni togosti in modulu elastičnosti vsake plasti so osnova njihovega deformacijskega odziva (Correa et al., 2015). Les s svojo higroskopnostjo ter ortotropnimi krčitvenimi in mehanskimi lastnostmi lahko uporabimo v dvoslojnih/dvomaterialnih kompozitih, kjer postane naraven aktuator, ki spreminja obliko s krivljenjem, ter bi se lahko uporabljal za samodejno senčenje, prezračevanje ali »ojačanje« strukture, glede na spremembo klime v okolici (Cheng et al., 2021; Reichert et al., 2015; Rüggeberg & Burgert, 2015). Zamisel o dvomaterialnih aktuatorjih, ki spreminjajo obliko, temelji na bimetalnih aktuatorjih (slika 1). Bimetalni aktuatorji uporabljajo dve kovini z različnim koeficientom toplotnega raztezanja. Sprememba oblike dvoslojnih pogonov je odvisna od lastnosti materiala in njegovega razmerja debeline v kompozitu (Timoshenko, 1953).



Slika 1. Načelo odziva higromorfnih kompozitov na podlagi diferencialne higroekspanzije in kontrakcije (tj. krčenja in nabrekanja) aktivne ter pasivne plasti.
Figure 1. Principle of the response of hygromorphic composites based on differential hygroexpansion and contraction (i.e., shrinkage and swelling) of the active and passive layers.

Raziskave obnašanja lesno-plastičnih kompozitov v 4D tiskanju so v velikem porastu (El-Dabaa & Salem, 2021; Le Duigou et al., 2016; Krapež Tomec et al., 2021; Vazquez et al., 2019), vendar je večina raziskav usmerjena na preskušanje v laboratorijskih pogojih, malo pa ob izpostavitvi na prostem, kjer na odziv vpliva veliko različnih dejavnikov (Rüggeberg & Burgert, 2015) ter tudi število ciklov izpostavitve.

V raziskavi smo za izdelavo dinamičnih struktur (princip 4D tiska) preizkušali uporabo 3D tiskanja lesno-plastičnih kompozitov, ki se odzivajo na spremembo vlažnosti okolice s spremembo oblike. Cilj raziskave je bil ugotoviti, ali lahko običajno nezaželene dimenzijske spremembe lesa v lesno-plastičnih filamentih ob spremembi vlažnosti uporabimo kot sprožilec spreminjanja oblike lesno-plastičnega kompozita ter uporabo lesno-plastičnega kompozita kot osnovo 4D tiska. Uporabili smo aktuatorje iz PLA in les-PLA kompozitov z različnim razmerjem debeline slojev posameznega materiala in preučili njihov odziv, zlasti spremembe oblike – amplitudo krivljenja, pri laboratorijskem izotermnem spreminjanju relativne zračne vlažnosti (RZV) in kombinaciji sprememb relativne zračne vlažnosti, temperature in sončnega obsevanja v okolju (zunanja izpostavitev).

2 MATERIALI IN METODE
2 MATERIALS AND METHODS

Raziskava je bila razdeljena na dva dela:

- spremljanje odziva 4D natisnjenih kompozitov v laboratorijskih pogojih in določitev osnovnih lastnosti uporabljenih materialov ter
- spremljanje odziva 4D natisnjenih kompozitov ob izpostavitvi zunanji klimi.

2.1 MATERIALI
2.1 MATERIALS

Za 3D tiskanje sta bila uporabljena dva materiala – komercialni PLA filament (Plastika Trček, Slovenija; označen kot PLA) ter lesno-plastični filament, izdelan iz PLA polimera s 25 % deležem lesnih delcev (velikosti 70 do 150 µm, Arbocel C100) (izdelan v Kompetenzzentrum Holz GmbH, Linz, Avstrija; označen kot WPL25).

Vsi preizkušanci so bili natisnjeni na Creality CR-10-V3 (Creality 3D Technology Co., Ltd, Shenzhen, China) 3D tiskalniku z direktnim ekstruderjem. Debelina sloja tiskanja je bila 0,3 mm, premer šobe

0,4 mm, temperatura tiskanja 200 °C, temperatura mize tiskalnika 50 °C. 3D model je bil pripravljen v SolidWorks programski opremi (SolidWorks Corp., Massachusetts, USA), shranjen v STL formatu ter pripravljen na tisk v Cura V4.10.0. programski opremi (Ultimaker, Utrecht, Netherlands). Preizkušanci so bili natisnjeni kot polni (solid), s 45-stopinjskim potekom linij tiskanja glede na dolžino preizkušanca (izmenično en sloj +45°, naslednji sloj -45° glede na dolžino preizkušanca).

2.2 UPOGIBNA TRDNOST IN MODUL ELASTIČNOSTI

2.2 BENDING STRENGTH AND MODULUS OF ELASTICITY

Pred testiranjem odzivanja materiala na zunanje dražljaje smo preizkušancem iz čistega PLA in iz lesno-plastičnega filamenta WPL25 določili upogibno trdnost in modul elastičnosti. Preizkušanci dimenzij (120 x 15 x 4) mm so bili po 7 dni uravnovešani v stacionarni klimi (RZV 20 %, 40 %, 65 % oziroma 80 %, temperatura 20 ºC). Preizkušance (7 vzporedno natisnjenih) smo po vsakem uravnovešanju testirali po postopku, prilagojenem glede na predhodne raziskave (čim daljši vzorci glede na obstoječo pripravo za testiranje), na 3-točkovnem upogibnem testu na univerzalnem preskusnem stroju Zwick Z005 (ZwickRoell GmbH, Ulm, Nemčija). Razpon med podporama je bil 80 mm, hitrost pomika pa 10 mm/min. Od vsake serije smo en preizkušanec po prvem kondicioniranju obremenili do loma, da smo določili maksimalno silo obremenjevanja, nato pa ostale obremenili samo do 50 % maksimalne sile. Tako smo paralelnim preizkušancem (6 kosov) lahko določili modul elastičnosti po uravnovešanju v različnih klimah.

Iz meritev so bili izračunani moduli elastičnosti po enačbi (Enačba 1):

$$E_m = \frac{l_1^3 \times (F_2 - F_1)}{4bt^3 \times (a_2 - a_1)} \qquad (1)$$

l …razdalja med podporama [mm],
b …širina preizkušanca [mm],
t …debelina preizkušanca [mm],
F_2…sila pri 40 % maksimalne obremenitve [N],
F_1…sila pri 10 % maksimalne obremenitve [N],
a_2…poves pri 40 % maksimalne obremenitve [mm],
a_1…poves pri 10 % maksimalne obremenitve [mm].

2.3 DIMENZIJSKA STABILNOST

2.3 DIMENSIONAL STABILITY

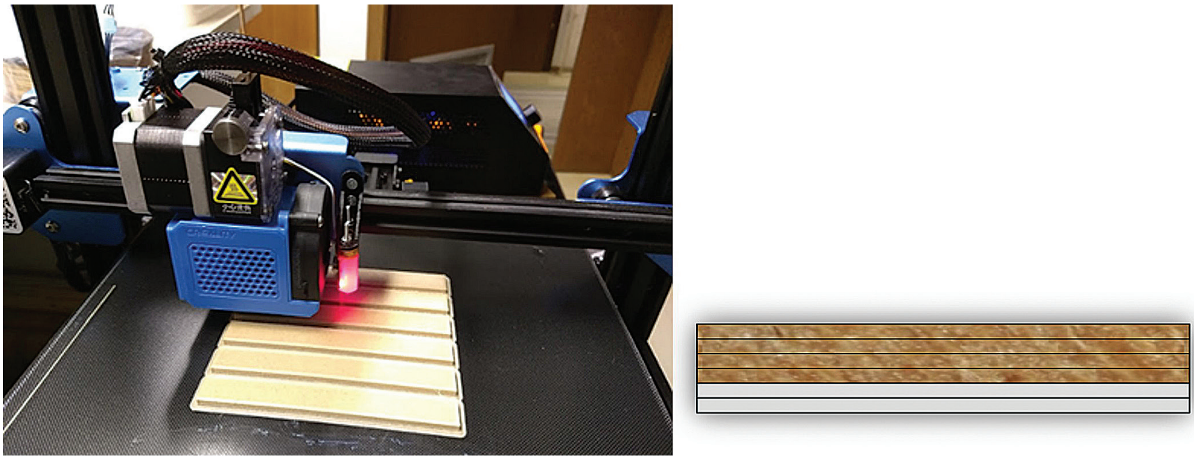
Preizkusi dimenzijske stabilnosti so bili izvedeni v laboratorijskem sušilnem kanalu TLS-01 (Kambič, Semič, Slovenija). V preskusni komori sušilnega tunela z dimenzijami 700 × 400 × 610 mm^3 (dolžina × višina × širina) sta bili na sredino rešetaste podlage postavljeni dve seriji po 7 preizkušancev. Proces vlaženja in sušenja je nadzoroval centralni mikroprocesorski krmilnik DPC-420, ki je omogočal nastavitev temperature zraka (T), relativne zračne vlažnosti (RZV) in hitrosti zraka (v) (ΔT = ± 1,0 °C, ΔRZV = ± 1,0 %, Δv = ± 0,1 m/s).

Po 3D tisku so bili preizkušanci sprva uravnovešani v klimatski komori na 20 % RZV. Za merjenje kinetike adsorpcije in desorpcije so bili preizkušanci (n = 7) najprej 168 ur (7 dni) izpostavljeni 80 % RZV in nato naslednjih 168 ur 20 % RZV. Temperatura je bila konstantna 20 °C, hitrost zraka pa 1 m/s. Postopek sorpcije 3D natisnjenih preizkušancev smo spremljali z intervalnim tehtanjem vsakega preizkušanca na laboratorijski tehtnici Exacta 300 EB (Tehtnica Železniki, Slovenija) z natančnostjo 0,01 g in z ročnim merjenjem treh dimenzij preizkušancev z digitalnim kljunastim merilom z natančnostjo 0,01 mm.

2.4 MERITVE ODKLONA ELEMENTOV, NATISNJENIH IZ DVEH RAZLIČNIH MATERIALOV

2.4 MEASUREMENTS OF DEFLECTION OF ELEMENTS, PRINTED FROM TWO DIFFERENT MATERIALS

Preizkušanci 200 x 12 x 1,8 mm^3 za meritve odklona elementov ob spreminjanju klimatskih pogojev so bili natisnjeni iz dveh materialov - spodnji (»pasivni«) sloji iz PLA, zgornji (»aktivni«) pa iz lesno-plastičnega kompozita WPL25 (slika 2). Debelina posameznega sloja je bila 0,3 mm, skupna debelina preizkušancev je bila vedno 1,8 mm, s spreminjanjem števila slojev posameznega materiala pa smo spreminjali delež pasivnega PLA in delež aktivnega WPL25 v sestavljenem preizkušancu (preglednica 1). Natisnjena sta bila tudi dva preizkušanca iz samo enega materiala - čisti PLA in čisti WPL25.



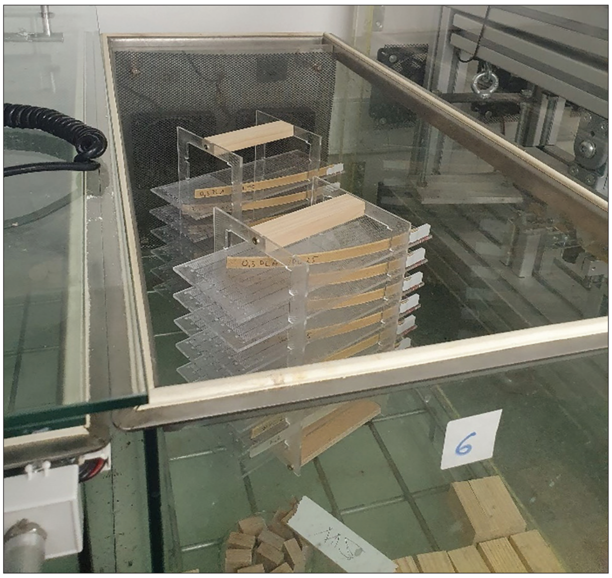
Slika 2. 3D tiskanje preizkušancev (levo; foto: M. Kokot) in sestava preizkušanca (0,6 PLA WPL25) - PLA sloji spodaj – 2x0,3 mm in lesno-plastični sloji nad njim 4x0,3 mm (desno).
Figure 2. 3D printing of specimens (left; photo: M. Kokot) and composition of the specimen (0,6 PLA WPL25) - PLA layers below – 2x0.3 mm and wood-plastic layers above it 4x0.3 mm (right).

Preglednica 1. Oznake posameznih preizkušancev in uporabljene kombinacije slojev v preizkušancu z razmerjem debeline pasivnega in aktivnega sloja v aktuatorju (m).
Table 1. Labels of individual samples and the used combination of layers in the sample with the thickness ratio of the passive and active layers in the actuator (m).

Oznaka preizkušanca	Število slojev/ skupna debelina slojev PLA [mm]	Število slojev/ skupna debelina slojev WPL25 [mm]	Skupna debelina preizkušanca [mm]	Razmerje debelin pasivnega in aktivnega sloja – m
Kontrola PLA	6/1,8	-	1,8	-
Kontrola WPL25	-	6/1,8	1,8	-
0,3 PLA WPL25	1/0,3	5/1,5	1,8	0,2
0,6 PLA WPL25	2/0,6	4/1,2	1,8	0,5
0,9 PLA WPL25	3/0,9	3/0,9	1,8	1,0
1,2 PLA WPL25	4/1,2	2/0,6	1,8	2,0

Preizkušanci, vpeti v merilno podlogo, so bili najprej izpostavljeni vlažni klimi (80 % RZV, 20 ºC, slika 3). Po vnaprej določenih časovnih intervalih (1, 2.5, 4, 6, 23, 27, 50, 54, 72, 168 ur) so bili merjeni odmiki preizkušancev. Ob vsaki meritvi smo merilno podlogo s preizkušancem stehtali, fotografirali (primer slika 5) ter odčitali odmik od začetne lege. Enak postopek meritev je bil nato ponovljen v suhi klimi (20 % RZV, 20 ºC) in v nadaljevanju ponovljen (3x navlaževanje, 3x sušenje).

V drugem delu raziskave (izpostavitev na prostem) so bili preizkušanci vpeti na večjo merilno podlogo ter izpostavljeni zunanjim vplivom (slika 4). Vsako uro je bil narejen posnetek vzorcev ter iz analize slike določen trenutni odmik od začetne lege preizkušanca. Temperatura zraka in relativna zračna vlažnost sta bili izmerjeni na lokaciji v vremenski postaji Davis (Davis Instruments, CA, USA). Na površini podloge je bil pritrjen termočlen, s katerim smo spremljali temperaturo na površini tik ob preizkušancih. Podatke termočlena smo zajemali s Thermofox data-logger (Scanntronic Mugrauer GmbH, Germany). Meritve so potekale na Oddelku za lesarstvo, Cesta VIII/34, Ljubljana v mesecu juliju. V času meritev ni bilo padavin, povprečno so bili izpostavljeni direktnemu soncu od 10. do 14. ure (4 ure), ostali del dneva so bili na lokaciji meritev v senci.

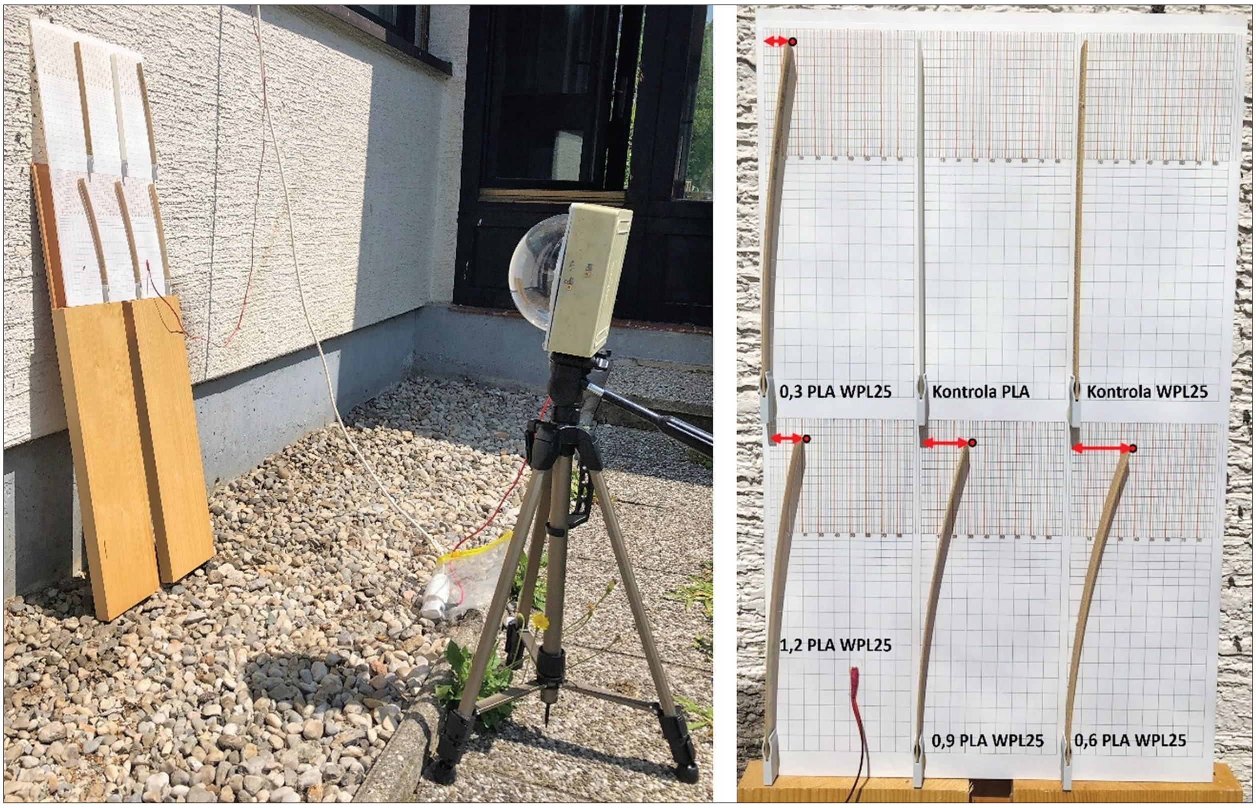


Slika 3. Preizkušanci med izpostavitvijo sorpciji/desorpciji v solni klima komori (foto: M. Kokot).
Figure 3. Samples during exposure to sorption / desorption in a climatic chamber (photo: M. Kokot).

2.5 VREDNOTENJE IZMERJENIH PODATKOV PRI STACIONARNIH PODATKIH NAVLAŽEVANJA
2.5 EVALUATION OF MEASURED DATA FOR STATIONARY HUMIDIFICATION DATA

Z metodo vrednotenja izmerjenih podatkov smo želeli ugotoviti difuzivnost vlage 4D natisnjenih elementov in s spreminjanjem razmerja pasivne in aktivne plasti ugotoviti, kako razmerje posameznih plasti vpliva na hitrost doseženega končnega odmika in na difuzivnost vlage.

Sprememba stanja preizkušancev pri navlaževanju v klima komori z RZV 80 % in T = 20 °C je bila proučena z odzivom sistema na hipno, konstantno zunanjo motnjo. Pri tem je karakterističen prehod sistema v novo stacionarno stanje, ki ga lahko opišemo kot sistem 1. reda z diferencialno enačbo (Bučar, 2007; Straže, 2010):



Slika 4. Postavitev preizkušancev na podlogo za merjenje odmika ob izpostavitvi zunanjim vplivom z merilno opremo (levo) in preizkušanci (desno), (foto: D. Krapež Tomec).
Figure 4. Placement of samples on the measuring template and measuring the deflection when exposed to external conditions with the measuring equipment (left) and samples (right), (photo: D. Krapež Tomec).

$$G\Phi(t)=\tau\frac{dm}{dt}+m \quad (2)$$

G = stacionaren odziv sistema [g],
Φ(t) = prehoden odziv sistema [ ],
τ = časovna konstanta Tau [s],
m = masa [g], v našem primeru odmik *x* [mm],
t = čas [s].

Zgornji izraz (enačba 2) je bil preoblikovan ob predpostavki, da je raztezek ali pa kontrakcija (krčenje) materiala v linearni zvezi s spremembo mase in s tem vlažnosti materiala - namesto mase *m* smo pisali odmik *x.* Predpostavljeno je, da je diferencialno nabrekanje oz. diferencialno krčenje, tj. sprememba dimenzije glede na spremembo vlažnosti materiala konstantna na njegovem celotnem higroskopskem območju. Tako je bilo v enačbo vpeljano začetno stanje preizkušanca (x_z), stanje preizkušanca v določenem času (x_t) ter končno oz. ravnovesno stanje (x_r), ekvivalentno stacionarnemu odzivu (*G*), ki je doseženo po dovolj dolgem času uravnovešenja. Zgornjo enačbo lahko nato za primer hipne obremenitve v času $t = 0$, z začetnim pogojem $x = x_z$ zapišemo v obliki:

$$x_{(t)}=x_{r(končna)}+\left(x_{z(začetna)}-x_{r(končna)}\right)*e^{-\frac{t}{\tau}} \quad (3)$$

S preoblikovanjem izraza (enačba 3) dobimo odvisnost povprečne brezdimenzijske spremembe odmika (*E*) od časa izpostavitve v klimi z določeno vlažnostjo:

$$\frac{x_{t(izbrana)}-x_{r(končna)}}{x_{z(začetna)}-x_{r(končna)}}=e^{-\frac{t}{\tau}} \quad (4)$$

$$E=\frac{\left(x_{t(izbrani)}-x_{r(končni)}\right)}{\left(x_{z(začetni)}-x_{r(končni)}\right)} \quad (5)$$

Spremenljivka (x_t) bo dosegla 63,2 % hipne obremenitve *G*, ko bo dosežen pogoj *t* = τ. Končni odziv sistema je praviloma dosežen po 5-kratniku časovne konstante τ.

S spremljanjem odmika preizkušancev v posameznih časovnih intervalih so bile z logaritmiranjem izraza (enačba 5) časovne konstante izračunane po enačbi:

$$\tau=-\frac{t}{\ln\left(\frac{x_t-x_r}{x_z-x_r}\right)} \quad (6)$$

3 REZULTATI
3 RESULTS

3.1 MODUL ELASTIČNOSTI IN DIMENZIJSKA STABILNOST
3.1 MODULUS OF ELASTICITY AND DIMENSIONAL STABILITY

Sprememba oblike aktuatorjev, kot smo jih uporabili v nadaljevanju raziskave, je odvisna od uporabljenih materialov, njihovih lastnosti (modula elastičnosti, dimenzijskih sprememb ob izpostaviti vlažni klimi) ter razmerju debelin materialov v sestavljenem aktuatorju (Le Duigou & Castro, 2017; Timoshenko, 1953), zato smo najprej določili lastnosti uporabljenih materialov.

Za vse preizkušance, testirane pri štirih vlažnostnih stanjih (20 %, 40 %, 65 % in 80 % RVZ), so bili izračunani moduli elastičnosti. Čisti PLA material je pri vseh testiranih vlažnostih izkazoval večje module elastičnosti kot lesno-plastični kompozit s 25 % deležem lesnih delcev (WPL25). Rezultat je pričakovan, saj je bil les v WPL25 dodan v obliki lesnega prahu/moke z majhnimi delci, in predvidevamo, da s tem ni imel ojačitvene vloge, temveč bolj vlogo polnila. Če bi bili dodani lesni delci v obliki vlaken, oziroma z večjim razmerjem med dolžino in debelino delcev, bi lahko izraziteje ojačali kompozit. Dodajanje delcev večjih dimenzij ter oblika vlaken pa povzroči težje 3D tiskanje, predvsem prihaja do mašenja šobe tiskalnika, potrebne so višje sile za ekstrudiranje, kar pa lahko povzroči večjo možnost napak v tisku (zastoji pri ekstrudiranju materiala, prazni prostori v tisku, neenakomeren tok materiala), pojavljanje šibkih točk ter s tem koncentracij napetosti v končnem izdelku ob hkratni nižji togosti.

Oba materiala sta dosegla najnižji modul elastičnosti po izpostavitvi v vlažni klimi RZV 80 % ter največje vrednosti v klimi z RZV 40 %, (PLA 3298 MPa, WPL25 2493 MPa). Z nižanjem RZV na 20 % so vrednosti padle, kar bi lahko kazalo na podobnost z masivnim lesom (Martikka et al., 2018). Rezultati zaradi majhnega števila preizkušancev in velikih odklonov niso statistično značilni. Ravno tako je togost padla z višanjem RZV in s tem vlažnosti kompozita. Adsorpcija vode v kompozit povzroči nabrekanje lesa, zmanjšanje njegove trdnosti ter lahko tudi zmanjšanje trdnosti vezi med (hidrofilnim) lesom in (nepolarnim) polimerom (Balatinecz & Park, 1997; Kariž et al., 2018a).

Preglednica 2. Modul elastičnosti (MOE) za PLA in PLA polimer s 25 % deležem lesnih delcev (WPL25) pri štirih različnih relativnih zračnih vlažnostih (RZV).
Table 2. Modulus of elasticity (MOE) for PLA and PLA polymer with 25% of wood particle content (WPL25) at four different relative humidities (RH).

	20% RZV			40% RZV			65% RZV			80% RZV		
	MOE [MPa]	St. odklon	Vlažnost [%]	MOE [MPa]	St. odklon	Vlažnost [%]	MOE [MPa]	St. odklon	Vlažnost [%]	MOE [MPa]	St. odklon	Vlažnost [%]
PLA	2907	168	0,10	3298	149	0,31	3107	222	0,4	2834	162	0,62
WPL25	2320	206	0,59	2493	252	1,86	2238	237	2,27	2001	218	3,41

Za določene biopolimere, kot je npr. PLA, je značilna adsorpcija vlage ter s tem higroekspanzija. Za PLA filamente za 3D tiskanje tako proizvajalci priporočajo shranjevanje v zaprti embalaži z dodajanem silica gel (SiO_2) sušilnega sredstva ali občasno sušenje filamenta v pečici. Dodajanje lesa oziroma drugih naravnih higroskopnih vlaken pa adsorpcijo še poveča. Meritve so pokazale, da je PLA adsorbiral vlago ob uravnovešanju v vlažnih klimah, vendar precej manj kot WPL25. Vzdolžni raztezek preizkušancev iz materiala PLA pa je bil približno 5x manjši od raztezka lesno-plastičnega kompozita s 25 % deležem lesnih vlaken (preglednica 3, 7 vzporednih preizkušancev).

Preglednica 3. Vzdolžni nabrek (RZV 80 %, T = 20 °C) ter diferencialni raztezek testiranih materialov
Table 3. Longitudinal swelling (80% RH, T = 20 °C) and differential swelling of the tested materials

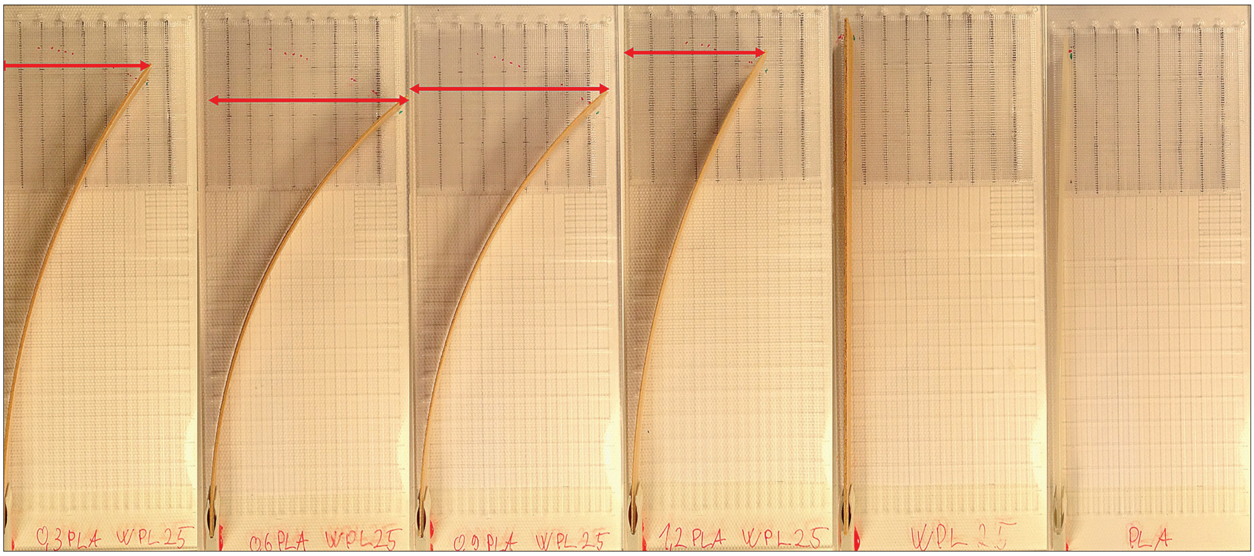
Material	Vzdolžni raztezek [%]	Diferencialni raztezek v % na % spremembe RZV
PLA	0,09	0,233
WPL25	0,47	0,222

3.2 MERITVE ODKLONA ELEMENTOV, NATISNJENIH IZ DVEH RAZLIČNIH MATERIALOV
3.2 MEASUREMENTS OF DEFLECTION OF ELEMENTS, PRINTED FROM TWO DIFFERENT MATERIALS

Pri izpostavitvi elementov (sistema dveh materialov) v solni klima komori z natrijevim nitratom ($NaNO_3$) - RZV 80 % in T = 20 °C ter zunanji izpostavitvi preizkušancev (nihajoča RZV ter temperatura) so bili spremljani odkloni v določenih časovnih intervalih. Preizkus je pokazal, da se preizkušanci, natisnjeni iz enega materiala, t.j. čisti PLA ali čisti WPL25, na navlaževanje ne odzivajo z odklanjanjem, temveč ostajajo v začetni legi (slika 5 skrajno desna preizkušanca). Najverjetneje gre rezultat pripisati stanju, kjer se preizkušanci po celotnem prerezu enakomerno vzdolžno dimenzijsko povečujejo, s čimer pa ne pride do nastanka upogibnega momenta.

Odmik dvoslojnih preizkušancev ob koncu navlaževanja (po 168 urah v laboratorijskih pogojih v vlažni klima komori na 80 % RZV in 20 ºC) je pokazal največji upogib pri aktuatorjih z debelino PLA 0,6 mm (WPL25 1,2 mm, m=0,5) in 0,9 mm (WPL25 0,9 mm, m=1) (slika 5). Rezultati so skladni s Timošenkovo teorijo (The Collected Papers of Stephen P. Timoshenko. (Book, 1953) [WorldCat. Org], n.d.).

Največji odklon je v linearni zvezi z naraščanjem mase preizkušanca med postopkom navlaževanja. Adsorpcija vlage je bila najvišja pri kompozitih z najnižjo vsebnostjo pasivne (PLA) plasti. Rezultati nakazujejo, da je zmanjšanje debeline pasivne (PLA) plasti v povezavi z opisa-



Slika 5. Maksimalni odmik preizkušancev - po 168 urah v laboratorijskih pogojih v vlažni klimi (80 % RZV, 20 ºC). Preizkušanci od leve proti desni: 0,3 PLA WPL25; 0,6 PLA WPL25; 0,9 PLA WPL25; 1,2 PLA WPL25; WPL25; PLA (foto: M. Kokot).

Figure 5. Maximum curvature of the sample - after 168 hours in laboratory conditions in a humid climate (80% RH, 20 ºC). Samples from left to right: 0,3 PLA WPL25; 0,6 PLA WPL25; 0,9 PLA WPL25; 1,2 PLA WPL25; WPL25; PLA (photo: M. Kokot).

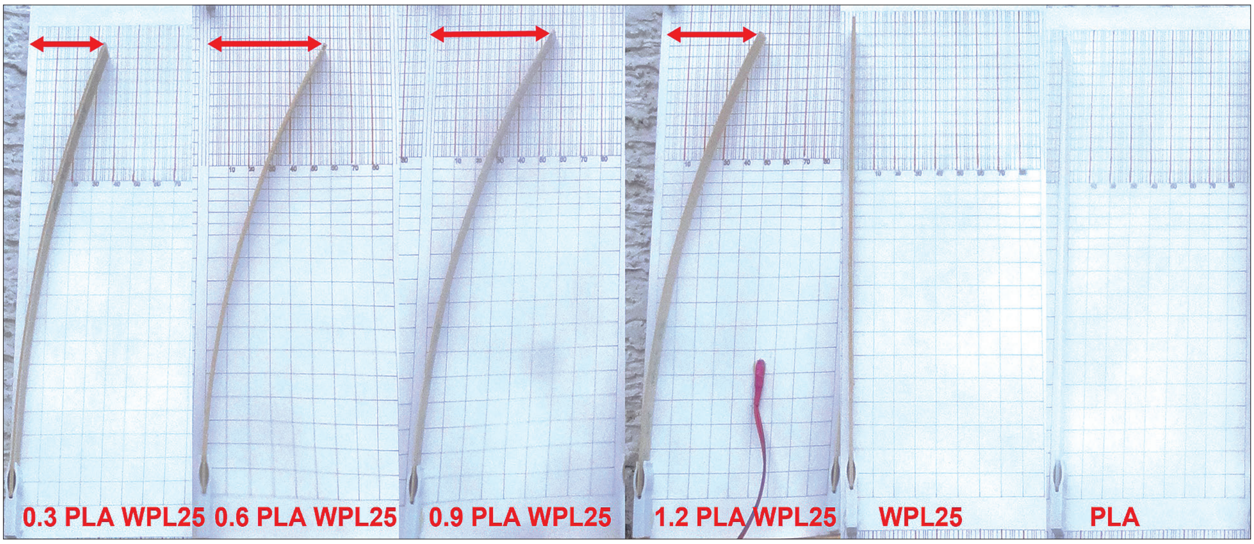
	Maksimalni odmik **1** [mm]	Relativni odmik **1** [mm]	Odmik **1** v [%]	Maksimalni odmik **2** [mm]	Relativni odmik **2** [mm]	Odmik **2** v [%]
0,3 PLA WPL25	70	52	289	40	15	60
0,6 PLA WPL25	90	60	200	60	19	46
0,9 PLA WPL25	83	56	207	63	27	75
1,2 PLA WPL25	63	41	186	54	19	54
WPL25	6	6	-	2	-1	-33
PLA	8	2	33	0	0	-

Preglednica 4. Primerjava maksimalnih in relativnih odmikov ter odmikov v % pri navlaževanju dvoslojnih aktuatorjev v **1)** klimatski komori (RZV 80 %, T = 20 °C) ter **2)** pri navlaževanju pri zunanji izpostavitvi (RZV 95 %, T = 16,2 °C, v senci, ob 7. uri zjutraj).

Table 4. Comparison of maximum and relative deflections and deflections in % when humidifying two-layer actuators in **1)** climatic chamber (80% RH, T = 20 °C) and **2)** when humidifying at external exposure (95% RH, T = 16.2 °C, in the shade, at 7 am).

nim povečanjem poroznosti (Kariž et al., 2018b) higroskopne plasti (WPL25), učinkovita strategija za zmanjšanje negativnih učinkov visoke upogibne togosti pri aktiviranju, hkrati pa poveča izmenjavo vlage in s tem odzivnost (preglednica 4).

Maksimalen odmik dvoslojnih preizkušancev pri zunanji izpostavitvi je bil zabeležen ob 6. uri zjutraj (90 % RZV, 16,3 ºC, brez direktne insolacije). Skladno z laboratorijskim navlaževanjem so imeli tudi pri zunanji izpostavitvi največji odklon aktuatorji z debelino PLA 0,6 mm (WPL25 1,2 mm, m=0,5) in 0,9 mm (WPL25 0,9 mm, m=1) (slika 5 in slika 6).



Slika 6. Maksimalni odmik preizkušancev – pri zunanji izpostavitvi ob 6. uri zjutraj (90 % RZV, 16,3 ºC) (foto: D. Krapež Tomec).
Figure 6. Maximum curvature of samples at external exposure at 6 o'clock in the morning (90% RH, 16.3 ºC) (photo: D. Krapež Tomec).

3.3 ANALIZA HITROSTI ODZIVA 4D NATISNJENIH ELEMENTOV
3.3 RESPONSE ANALYSIS OF 4D-PRINTED ELEMENTS

Dobljene meritve odklona in spremembe mase 4D natisnjenih elementov so bile dodatno analizirane z vidika dinamike sistema. Iz dobljenih meritev je bila izračunana hitrost odziva sistema na spremembo klime v okolici. To je bilo izračunano za upogibni odklon (dx), ki je bil proučevan brezdimenzijsko (E) z določanjem časovne konstante sistema (τ) (enačba 6).

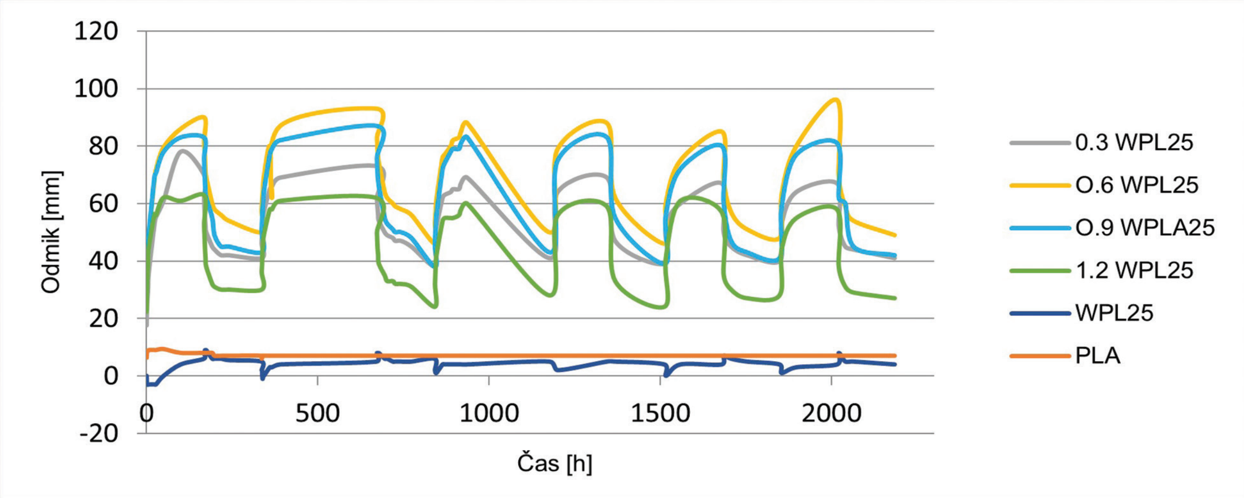
Rezultati nakazujejo, da se elementi hitreje upogibno odklonijo, kadar imajo večji delež pasivnega sloja (PLA) (preglednica 5). Petkratnik časovnega odziva (τ,Tau (h)) predstavlja čas do končnega odziva sistema. Podrobnejša analiza dinamike sorpcije je opisana v raziskavi Krapež Tomec in sod. (Krapež Tomec et al., 2021).

Preglednica 5. Delež in razmerje med pasivno in aktivno plastjo, časovni odziv (τ,*Tau* (h)) pri navlaževanju ter pri sušenju posameznih dvoslojnih aktuatorjev v laboratorijskih pogojih
Table 5. Proportion and ratio between passive and active layers, time constant *(τ, Tau (h)) during humidification and drying of individual two-layer actuator*s under laboratory conditions.

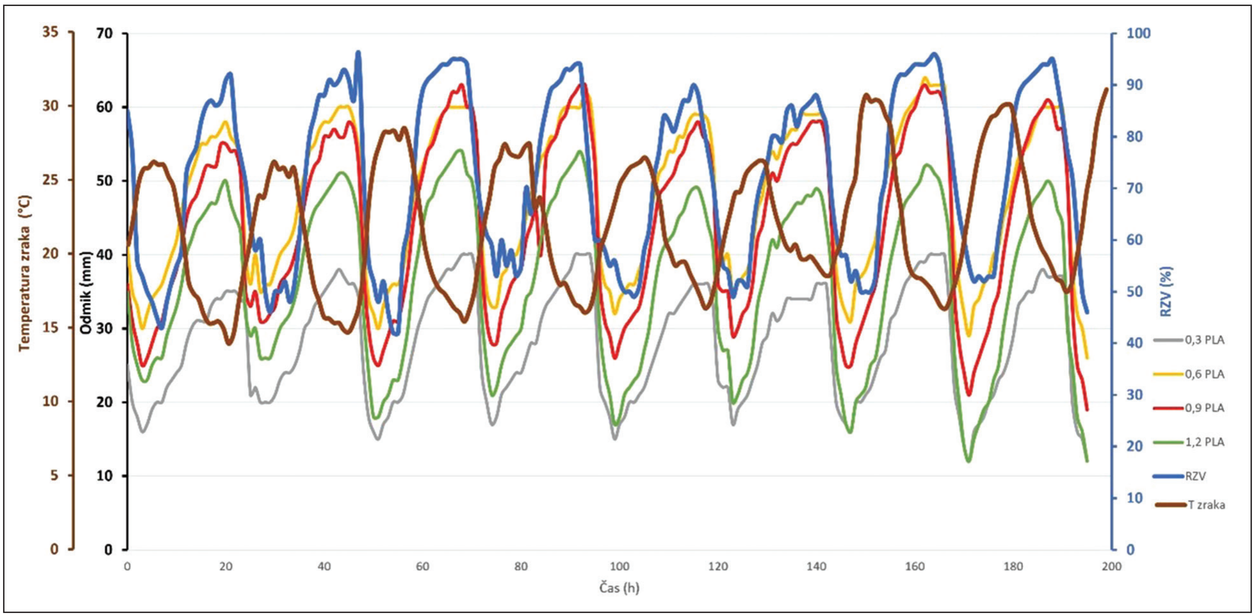
	PLA	WPL25	Razmerje	Navlaževanje	Sušenje
	t_p [mm]	t_a [mm]	m	Tau [h]	Tau [h]
0,3 PLA WPL25	0,3	1,5	0,2	20,1	10,1
0,6 PLA WPL25	0,6	1,2	0,5	20,9	9,5
0,9 PLA WPL25	0,9	0,9	1,0	15,9	9,3
1,2 PLA WPL25	1,2	0,6	2,0	7,0	4,5
WPL 25	0,0	1,0	0,0	2,5	1,6
PLA	1,0	0,0	0,0	-	-

Sliki 7 in 8 prikazujeta reverzibilnost gibanja v več zaporednih ciklih sorpcije/desorpcije. Pri izpostavitvi v solni klima komori (slika 7), je opazno zmanjšanje amplitude ukrivljenosti, ki je kot poročata Le Duigou in Castro (2015), verjetno posledica pojava poškodb, kot je razslojitev (debonding – ang.) na vmesnikih med vlakni in matrico in delitev snopov vlaken (fiber bundle division – ang.).

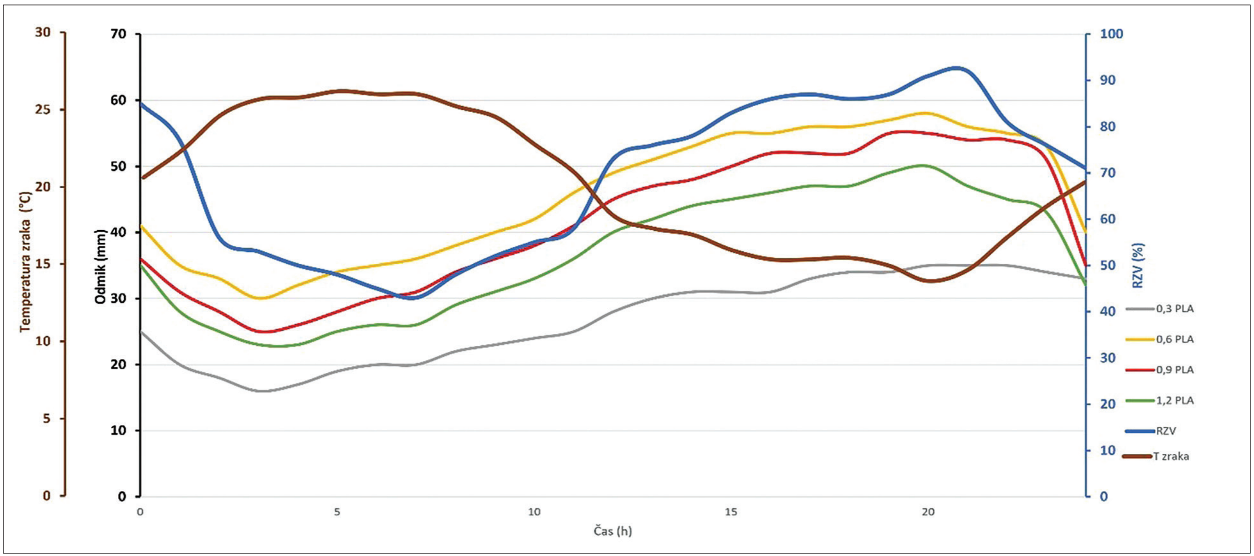
Za oceno učinkovitosti dvomaterialnih aktuatorjev so bili preizkušanci 7 dni podvrženi zunanji izpostavitvi. Ob razširitvi vplivnih vremenskih dejavnikov (temperatura, UV svetloba in relativna zračna vlažnost) in dnevno-nočnega ritma so preizkušanci prav tako dosegali sorpcijske in desorpcijske cikle (slika 8, slika 9, slika 10).



Slika 7. Odmiki posameznih dvoslojnih aktuatorjev med cikli navlaževanja in sušenja (6 ciklov) v laboratorijskih solnih klima komorah.
Figure 7. Deflection of the individual two-layer actuators during humidification and drying cycles (6 cycles) in a laboratory salt climate chambers.



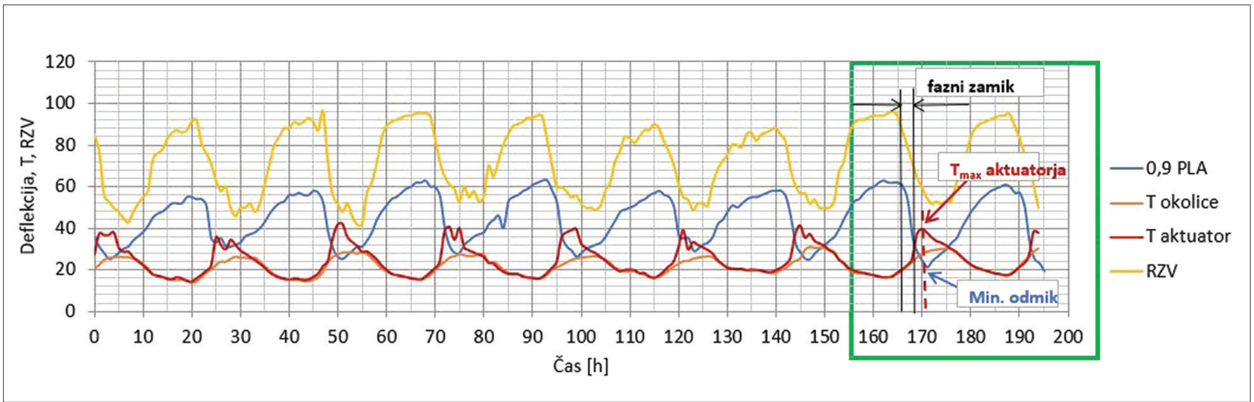
Slika 8. Odmik preizkušancev s temperaturo in RZV (zunanja izpostavitev).
Figure 8. Deflection of samples with temperature and RH (external exposure).



Slika 9. Odmik preizkušancev s temperaturo in RZV (zunanja izpostavitev) v 24 urah.
Figure 9. Deflection of samples with temperature and RH (external exposure) within 24 hours.

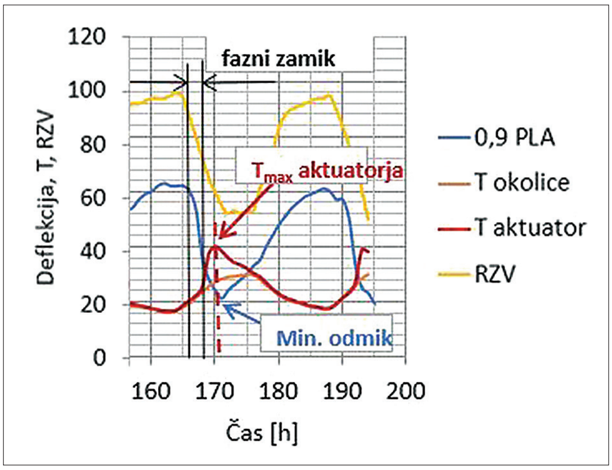
Dinamika navlaževanja in sušenja preizkušancev pri zunanji izpostavitvi izkazuje podobne značilnosti kot dinamika preizkušancev v klimatski komori (preglednica 5) – navlaževanje je približno dvakrat počasnejše od sušenja. Pri izpostavitvi preizkušancev na prostem je bil običajno čas od najmanjšega do največjega odmika 15-17 h, od največjega do najmanjšega odmika pa 6-9 h (slika 9).

Poleg amplitude in odzivnega časa sta trajnost aktuatorjev in stabilnost aktiviranja v daljšem časovnem obdobju ključna dejavnika za njihovo praktično uporabo. V pretekli raziskavi (Rüggeberg & Burgert, 2015) poročajo, da prihaja poleg velikih dnevih nihanj amplitude tudi do sezonskih nihanj. V poznopoletnih in jesenskih mesecih so opazili postopno povečanje povprečne relativne vlažnosti in postopno nižanje povprečne temperature. Te sezonske spremembe klime v zmernih geografskih pasovih povzročajo višjo vsebnost vlage v lesu in tako vplivajo na ukrivljenost dvoslojnih materialov, ki se postopoma bolj upogibajo. Kljub zaznanim površinskim poškodbam (razpoke) aktuatorjev se je amplituda aktiviranja sčasoma le nekoliko zmanjšala.



Slika 10. Odmik preizkušanca 0,9 PLA WPL25, zunanja temperatura in temperatura aktuatorja ter RZV v odvisnosti od časa zunanje izpostavitve. Zeleni pravokotnik označuje del grafa, ki je na Sliki 11 povečan.
Figure 10. Deflection of sample 0.9 PLA WPL25, external temperature, temperature of the actuator and RH as a function of the duration of external exposure. The green rectangle indicates the part of the graph that is magnified in Figure 11.

Relativna zračna vlažnost zraka je bila pričakovano najvišja pri dnevnem temperaturnem minimumu, kjer so aktuatorji dosegali tudi najvišje odklone od izhodiščne lege (slika 10, slika 11). V taki legi so aktuatorji vztrajali še krajši čas, ko je sicer relativna zračna vlažnost v okolici že pričela padati zaradi dviganja temperature zraka v okolici. Desorpcija vlage, sprva le s površine aktuatorjev, ob prisotnem vlažnostnem gradientu v bikompozitu ne povzroča takojšnjega značilnega zmanjševanja upogibnega momenta. Upadanje odklona aktuatorja se posledično zgodi z zakasnitvijo, t.j. s faznim zamikom. Slednji je povprečno znašal 2 uri, večji pa je bil pri aktuatorjih z večjim deležem aktivne komponente.



Slika 11. Fazni zamik (najvišja RZV, ki ji z zamikom sledi največji odmik aktuatorja) ter maksimalna temperatura aktuatorja, ki ji z zamikom sledi minimalni odmik aktuatorja.

Figure 11. Phase lap (maximum RH followed by the maximum actuator curvature with a delay) and the maximum actuator temperature followed by the minimum actuator deflection.

Preglednica 6. Fazni zamik za posamezen aktuator. Oznaka »m« označuje razmerje debelin aktivnega in pasivnega sloja.

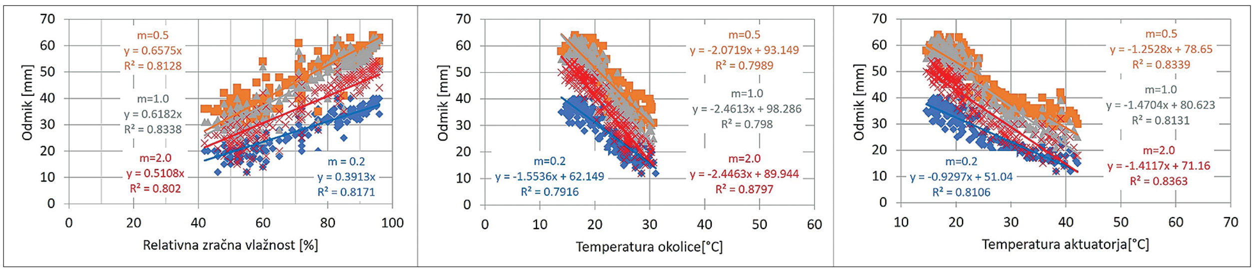
Table 6. Phase lap for an individual actuator. Label "m" indicates the thickness ratio of the active and passive layers.

Povprečni fazni zamik [h]			
0,3 PLA WPL25	0,6 PLA WPL25	0,9 PLA WPL25	1,2 PLA WPL25
m = 0,2	m = 0,5	m = 1,0	m = 2,0
2,5	2,3	1,4	1,7

Rezultati kažejo, da se intenziven prehod v sušenje dvoslojnega kompozita ter s tem manjšanje odklona zgodi ob naraščanju temperature aktuatorja nad temperaturo okolice, kot posledica direktne insolacije (UV sevanje) (slika 11). Iz aktuatorjev v okolico se v tem primeru vzpostavlja dodatni toplotni tok in inducira termodifuzijo vlage. Postopek sušenja je posledično bistveno krajši kot postopek navlaževanja aktuatorjev. Rezultati kažejo, da se sušenje aktuatorjev zaključi kmalu po doseženi največji temperaturni razliki med aktuatorjem in okolico. UV radiacija je tako zaznana kot dodatno gonilo aktuatorja.

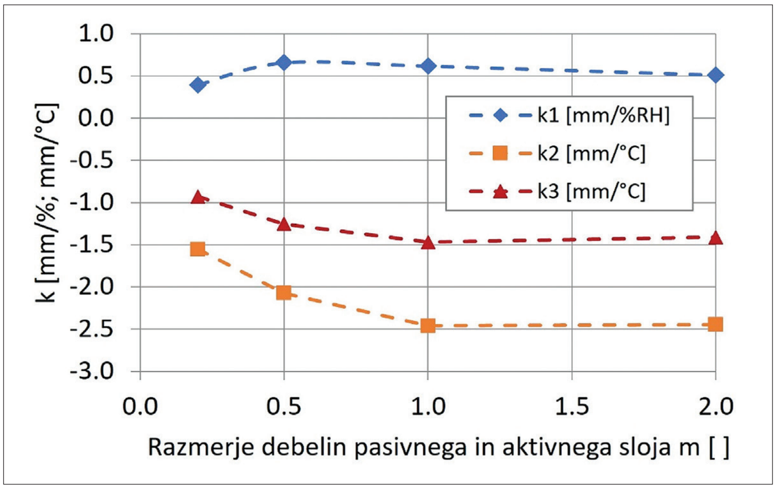
Do podobnih ugotovitev sta prišla (Rüggeberg & Burgert, 2015), namreč, da za ukrivljenost obstaja fazni zamik, vendar je zanimivo, da je ta fazni zamik manjši od zamika vsebnosti vlage v lesu (zmanjšanje z 1,6 ure na 0,6 ure), kar pomeni, da je sprememba ukrivljenosti opazna pred kakršno koli merljivo spremembo vlažnosti lesa.

Če odklone aktuatorjev primerjamo in koreliramo z relativno zračno vlažnostjo v okolici (slika 8), lahko tudi pri izpostavitvi v zunanjih pogojih preverimo njihovo dinamiko odziva. Enako primerjavo lahko izvedemo tudi glede na temperaturo aktua-



Slika 12. Koeficienti premic za odmik aktuatorja v odvisnosti od RZV / temperature okolice / temperature aktuatorja.

Figure 12. Coefficients for actuator deflection depending on RH / ambient temperature / actuator temperature.



Slika 13. Diferencialni odmik aktuatorja glede na spremembo relativne zračne vlažnosti, temperaturo okolice in temperaturo aktuatorja v odvisnosti od razmerja debelin pasivnega in aktivnega sloja v dvomaterialnem kompozitu (m).

Figure 13. Differential deflection of the actuator depending on the change in relative air humidity, ambient temperature and actuator temperature as a function of the thickness ratio of the passive and active layers in the bi-material composite (m).

torjev in okolice. Z izračunanimi smernimi koeficienti premic doseženega odmika aktuatorjev lahko izračunamo diferencialno spremembo odmika, t.j. glede na odstotek spremembe okoliške zračne vlažnosti ali pa glede na dvig temperature (slika 12).

Na odstotek spremembe RZV se najmočneje odzivata 0,6PLA WPL25 (m=0,5) in 0,9PLA WPL25 (m=1,0). Na stopinjo spremembe temperature v okolici ter na stopinjo spremembe temperature na aktuatorju pa se najmočneje odzoveta 0,9PLA WPL25 (m=1,0) in 1,2PLA WPL25 (m=2,0) (slika 13).

Na podlagi Timošenkove teorije, ki je že bila uveljavljena za higroskopske dvoslojne materiale (bilayers – ang.), mora biti debelina aktivne plasti večja od debeline pasivne plasti (Le Duigou et al., 2017). Zmanjšanje debeline pasivne plasti v povezavi s povečanjem poroznosti higroskopske (aktivne) plasti je učinkovita strategija za zmanjšanje negativnih učinkov visoke upogibne togosti na aktiviranje, hkrati pa poveča izmenjavo vlage in s tem odzivnost.

4 RAZPRAVA IN SKLEPI
4 DISCUSSION AND CONCLUSIONS

Dodatek lesa v PLA ustvari higroskopsko aktiven kompozit, ki zagotavlja deformacijo med adsorpcijo in desorpcijo v spremenljivih klimatskih pogojih. Ko je vzorec dovolj tanek, se material odzove z razbremenitvijo napetosti z elastično deformacijo, to je s krčenjem in raztezanjem materiala. Obratno lahko počasnejšo dinamiko dvoslojnih kompozitov dosegamo z večanjem dimenzij in nižanjem higroskopnosti.

Kot je bilo zapisano v raziskavah Le Duigouja in soavtorjev (2017) na higroskopske lastnosti (koeficienti sorpcije in nabrekanja) biokompozitov vpliva narava vlaken, to je njihova mikrostruktura (mikrofibrilarni kot celuloze in velikost lumna) ter biokemična sestava (pektini, hemiceluloze in lignin).

Oba parametra, največja ukrivljenost in prirast mase preizkušanca sta nedvomno povezana s higroskopnostjo lesa, ki sta opredeljena kot sposobnost izmenjave vlage z okoljem s postopki adsorpcije in desorpcije (Hoadley, 2000). Dimenzijske spremembe, ki jih povzroča prisotnost proste vode, so običajno zanemarljive, zaradi česar je količina vezane vode glavni dejavnik, ki vpliva na nabrekanje (higroekspanzijo) (Skaar, 1988).

4D tiskanje izvira iz 3D tiskanja, vendar presega 3D tiskanje. Čeprav 4D tiskanje temelji predvsem na 3D tisku in postaja novo področje dodajalnih tehnologij, predmeti niso več statični in jih je mogoče spremeniti v zapletene strukture s spreminjanjem velikosti, oblike, lastnosti in funkcionalnosti pod zunanjimi dražljaji, kar naredi 3D tiskanje živo (Chu et al., 2020).

Dvoslojni sistemi z lesnimi delci so še posebej primerni za pogon zunanjih konvertibilnih elementov, saj dnevna sprememba relativne zračne vlažnosti, ki jo poganja sončna energija, ostaja vir energije in se aktiviranje kljub vremenskim vplivom (oz. naravnemu staranju materiala) nadaljuje. Zahtev za aktiviranje ni potrebno vgraditi v material s pomočjo zapletenega proizvodnega procesa, temveč so vanj že neločljivo vključene (Rüggeberg & Burgert, 2015).

Ker je dinamika higromorfizma hitrejša pri kompozitih z manjšim deležem aktivne plasti, je potrebno pri uporabi dvomaterialnih aktuatorjev najti kompromis med hitrostjo in amplitudo odmika (Krapež Tomec et al., 2021).

Dvomaterialni aktuatorji iz PLA in les-PLA kompozita imajo potencial za izdelke s spreminjanjem oblike, ki jo povzroča higroskopnost. Študija potrjuje pomen analize različnih higromehanskih vrednosti dvomaterialnih kompozitov za razumevanje in predvidevanje njihovega higromorfizma v različnih izpostavitvah (zunanji in laboratorijski pogoji). Upoštevati moramo, da so ponovljivost, natančnost in optimizacija parametrov tiskanja in parametrov pri proizvodnji filamentov bistvenega pomena. Raziskava je pokazala, da se kombinacija PLA z les-PLA materiali lahko uporablja za 3D-natisnjene aktuatorje, ki spreminjajo obliko v izmeničnih klimatskih pogojih. Vsekakor pa so potrebne še nadaljnje raziskave za ovrednotenje dolgoročnega vedenja aktuatorjev v različnih aplikacijah.

5 POVZETEK

5 SUMMARY

Three-dimensional printing with wood-plastic composites is already well known, and the use of wood in four-dimensional (4D) printing is being increasingly explored. 4D printing is an evolving area of additive technologies where, with the right design of 3D printing and the use of appropriate materials, we can create products that change shape and form dynamic structures in response to appropriate external triggers. In 4D printing, the hygroscopicity of wood – usually understood as a disadvantage – can be used as a positive feature to design products that change shape according to changes in climatic conditions, especially humidity. The shape-memory effect can be used in artificial bioinspired actuators and has become a new field of research.

In this study, the basic mechanical properties and dimensional stability of 3D-printed samples made of two different materials were studied under changing climatic conditions. Pure PLA and wood-plastic composites, with a wood content of 25%, were used.

The samples were first conditioned in a climate with 20% RH and a temperature of 20 °C and then moistened in a climate with 80% RH and a temperature of 20 °C. It was found that the samples increased in size (swelled) and the amount of adsorbed water varied depending on the material. The WPL25 filament was made in a laboratory with a specific amount of wood. No significant dimensional changes occurred with the PLA material.

The dimensional stability test also sought to determine if the sample could be reduced to the original dimensions by drying in a climate with 20% RH and a temperature of 20 °C (equilibrium conditions). The test confirmed that the samples gradually decrease in size during drying and the results were very similar to those obtained before humidification, although they were never fully achieved. Moreover, for wood the difference between humidifying (adsorption) and drying (desorption) is normally noted, in a form of hysteresis.

The modulus of elasticity was determined for the samples on the Zwick / Roell Z005 testing machine. The results showed that pure PLA material had the best mechanical properties (highest modulus of elasticity), followed by WPL25 material. An interesting finding was that the tested samples reached the highest values after being exposed to a climate with a RH of 40%. Thus, the samples of both materials reached the lowest values after being exposed to a humid climate with a RH of 80%.

After determining the properties of each material, bimaterial samples were printed from two different materials – the principle of 4D printing with a change in climate to trigger the shape change. The combination of passive (PLA) and active (WPL25) layers in one sample to produce products with a changing shape was used.

After 3D printing, the samples were conditioned/equilibrated and then exposed in a climate chamber with a RH of 80% and a temperature of 20 °C. The curvature/deflection of the samples was measured for 168 hours (7 days). The same procedure was used when the samples were exposed to a dry climatic chamber with a RH of 20% and a temperature of 20 °C for 168 hours. The alternation between humid and dry climates was continued for several weeks.

The samples were also exposed outdoors, where the amplitude of curvature was monitored due to changes in relative humidity, temperature and UV radiation in the outdoor environment. The deflection of the bilayers was tracked every hour, for 8 days (day and night).

For both types of exposure (climatic chamber and outdoor), the maximum deflection was obtained with the combination in the ratio of 2:4 to 3:3 (PLA:WPL25) (Figure 9 and Figure 10).

The incorporation of wood into a material for 3D printing not only affects the aesthetic appearance of the finished products, but the addition of wood to the material also affects its properties. Materials that are able to respond independently to changes in the environment in this way can be controlled in their response or change by combining them with other materials and altering the shapes.

ZAHVALA
ACKNOWLEDGEMENTS

Avtorji se zahvaljujemo za finančno podporo ARRS (financiranje raziskovalnega programa št. P4-0015, „Les in lignocelulozni kompoziti" ter LesGoBio (CRP V4-2016 »Možnosti rabe lesa listavcev v slovenskem biogospodarstvu«).

LITERATURA IN VIRI
LITERATURE

Ayrilmis, N., Kariz, M., Kwon, J. H., & Kitek Kuzman, M. (2019). Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials. International Journal of Advanced Manufacturing Technology, 102(5–8), 2195–2200. DOI: https://doi.org/10.1007/s00170-019-03299-9

Balatinecz, J. J., & Park, B. D. (1997). The effects of temperature and moisture exposure on the properties of wood-fiber thermoplastic composites. Journal of Thermoplastic Composite Materials, 10(5), 476–487. DOI: https://doi.org/10.1177/089270579701000504

Chen, D., Liu, Q., Han, Z., Zhang, J., Song, H. L., Wang, K., … & Shi, Y. (2020). 4D Printing Strain Self-Sensing and Temperature Self-Sensing Integrated Sensor–Actuator with Bioinspired Gradient Gaps. Advanced Science, 7(13), 1–9. DOI: https://doi.org/10.1002/advs.202000584

Cheng, T., Thielen, M., Poppinga, S., Tahouni, Y., Wood, D., Steinberg, T., Menges, A., & Speck, T. (2021). Bio-Inspired Motion Mechanisms: Computational Design and Material Programming of Self-Adjusting 4D-Printed Wearable Systems. Advanced Science.

Cheng, T., Wood, D., Wang, X., Yuan, P. F., & Menges, A. (2021). Programming material intelligence: an additive fabrication strategy for self-shaping Biohybrid components. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 12413 LNAI, 36–45. DOI: https://doi.org/10.1007/978-3-030-64313-3_5

Chu, H., Yang, W., Sun, L., Cai, S., Yang, R., Liang, W., Yu, H., & Liu, L. (2020). 4D printing: A review on recent progresses. In Micromachines (Vol. 11, Issue 9). MDPI AG. DOI: https://doi.org/10.3390/MI11090796

Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Reichert, S., Menges, A., & Tibbits, S. (2015). 3D-Printed Wood: Programming Hygroscopic Material Transformations. 3D Printing and Additive Manufacturing, 2(3), 106–116. DOI: https://doi.org/10.1089/3dp.2015.0022

Correa, D., Poppinga, S., Mylo, M. D., Westermeier, A. S., Bruchmann, B., Menges, A., & Speck, T. (2020). 4D pine scale: Biomimetic 4D printed autonomous scale and flap structures capable of multi-phase movement. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 378(2167). DOI: https://doi.org/10.1098/rsta.2019.0445

El-Dabaa, R., & Salem, I. (2021). 4D printing of wooden actuators: encoding FDM wooden filaments for architectural responsive skins. Open House International, ahead-of-print(ahead-of-print). DOI: https://doi.org/10.1108/OHI-02-2021-0028

Erb, R. M., Sander, J. S., Grisch, R., & Studart, A. R. (2013). Self-shaping composites with programmable bioinspired microstructures. Nature Communications 2013 4:1, 4(1), 1–8. DOI: https://doi.org/10.1038/ncomms2666

Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000-2010. Progress in Polymer Science, 37(11), 1552–1596. DOI: https://doi.org/10.1016/j.progpolymsci.2012.04.003

Kariž, M., Šernek, M., & Kitek Kuzman, M. (2018a). Effect of humidity on 3d-printed specimens from wood-pla filaments.

Kariž, M., Šernek, M., Obućina, M., & Kuzman, M. K. (2018b). Effect of wood content in FDM filament on properties of 3D printed parts. Materials Today Communications, 14, 135–140. DOI: https://doi.org/10.1016/J.MTCOMM.2017.12.016

Krapež Tomec, D., Straže, A., Haider, A., & Kariž, M. (2021). Hygromorphic Response Dynamics of 3D-Printed Wood-PLA Composite Bilayer Actuators. Polymers, 13, 3209.

Le Duigou, A., & Castro, M. (2015). Moisture-induced self-shaping flax-reinforced polypropylene biocomposite actuator. Industrial Crops and Products, 71, 1–6. DOI: https://doi.org/10.1016/j.indcrop.2015.03.077

Le Duigou, A., & Castro, M. (2017). Hygromorph BioComposites: Effect of fibre content and interfacial strength on the actuation performances. Industrial Crops and Products, 99, 142–149. DOI: https://doi.org/10.1016/j.indcrop.2017.02.004

Le Duigou, A., Castro, M., Bevan, R., & Martin, N. (2016). 3D printing of wood fibre biocomposites: From mechanical to actuation functionality. Materials & Design, 96, 106–114. DOI: https://doi.org/10.1016/J.MATDES.2016.02.018

Le Duigou, A., Requile, S., Beaugrand, J., Scarpa, F., & Castro, M. (2017). Natural fibres actuators for smart bio-inspired hygromorph biocomposites. Smart Materials and Structures, 26(12), 125009. DOI: https://doi.org/10.1088/1361-665X/aa9410

Le Duigou, A., Correa, D., Ueda, M., Matsuzaki, R., & Castro, M. (2020). A review of 3D and 4D printing of natural fibre biocomposites. In Materials and Design (Vol. 194). Elsevier Ltd. DOI: https://doi.org/10.1016/j.matdes.2020.108911

Le Duigou, A., Requile, S., Beaugrand, J., Scarpa, F., & Castro, M. (2017). Natural fibres actuators for smart bio-inspired hygromorph biocomposites. Smart Materials and Structures, 26(12), 125009. DOI: https://doi.org/10.1088/1361-665X/aa9410

Manen, T. van, Janbaz, S., & Zadpoor, A. A. (2017). Programming 2D/3D shape-shifting with hobbyist 3D printers. Materials Horizons, 4(6), 1064–1069. DOI: https://doi.org/10.1039/C7MH00269F

Martikka, O., Kärki, T., & Wu, Q. L. (2018). Mechanical Properties of 3D-Printed Wood-Plastic Composites. Key Engineering Materials, 777, 499–507.

Rayate, A., & Jain, P. K. (2018). A Review on 4D Printing Material Composites and Their Applications. Materials Today: Proceedings, 5(9), 20474–20484. DOI: https://doi.org/10.1016/J.MATPR.2018.06.424

Reichert, S., Menges, A., & Correa, D. (2015). Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. Computer-Aided Design, 60, 50–69. DOI: https://doi.org/10.1016/j.cad.2014.02.010

Rüggeberg, M., & Burgert, I. (2015). Bio-Inspired Wooden Actuators for Large Scale Applications. PLOS ONE, 10(4), e0120718. DOI: https://doi.org/10.1371/JOURNAL.PONE.0120718

Ryan, K. R., Down, M. P., & Banks, C. E. (2021). Future of additive manufacturing: Overview of 4D and 3D printed smart and advanced materials and their applications. Chemical Engineering Journal, 403, 126162. DOI: https://doi.org/10.1016/J.CEJ.2020.126162

Timoshenko, S. P. (1953). The Collected Papers of Stephen P. Timoshenko. (Book, 1953) [WorldCat.org]. (n.d.). Retrieved June 10, 2021, from https://www.worldcat.org/title/collected-papers-of-stephen-p-timoshenko/oclc/472247871

Vazquez, E., Randall, C., & Duarte, J. P. (2019). Shape-changing Architectural Skins A Review on Materials, Design and Fabrication Strategies and Performance Analysis. Journal of Facade Design and Engineering, 7(2), 93–114. DOI: https://doi.org/10.7480/jfde.2019.2.3877

Zhou, J., & Sheiko, S. S. (2016). Reversible shape-shifting in polymeric materials. Journal of Polymer Science, Part B: Polymer Physics, 54(14), 1365–1380. DOI: https://doi.org/10.1002/polb.24014

LES/WOOD Vol. 70, No. 2, 71-85
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a06

WOOD ANALYSES HELPED TO DETERMINE THE LOCATION AND APPROXIMATE CONSTRUCTION PERIOD OF THE ROMAN BRIDGE OVER THE DRAVA RIVER IN ANCIENT POETOVIO (PTUJ, SLOVENIA)

ANALIZA LESA JE POTRDILA LOKACIJO IN OKVIRNO OBDOBJE POSTAVITVE RIMSKEGA MOSTU ČEZ REKO DRAVO V ANTIČNEM POETOVIJU (PTUJ V SLOVENIJI)

Andrej Gaspari[1], Katarina Čufar[2], Maks Merela[2*]

UDK 630*561.24:930.85(497.4 Ptuj)
Original scientific article / Izvirni znanstveni članek

Received / Prispelo: 5. 11. 2021
Accepted / Sprejeto: 19. 11. 2021

Abstract / Izvleček

Abstract: We present the results of a dendrochronological study and radiocarbon dating of the wooden piles of the bridge over the Drava River in Ptuj. The piles, together with stone elements (a fragment of an imperial building inscription and parts of the architectural decoration) were retrieved from the riverbed in 1913 and are now in the Regional Museum Ptuj - Ormož. Using dendrochronology, radiocarbon dating of carefully selected annual rings in the wood and calibration with the wiggle-matching method, the date of the last (outermost) annual ring on the pile was determined to be 161 ± 27 cal AD (1σ) or 160 ± 32 cal AD (2σ). Since the pile contained no sapwood, the dating approximately agrees with the date of the building inscription on the stone slab, which attributes the commission for the reconstruction or construction of the bridge to Emperor Hadrian in the last years of his reign (117-138 AD). The dating of the wood has thus confirmed that the remains examined do indeed belong to a Roman bridge, probably built or renovated during the reconstruction of the road network in the area of the colony of Poetovio under Hadrian or one of his successors.

Keywords: Roman bridge, Poetovio, Ptuj-Slovenija, archaeological wood, oak (*Quercus* sp.), dendrochronology, radiocarbon dating, wiggle-matching

Izvleček: Predstavljamo rezultate dendrokronološke raziskave in radiokarbonske datacije lesenih pilotov mostu čez Dravo na Ptuju. Piloti so bili skupaj s kamnitimi elementi (odlomek cesarskega gradbenega napisa in kamniti deli arhitekturnega okrasa) leta 1913 dvignjeni z rečnega dna in jih danes hrani Pokrajinski muzej Ptuj - Ormož. S pomočjo dendrokronologije, radiokarbonskega datiranja natančno izbranih branik lesa in kalibracije z metodo wiggle-matching, je bil na raziskanem pilotu brez ohranjene beljave določen datum zadnje branike 161 ± 27 kal. n. št. (1σ) ali 160 ± 32 kal. n. št. (2σ). Upoštevaje manjkajočo beljavo, datacija okvirno sovpada s časovno opredelitvijo rekonstruiranega gradbenega napisa s kamnite plošče, ki naročilo obnove oziroma novogradnje mostu pripisuje cesarju Hadrijanu v zadnjih letih njegove vladavine (117-138 n. št.) al. Datacija lesa je tako potrdila, da raziskani ostanki res pripadajo rimskemu mostu, domnevno postavljenem oziroma obnovljenem ob prenovi cestnega omrežja na območju kolonije Poetovio pod cesarjem Hadrijanom ali enim od njegovih naslednikov.

Ključne besede: rimski most, Poetovio, Ptuj Slovenija, arheološki les, hrast (*Quercus* sp.), dendrokronologija, radiokarbonsko datiranje, wiggle-matching

1 INTRODUCTION
1 UVOD

The Regional Museum Ptuj - Ormož (PMPO) in Slovenia holds in its collections a group of 8 wooden piles and several stone fragments which, according to museum documentation, allegedly belong to the remains of a Roman bridge over the Drava River in Ptuj, ancient Poetovio. The epigraphy of Hadrian's building inscription and other architectural elements of the alleged bridgehead as well as urbanistic-historical aspects of the connection between the bridge and the centre of the Roman colony on the left bank of the Drava have recently been elaborated by Zsolt Mráv (Mráv, 2002, 2003), whose study provides an overview of documented Roman bridges in Pannonia. Findings

[1] Univerza v Ljubljani, Filozofska fakulteta, Oddelek za arheologijo, Zavetiška ulica 5, 1000 Ljubljana, SLO
[2] Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za lesarstvo, Jamnikarjeva 101, 1000 Ljubljana, SLO
* e-mail: maks.merela@bf.uni-lj.si

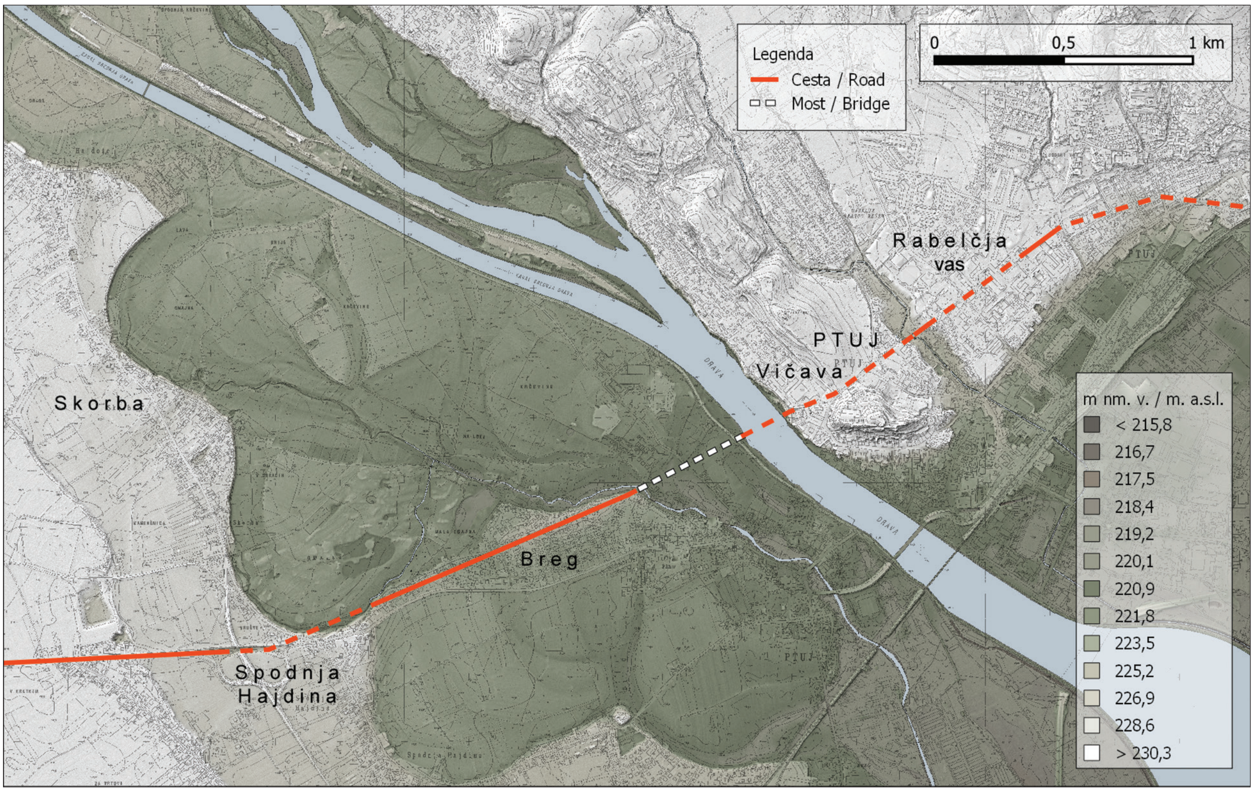


Figure 1. Lidar image of the wider surroundings of present-day Ptuj, with the clearly recognizable Pleistocene terraces of the Drava River and the southern slopes of the Slovenske gorice hills. The course of the Roman itinerary road (red) and the bridge (white) are marked. The reconstructed course of the bridge leads over the floodplain between the present right bank of the river and Studenčnica Stream (made by: Blaž Kumer).

Slika 1. Lidarski posnetek širšega območja današnjega Ptuja z jasno prepoznavnimi pleistocenskimi terasami reke Drave in južnimi obronki Slovenskih goric. Označena sta potek rimske itinerarske ceste (rdeče) in mostu (belo). Rekonstruiran potek mostu prečka poplavno ravnino med današnjim desnim bregom reke in potokom Studenčnica (izdelal: Blaž Kumer).

and assumptions about the structural characteristics and topography of the bridge in Ptuj (Figure 1) are synthesized in an article by the co-author of the present paper (Gaspari, 2001), and Andrej Preložnik made an important contribution to the history of the research supplementing the information on the observations at the beginning of the 19th century (Preložnik, 2020).

The earliest references to stone elements and wooden piles in connection with the Roman bridge over the Drava in Ptuj come from observations made by the local resident Leopold Schickelgruber in 1798 (Skrabar, 1914). Beneath the water surface near the right bank, in the company of friends, he observed stone blocks, mostly of "white and black marble", allegorical representations, and massive wooden piles standing in a row, from which he inferred the existence of a colossal building. The report of Ritter von Rittersberg (Ritter von Rittersberg, 1818) probably refers to the same site. The blocks are said to occur in an area of about 19 x 19 m, at a depth of a little more than 2.5 m. Twenty years before his visit, the Drava River flowed through the site, which, according to the accounts of boatmen and fishermen, created a strong whirlpool at the spot. Locals observed the stones from anchored boats in the water, the highest of which was 2.4 m below the surface. According to Klein, a local brewer, several stones bore inscriptions in metal letters (Ritter von Rittersberg, 1818; Preložnik, 2020).

The remains of the Roman bridge on the Celeia - Poetovio road, which are said to be visible near the right bank of the river above the Dominican monastery, were again reported by Professor Franc Ferk in 1893. The worked stone blocks, visible again in 1896, were attempted to be lifted by the Museum Society, but they proved to be too heavy. The 1903 high water level caused the blocks to be covered by debris again (Skrabar, 1914; Gaspari, 2001), although the remains were again exposed by the extremely low water level in January 1912, when the tops of vertically driven wooden piles and a mass of smaller and larger worked stone blocks were exposed in a small bay on the right bank of the Drava, just opposite the command building of the old barracks complex (now the building of the Historical Archive and the Slovenian Institute for the Protection of Cultural Heritage) and 580 m upstream of the old Ptuj bridge at a depth of 2-3 m (Figure 2: site 1). The recovery of the remains, which took place in two campaigns in the summer of 1912 and in March 1913, was carried out by military engineers under the direction of the jurist, conservator and archaeologist Viktor Skrabar.

Published reports of the find mention a cracked part of a marble column, several limestone blocks with grooves for iron clamps, part of a massive relief slab with an ornate border and the remains of a representation of a bundle of lightning bolts in the claws of an eagle, an attribute of Jupiter (see Skrabar, 1914; Mráv, 2002), a part of a white marble slab with the remains of a four-line building inscription (AIJ 361) and some "charred" wooden piles.[1] Among the latter, Skrabar mentions a 3 m long oak pile of square cross-section with 25 cm long sides (Skrabar, 1914).

The first three lines of the building inscription bear part of the imperial titulature, while the fourth bears a remnant of the word *[p]onte[m]*, on the basis of which Skrabar had already established the undoubted connection of the epigraphic find with the Drava Bridge (Skrabar, 1914). Based on the size of the letters and the arrangement of the titulature, he considered it likely the emperors between Hadrian (117–138 AD) and Septimius Severus (193–211 AD) were the patrons. In view of the correspondence of the preserved titulature in the third line with the corresponding parts of the inscriptions on Hadrian's three milestones on the Norican and Pannonian part of the Amber Road, it is generally assumed that the reconstruction or even the new construction of the Drava Bridge took place at about the same time or even in connection with the reconstruction of the above-mentioned road section between 10 December 131 and 9 December 132 (Skrabar, 1914; Mráv, 2002, 2003).

According to Zsolt Mráv (Mráv, 2002), the reconstructed inscription, carved on the original slab, about 5 m long, reads as follows: *[I]mp(erator) C[aes(ar) divi Traiani Parthici fil(ius)] / divi [Nervae nep(os) Traianus Hadrianus Aug(ustus)] / pon[t(ifex) max(imus) trib(unicia) pot(estate) XVI co(n)s(ul) III p(ater) p(atriae) proco(n)s(ul)] / [p]onte[m ---].*

Skrabar also excavated in the nearby meadow in the direction of the presumed course of the bridge, belonging to Mrs Kreuzwirt (Figure 2: site 2), where he found at a depth of 2 m the remains of charred piles similar to those in the channel along the right bank. He considered that they either belonged to a bridge on wooden piers (German: Jochbrücke), which was replaced by a stone bridge, or that they had served as part of the foundation for the construction of a bridge with stone piers. No remains were observed during a boat survey of the riverbed in February 1914, leading Skrabar to conclude that the site in the riverbed represented the Roman left bank and that the remains themselves represented the remains of the northern bridgehead with exposed cult images and an imperial building inscription (Skrabar, 1914). The size of the complex of ruins on the present right bank, reported by Rittersberg in 1818, could correspond to the dimensions of a bridgehead with a single-arched structure (on the dimensions of monumental arches at the entrances to bridges (see Roth Congès, 2011); it is also possible that another building stood right next to the entrance to the bridge. According to Mráv, the monumental gate with an arch bearing the imperial inscription marked the sacred boundary of the narrower urban space (*pomerium*) and thus functioned both as a triumphal arch and *arcus pomeriale*. For the passage of the gate, users paid a fee (*portorium*), which went into the

1 Most likely, the blackened condition of the piles can be explained by the environmental conditions in the river sediments. It is also possible that Skrabar's observation refers to some deliberately burnt piles to ensure their longevity in water, but among the material preserved in the PMPO there are no such piles.

city treasury and represented a significant and reliable source of revenue, as it was a river crossing to which there was no alternative on the Amber Road (Mráv, 2002). The spatial connection between the town centre of Poetovio and the bridge (and thus the course of the itinerary road) is undeniable, with the main connection to the northern bridgehead most likely lying to the east of the forum area. The demolished walls of Roman buildings on the edge of the Vičava terrace (Figure 2, 3) and the finds of washed-out marble blocks, stone sculptures and gravestones in the riverbed, even far from the left bank (Skrabar, 1914; Horvat et al., 2003), indicate that the Lower Terrace with the forum of Poetovio and the early medieval "Lower Town" extended southwards over a good width of the present-day riverbed of the Drava (Curk 1999; Lubšina Tušek & Erič, 2012). It is assumed that the river washed away two thirds of the town centre on the left bank (Mikl-Curk & Tušek, 1985).

The approximate location of the southern bridgehead on the ancient right bank of the Drava, which in this section may have been in roughly the same position as the present Studenčnica stream, was thought to be east of the Švabov mlin (mill). A block of masonry found 60 m downstream of the mentioned mill in the stream bed was cautiously interpreted by Skrabar as the remains of an eroded bridge abutment (Figure 2: site 4). He noted that the location of the block was opposite the meadow belonging to Mrs. Kreuzwirt (Skrabar, 1914). The approximate location of the right bridgehead

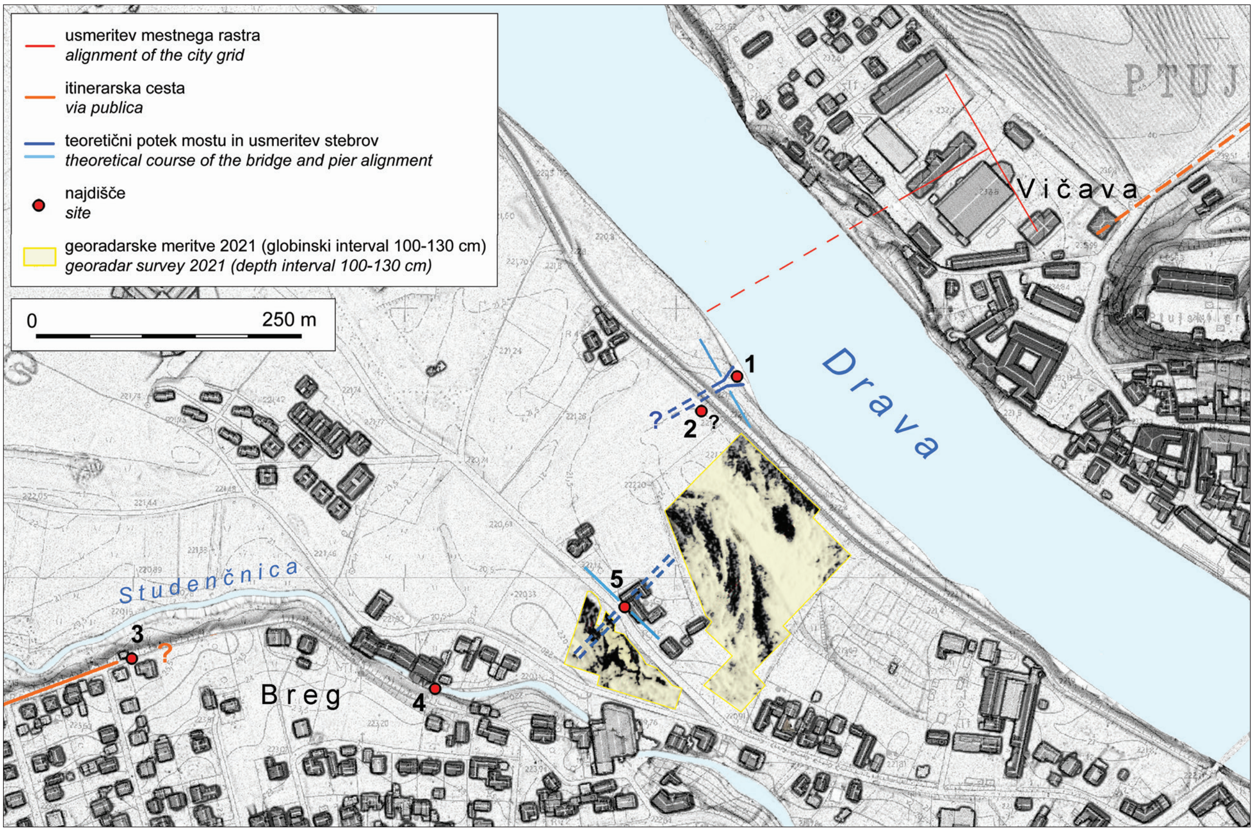


Figure 2. Ptuj: (1) presumed northern bridgehead (1913); (2) approximate location of piles on the meadow belonging to Mrs. Kreuzwirt (1913); (3) place where the itinerary road disappears from the terrace; (4) block of wall in the Studenčnica riverbed; (5) group of piles (1975) (made by: Andrej Gaspari); the results of the georadar survey: Branko Mušič, courtesy of Primož Stergar).

Slika 2. Ptuj. Drava in poplavno območje med Zgornjim Bregom in Vičavo z obravnavanimi najdišči. (1) domnevna severna mostna glava (1913); (2) približna lokacija pilotov na travniku gospodične Kreuzwirt (1913); (3) mesto, kjer itinerarska cesta izgine s terase; (4) blok zidu v strugi Studenčnice; (5) skupina pilotov (1975) (izdelal: Andrej Gaspari); rezultati georadarskih meritev: Branko Mušič, z dovoljenjem Primoža Stergarja).

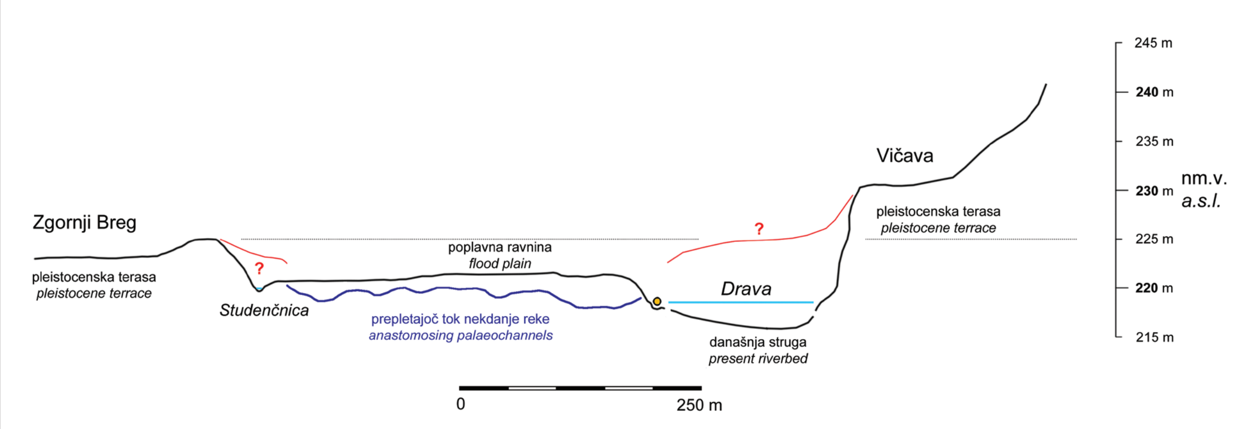


Figure 3. Ptuj. Schematized cross-section of the area in the presumed axis of the Roman bridge between Vičava and Zgornji Breg. The reconstructed parts of ancient terraces and banks (red); presumed elevations of the ancient riverbed with anastomosing channels (dark blue); the present level of the river (light blue); the location of the stone remains and piles (yellow dot) of the presumed northern bridgehead in the Figure 2: site 1; the elevations are exaggerated in comparison with the longitudinal extent of the cross-section (made by: Andrej Gaspari).

Slika 3. Ptuj. Shematizirani presek območja v domnevni osi rimskega mostu med Vičavo in Zgornjim Bregom. Rekonstuirani deli antičnih teras in bregov (rdeče); domnevne višine antične struge s prepletajočimi tokovi; lokacija kamnitih ostankov in pilotov (rumena pika) na Sliki 2: mesto 1. Višine so pretirane v primerjavi z dolžinskim obsegom preseka (izdelal: Andrej Gaspari).

is confirmed by the section of the road identified in Zgornji Breg, which runs along the raised northern edge of the terrace almost to the end of the upper part of the flat ridge, where it turns east into the floodplain. The continuation of the road disappears at the edge of the terrace (Figure 2: site 3). The access or even entrance to the bridge itself is associated with the 3rd century altars dedicated to Dravus Avgustus (AIJ 267) found in the eastern part of Zgornji Breg (Skrabar, 1914; Horvat et al., 2003).

Assuming that the remains on the right bank of the present river-bed do indeed represent the northern bridgehead, and that the southern one was somewhere to the north-east of the said part of the terrace-ridge of Zgornji Breg, and that the bridge crossed the narrowest part of the floodplain in a straight line perpendicular to the main riverbed, we indeed obtain the axis of the bridge (Figure 2), which corresponds almost entirely to the documented grid of the street network of the Poetovio city centre at Vičava (Mikl-Curk & Tušek, 1985); for recent research and discoveries of a possible module, see Janežič and Lazar (2015) and Lazar (2013). This would mean that urban planning was guided by the course of the riverbed at that time, whose axis (NW-SE) had a slightly smaller deviation from the north than today (Figure 2). Because of the uncertainty about the width of the floodplain and the length of this bridge, we can only estimate it to be about 350 to 400 m. It should be noted again that these assumptions are based on the premise of a straight axis of the bridge perpendicular to the river bed, but this is not the only possible solution given the presumably braided river-channel with islands and dunes.[2] After all, after a straight crossing of the main riverbed on such an island or a major dune, the bridge could change its direction by diverting the axis downstream, as is the case with Roman bridge over the Danube in Aquincum; see (Mráv, 2002).

In the middle of the floodplain south of the presumed axis of the bridge in question, a group of 8 piles with a round cross-section was discovered along the Mlinska cesta (Figure 2: site 5) during the

2 The course of the palaeochannels and point bars of anastomosing river south of the reconstructed bridge axes was identified by geophysical surveys and test excavations carried out by Primož Stergar, an independent contractor, and the company Gearh in 2021.

control of the canalization excavation to the Recreation and Tourism Centre in 1975. The head of the archaeological control, Blagoj Jevremov, conditionally assigned them to the bridge over the Drava in his field report (Jevremov, 1975). Contrary to the statement in our earlier study that the remains found most probably do not belong to the construction of the ancient bridge (Gaspari, 2001), after re-examining the field report we believe that this cannot be ruled out. The described and sketched arrangement of the piles suggests that they are the remains of an elongated group, about 5 m long, with the longer axis pointing in the NW-SE direction, indicating the direction of flow and identical or very similar to the alignment of the present riverbed. The piles are not arranged in an orthogonal grid and do not have the usual square or octagonal hewn sides, but the extreme north-western three form a characteristic triangular breakwater. If they are indeed the remains of a pier, it probably belonged to another Roman bridge, either an older or a younger one.

From the surviving remains and Skrabar's description of the site on the present right bank of the Drava, it appears that the construction of the northern bridgehead was a massive stone structure on a wooden foundation, consisting of vertically driven oak piles and a horizontal beam framework filled with stones. Given the importance of the Ptuj bridgehead and the assumed width and strength of the river, we might expect the piers of the bridge in the riverbed itself to have been constructed in a similar manner. Bridges with wooden piers required frequent repairs due to increased exposure to the damage at the contact between water and air, as well as by ice and floating wood. After the middle of the 1st century AD, they were replaced on a larger scale at important crossings in the northern provinces by structures with stone piers on a wooden foundation with a pentagonal plan and with a wooden superstructure (Figure 4; Cüppers, 1969; Mensching, 1981; Goudswaard, Kroes & Van der Beek, 2001). The very massive piers of the bridge over the Drava at Mursa (Osijek, Croatia), probably built at the end of the 1st or in the first half of the 2nd century and later renewed several times, were also built on a foundation of densely driven piles with tips, fitted with iron shoes. Six piers, originally more than 7 m high, have been reported, tapering in steps towards the top. The distances between the piers in the middle of the river (about 24 and 20 m) were greater than those closer to the bank, which distinguishes the bridge from most bridges of mixed construction in the northern provinces of the empire, which usually have equal distances between the piers. Judging by the monumental dimensions of the piers, fences and slabs, the structure over the Drava at Mursa is one of the few Roman bridges with a stone superstructure outside the Mediterranean (Gardaš, 2003).

In assessing the type of the construction to which the Roman bridge in Ptuj belonged, it should be emphasized that no stone remains are mentioned either from the location of the piles in the meadow slightly west of the present right bank (Skrabar, 1914; Figure 2: site 2), or from the vicinity

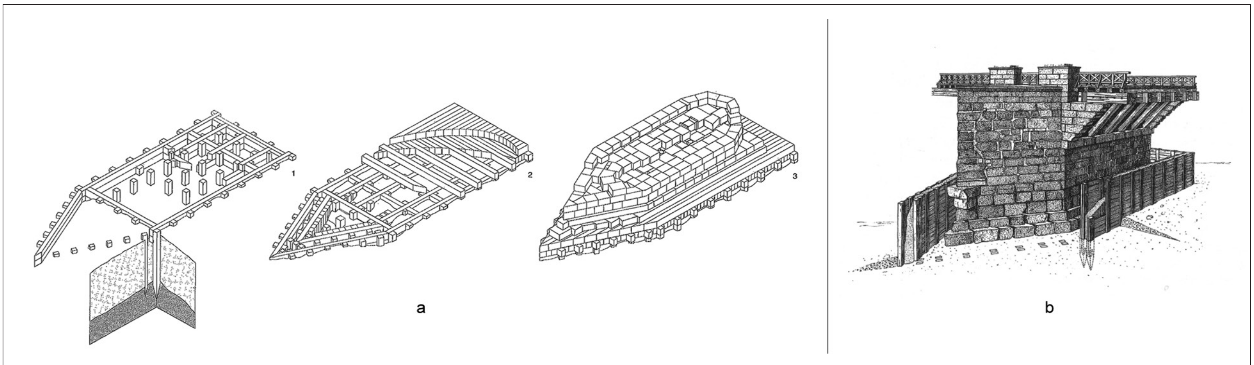


Figure 4. Structural analysis of the Late Roman bridge over the Meuse in Cuijk (a); reconstruction of the bridge pier over the Moselle in Trier (b) (a after Goudswaard, Kroes & Van der Beek, 2001; b after Cüppers, 1969).
Slika 4. Analiza konstrukcije poznorimskega mostu čez reko Meuse v Cuijku (a); rekonstrukcija stebra mostu čez reko Mozelo v Trierju (b) (a po Goudswaard, Kroes & Van der Beek, 2001; b po Cüppers, 1969).

of the piles discovered in 1975 (see Footnote 2; Figure 2: site 5). The stone blocks might otherwise have been washed away because they were more exposed to the rising water during storms, perhaps also because of the less massive structure of the piers in the middle part of the watercourse compared to the bridgeheads. However, the absence of stone remains in the central part of the former riverbed also supports the assumption of a bridge structure with piers built entirely of wood. These usually consisted of three parallel types of vertical piles, but a more durable box construction (caisson) of bridges of the so-called transitional type, consisting of horizontal beams and internally reinforced with vertically driven piles; see (Dumont, 2011; Dumont & Bonnamour, 2011) cannot be excluded either. At the same time, we reiterate that the remains found at the narrowest part of the floodplain probably belong to the construction of an older or younger bridge with a different alignment, a question that can only be answered by targeted research or accidental discoveries.

According to the museum curators, the remains of 8 wooden piles came from Skrabar's intervention in 1913. The wood remained undated and for a long time there was no confirmation that the piles came from a Roman bridge. In January 1999, Tom Levanič, then an employee of the Department of Wood Science and Technology at the Biotechnical Faculty of the University of Ljubljana, in collaboration with Andrej Gaspari and curator Ivan Žižek, carried out sampling for wood identification and dendrochronological analyses. The analyses revealed that all the piles were made of oak, while the dendrochronological analysis did not lead to their absolute dating for objective reasons, and it was not possible to confirm whether they belonged to the Roman bridge. The aim of the current study is to re-examine the wooden piles using dendrochronology, radiocarbon dating and wiggle-matching analysis.

2 MATERIALS AND METHODS
2 MATERIAL IN METODE

The remains of 8 piles underwent re-examination in early 2019. In collaboration with the museum's curator, Aleksandra Nestorović, we examined the remains of all eight piles in the museum's depot on 20 February 2019. We focused on their suitability for dendrochronological dating, which depends on the number of tree-rings and available reference chronologies. The remains were labelled

Figure 5. Wooden piles from the collection of the Regional Museum Ptuj - Ormož were cut at the widest part of the pile during sampling for dendrochronological and radiocarbon analysis in 1999 (photo: Andrej Gaspari)
Slika 5. Leseni piloti v hrambi Pokrajinskega muzeja Ptuj - Ormož, ki so bili prežagani ob odvzemu vzorcev za dendrokronološko analizo na najširšem delu pilota v letu 1999 (foto: Andrej Gaspari)

with codes RMO-01 through RMO-09, which were assigned during the 1999 study (Figure 5).

An approximately 3 cm thick section of each pile was available for analyses. Surface preparation of the samples was carried out in the Department of Wood Science & Technology, Biotechnical Faculty, University of Ljubljana. The surface of the section was ground smooth so that the cell structure could be examined under a stereomicroscope at up to 100x magnification and wood identification could be verified. The width of the annual rings was measured for all samples using a RINNTECH LinTab TM5 measuring stage and TsapWin 4.81 software. The tree ring series of the samples were cross-dated with each other and with the existing reference chronologies of the Department of Wood Science (Čufar et al., 2019).

In addition, two piles, PMO-08 and PMO-09, with the largest number of rings were studied in detail and finally PMO-09 was selected to sample exactly defined tree rings for radiocarbon dating (Figures 6, 7). After measuring the tree rings in

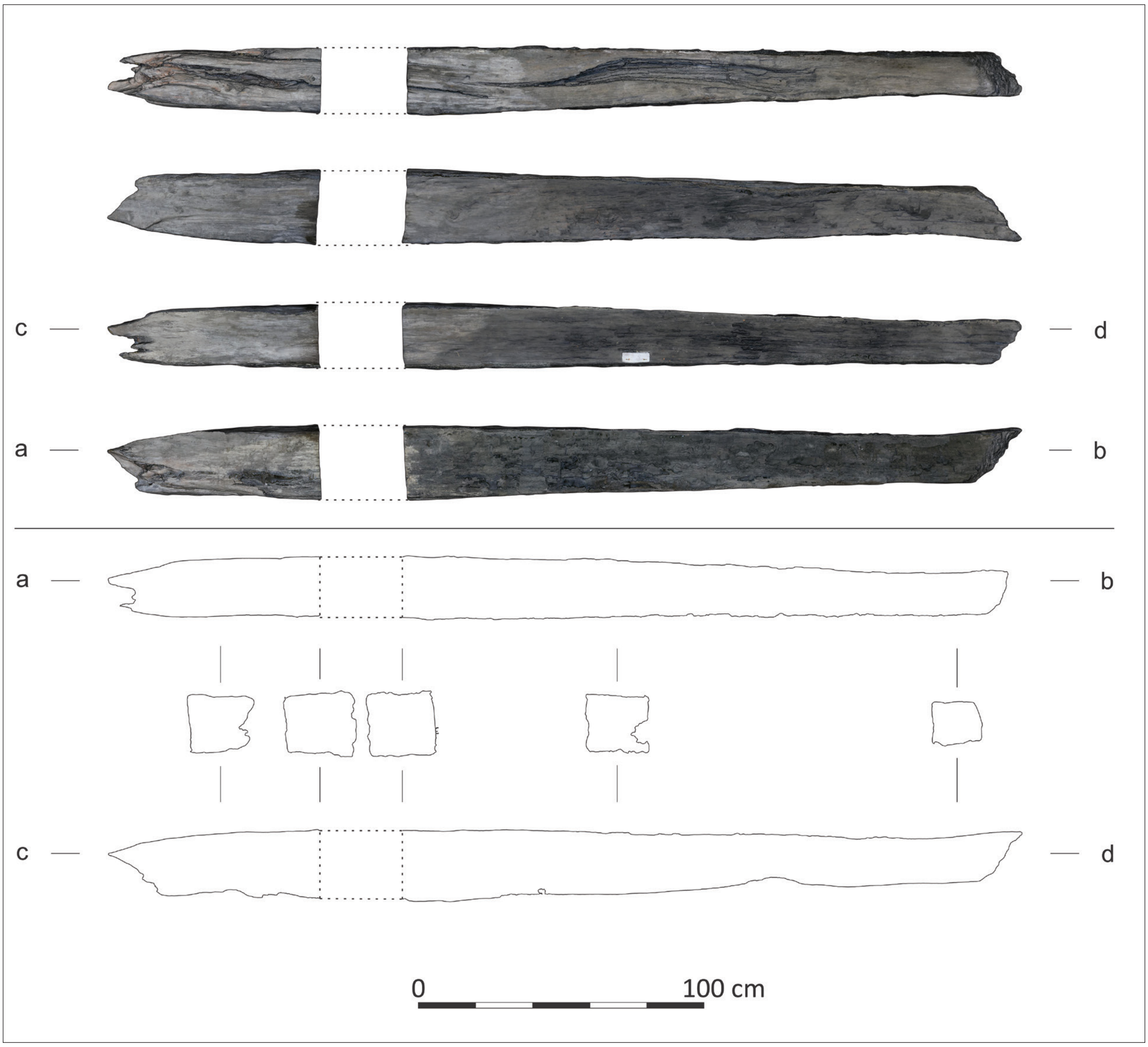


Figure 6. The oak pile RMO-09 with the highest number of annual rings was selected for dendrochronological and radiocarbon analysis.
Slika 6. Pilot iz lesa hrasta RMO-09, ki je imel največje število branik in je bil izbran za dendrokronološko in radiokarbonsko analizo.

Figure 7. Cross-section of sample RMO-09; marked longest measured timeline (red line) and sampling spots for radiocarbon dating (blue frame).
Slika 7. Prečni prerez vzorca RMO-09: označena smer meritve najdaljše časovne serije (rdeča črta) in označena mesta odvzema vzorcev za radiokarbonsko datacijo (moder okvir).

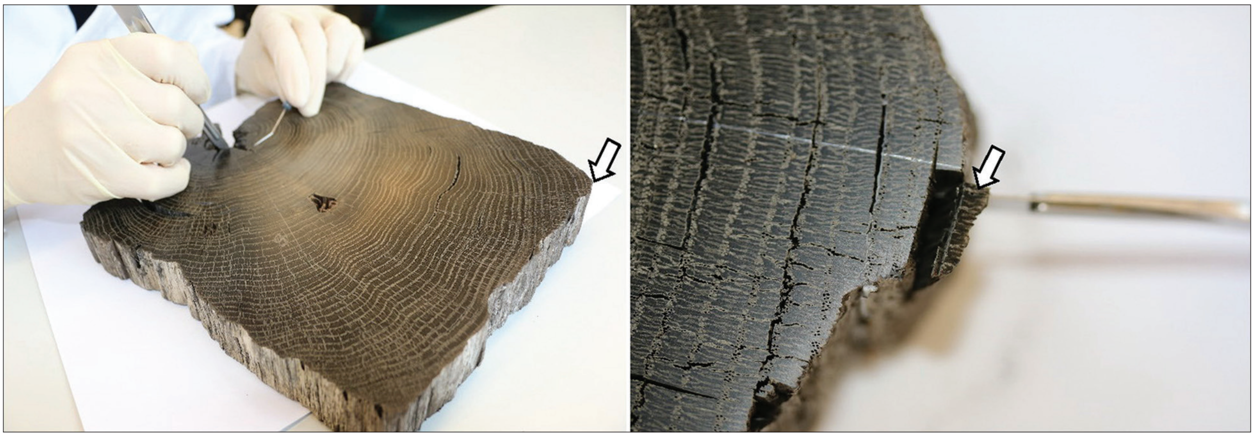


Figure 8. Sample RMO-09: Isolation of annual rings for radiocarbon analysis near the pith (left) and the youngest (outer) annual ring (arrow on both images).
Slika 8. Odrezek RMO-09; izolacija branik za radiokarbonsko analizo ob strženu (levo) in odvzem najmlajše (zunanje) branike (puščica na obeh slikah).

RMO-09, we collected two subsamples for radiocarbon dating and calibration by wiggle matching (Čufar et al., 2010). The RMO-09-P subsample contained two tree rings near the pith, and the RMO-09-B subsample consisted of the last (outermost and youngest) tree ring (Figure 8). Finally, the dry samples were sent to Beta Analytic, Miami, Florida, USA, for radiocarbon dating using the Accelerated Mass Spectrometry (AMS) method, which allows radiocarbon dating of small quantities of wood. When Beta Analytic provided the radiocarbon dates for the two samples, calibration was performed with the Wiggle matching method using the OxCal v4.4.4 program (Ramsey, 2021) and the IntCal 20 atmospheric curve (Reimer et al., 2020).

3 RESULTS AND DISCUSSION
3 REZULTATI IN DISKUSIJA

We confirmed that all piles were oak (*Quercus* sp.), possibly pedunculate oak (*Quercus robur*) or sessile oak (*Quercus petraea*), which cannot be distinguished by wood anatomy alone (Merela & Čufar, 2013). The piles did not contain sapwood.

The remains of the smaller piles RMO-01 through RMO-07, ranging in length from 105 to 233 cm, appeared to be composed primarily of low-grade, rectangular-hewn logs, ranging from 9 x 10 to 14 x 14 cm (Gaspari, 2001). These piles contained between 19 and 31 growth rings, which is considered too low for successful tree-ring analysis (Čufar et al., 2015).

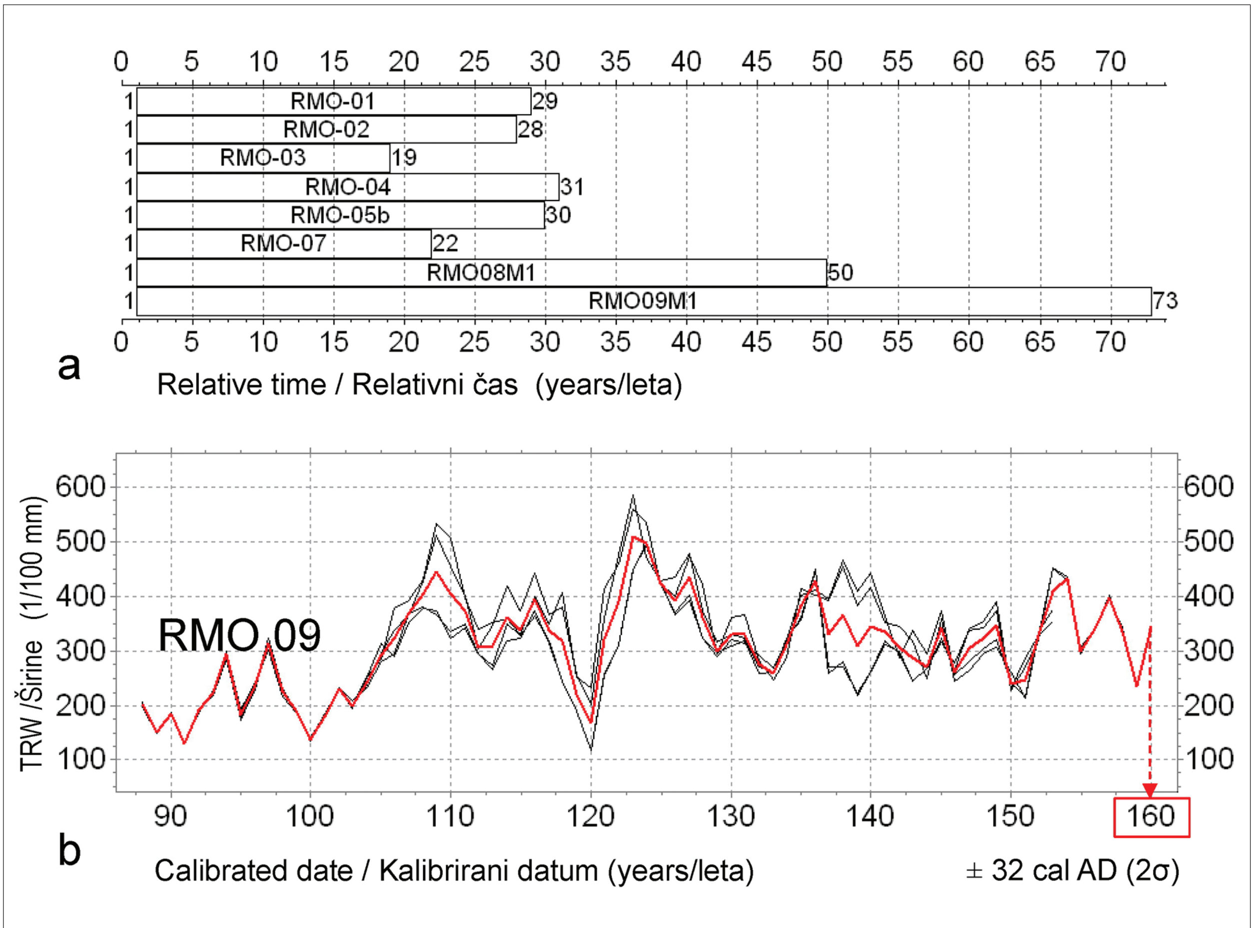


Figure 9. Graphical representation of (a) number of tree rings in piles in relative time and (b) tree-ring series of RMO-09 measured along multiple radii (black) and average of all (red) with the date of the last ring obtained by wiggle-matching.

Slika 9. Grafični prikaz (a) števila branik merjenih pilotov v relativnem času in (b) zaporedij širin branik vzorca RMO-09, merjenih vzdolž različnih radijev (črno), povprečje vseh meritev (rdeče) ter datum zadnje branike, ugotovljen z metodo wiggle-matching.

The largest rectangular pile, RMO-09 (L. 320 cm; W. 20 x 25 cm) (Figure 6), with 73 preserved annual rings, is almost certainly identical to the pile in Skrabar's description. Its thickness tapers fairly evenly from one preserved end to the other, but the tip is broken off. The other pile RMO-08 (L. 166 cm; W. 23 x 15 cm) (Figure 5) with 50 tree rings preserved had a tip with a round cross-section and showed no traces of rust or nails, which would indicate the use of possible iron shoes. The tip was driven towards the root, while examination of the tips of smaller piles shows that they were aligned with the crown downwards when driven into the ground. Neither sample had preserved sapwood or bark.

Nevertheless, analyses of tree-ring widths along several radii were performed on all samples and averaged for further cross-dating (Figure 9). We were not able to cross-date the tree-ring series of the different samples. Therefore, we were not able to confirm whether the studied piles belong to the same construction phase, i.e. whether they were used for construction at the same time. The attempt to date the mean tree ring series of piles RMO-08 and RMO-09 using different reference chronologies was not successful.

When calibrating the results of radiocarbon dating (Table 1) using the wiggle-matching method, OxCal v4.4.4 programme (Ramsey, 2021), and IntCal 20 atmospheric curve (Reimer et al., 2020), we had to note that the "gap" between the two radiocarbon dates was 70 years, which is based on the distance between the numbers of the "centre rings" of the two radiocarbon samples on the tree-ring sequence (Figures 9, 10).

The result for the calibrated date of the last tree ring on sample PTRO_P9_VZ_B, i.e. tree ring number 73, is 161 ± 27 cal AD (1σ) or 160 ± 32 cal AD (2σ) (Figure 11). To estimate the actual age of the pile, i.e., the time when the tree was felled for the pile, we must note that the pile did not contain sapwood.

The estimated date of tree felling confirms that the pile was part of a Roman structure possibly built or rebuilt at the end of the reign of Emperor Hadrian (117-138 AD) or one of his successors, as archaeologists suspect from the inscription on the stone slab found at the bottom of the river at the place where Roman engineers had driven the discussed piles into the riverbed.

The results presented above confirm that it is useful to analyse wood from Roman buildings, that it is necessary to analyse all the available material

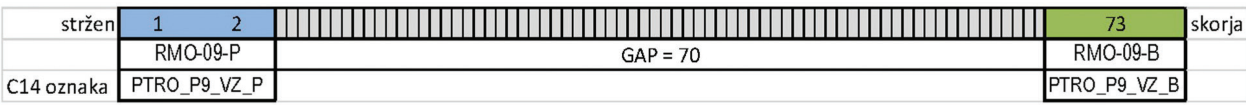


Figure 10. Schematic representation of sampling for radiocarbon dating: position of samples PTRO_P9_VZ_P (1st and 2nd annual rings near the pith) and PTRO_P9_VZ_B (73rd annual ring on the outside of the disk, which contained no sapwood or bark); the GAP between samples is 70 annual rings, which means that the sample near the pith is 70 years older than the outer one.
Slika 10. Shematski prikaz protokola odvzema vzorcev za radiokarbonsko datacijo: lega vzorca PTRO_P9_VZ_P (1. in 2. branika ob strženu), ter PTRO_P9_VZ_B (73. branika na zunanji strani odrezka, (brez beljave in brez skorje); časovna razdalja (GAP) med vzorci je 70 branik, kar pomeni, da je vzorec ob strženu 70 let starejši od zunanjega vzorca.

Table 1. Uncalibrated radiocarbon dates of the two samples analysed by Beta Analytic, Miami, Florida, USA
Preglednica 1. Nekalibrirani radiokarbonski datumi dveh vzorcev, ki sta bila analizirana v Beta Analytic, Miami, Florida, ZDA

Sample code	Code Beta Analytic	Centre ring – in relative time	14C date
Šifra vzorca	Šifra laboratorija Beta Analytic	Srednja branika – v relativnem času	Radiokarbonska datacija
PTRO_P9_VZ_P	Beta-521047	3	1948 ± 17 BP
PTRO_P9_VZ_B	Beta-521048	73	1858 ± 22 BP

and to repeat the analyses if the first attempts have not produced tangible results. We have analysed the wood from all 8 piles of the same construction curated by the museum. The number of piles is small compared to a famous Roman bridge over the Rhine in Cologne, where over 100 piles have been excavated and dendrochronologically dated. Investigations began in the 1960s and were completed with the publication of Frank and Hanel (Frank & Hanel, 2019). This study allowed the dating of the oldest group with an end date of 378 AD, and three phases of reconstruction with dendrochronological end dates of 1175, 1546 and 1795 AD (Frank & Hanel, 2019).

When examining piles, it is important to note that they can often remain *in situ* for millennia, as illustrated by the case of the 4th millennium BC pile-dwelling settlement of Resnikov prekop,

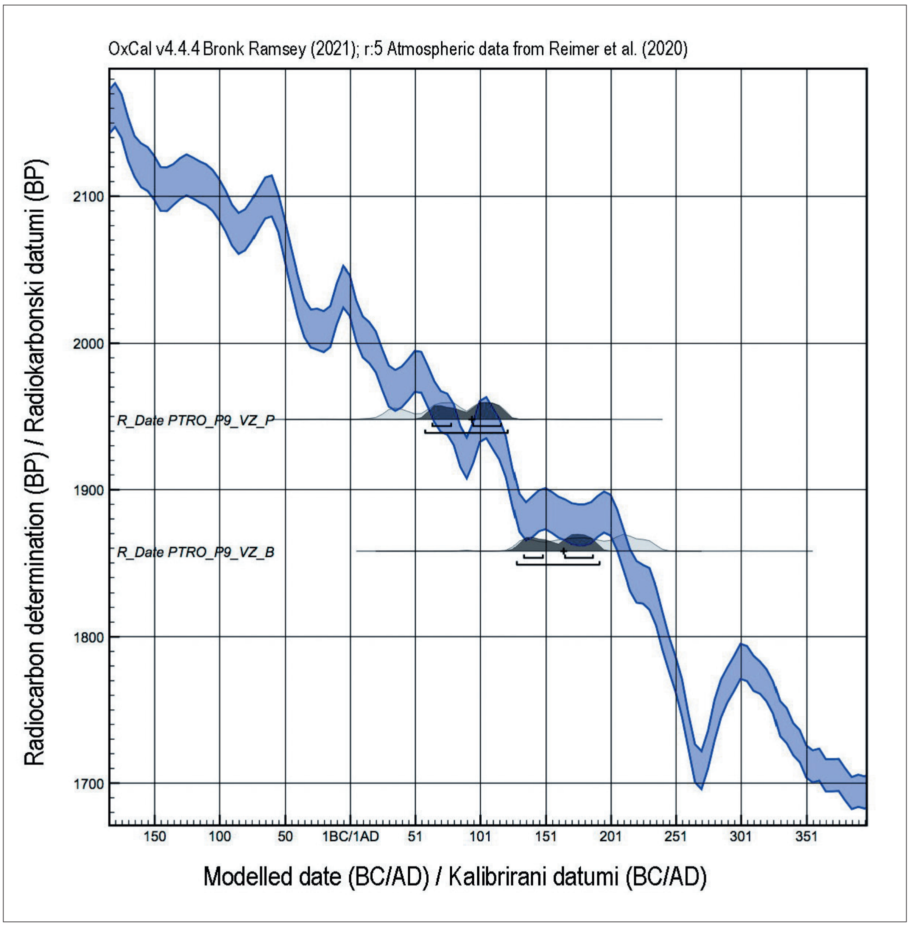


Figure 11. Calibration of the radiocarbon determination (BP) of the older sample PTRO_P9_VZ_P and the younger sample PTRO_P9_VZ_B vs. modelled calibrated dates (BC) on the time axis using OxCal v4.4.4 software (Ramsey, 2021) and IntCal 20 atmospheric curves (Reimer et al., 2020). The actual age difference between the two samples is 70 years. The dating of the younger sample is 161 ± 27 cal AD (1σ) or 160 ± 32 cal AD (2σ).

Slika 11. Kalibracija radiokarbonskega datuma (BP) starejšega vzorca PTRO_P9_VZ_P in mlajšega vzorca PTRO_P9_VZ_B ter prikaz kalibriranih datumov (BC/AD) na časovni osi, pridobljenih s programom OxCal v4.4.4 (Ramsey, 2021), in atmosferske krivulje IntCal 20 (Reimer et al., 2020). Dejanska razlika v starosti vzorcev je 70 let, datacija mlajšega vzorca je 161 ± 27 kal. n. št. (1σ) ali 160 ± 32 kal. n. št. (2σ).

where dated piles at the original site in the ground helped in the dating and interpretation of other archaeological artefacts that could be 'displaced' due to erosion or sedimentation (Čufar & Tolar, 2006).

It is important to note that in the present study all 8 piles from the Drava River were re-analysed, although most of them showed only a small number of tree rings. However, the selection of pile RMO09 for detailed analyses, the application of the AMS (Accelerated Mass Spectrometry) method, which allows radiocarbon dating of small amounts of wood (in our case one or two tree rings), and the use of wiggle-matching have helped us to confirm that the pile and the stone elements belong to a Roman bridge over the Drava.

5 CONCLUSIONS

5 ZAKLJUČKI

Dendrochronology, radiocarbon dating, and wiggle-matching calibration determined the date of the last (outer) tree ring of the RMO-09 pile, 161 ± 27 cal AD (1σ) or 160 ± 32 cal AD (2σ). The estimated date of tree felling for the pile that did not contain sapwood is approximately 15 years after the determined dates. The dating thus provisionally agrees with the presumed dating based on the building inscription, which attributes the commission to build or rebuild the bridge to Emperor Hadrian in the last years of his reign, and places the intervention in the context of the reconstruction of the road network in the wider area of the Poetovio colony (Horvat et al., 2003; Šašel Kos & Belak, 2013). According to the calibration curve and wiggle-matching dates, however, it cannot be excluded that the construction or renovation took place under one of Hadrian's successors. In this way, more than 100 years after the recovery, wood research has contributed to solving the mystery and confirmed that the remains of the wooden piles and adjacent stones found in the Drava River belong to a Roman bridge.

6 SUMMARY

6 POVZETEK

Pokrajinski muzej Ptuj - Ormož v svojih zbirkah hrani skupino 8 lesenih pilotov, ki po muzejski dokumentaciji pripadajo ostankom rimskega mostu čez Dravo in so bili pridobljeni med posegi pod nadzorom kustosa Viktorja Skrabarja v letih 1912 in 1913 (Skrabar, 1913, 1914). Epigrafijo Hadrijanovega gradbenega napisa ter drugo arhitekturno opremo domnevne mostne glave ter zgodovinsko-urbanistične vidike povezave med mostom in središčem kolonije na levem dravskem bregu je pred časom celovito obdelal Zsolt Mráv, katerega študija prinaša pregled dokumentiranih rimskih mostov v Panoniji (Mráv, 2002). Spoznanja in domneve o gradbeno-tehničnih značilnostih in topografiji mostu na Ptuju so sintetično predstavljena v članku soavtorja pričujočega dela (Gaspari, 2001), pomemben prispevek k zgodovini raziskav pa je dal Andrej Preložnik z zaznamkom k prvim opažanjem zgradb na desnem dravskem bregu na začetku 19. stoletja (Preložnik, 2020). Ob odsotnosti novih terenskih odkritij je bilo v okviru priprave članka iz leta 2001 izvršeno vzorčenje hrastovih pilotov iz muzejskega depoja. Pregled z vzorčenjem za preiskave lesa in dendrokronološko analizo, ki ga je izvedel Tom Levanič, takrat zaposlen na Katedri za tehnologijo lesa Oddelka za lesarstvo Biotehniške fakultete v Ljubljani, v spremstvu Andreja Gasparija in kustosa Ivana Žižka, je pokazal, da gre v vseh primerih za pilote iz lesa hrasta. Dendrokronološko datiranje vzorcev, ki so bili odvzeti z motorno žago iz najširšega dela pilotov, v letu 1999 ni bilo mogoče, izostala pa je tudi radiokarbonska analiza (Gaspari, 2001).

Potencial ostankov pilotov je bil predmet ponovne preverbe v začetku leta 2019. V sodelovanju z muzejsko kustosinjo Aleksandro Nestorović je bil 20. februarja 2019 opravljen ponoven pregled ostankov vseh osmih pilotov. Pregled se je osredotočil na njihovo primernost za dendrokronološko analizo oz. število branik, vidnih v prerezih ostankov pilotov, vzorčenih leta 1999. Za podrobnejšo preiskavo sta bila zaradi ustreznega števila branik izbrana dva pilota, PMO-08 in PMO-09, od katerih je bil ob mestu vzorčenja iz leta 1999 odrezan po en odrezek debeline 3 cm.

Na Oddelku za lesarstvo Biotehniške fakultete, Univerze v Ljubljani smo izvedli pripravo površin vzorcev za pregled pod stereo lupo. Ponovna

identifikacija lesa je potrdila, da je vseh 8 pregledanih pilotov iz lesa hrasta, doba (*Quercus robur*) ali gradna (*Quercus petraea*), ki ju po lesu ne moremo razlikovati (Merela & Čufar, 2013).

Merjenje širin branik smo opravili z merilno mizico RINNTECH LinTab TM5 in programsko opremo TsapWin 4.81. Šest vzorcev (številke 1, 2, 3, 4, 5, 7) je imelo 19–31 branik, kar je premalo za uspešno datiranje, vzorca RMO-08 in RMO-09 pa sta imela 50 in 73 branik.

Zaporedij širin branik različnih pilotov nismo mogli medsebojno sinhronizirati. Tako nismo mogli potrditi, ali piloti pripadajo isti gradbeni fazi in ali so bili uporabljeni za gradnjo istočasno. Zaporedja širin branik pilotov RMO-08 in RMO-09 smo skušali datirati z različnimi referenčnimi kronologijami Oddelka za lesarstvo (Čufar et al., 2019), vendar datiranje ni bilo uspešno.

Iz vzorca RMO-09, ki je imel največ branik, smo nato odvzeli še dva vzorca za radiokarbonsko datacijo in kalibriranje po metodi wiggle-matching (Čufar et al., 2010). Vzorec RMO-09-P je vseboval prvi dve braniki ob strženu, vzorec RMO-09-B pa zadnjo zunanjo (najmlajšo) braniko.

Rezultate radiokarbonskih datacij dveh vzorcev smo kalibrirali s pomočjo metode wiggle-matching ob uporabi programa OxCal v4.4.4 (Ramsey, 2021) in atmosferske krivulje IntCal 20 (Reimer et al., 2020). Ugotovljeni datum zadnje branike na vzorcu PTRO_P9_VZ_B, branika 73 je bil 161 ± 27 kal. n. št. (1σ) ali 160 ± 32 kal. n. št. (2σ) (sl. 10).

Pri oceni starosti pilota moramo ugotovljenemu datumu zadnje branike prišteti še vsaj 15 let za manjkajočo beljavo. Datacija bi tako lahko okvirno sovpadala s časovno opredelitvijo rekonstruiranega gradbenega napisa, ki naročilo obnove oz. novogradnje mostu pripisuje cesarju Hadrijanu v zadnjih letih njegove vladavine in poseg umešča v okvir prenove cestnega omrežja na širšem območju kolonije Poetovio (glej Horvat et al., 2003; Šašel Kos & Belak, 2013). Glede na obliko kalibracijske krivulje za datiranje z metodo wiggle-matching ni izključeno, da je bila postavitev mostu ali njegova obnova izvršena pod katerim od Hadrijanovih naslednikov.

Predstavljeni rezultati potrjujejo, da je smiselno analizirati les iz rimskih konstrukcij ter da je treba analizirati ves razpoložljivi material in ponoviti analize, če prvi poskusi ne prinesejo oprijemljivih rezultatov. Število pilotov s Ptuja je majhno v primerjavi z znamenitim rimskim mostom čez Ren v Kölnu, kjer je bilo proučenih in dendrokronološko datiranih več kot 100 pilotov. Tudi tam so se raziskave začele v šestdesetih letih 20. stoletja in so se zaključile z objavo, ki sta jo pripravila Frank in Hanel (Frank & Hanel, 2019). Ta študija je omogočila datiranje najstarejše skupine pilotov s končnim datumom 378 n. št. in treh faz rekonstrukcije z dendrokronološkimi datumi 1175, 1546 in 1795 n. št. (Frank & Hanel, 2019).

Pomembno je poudariti, da je bil izbor pilota RMO09 za podrobne ponovne analize lesa smiseln, saj sta razvoj metode AMS (Accelerated Mass Spectrometry), ki omogoča radiokarbonsko datiranje majhnih količin lesa (v našem primeru ene ali dveh branik) in kalibriranje wiggle-matching, pomagala potrditi, da pilot in ob njem najdeni kamniti elementi zares pripadajo rimskemu mostu čez reko Dravo, ki je bil najverjetneje zgrajen ob koncu vladavine cesarja Hadrijana.

ACKNOWLEDGEMENTS
ZAHVALA

This study was supported by the Slovenian Research Agency (programmes P4-0015 and P6-0247). We would like to thank Aleksandra Nestorović, the museum curator, for her help and support with sampling in the museum depot, Luka Krže for sample collection and preparation, Blaž Kumer for help with graphic design and Primož Stergar and Branko Mušič for permission to use the results of the latest geophysical survey and test excavations (2021).

REFERENCES
VIRI

AIJ = Antike Inschriften aus Jugoslawien. Heft I: Noricum and Pannonia Superior. Hoffiler, V. & Saria, B. Zagreb, 1938.

Curk, J. (1999). O nekaterih nerešenih problemih ptujske topografije / Über einige ungelöste Probleme der historischen Topographie von Ptuj (Zussamenfassung). Kronika, 47, 1–10.

Cüppers, H. (1969). Die Trierer Römerbrücken (Trierer Grabungen und Forschungen, Band V). Mainz: Philipp von Zabern.

Čufar, K., & Tolar, T. (2006). Raziskave lesa z Resnikovega prekopa in radiokarbonsko datiranje. V: Velušček, A (ur.), Resnikov prekop : najstarejša koliščarska naselbina na Ljubljanskem barju (123-127). Ljubljana: Inštitut za arheologijo ZRC SAZU.

Čufar, K., Kromer, B., Tolar, T., & Velušček, A. (2010). Dating of 4th millennium BC pile-dwellings on Ljubljansko barje, Slovenia. Journal of Archaeological Science, 37, 2031–2039. DOI: https://doi.org/10.1016/j.jas.2010.03.008

Čufar, K., Tegel, W., Merela, M., Kromer, B., & Velušček, A. (2015). Eneolithic pile dwellings south of the Alps precisely dated with tree-ring chronologies from the north. Dendrochronologia, 35, 91–98, DOI: https://doi.org/10.1016/j.dendro.2015.07.005

Čufar, K., Horvat, J., Tolar, T., Berden, T., & Merela, M. (2019). Research potential of wood of barrels from Roman water wells - Raziskovalni potencial lesa sodov iz rimskih vodnjakov. Les/Wood, 68, 47–60. DOI: https://doi.org/10.26614/les-wood.2019.v68n01a05

Dumont, A., & Bonnamour, L. (2008). Du pont de bois au pont mixte en Gaule. In G. Barruo, J.-L. Fiches, & P. Garmy (Eds.), Les ponts routiers en Gaule romaine, Revue archéologique de Narbonnaise, Supplément 41, 589–614.

Dumont, A. (2011). Neue Entdeckungen römischer Brücken in Holz- und Mischbauweise in Frankreich. In, Archäologie der Brücken. Bayerische Gesellschaft für Unterwasserarhäologie, 122–130.

Frank, T., & Hanel, N. (2019). Die Frankenfeldzüge der Kaiser Konstantin I. und Valentinian I. – Überlegungen zur spätrömischen Rheinbrücke zwischen der Colonia Agrippina und dem rechtsrheinischen castrum Divitensium anhand dendrochronologischer Daten. Archäologische Berichte, 30, 125–164.

Gardaš, M. (2003). Neke pretpostavke o izgledu rimskog mosta pokraj Murse. Anali Zavoda Za Znanstveni i Umjetnički Rad u Osijeku, 9, 7–15.

Gaspari, A. (2001). Raziskave rimskega mostu na Ptuju (Zussamenfassung. Ein Überblick über die Forschungsergebnisse zur römischer Brücke in Ptuj). In M. Vomer Gojkovič & N. Kolar (Eds.), Ptuj v rimskem cesarstvu - mitraizem in njegova doba. Ptuj im Römischen Reich - Mithraskult und seine Zeit. Ptuj in the Roman Empire - Mithraism and its era (51–61). Ptuj, Pokrajinski Muzej Ptuj.

Goudswaard, G., Kroes, R., & Van Der Beek, G. K. (2001). The Late Roman Bridge at Cujik. Berichten Vande Rijksdienst Voor Het Oudheidkundig Bodemonderzoek, 44, 439–560.

Horvat, J., Lovenjak, M., Dolenc Vičič, A., Lubšina Tušek, M., Tomanič-Jevremov, M., & Šubic, Z. (2003). Poetovio : development and topography. The Autonomous Towns of Noricum and Pannonia. Pannonia I, Situla 41 (153–190). Narodni muzej Slovenije.

Janežič, M., & Lazar, E. (2015). Roman military equipment from the town centre of Poetovio = Rimska vojaška oprema iz središča Poetovione. In J. Istenič, B. Lahamar, & J. Horvat (Eds.), Evidence of the Roman army in Slovenia = Sledovi rimske vojske na Slovenskem, Katalogi in monografije = Catalogi et monographiae 41 (257–268). Narodni muzej Slovenije.

Jevremov, B. (1975). Kanalizacija za RTC, nadzor. Unpublished report/ Neobjavljeno poročilo. Zavod za varstvo kulturne dediščine Slovenije, Območna enota Maribor.

Lazar, E. (2013). 97. Ptuj. Varstvo spomenikov. Poročila, 48, 216–220.

Lubšina Tušek, M., & Erič, M. (2012). Zaščitne raziskave poznosrednjeveškega in novoveškega mostiča na Ptuju / Rescue investigation of the Late Medieval and Modern Age bridges at Ptuj. In A. Gaspari & M. Erič (Eds.), *Potopljena preteklost. Arheologija vodnih okolij in raziskovanje podvodne kulturne dediščine v Sloveniji/ Submerged Past: archaeology of the aquatic environments and underwater cultural heritage exploring in Slovenia.* Didakta, 355–362.

Mensching, E. (1981). Die Koblenzer Rheinbrücke, P. Pomponius Secundus und der Brückenbau an Rhein und Mosel. Bonner Jahrbücher, 181, 325–354.

Merela, M., & Čufar, K. (2013). Density and Mechanical Properties of Oak Sapwood Versus Heartwood. Drvna Industrija, 64, 323–334. DOI: https://doi.org/10.5552/drind.2013.1325

Mikl-Curk, I., & Tušek, I. (1985). O središču Poetovione. Arheološki vestnik, 36, 285–314.

Mráv, Z. (2002). Die Brückenbauinschrift Hadrians aus Poetovio. Communicationes Archæologogicæ Hungariæ, 43, 15–57.

Mráv, Z. (2003). Kaiserliche Bautätigkeit zur Zeit Hadrians in den Städten Pannoniens. Acta Antiqua, 43, 125–137. DOI: https://doi.org/10.1556/AAnt.43.2003.1-2.12

Preložnik, A. (2020). Izgubljeno s citatom: kaj zares vemo o lokaciji četrtega ptujskega mitreja?/ Lost in citation: what do we really know about the location of the fourth Ptuj mithraeum? Predavanje Na Simpoziju Poetoviona in njen Ager, 18. november 2020 / Lecture at the Conference Poetovio and Its Ager, 18 November 2021.

Ramsey, C. B. (2021). OxCal 4.4.4 Computer program, https://c14.arch.ox.ac.uk/oxcal/; [16.11.2021].

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., & Talamo, S. (2020). The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon, 62, 725 – 757. DOI: https://doi.org/10.1017/RDC.2020.41

Ritter von Rittersberg, L. (1818). Archäologische Bluthenlese (Fortsetzung). Archiv Für Geographie, Historie, Staats- Und Kriegskunst, 83, 325–327.

Roth Congès, A. (2011). Les arcs d'entrée de ponts en Gaule. In G. Barruol, J.-L. Fiches, & P. Garmy (Eds.), Les ponts routiers en Gaule romaine. Revue archéologique de Narbonnaise, Supplément 41, 555–571.

Šašel Kos, M., & Belak, M. (2014). Poetovio before the Marcomannic Wars: from legionary camp to Colonia Ulpia. In I. Pusi & R. Varga (Eds.), Trajan und seine Städte, Colloquium Cluj-Napoca, 29. September – 2. Oktober 2013 (139-165). Cluj-Napoca.

Skrabar, V. (1913). Die römische Draubrücke bei Pettau. Tagespost, 20. April 1913.

Skrabar, V. (1914). Die römische Draubrücke bei Pettau. Jahreshefte Der Österreichischen Archäologischen Institutes, 17, 155–160.

LES/WOOD Vol. 70, No. 2, 87-98
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a07

MOTIVACIJA ZA IZOBRAŽEVANJE IN USPOSABLJANJE GENERACIJ Y IN Z V LESARSTVU

EDUCATIONAL MOTIVATION OF GENERATIONS Y AND Z IN THE WOOD SECTOR

Luka Goropečnik[1], Rafael Šenk[1], Matej Jošt[1], Katarina Čufar[1], Jože Kropivšek[1*]

UDK 674:37.015.3:005.32
Izvirni znanstveni članek / Original scientific article

Prispelo / Received: 5. 11. 2021
Sprejeto / Accepted: 16. 11. 2021

Izvleček / Abstract

Izvleček: Z industrijo 4.0 vstopamo v digitalno dobo, kjer se bodo tudi v lesnopredelovalnih podjetjih bistveno spremenile zahteve po znanjih in kompetencah zaposlenih. To vpliva tudi na izobraževanje na področju lesarstva. Cilj raziskave je bil ugotoviti, kateri načini poučevanja in učenja najbolj motivirajo predstavnike generacij Y in Z, na različnih nivojih izobraževanja (od poklicnega izobraževanja do magistrskega študijskega programa) v lesarstvu, kakšen način izvedbe izobraževanja je zanje najprimernejši in kaj menijo o študiju na daljavo. V ta namen smo izvedli anketiranje s pomočjo družabnih omrežij in e-učilnice. Rezultati so pokazali, da anketirane najbolj motivira okolje, naravnano k razvoju, je varno in stabilno ter delo v delovni skupini, medtem ko si ne želijo tekmovalnega okolja. Med skupinami na različnih ravneh in načinih izobraževanja (redno, vseživljenjsko) nismo opazili večjih razlik v motivacijskih dejavnikih. Sicer pa glavno motivacijo učečih se v lesarstvu ne glede na generacijo predstavljajo notranje spodbude posameznika, medtem ko se zunanje spodbude med generacijami bolj razlikujejo.

Ključne besede: izobraževanje, lesarstvo, digitalna doba, motivacija, generacija Y in generacija Z

Abstract: With Industry 4.0, we are entering the digital age, which will significantly change the profiles of employees and their necessary competencies. This also affects education in the wood sector. The aim of the research was to find out which teaching methods in learning motivate representatives of generations Y and Z at different levels of education (from vocational to master's degree education) in the wood sector, which form of education is most suitable and what younger people think about distance learning. To this end, we conducted a survey using social media and an e-classroom. The results showed that learners are most motivated by an environment that strives for development, is safe and stable, and is also characterized by teamwork rather than a competitive environment. We did not find much difference in motivational factors between groups at different levels of education or forms of education (full-time, lifelong). Otherwise, the main motivation of learners with regard to the wood sector, regardless of generation, is the internal incentives of the individual, while the external incentives differ more between generations.

Keywords: education, wood sector, digital age, motivation, generation Y and generation Z

1 UVOD
1 INTRODUCTION

Zaradi hitrega tehnološkega razvoja in naraščajoče digitalizacije se poslovno okolje v lesni industriji pospešeno spreminja, kar pa ima močan vpliv tudi na koncept izobraževanja. Svet vstopa v novo industrijsko revolucijo, v tako imenovano industrijo 4.0. Digitalna industrijska revolucija, kot je le-ta tudi pogosto poimenovana, prinaša večjo prilagodljivost, večjo hitrost, boljšo kakovost in večjo storilnost (Davies, 2015). Očitno je, da industrija 4.0 ni samo revolucija stroja in tehnologije, temveč bo v lesnopredelovalnih podjetjih bistveno spremenila tudi profile zaposlenih in njihove potrebne kompetence (IN4WOOD, 2017). Pomanjkanje digitalnih kompetenc je eden večjih problemov sedanjega poslovnega okolja (Kropivšek, 2018). Na to se bodo morale odzvati tudi izobraževalne institucije na področju lesarstva, ki bodo morale ponujati drugačne vsebine, predvsem pa spremeniti obstoječe koncepte in načine izobraževanja ter jih podpreti z novimi tehnologijami in storitvami. Uvajanje novih tehnologij in načinov izobraževanja ima velik vpliv praktično na vsa področja izobraževalnega procesa.

[1] Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za lesarstvo, Jamnikarjeva 101, 1000 Ljubljana, SLO
[*] e-mail: joze.kropivsek@bf.uni-lj.si

Eden pomembnejših izzivov je zagotavljati visoko motivacijo učečih se, ki se odraža v njihovem angažiranju in prispevku k učnemu okolju. Pomanjkanje motivacije je pomembna ovira pri izobraževanju, ki se kaže v občutkih frustracije in neprijetnosti in dolgoročno ovira produktivnost ter dobro počutje (Legault et al., 2006). Na celotni vertikali od poklicnega do magistrskega študijskega programa se trenutno izobražujejo predvsem pripadniki generacije Z, rojeni med leti 1997 in 2012 in deloma pripadniki generacije Y, rojeni med leti 1981 in 1996. Mlajše generacije (predvsem Z) se slabše odzivajo na klasično izvedbo predavanj, želijo si večjo interaktivnost. Z razvojem tehnologij se tradicionalni pristopi izobraževanja zdijo zastareli in mlajšim postajo neučinkoviti oziroma odvečni (Postolov et al., 2017; Šenk, 2021). Zato so tudi s tega vidika spremembe na področju izobraževanja ključne, za zagotavljanje ustreznih kadrov, ki jih bo lesna industrija potrebovala v prihodnosti. Z vključevanjem novih sodobnih vsebin in tehnologij naj bi izobraževalni proces postal bolj dinamičen, interaktiven in predvsem bolj učinkovit, še posebej za mlajše generacije (Z) (Innovae, 2021).

Glavni cilj raziskave je ugotoviti, kateri načini poučevanja in učenja predstavljajo največjo motivacijo učečim se v lesarstvu, tako pri rednem izobraževanju generacije Z (od poklicnega do magistrskega študijskega programa) kot pri vseživljenjskem izobraževanju (generacija Y in druge). Poleg tega smo želeli ugotoviti, kakšen način izvedbe izobraževanja je zanje najprimernejši in kaj menijo o študiju na daljavo.

V besedilu so izrazi učeči se, dijak, študent, učitelj, mentor in podobno zapisani v slovnični obliki moškega spola, uporabljeni kot nevtralni in veljajo enakovredno za oba spola.

1.1 ZNAČILNOSTI GENERACIJ Y IN Z
1.1 CHARACTERISTICS OF GENERATIONS Y AND Z

Predstavniki generacije Y so nasledniki generacije X (posamezniki, rojeni med leti 1965 in 1980) in predhodniki generacije Z. V to generacijo spadajo posamezniki, rojeni med leti 1981 in 1996 (Dimock, 2019). Najpomembnejši dogodki, ki zaznamujejo to obdobje, so na primer tehnološka eksplozija z internetom, družbenimi mediji, razpad Sovjetske zveze. Ta generacija ni živela v svetu brez računalnikov, interneta in mobilnih telefonov. Denar jim ni tako pomemben, veliko pa jim pomeni prispevanje k družbi in njihova družina (Crampton & Hodge, 2009). V literaturi lahko najdemo več različnih imen za generacijo Y. Najbolj je znan naziv milenijci, ki sta ga v svoji knjigi Generations skovala Strauss in Howe (Sharf, 2015). Definicija besede milenijci pa se nanaša na človeka, ki doseže polnoletnost v začetku 21. stoletja (Oxford living dictionaries, 2021). Poznamo tudi druga imena, kot so generacija jaz, Peter Pan generacija, saj dlje časa ostajajo doma in ne izražajo velike želje po odraščanju; net generacija ali generacija interneta, ker so bili rojeni v obdobju interneta; izgorela generacija; digitalni domorodci; generacija zakaj, v angleščini se črka y uporablja za okrajšavo angleške besede „why‘‘, ki pomeni zakaj. Njihova najbolj izrazita lastnost je njihova nagnjenost k tehnologiji. Za razliko od predhodnih generacij so predstavniki Y odraščali s prisotnostjo tehnologije in od otroštva sledijo njenemu vsakodnevnemu razvoju ter so prilagodljivi na spremembe že od malega. Pripadniki generacije Y razmišljajo bolj globalno kot druge generacije, saj so se rodili v globaliziranem svetu. Spoštujejo druge rase, spole, etnične izvore, kulturne vrednote in spolne odločitve. Želijo si tudi bolj smiselnega in vključevalnega dela. Poudarek dela se je preusmeril v ravnovesje med interesi posameznikov in organizacijskimi potrebami, s povečanimi možnostmi za samorazvoj in avtonomijo (Buckley et al., 2001). Predstavniki te generacije želijo tudi, da bi bilo njihovo delo plodno, ker so odločni in samozavestni, imajo visoko motivacijo. Če so motivirani, lahko delajo več stvari hkrati (Berkup, 2014). Generacija Y razmišlja in se uči drugače kot prejšnje generacije, zlasti zaradi hitro spreminjajočega se visoko tehnološkega okolja, v katerem so bili vzgojeni. Izobraževanje jim predstavlja ključ do uspešnega poslovnega življenja.

Generaciji Y sledi generacija Z, ki trenutno prevladuje med tistimi, ki se redno izobražujejo, tako na osnovnošolski kot na srednješolski in univerzitetni ravni. Različni viri to generacijo postavljajo v različne časovne okvire, največkrat vanjo uvrščajo rojene med leti 1997 in 2012 (Dimock, 2019). Tudi za generacijo Z uporabljamo več imen. V zadnjem času se je zaradi epidemije COVID-19 zanjo zelo prijelo ime Zoomerji, zaradi uporabe spletne aplikacije Zoom pri spremljanju pouka na daljavo.

Ostala imena, s katerimi nagovarjamo to skupino ljudi, so na primer iGeneracija, net generacija, digitalni domorodci, otroci interneta. Generacija Z predstavlja največji generacijski premik na delovnem mestu doslej (Tulgan, 2013). Obdobje, ko so se rodili predstavniki generacije Z, najbolj zaznamuje razvoj novih tehnologij, socialno gospodarski trendi, odraščanje v svetu po 11. septembru 2001 in velika recesija leta 2008. Rodili so se in odraščali v digitalnem svetu in kar jih ločuje od drugih generacij, je, da je njihovo bivanje bolj povezano s tehnologijo in digitalnim svetom. Za generacijo Z je značilna uporaba pametnih telefonov, iskanje informacij prek spleta in uporaba socialnih omrežij. Na splošno obstaja vsaj 20 skupnih značilnosti te generacije, kot npr. poznavanje tehnologije, uporaba spletnih iskalnikov za iskanje informacij, zanima jih večpredstavnost, ustvarjanje internetnih vsebin, delujejo hitro, učijo se z induktivnim odkrivanjem, učijo se s poskusi in napakami, kratek razpon pozornosti, vizualno komuniciranje, hrepenijo po fizični interakciji itd. (Maulina et al., 2020). Nenehni napredek tehnoloških izdelkov in popularnost družbenih omrežij (Instagram, Facebook, Twitter, WhatsApp, TikTok, ipd.), ki jih uporablja na stotine milijonov uporabnikov, predvsem mladih, povzroča zasvojenost pri generaciji Z in tudi pri generaciji Y. Predstavniki obeh generacij so rojeni v tehnološko-globalnem svetu, v katerem se lahko vzpostavi stik s skoraj katero koli osebo na kateri koli lokaciji na svetu v le nekaj sekundah. Lahko jih imenujemo odvisniki od tehnologije, obvladajo internetno tehnologijo, igranje internetnih iger, druženje v internetnem okolju, saj so povezani s spletom 24 ur na dan 7 dni na teden. Digitalna vez z internetom pomaga mladim pobegniti iz čustvenih in duševnih bojev, s katerimi se spopadajo v življenju brez interneta (Turner, 2015). Živijo bolj počasi, ne tvegajo radi, so izobraženi, se lepo obnašajo, obenem pa jih spremlja stres in depresija (The Economist, 2019). Več časa preživijo za elektronskimi napravami in manj časa pri branju knjig (Ferguson, 2020). Komunicirajo preko socialnih omrežij, kar jim omogoča kontakt s prijatelji, obenem pa nimajo stika v živo, zato se počutijo osamljene in zapuščene. Raje uporabljajo telefone kot računalnike in raje izberejo video vsebine kot besedilne. Tradicionalen način izobraževanja pri mlajših generacijah postaja manj učinkovit. Na trgu dela so potrebe po dobro izobraženih in usposobljenih delavcih velike, hkrati pa upadajo potrebe po slabo plačanih delih in slabo usposobljenih delavcih. Za sodobne generacije potrebujemo kulturo in izobraževalni sistem, ki bo promoviral vseživljenjsko učenje (Schwab, 2015).

1.2 MOTIVACIJA
1.2 MOTIVATION

Motivacija je „gonilna sila“, s katero si ljudje prizadevamo doseči svoje cilje in izpolniti potrebo ali ohraniti vrednost, kot jo je leta 2002 opredelil Mullins (OpenLearn, 2014). Isti vir pravi, da so gradniki motivacije potrebe (osnovne zahteve za preživetje in so lahko fizične ali psihične; na primer lakota, žeja, ljubezen ali prijateljstvo), vrednote (so stvari, za katere menimo, da so najpomembnejše; na primer družina, zdravje ali bogastvo) in cilji (so rezultati, za katere si prizadevamo). Motivacija kot proces poteka po naravnih zakonitostih v človeku in ga ne znamo v celoti pojasniti (Možina et al., 2002). Med psihologi in drugimi raziskovalci je najbolj v rabi teorija motivacije, ki jo je razvil Maslow na podlagi preučevanja človekovih potreb. Maslow je ugotovil, da ima človek več vrst potreb, ki so razvrščene po hierarhiji. Najprej mora imeti oseba zadovoljene fiziološke potrebe, nato potrebe po varnosti, sledi potreba po pripadnosti in ljubezni, kot četrta nastopi potreba po spoštovanju, zadnja in najvišja potreba je potreba po samouresničevanju (Brečko, 1996). Poznamo pa tudi druge motivacijske teorije, kot so na primer McClellandova motivacijska teorija dosežkov, analiza motivacijskih dejavnikov, motivacijska teorija pričakovanj, motivacijska teorija postavljanja ciljev (Rozman & Kovač, 2012).

Motivi posameznika so različni, saj ima vsak različne potrebe in cilje. Motive avtorji pogosto razdelijo v notranje oz. primarne in zunanje oz. sekundarne (LaBelle, 2005). V osnovi lahko izvor motivov pri posamezniku razdelimo na dve skupini. V prvo se uvrščajo dejavniki, ki izhajajo iz posameznika. V drugo uvrščamo spremenljivke, ki izhajajo iz dela in okolja (Hitt et al., 2009). Notranja motivacija izhaja iz človeka samega. Določeno akcijo izpelje zato, ker mu to narekuje neka notranja potreba, notranji glas. Za to posameznik ne potrebuje dodatnih, zunanjih spodbud niti zgledov. Pod okriljem notranje motivacije se ljudje izobražujemo zaradi lastnega izpopolnjevanja in osebnostnega razvoja. Zunanji motivi za izobraževanje pa so najpogosteje možnost pridobiti več denarja, višji položaj, boljšo službo, včasih gre tudi zgolj za tekmovanje z drugimi. Zunanji motivi so načeloma šibkejši, saj utegnejo nenadoma usahniti. Pri izobraževanju se kot zunanji motiv velikokrat javlja tudi potreba po druženju in navezovanju družabnih stikov pa tudi strah pred sankcijami in odgovornost do ustanove (Brečko, 1996). V kontekstu izobraževanja moč volje povezuje študente z akademskimi dejavnostmi. Motivacija učencev se odraža v njihovem angažiranju in prispevku k učnemu okolju. Motivirani učenci so običajno aktivno in spontano vključeni v dejavnosti in se jim zdi učenje prijetno, ne da bi pričakovali nagrade. Po drugi strani pa bodo učenci, ki imajo nizko stopnjo motivacije za učenje, pogosto odvisni od nagrad, ki jih bodo spodbudile k sodelovanju v dejavnostih, ki se jim ne zdijo prijetne (Skinner & Belmont, 1993). Pomanjkanje motivacije je pomembna ovira pri izobraževanju, kaže se v občutkih frustracije in neprijetnih občutkov, ki jih imajo tisti, ki se učijo in tisti, ki poučujejo, ter dolgoročno ovira doseganje ciljev in dobro počutje (Legault et al., 2006).

2 MATERIALI IN METODE

2 MATERIALS AND METHODS

2.1 ANKETA O MOTIVIRANOSTI UČEČIH SE V LESARSTVU

2.1 SURVEY ON THE MOTIVATION OF LEARNERS IN THE WOOD SECTOR

Želeli smo preveriti, kaj dijake in študente na področju lesarstva najbolj motivira, zato smo izvedli spletno anketo preko spletnega portala 1ka (1KA, 2021). Anketo smo 29. 7. 2021 najprej poslali v zaprto Facebook skupino, v kateri je 25 študentov iz Oddelka za lesarstvo Biotehniške fakultete in tako preverili ustreznost ter razumljivost vprašalnika. Na podlagi njihovih povratnih informacij smo sklepali, da je anketa ustrezna. Anketa je bila v obdobju od 1. 8. 2021 do 9. 8. 2021 objavljena v več Facebook skupinah, povezanih z lesarstvom: Mizarski stroji, orodje, izdelki, Čar lesa, Mizarji, Znanje za les in oblikovanje, ALUMNI Oddelka za lesarstvo, Les je lep (*Facebook*, 2021). Skupno število članov vseh skupin je bilo okoli 43 tisoč. Da bi dosegli študente, smo uporabili tudi spletno učilnico Biotehniške fakultete Moodle (*Moodle*, 2021). Do 12. 8. 2021, ko smo anketo zaključili, je na nagovor kliknilo 693 oseb. Od tega jih je 210 nadaljevalo z reševanjem ankete. Na koncu smo prejeli 86 v celoti izpolnjenih anket, odgovorilo je 18 dijakov, 50 študentov in 18 ostalih (zaposleni, brezposelni, samozaposleni in drugi) anketirancev s področja lesarstva.

Anketa je bila sestavljena iz štirih socialno-demografskih vprašanj, ki so spraševala po spolu, starostni skupini, področju izobraževanja in trenutnem statusu. Nato so sledila štiri vprašanja, ki so spraševala o motivaciji. Na koncu so sledila še tri sestavljena, bolj kompleksna vprašanja o aktualnih vsebinskih področjih (industrija 4.0, krožno gospodarstvo in družbena odgovornost). Večino vprašanj v vprašalniku je bilo zaprtega tipa, nekatera pa polodprtega tipa in so vključevala možnost „drugo''. Pri nekaterih vprašanjih so anketiranci lahko izbirali med več odgovori, pri večini pa so lahko izbrali samo enega. Vsa vprašanja so bila obvezna. Tako je torej anketa vsebovala 10 vprašanj. Če zraven prištejemo še vprašanja znotraj sestavljenih vprašanj (industrija 4.0, krožno gospodarstvo in družbena odgovornost), je anketa skupaj vsebovala 17 vprašanj. V tem prispevku bomo predstavili le nekaj odgovorov iz te raziskave in sicer tiste, ki se navezujejo na motivacijo (slika 1, 2, in 3). Iz vseh odgovorov pa bomo izluščili le odgovore anketirancev s področja lesarstva.

2.2 ANKETA O ŠTUDIJU NA DALJAVO V LESARSTVU

2.2 SURVEY OF DISTANCE STUDY IN THE WOOD SECTOR

Na splošno velja, da imajo povratne informacije zelo pomembno vlogo pri poučevanju (Hattie & Timperley, 2007). Med študenti Oddelka za lesarstvo Biotehniške fakultete smo izvedli anketo, katere namen je bil pridobiti vpogled v mnenje študentov o študiju na daljavo, kot odgovor na pandemijo Covid-19, saj je bila ta oblika študija tako za študente kot za predavatelje dokaj nova in se je zaradi epidemioloških razmer vsaj na začetku izvedla precej improvizirano (Kropivšek et al., 2021). Anketa je bila izvedena v spletni učilnici Moodle (Moodle, 2021), kjer so bili vsi aktivni študenti na Oddelku za lesarstvo povabljeni k izpolnitvi vprašalnika. Raziskava je bila izvedena ob koncu tretjega vala pandemije 16. aprila 2021. Pri raziskavi je sodelovalo

74 študentov lesarstva. Anketa je bila anonimna in je obsegala 86 vprašanj. Večina vprašanj je bila zaprtega tipa v obliki petstopenjske Likertove lestvice z enim možnim odgovorom, nekatera pa so bila odprta. V tem prispevku bomo predstavili odgovore za izbrana vprašanja (slika 4 in 5).

Podatke anket smo analizirali v programu Microsoft Excel 365. Podlaga za analizo je bila frekvenčna distribucija, to je tabelarični povzetek podatkov, ki kažejo pogostost opazovanj v vsaki od več kategorij ali razredov, ki se ne prekrivajo (Anderson et al., 2015; Košmelj, 2007). Frekvenca razreda j je označena kot fj. Za primerjavo frekvenc različnih razredov se uporablja relativna frekvenca. To pomeni, da je frekvenca razreda enaka deležu opazovanj

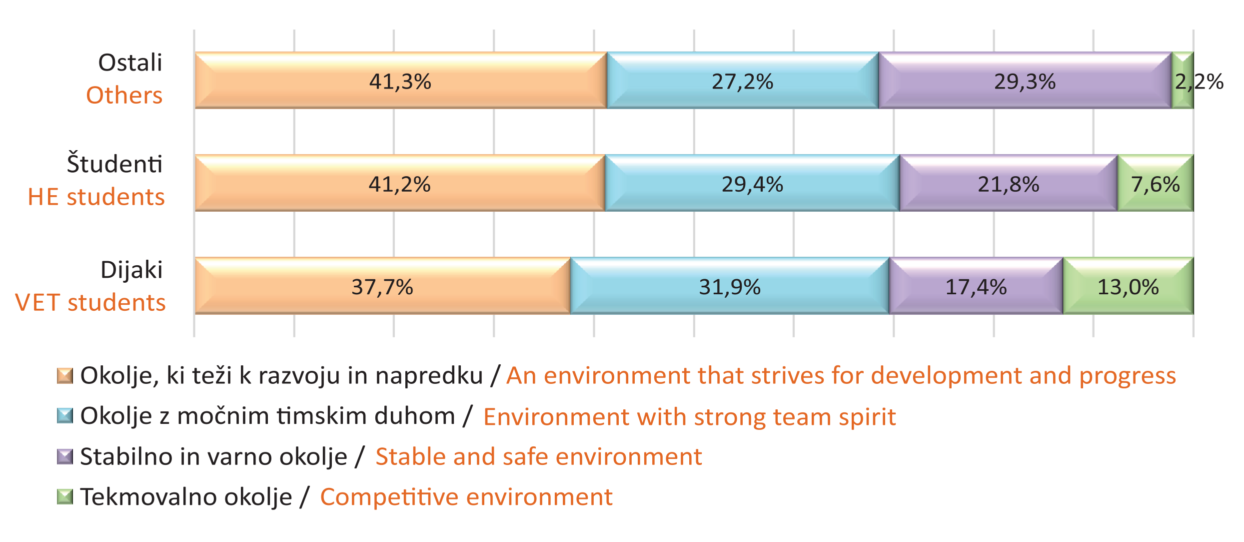
$$f_j\% = \frac{f_j}{N} * 100$$

kjer je: f_j frekvenca razreda *j* in *N* število opazovanj.

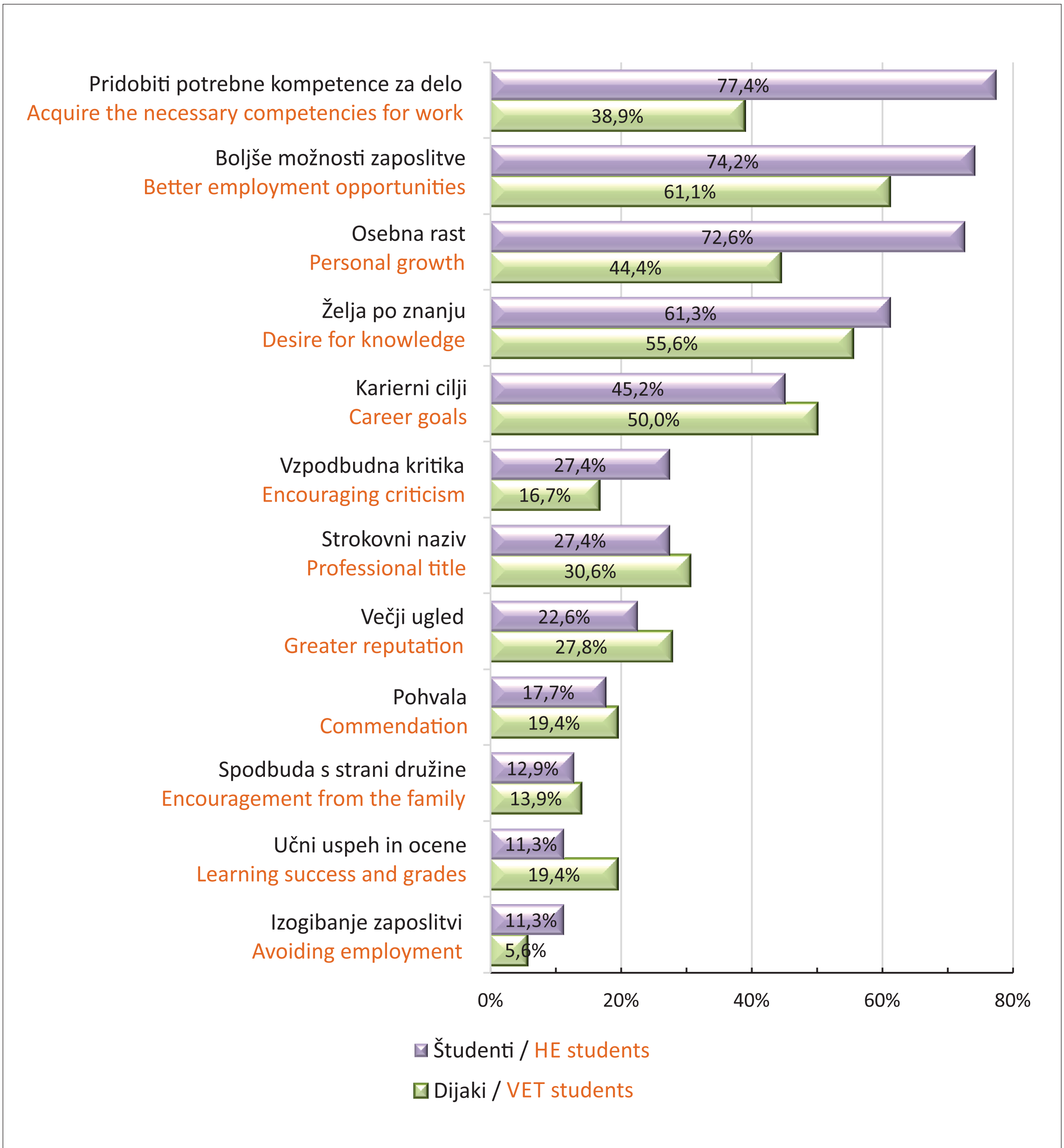
3 REZULTATI
3 RESULTS

Na vprašanje, kakšno izobraževalno/delovno okolje jih najbolj motivira, so vse generacije odgovorile podobno (slika 1). Na vprašanje je bilo možno podati več odgovorov. Vse generacije najbolj motivira okolje, ki teži k razvoju in napredku, najmanj pa jih motivira tekmovalno okolje. Veliko motivacijo jim predstavlja tudi okolje z močnim timskim duhom. Opazimo tudi, da bolj kot se posamezniki bližajo zaposlitvi, več motivacije jim predstavlja stabilno in varno okolje, medtem ko jim tekmovalno okolje predstavlja manj motivacije.

Pri vprašanju: „Kaj vam predstavlja največjo motivacijo pri rednem izobraževanju in usposabljanju?‘‘ je bilo možnih več odgovorov, na voljo pa je bila tudi možnost „drugo‘‘. Dijakom lesarstva največjo motivacijo pri rednem izobraževanju predstavljajo boljše zaposlitvene možnosti (61,1 %), želja po znanju (55,6 %) in karierni cilji (50 %), najmanjšo pa izogibanje zaposlitvi (5,6 %). Študenti pa so odgovorili, da jim največjo motivacijo pri rednem izobraževanju predstavljajo pridobitev potrebnih kompetenc za delo (77,4 %), boljše možnosti zaposlitve (74,2 %), osebna rast (72,6 %) in želja po znanju (61,3 %). Najmanjšo motivacijo jim predstavlja izogibanje zaposlitvi in učni uspeh/ocene (11,3 %). Vrzeli med motiviranostjo pri izobraževanju dijakov in študentov so najbolj opazne pri vprašanjih izobraževanja za pridobitev potrebnih kompetenc za delo in izobraževanja za osebno rast. Večini študentov (≈70 %) oboje predstavlja visoko motivacijo, pri dijakih pa je ta delež manjši (≈40 %). Drugi odgovori pa so med dijaki in študenti podobni. Na splošno se izobražujejo zaradi boljše možnosti zaposlitve, kariernih ciljev in znanja, ne pa zaradi ocen, izogibanja zaposlitvi, pohval in tekmovanja (slika 2).

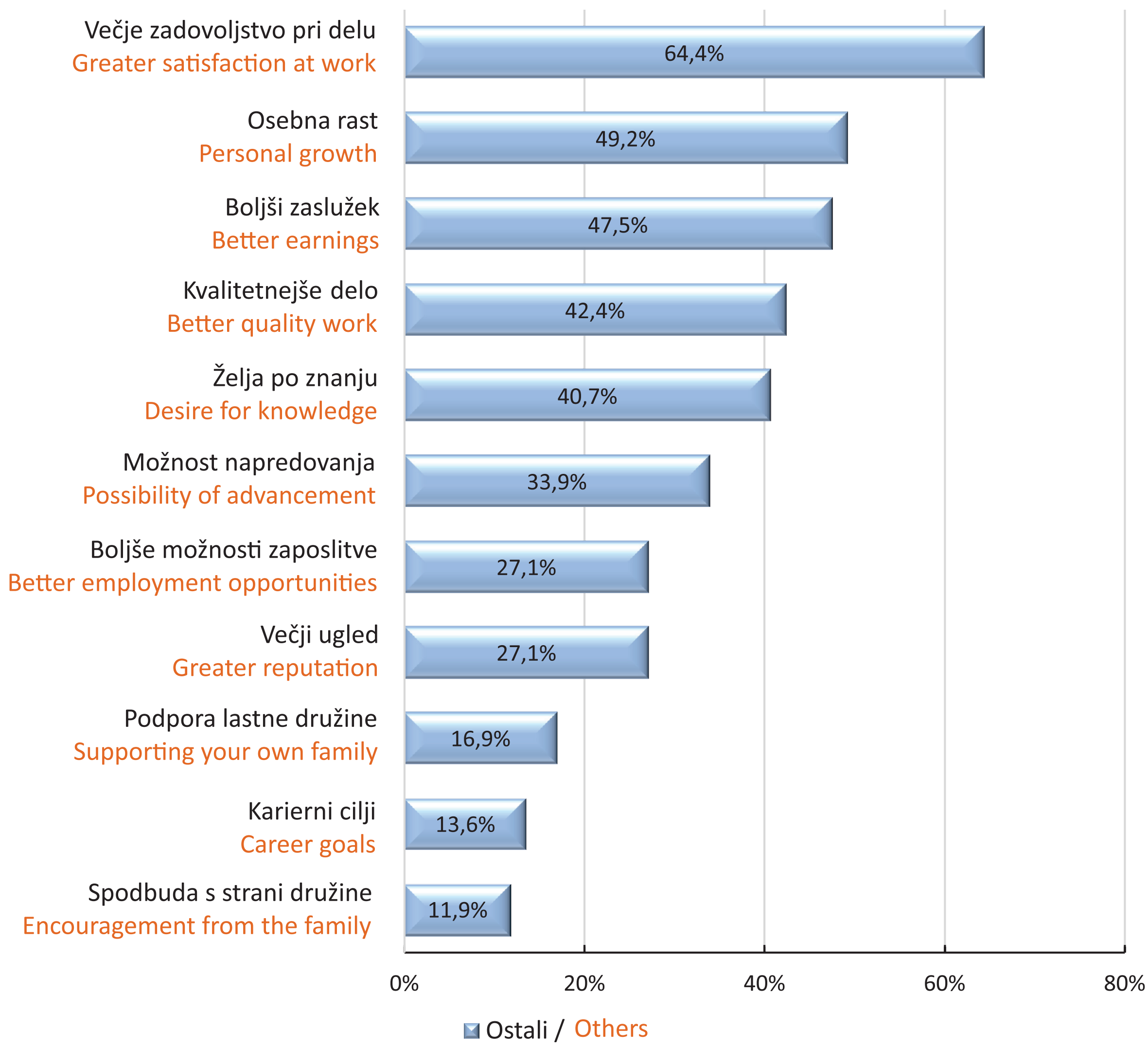


Slika 1. Odgovori na vprašanje: „Kakšno izobraževalno / delovno okolje me najbolj motivira?‘‘ (n = 68)
Figure 1. Answers to the question: „What educational / work environment motivates me the most?” (n = 68)



Slika 2. Primerjava elementov motivacije dijakov in študentov pri rednem izobraževanju. (n = 68)
Figure 2. Comparison of motivational elements of students in regular education. (n = 68)

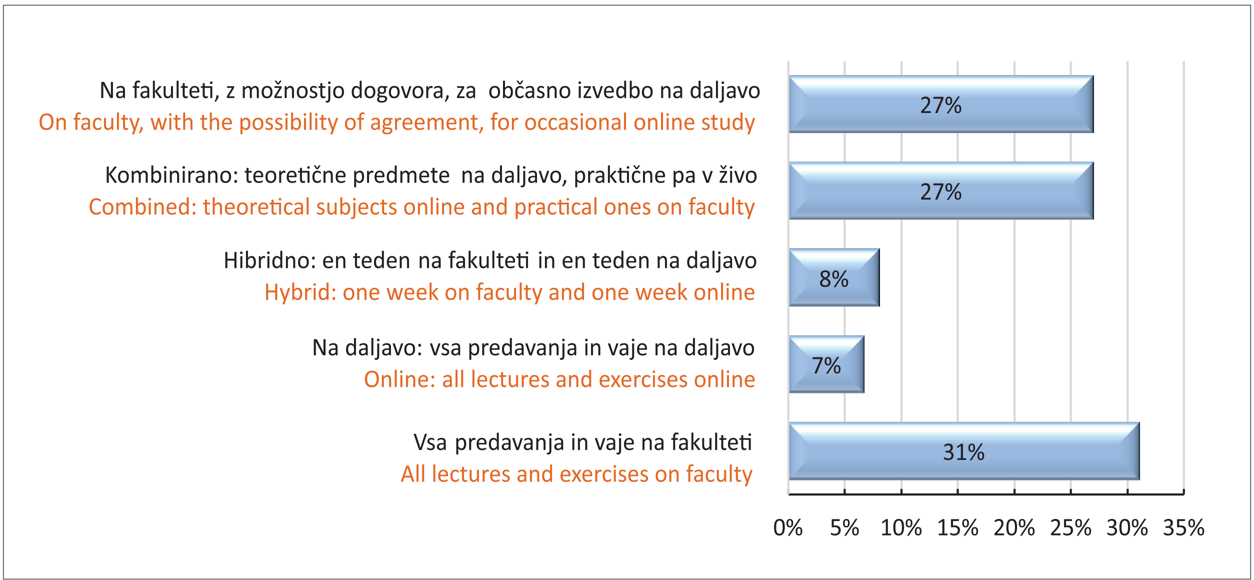
Slika 3 prikazuje odgovore ostalih v lesnem sektorju (tistih, ki niso več del rednega izobraževanja), na enako vprašanje kot na sliki 2 z razliko, da se vprašanja navezujejo na vseživljenjsko in ne na redno izobraževanje. Tudi tukaj je bilo možnih več odgovorov in možnost navedbe svojega razloga pod „drugo''. Največjo motivacijo pri vseživljenjskem izobraževanju anketirancem predstavlja večje zadovoljstvo pri delu (64,4 %), osebna rast (49,2 %) in boljši zaslužek (47,5 %). Malo jih motivira spodbuda s strani družine (11,9 %) in karierni cilji (13,6 %), ki pri dijakih in študentih predstavljajo znatno večji delež motiviranosti.



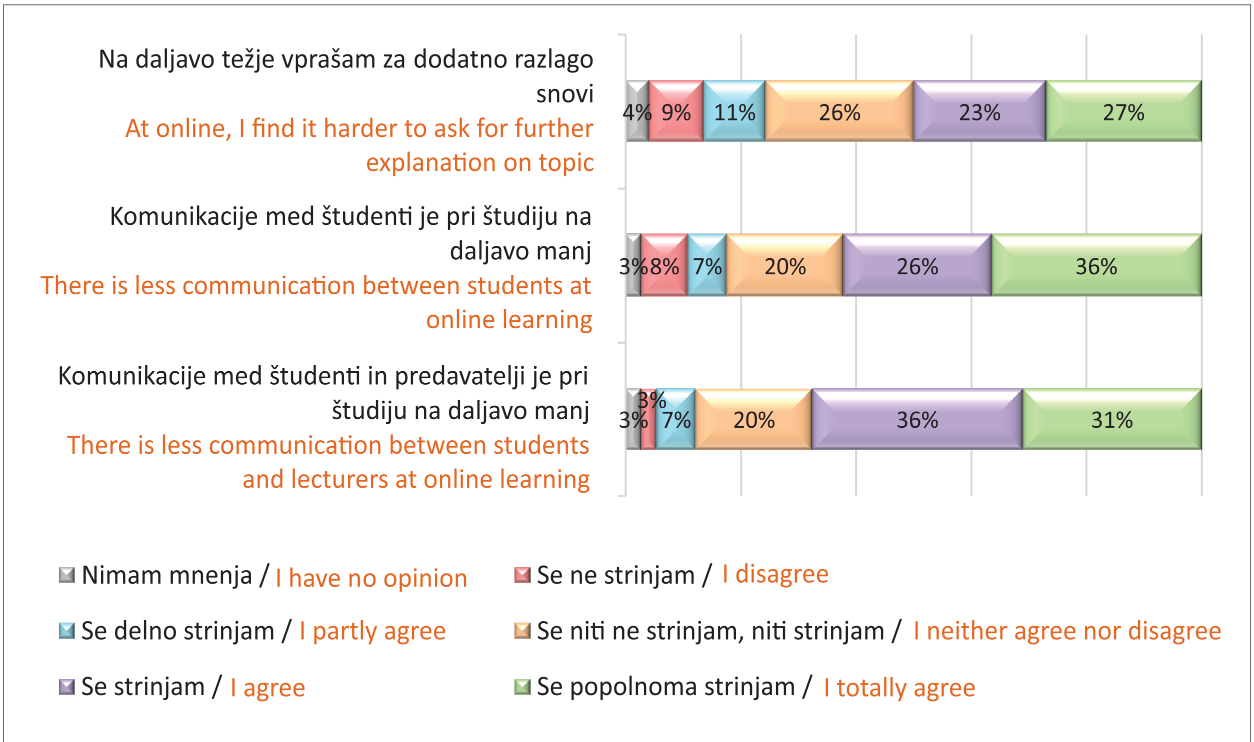
Slika 3. Motivacija ostalih (izven rednega izobraževanja) pri vseživljenjskem izobraževanju. (n = 18)
Figure 3. Motivation of others (outside of regular education) in lifelong learning. (n = 18)

Slika 4 prikazuje odgovore študentov lesarstva na vprašanje: „Kakšen način izvedbe predavanj/vaj vam bi bil ljubši, če ne bi bilo pandemije (ob normalnih razmerah)?‘‘, za katerega so lahko izbrali samo en odgovor. Največ študentov lesarstva bi imelo vsa predavanja in vaje v živo na fakulteti (31 %). Veliko bi jih teoretične predmete imelo na daljavo, praktične pa v živo (27 %), prav tako bi 27 % študentov želelo občasno izvedbo predavanj oziroma vaj na daljavo. Najmanj študentov bi imelo vsa predavanja in vaje na daljavo (7 %) in le 8 % bi jih želelo hibridno izvedbo predavanj in vaj (en teden v živo na fakulteti in en teden v živo na daljavo).

Pri naslednjem sklopu vprašanj (slika 5) smo študente spraševali o komunikaciji med študenti in predavatelji pri študiju na daljavo. S prvo trditvijo: „Pri študiju na daljavo težje vprašam za ponovno/dodatno razlago snovi.‘‘, se večina študentov popolnoma strinja (27 %) ali strinja (23 %), nekaj jih je neopredeljenih (26 %), manj se jih delno strinja (11 %), ostali pa se s trditvijo ne strinjajo (9 %) ali nimajo mnenja (4 %). Tudi s trditvijo, da je komunikacije med študenti pri študiju na daljavo manj, se največ študentov popolnoma strinja (36 %) manj pa se jih strinja (26 %), delno strinja (7 %), ne strinja (8 %), ali pa so neopredeljeni (3 %). Podoben vzorec opazimo pri odgovorih na trditev, da je komunikacije pri študiju na daljavo med predavatelji in študenti manj.



Slika 4. Mnenja študentov o izvedbi predavanj/vaj, če ne bi bilo pandemije. (n = 74)
Figure 4. Students' opinions on the implementation of the lectures / exercises if there were not a pandemic. (n = 74)



Slika 5. Komunikacija pri študiju na daljavo. (n = 74)
Figure 5. Communication in online learning. (n = 74)

4 RAZPRAVA IN ZAKLJUČEK
4 DISCUSSION AND CONCLUSION

Vse tri anketirane skupine (dijaki in študenti lesarstva ter drugi v lesni panogi) so najbolj motivirane v razvojnem okolju, ki teži k napredku in bi jih prisotnost novih konceptov, vsebin in vključevanje orodij industrije 4.0 zagotovo lahko motiviralo pri delu. Da bi bili čim uspešnejši v svojem poklicu, smo se na splošno začeli „specializirati‟ (Žorga, 1997), kar pomeni enostranski razvoj naših sposobnosti, ki pa ne omogoča celovitega osebnostnega razvoja. Ljudje se iz dneva v dan bolj zavedajo, da je učenje za osebnostni razvoj in uspešno strokovno delovanje najboljši recept za ohranjanje konkurenčnosti na trgu dela (Cukor, 2019). Videti je, da ima veliko anketirancev visok timski duh, kar pomeni, da so pripravljeni deliti svoje znanje z drugimi in so pripravljeni druge podpreti ter jim pomagati pri njihovih nalogah (Burnett & James, 1994; Ibbetson & Newell, 1996). McHugh in Bennett (1999) domnevata, da timsko delo deluje kot protistrup proti nizki stopnji motivacije in morale. Na sploh pa si anketiranci želijo, da je delovno okolje varno in stabilno, vendar manj tekmovalno. Tekmovalno okolje ima lahko nekaj prednosti, npr. spodbudi inovacije, zmanjša brezbrižnost in lenobo, povečuje produktivnost tekmovalnih ljudi, prav tako pa nekaterim predstavlja zabavo in jim daje veselje. Vsekakor pa ima tudi veliko slabosti, kot so: (1) sabotiranje timskega dela in sodelovanja, (2) če je tekmovalnost vezana na odpuščanje, se lahko zmanjša morala zaposlenih, (3) ko posameznik ne zmaga, ga lahko to demotivira in nasploh zmanjša njegovo učinkovitost, (4) stalna primerjava je lahko naporna in sčasoma zmanjšuje motivacijo zaposlenih ter ustvarja stresno okolje vsem zaposlenim (Miller, 2014). Ugotovili smo, da bolj ko se anketiranci bližajo zaposlitvi, več motivacije jim predstavlja varno in stabilno okolje, tekmovalno okolje pa se jim zdi nespodbudno. Dijake pri rednem izobraževanju najbolj motivirajo boljše zaposlitvene možnosti, želja po znanju in karierni cilji, študente pa pridobitev potrebnih kompetenc za delo ter prav tako boljše možnosti zaposlitve, osebna rast in želja po znanju. Dijaki in študenti se torej izobražujejo, ker si želijo večjih zaposlitvenih možnosti in nikakor ne zaradi izogibanja zaposlitvi. Tistim, ki pa se ne izobražujejo več redno, največjo motivacijo pri vseživljenjskem izobraževanju predstavlja večje zadovoljstvo pri delu, osebna rast in boljši zaslužek. Manj pomembne se jim zdijo spodbude s strani družine in karierni cilji, ki dijake in študente zelo motivirajo.

Presenetili so nas odgovori študentov glede izvedbe predavanj oziroma vaj, saj se jim zdita načina izvedbe študijskih obveznosti v živo preko spleta in hibridno najmanj zanimiva. Res pa je, da je bil prehod zaradi pandemije Covid-19 nenaden in je bil študij vsaj na začetku izveden precej improvizirano (Kropivšek et al., 2021), študenti pa so bili prisiljeni delati od doma, kar je pomenilo tudi več sedenja pred računalnikom in opravljanja šolskih obveznosti preko spleta (Vamberger, 2020). Tako pozitivne kot negativne odzive študentov glede študija na daljavo navaja raziskava, v kateri je mnogo študentov imelo negativno mnenje o poučevanju na daljavo zaradi pomanjkanja socialnega življenja in ker so se ob tem počutili osamljene, hkrati pa so izrazili, da ne želijo biti ves čas doma, saj jih to demotivira (Mucci-Ferris et al., 2021). Dietinger (2003) pravi, da je vsak posameznik pri šolanju na daljavo socialno izoliran in da imajo tisti, ki svojih socialnih potreb ne zadovoljijo zunaj procesa izobraževanja, s takim izobraževanjem resne težave, kar je bilo med pandemijo ob zaprtju države še posebej prisotno. Glede na negativna mnenja, zabeležena v številnih raziskavah, nas ne preseneča, da bi večina študentov želela imeti vsa predavanja in vaje v živo na fakulteti ter da bi jih veliko na fakulteti želelo imeti vsaj praktične predmete oziroma vaje. Znaten delež študentov bi se želel o načinu izvedbe študijskih obveznosti dogovoriti sproti. Študij na daljavo je trenutno v veliki meri nepriljubljen zaradi epidemije, saj je veliko razlogov za nepriljubljenost povezanih prav z njo. Študenti si želijo kakovostno dvosmerno komunikacijo, saj ta izboljša sprejemanje informacij, njihovo izmenjavo ter zaznavanje drugačnih mnenj (Jereb & Ferjan, 2007). Večina študentov lesarstva meni, da je dvosmerne komunikacije pri študiju na daljavo manj kot pri klasičnem študiju, saj virtualno okolje otežuje postavljanje vprašanj oz. izmenjave mnenj. To vsekakor ni spodbudno za učeče se, zato mora učitelj, ki izvaja študij na daljavo, premišljeno podajati snov. Pomembno je, da učečim se omogoči komuniciranje in jih vsestransko spodbuja in vzpostavi okolje, kjer vsi skupaj rešujejo probleme, si izmenjujejo mnenja, nove ideje ter gradijo medsebojne odnose (Jereb & Ferjan, 2007).

Z večjo interaktivnostjo bi lahko izboljšali dvosmerno komunikacijo med udeleženci pri klasičnem načinu in pri izobraževanju na daljavo. Tu bi si lahko pomagali z novimi sodobnimi digitalni tehnologijami (Goropečnik, 2021). Te tehnologije bi bile lahko spodbudne za mlajše generacije, pri katerih tradicionalni pristopi postajajo neučinkoviti in se jim zdijo odvečni (Postolov et al., 2017). Kot kaže pri vseh generacijah, ki se izobražujejo na področju lesarstva, prevladuje motivacija, ki izhaja iz notranjih spodbud posameznika. To je dobro, saj so zunanji motivi običajno šibkejši kot notranji in lahko hitro usahnejo (Brečko, 1996). Hkrati ne smemo prezreti, da so tudi zunanji motivi pogosto potrebni in učinkoviti, saj nam pomagajo, da lažje opravimo naloge, ki so nam neprijetne in celo dolgočasne ter od nas zahtevajo veliko truda in vztrajnosti (Kure, 2019). Med zunanjimi motivi pri izobraževanju v lesarstvu največjo motivacijo predstavlja boljša možnost zaposlitve/boljši zaslužek. Ko želimo motivirati sebe ali druge, je dobro vedeti, kateri zunanji motivator je za nas ali drugega najbolj učinkovit, saj se s tem lahko hitreje približamo ciljem, ki jih želi doseči posameznik ali skupina (Kure, 2019). Ker je bila naša anketa zaprtega tipa in so bili anketiranci z odgovori omejeni, bi bilo v prihodnje potrebno izvesti raziskavo tudi brez v naprej postavljenih odgovorov, morda tudi v obliki intervjujev. Prav tako bi v prihodnje lahko posvetili več pozornosti željam in pričakovanjem učečih se v lesarstvu. Upoštevati moramo, da smo ljudje različni in da so zato za posameznike in skupine različni tudi zunanji motivatorji. Rezultati te raziskave kažejo, da bi veljalo tovrstne raziskave izvajati kontinuirano, saj bi samo na takšen način lahko izobraževalni proces sproti prilagajali potrebam različnih generacij učečih.

5 POVZETEK
5 SUMMARY

The current development of technology is leading to major changes in the business world and society in general. The world is at the beginning of a new industrial revolution, Industry 4.0, which is not only a revolution of machines and technologies, but will also significantly change the profiles of employees and their necessary competencies in the wood sector (IN4WOOD, 2017). The lack of digital competences is one of the major problems faced by the current business environment in woodworking enterprises (Kropivšek, 2018). Educational institutions in the wood sector will have to respond to current developments, as they will have to offer up-dated contents and, above all, change existing educational concepts and methods which should be supported with new technologies and services. The introduction of new technologies and educational methods has a great impact on all areas of the educational process. Among the most important ones is to ensure the high motivation of the learners, as a lack of motivation is a major barrier in education, leading to frustration and discomfort, and it is also a long-term obstacle to productivity and well-being (Legault et al., 2006). Generation Z currently makes up most of the population in full-time education, while most people just entering the labour market are members of the Generation Y. These generations are different from the previous ones as they have been exposed to modern technologies and the internet practically from birth, and are therefore less responsive to the traditional delivery of lectures as they are used to greater interactivity. With the development of new technologies, traditional educational approaches seem to become obsolete, inefficient or even redundant for the younger generations (Postolov et al., 2017). Therefore, changes in education are also crucial to equip future employees with the appropriate skills that the wood sector will need in the future. The incorporation of modern contents and technologies would make the educational process more dynamic, interactive and, above all, effective, especially for younger people (Innovae, 2021).

The main objective of the present research is to find out which teaching and learning ways motivate learners in the wood sector the most, both in full-time education (from vocational training to higher education) with most learners from generation Z, and in lifelong learning (mainly generation Y). We also wanted to find out what type of teaching the students like, and what was their experience with online learning.

The results showed that the learners in the wood sector are most motivated in an environment that strives for development and teamwork and is safe and stable. A competitive environment does not motivate either generation, and is even less motivating if the students are close to employment or are already employed. We found that the most important reasons for education are better

employment opportunities, personal growth, and acquiring the skills needed for work. The greatest motivation for those in the process of lifelong learning is greater job satisfaction. Students in the wood sector prefer to fulfil their study obligations in-person at the faculty, with exception of few who think that theoretical subjects and topics could take place online. A small number of students would like to have an influence on the way the individual courses take place. The experience of the pandemic is probably the main reason why online learning was less popular. Two-way communication, which is desirable and important for students, was also limited during distance learning, and this was missed by both students and lecturers during the pandemic. With more interactivity, during both traditional teaching and distance learning, two-way communication could be improved, and this could be achieved with today's digital technologies. Especially for the younger generations, such technologies could also be a great motivation to work better. The results indicate that in all generations educated in the wood and furniture sector most motivation is from internal stimuli, which is good since external stimuli are in principle weaker and can suddenly disappear (Brečko, 1996). Nevertheless, external motivation can be very effective, as it helps us to perform tasks which we consider inconvenient or even boring. When we want to motivate ourselves or others, it is good to know which external stimuli are the most effective, as this can help us to achieve our own personal goals or those of a group (Kure, 2019). In the future, we should also pay more attention to students' expectations and desires. It is good to know that everyone is different and that external motivators can also be different for each of us. It would thus be useful to do continuous research on motivation and teaching, to better address the needs of the different generations of learners.

ZAHVALA
ACKNOWLEDGEMENT

Raziskave je finančno podprla Javna agencija za raziskovalno dejavnost Republike Slovenije (ARRS), v okviru programa Les in lignocelulozni kompoziti (P4-0015). Del raziskave je bil opravljen v okviru Erasmus+ projekta Allview (GA: 621192-EPP-1-2020-1-ES-EPPKA3-VET-COVE).

VIRI
REFERENCES

1KA (2021). Spletne ankete. (06.10.2021). https://www.1ka.si/

Anderson, D. R., Sweeney, D. J., & Williams, T. A. (2015). Essentials of modern business statistics with Microsoft Office Excel (6th ed.). Cengage Learning.

Berkup, S. B. (2014). Working With Generations X And Y In Generation Z Period: Management Of Different Generations In Business Life. Mediterranean Journal of Social Sciences, 5(19), 218–229. DOI: https://doi.org/10.5901/mjss.2014.v5n19p218

Brečko, D. (1996). Motivacija pri izobraževanju na daljavo. Andragoška Spoznanja, 2(1). DOI: https://doi.org/10.4312/as.2.1.22-32

Buckley, R., Beu, S. D., Novicevic, M. M., & Sigerstad, D. T. (2001). Managing Generation NeXt: Individual and Organizational Perspectives. Review of Business. 22(1/2), 5.

Burnett, D., & James, K. (1994). Using the Outdoors to Facilitate Personal Change in Managers. Journal of Management Development, 13(9), 14–24.

Crampton, S. M., & Hodge, J. W. (2009). Generation Y: Unchartered Territory. Journal of Business & Economics Research, 7(4), 6.

Cukor, M. (2019). Supervizija kot podpora za osebnostni in profesionalni razvoj. Univerza v Ljubljani.

Davies, R. (2015). Industry 4.0 Digitalisation for productivity and growth.

Dietinger, T. (2003). Aspects of E-Learning Environments. University of Technology.

Dimock, M. (2019). Where Millennials end and Generation Z begins. Pew Research Center. https://www.pewresearch.org/fact-tank/2019/01/17/where-millennials-end-and-generation-z-begins/

Facebook (2021). Spletna platforma. (07.10.2021). https://www.facebook.com/

Ferguson, D. (2020). Children are reading less than ever before, research reveals. The Guardian. https://www.theguardian.com/education/2020/feb/29/children-reading-less-says-new-research

Goropečnik, L. (2021). Strategije in modeli za uskladitev izbranih učnih vsebin in konceptov med poklicnim in visokošolskim izobraževanjem v lesarstvu. Magistrsko delo, Oddelek za lesarstvo, Biotehniška fakulteta, Univerza v Ljubljani.

Hattie, J., & Timperley, H. (2007). The Power of Feedback. Review of Educational Research, 77(1). DOI: https://doi.org/10.3102/003465430298487

Hitt, M. A., Black, S., & Porter, L. W. (2009). Management (2nd ed.). Pearson Prentice Hall.

Ibbetson, A., & Newell, S. (1996). Winner Takes all. Management Learning, 27(2). DOI: https://doi.org/10.1177/1350507696272001

IN4WOOD (2017). Industry 4.0 for Wood and Furniture Manufacturers. Training Path and Learning Content.

Innovae (2021). Innovae - Industry 4.0 and Augmented and Virtual Reality. (06.10.2021). https://www.innovae.eu/en/industry-40-augmented-and-virtual-reality/

Jereb, E., & Ferjan, M. (2007). Socialni vidiki izobraževanja po internetu. Socialno Delo, 46(4/5), 213–220.

Košmelj, K. (2007). Uporabna statistika. Druga dopolnjena izdaja. Ljubljana, Biotehniška Fakulteta. 239.

Kropivšek, J. (2018). Konceptualni model digitalizacije izobraževanja: Primer visokošolskega izobraževanja v lesarstvu v Sloveniji. Les/Wood, 67(2). DOI: https://doi.org/10.26614/les-wood.2018.v67n02a06

Kropivšek, J., Jošt, M., Oblak, L., Zupančič, A., Kitek Kuzman, M., & Goropečnik, L. (2021). Challenges of the transition to the on-line educational process during the pandemic. In JOšt, M. & Bertoncelj, J. (Eds.), The response of forest-based sector to changes in global economy (pp. 229–238). International Association for Economics and Management in Wood Processing and Furniture Manufacturing - WoodEMA, i.a.

Kure, M. (2019). Motivacija - kako se motivirati, tudi ko nimaš motivacije? Inštitut Za Neodvisnost. (19.10.2021) https://neodvisnost.si/motivacija-kako-se-motivirati-tudi-ko-nimas-motivacije/

LaBelle, J. E. (2005). The Paradox of Safety Hopes and Rewards. Professional Safety, 36(3), 37–42.

Legault, L., Green-Demers, I., & Pelletier, L. (2006). Why do high school students lack motivation in the classroom? Toward an understanding of academic amotivation and the role of social support. Journal of Educational Psychology, 98(3). DOI: https://doi.org/10.1037/0022-0663.98.3.567

Maulina, H., Abdurrahman, A., Sukamto, I., Kartika, N., & Nurulsari, N. (2020). Z-generation learner characteristic and expectation in the RI 4.0 era: a preliminary research in physics teacher college in Lampung. Journal of Physics: Conference Series, 1572, 6. DOI: https://doi.org/10.1088/1742-6596/1572/1/012091

Mchugh, M., & Bennett, H. (1999). Introducing teamworking within a bureaucratic maze. Leadership & Organization Development Journal, 20(2), 81–93.

Miller, B. (2014). Does Competition Among Employees Work as a Motivator? HR Management & Compliance, Learning & Development. https://hrdailyadvisor.blr.com/2014/12/12/does-competition-among-employees-work-as-a-motivator/

Moodle (2021). Spletna učilnica. (07.10.2021). https://moodle.org/

Možina, S., Rozman, R., Glas, M., Tavčar, M., Pučko, D., Kralj, J., Ivanko, Š., Lipičnik, B., Gričar, J., Tekavčič, M., Dimovski, V., & Kovač, B. (2002). Management: nova znanja za uspeh (Možina, S. (Ed.)). Didakta.

Mucci-Ferris, M., Grabsch, D. K., & Bobo, A. (2021). Positives, Negatives, and Opportunities Arising in the Undergraduate Experience During the COVID-19 Pandemic. Journal of College Student Development, 62(2). DOI: https://doi.org/10.1353/csd.2021.0017

OpenLearn (2014). Motivation and factors affecting motivation: 3 Definitions and dimensions of motivation. (06.10.2021). https://www.open.edu/openlearn/health-sports-psychology/motivation-and-factors-affecting-motivation/content-section-3

Oxford living dictionaries (2021). Lexico. (06.10.2021). https://www.lexico.com/definition/millennial

Postolov, K., Magdinceva Sopova, M., & Janeska Iliev, A. (2017). E-learning in the hands of generation Y and Z. Poslovna Izvrsnost - Business Excellence, 11(2). DOI: https://doi.org/10.22598/pi-be/2017.11.2.107

Rozman, R., & Kovač, J. (2012). Motiviranje. In Kozarov, A. (Ed.), Management (pp. 410–420). GV Založba.

Schwab, K. (2015). The Fourth Industrial RevolutionWhat It Means and How to Respond. Foreign Affairs. https://www.foreignaffairs.com/articles/2015-12-12/fourth-industrial-revolution

Šenk, R. (2021). Izobraževanje in usposabljanje generacije Y in Z v lesarstvu. Diplomsko delo, Oddelek za lesarstvo, Biotehniška fakulteta, Univerza v Ljubljani.

Sharf, S. (2015). What Is A “Millennial” Anyway? Meet The Man Who Coined The Phrase. Forbes. https://www.forbes.com/sites/samanthasharf/2015/08/24/what-is-a-millennial-anyway-meet-the-man-who-coined-the-phrase/?sh=611c89994a05

Skinner, E. A., & Belmont, M. J. (1993). Motivation in the classroom: Reciprocal effects of teacher behavior and student engagement across the school year. Journal of Educational Psychology, 85(4). DOI: https://doi.org/10.1037/0022-0663.85.4.571

The Economist. (2019). Generation Z is stressed, depressed and exam-obsessed. https://www.economist.com/graphic-detail/2019/02/27/generation-z-is-stressed-depressed-and-exam-obsessed

Tulgan, B. (2013). Meet Generation Z: The second generationwithin the giant “Millennial” cohort. Rainmaker Thinking, 13.

Turner, A. (2015). Generation Z: Technology and Social Interest. The Journal of Individual Psychology, 71(2). DOI: https://doi.org/10.1353/jip.2015.0021

Vamberger, T. (2020). Opinions and Responses of Primary School Students about Teleworking. Challenges and New Opportunities of Distance Learning, 60–75.

Žorga, S. (1997). Odprte dileme ob izvajanju profesionalne supervizije : funkcije supervizije in kako jo izvajati. Socialno Delo, 36(1), 10.

LES/WOOD Vol. 70, No. 2, 99-109
DOI: https://doi.org/10.26614/les-wood.2021.v70n02a08

DIETER ECKSTEIN, 1939-2021 AND HIS RICH LEGACY OF DENDROCHRONOLOGY IN SLOVENIA AND THE WORLD

DIETER ECKSTEIN, 1939-2021 IN NJEGOVA BOGATA ZAPUŠČINA ZA DENDROKRONOLOGIJO V SLOVENIJI IN PO SVETU

Katarina Čufar[1*]

Abstract / Izvleček

Abstract: Prof. Dr. Dieter Eckstein (1939-2021) was a leading scientist, teacher, mentor, leader, promoter and motivator in the field of dendrochronology and wood biology. After graduating in wood science and receiving a PhD in dendrochronology, he was professor of wood biology at the University of Hamburg. From 1995-2004, he was Director of the Department of Wood Biology, University of Hamburg, and of the Institute of Wood Biology and Wood Protection at the Federal Research Centre for Forestry and Forest Products in Hamburg, Germany. His work had a decisive influence on the development of wood anatomy, wood biology and dendrochronology and his laboratory was a reference point for dendrochronology worldwide. He supported dendrochronologists throughout Europe and around the world in their pioneering work to establish dendrochronology laboratories and develop dendrochronology in numerous countries, including Slovenia.

Keywords: dendrochronology, wood biology, wood anatomy, tree-ring chronologies, dendrochronology community

Izvleček: Prof. dr. Dieter Eckstein (1939-2021) je bil vodilni znanstvenik, učitelj, mentor, vodja in motivator na področju dendrokronologije in biologije lesa. Po diplomi iz lesarstva in doktoratu iz dendrokronologije je deloval kot univerzitetni profesor za biologijo lesa na Univerzi Hamburg. Med leti 1995-2004 je bil vodja Ordinariata za biologijo lesa, Univerze Hamburg in direktor Inštituta za biologijo in zaščito lesa pri Zveznem raziskovalnem centru za gozdarstvo in lesarstvo v Hamburgu. Njegovo delo je imelo ključen vpliv na razvoj anatomije in biologije lesa ter dendrokronologije, njegov laboratorij pa je bil referenčna točka za dendrokronologijo v svetovnem merilu. V svoji karieri je podpiral ustanavljanje novih dendrokronoloških laboratorijev in promocijo dendrokronologije v številnih državah po Evropi in svetu, tudi v Sloveniji.

Ključne besede: dendrokronologija, biologija lesa, anatomija lesa, kronologije širin branik, dendrokronološka skupnost

1 DIETER ECKSTEIN A SCIENTIST, TEACHER AND LEADER

1 DIETER ECKSTEIN ZNANSTVENIK, UČITELJ IN VODJA

The worldwide dendrochronology community mourns the loss of Prof. Dr. Dieter Eckstein (March 15, 1939 - November 10, 2021), our teacher, professor, leader, mentor, supporter, outstanding scientist and motivator, colleague, and above all, a good friend. The community extends its deepest condolences to his wife Ursula Eckstein, his son Prof. Dr. Lutz Eckstein and family, as well as to all

Figure 1. Dieter Eckstein, Eurodendro 2015, Antalya, Turkey.
Slika 1. Dieter Eckstein, Eurodendro 2015, Antalya, Turčija.

[1] University of Ljubljania, Biotechnical Faculty, Department of Wood Science and Technology, Jamnikarjeva 101, 1000 Ljubljana, Slovenia
[*] e-mail: katarina.cufar@bf.uni-lj.si

other relatives and friends around the world.

Because of Dieter's leading role in dendrochronology and wood biology, several articles in memoriam are in preparation. This is just an attempt to remember him as a person, and to report on his immense support of dendrochronology in Slovenia.

Dieter was born into a family of foresters in Glashütten in Germany (Sass-Klaassen, 2005). He graduated in wood science at the University of Hamburg and did his thesis in the field of wood pathology in the laboratories at Reinbek Castle, Germany, at that time.

Early in his career, Dieter Eckstein, in collaboration with Prof. Dr. Josef Bauch and Prof. Dr. Walter Liese, began to work on crucial issues in dendrochronology and wood biology, such as the dating of oak wood from Northern Germany and of panels used by Dutch painters (Bauch et al., 1967; Bauch & Eckstein, 1970). His dissertation "Development and application of dendrochronology for the age determination of the Viking settlement of Hedeby (Haithabu) in Schleswig, Northern Germany" (Eckstein, 1969), supervised by Walter Liese, led to the absolute dating of Haithabu (Eckstein, 1976) and resulted in the development and wide application of dendrochronology in Northern Germany and the wider region as well as invention and wide application of dendroprovenancing (e.g. Wazny & Eckstein, 1987, 1991).

Dieter was one of the inventors of digital techniques in dendrochronology (Eckstein & Bauch, 1969) and contributed to early application of histometric techniques for quantitative wood anatomy (Liese et al., 1975). This pioneering work had a decisive influence on the development of our current understanding of wood biology, particularly quantitative wood anatomy (e.g., Sass & Eckstein, 1994, 1995; Sander et al., 1996; Garcia Gonzalez & Eckstein, 2003) and dendrochronology. The early work was just the prelude to many years of Dieter's successful scientific career, which produced around 300 publications (Wazny, 2021; Bibliography of dendrochronology WSL, 2021; Scopus, 2021; Thuenen, 2021).

Figure 2. Dieter Eckstein with colleagues dendrochronologists 1983, Athens, Greece.
Slika 2. Dieter Eckstein z dendrokronologinjami in dendrokronologi, 1983, Atene, Grčija.

In the 1970s, the Institute of Wood Biology under the direction of Walter Liese and the auspices of the University of Hamburg and the Federal Research Centre for Forestry and Forest Products (BFH), became one of the world's leading centres for wood biology. Within the Institute was the Dendrochronological Laboratory under Dieter's direction. This laboratory became a popular meeting place for many young scientists engaged in pioneering dendrochronology throughout Europe and worldwide. Between 1993 and 2004 Dieter Eckstein served as Director of the Department of Wood Biology (University of Hamburg), and Director of the Institute of Wood Biology and Wood Conservation (Federal Research Institute for Forestry and Forest Products). From 2000 to 2003 he was also Director General of the Forest Research Centre in Hamburg. Despite the burden of administrative work, he remained a scientist, professor and mentor to his growing dendro family.

Dieter was a teacher, supervisor of numerous doctoral students from Germany and around the world, served as a sought-after reviewer and member of doctoral dissertation committees. He also did tremendous work as an editor and reviewer. He contributed to the development of the scientific journals, especially *Dendrochronologia* (c.f. Eckstein & Wobel, 1983), *Tree-Ring Bulletin* (now *Tree-Ring Research*), and the *IAWA Journal*.

Dieter was involved with the worldwide dendro community and served the Tree Ring Society (TRS) and supported World Dendro Conferences. Of note here is the 1994 International Conference on Tree Rings, Environment and Humanity in Tucson, Arizona, which brought together the worldwide dendro community (Dean et al., 1996). At the 7th International Conference on Dendrochronology - Cultural Diversity, Environmental Variability in Beijing, China (Zhang & Shao, 2007), Dieter Eckstein received a lifetime achievement award for tree ring research. In China, he had a particularly fruitful collaboration with Eryuan Liang, addressing many original questions and applications of dendrochronology (e.g. Liang and Eckstein, 2006; Liang et al., 2014).

Dieter also attended the 8th International Conference on Dendrochronology - WorldDendro 2010 in Rovaniemi, Finland (Eckstein & Cherubini, 2012), the area where he supported extensive research on trees from boreal environments together with Risto Jalkanen, Jeong Wook Seo and Uwe Schmitt (e.g. Seo et al., 2013 and the references therein).

Dieter also met with colleagues and an ever-expanding network of students and investigators at Eurodendro conferences (Figures 1, 5, 8), established as a common platform for the diverse community of tree-ring researchers in Europe and beyond (Čufar, 2007). Dieter and Sigrid Wrobel were the motivating spirits of the Eurodendro conferences, twenty of which were organized between 1989 and 2018. In almost all of them he was a member of the scientific, advisory or the organizing committee and provided a great deal of support to the local organizers (e.g., Eckstein, 2006). Dieter, Sigrid, and colleagues organized two Eurodendro conferences in Northern Germany: in Travemünde (1994) and Rendsburg (2004), the latter to celebrate Dieter's retirement which was attended by his numerous friends from all over the world (Sass-Klaassen, 2005).

Dieter officially retired in 2004, but he remained active and his laboratory continued to be open to guests from all over the world. Dieter's extensive bibliography shows that despite "official retirement", he continued his personal and collaborative research with 53 wide-ranging articles and book chapters published from 2005-2020 (Wazny, 2021; Scopus, 2021). In addition, he continued to supervise doctoral students, serving as a sought-after editor, reviewer and member of doctoral dissertation committees and he continued to attend other events like World Dendro and Eurodendro conferences (Figure 8).

2 DIETER ECKSTEIN AND DENDROCHRONOLOGY IN SLOVENIA
2 DIETER ECKSTEIN IN DENDROKRONOLOGIJA V SLOVENIJI

My first encounter with Dieter Eckstein took place in 1985 during my stay as a PhD student in the group of Josef Bauch at the Institute of Wood Biology headed by Walter Liese. When studying silver fir dieback we came across the problem of missing and disappearing tree-rings, and it was clear that the problem could not be solved without dendrochronology and Dieter Eckstein.

After we examined the tree-ring series printed on rolls of paper on a light table, he confirmed that our trees had numerous missing rings. This changed the research plan of my dissertation, shifting the methodology of stem analysis (Čufar, 1990). The encounter with dendrochronology was both difficult and exciting because the work in Slovenia had to be done without any specialized hardware and software, at a time when personal computers and user-friendly dendrochronology programs were not widely available. The missing rings therefore helped me to get to know Dieter and his group, as well as his PhD students and numerous guests from all over the world, many of whom became leading scientists.

In 1993, when researchers of Slovene cultural heritage, forest restoration, and archaeology realized that Slovenia needed dendrochronology, we started to set up the dendrochronology laboratory at the Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana. Dieter helped us a lot with advice and action. In 1994 he visited the emerging dendro-lab in Ljubljana, which in the meantime had gained a new PhD student, Tom Levanič.

With Tom Levanič, we will never forget the Eurodendro 1994 in Travemünde, Germany, organized by Dieter Eckstein and Sigrid Wrobel. We met a community there that was dealing with similar issues and frustrations and, most importantly, enthusiasm for dendrochronology. After the conference, many participants visited Dieter's laboratory in Hamburg and many of them stayed in the house of Dieter and Ursula Eckstein (Figure 4). In this way we became members of the dendro family with Dieter and Ursula as dendro father and dendro mother. Many of us became regular guests in Dieter's laboratory and often guests in their home. In the laboratory we got to know PhD students, including Ute Sass, Constantin Sander, Nathsuda Pumijumnong, and many others from Germany and all over the world (Figure 3).

Most of us regularly attended Eurodendro conferences in the following years and many of us also organized them so they took place in a different country each time. Our team organized Eurodendro 2001 in Gozd Martuljek, Slovenia (Figure 5).

With Dieter, we established a collaboration that included student and professional exchanges

Figure 3. Dieter and Ursula Eckstein with guests in front of their house on Husumerstrasse 63 in Reinbek, November 2006.
Slika 3. Dieter in Ursula Eckstein z gosti, pred njuno hišo, Husumerstrasse 63, Reinbek, Nemčija, novembra 2006.

(Figures 6). The Institute of Wood Biology hosted many PhD and graduate students from Slovenia. Dieter was a member of doctoral disputation committees of Tom Levanič and Jožica Gričar in Ljubljana (Figure 7) and our team had the opportunity to meet and co-supervise Dieter's students, especially Birgit Schichler (Schichler et al., 1997) and be part of doctoral committees of Micha Beuting, Jeong Wook Seo and Claus Frankenstein.

To serve the needs of environmental and archaeological research, the initial primary goal of Slovene dendrochronology was to develop a long reference chronology for oak. Initial attempts to build a chronology were not encouraging. The obstacles, including a unique dendrochronological signal and the lack of teleconnection, were similar to those Dieter had encountered during his pioneering work in Northern Germany. In Slovenia, it took us almost 15 years to establish a 548-year tree-ring chronology of oak, which was reported in articles (Čufar et al., 2008a, b) we wrote during my extended stay in Hamburg in 2006. The chronology was useful for reconstructing climate and especially for dating buildings (Čufar et al., 2009). It took us another seven years to establish a chronology for prehistoric pile dwellings and to date them using a long-distance link with the combined Swiss-South German chronology (Čufar et al., 2015), and there is still a lot to be done in future.

A similar background in wood science with roots in wood anatomy and wood biology also

Figure 4. Coffee in the lab with guests, December 2006.
Slika 4. Pri jutranji kavi v laboratoriju z gosti, december 2006.

Figure 5. Dieter Eckstein and participants of Eurodendro 2001 in Ljubljana.
Slika 5. Dieter Eckstein in udeleženci Eurodendro 2001 v Ljubljani.

Figure 6. Dieter Eckstein with colleagues from the University of Hamburg and Tom Levanič and Katarina Čufar from the University of Ljubljana (left) and with his students (right) in Piran during the field trip in Slovenia in 1998.
Slika 6. Dieter Eckstein s kolegoma z Univerze Hamburg ter Tomom Levaničem in Katarino Čufar z Univerze v Ljubljani (levo) ter s svojimi študenti (desno) v Piranu, na strokovni ekskurziji v Sloveniji 1998.

Figure 7. Dieter Eckstein with the committee and the new doctor Jožica Gričar after the defence of her doctoral thesis in Ljubljana 2006.
Slika 7. Dieter Eckstein s komisijo in novo doktorico znanosti Jožico Gričar po zagovoru njenega doktorata v Ljubljani 2006.

Figure 8. On a field trip during World Dendro 2010, Rovaniemi, Finland (left), and Eurodendro 2015, Turkey (right).
Slika 8. Na ekskurziji v okviru konference World Dendro 2010, Rovaniemi, Finska (levo) in Eurodendro 2015, Turčija (desno).

connected us to Dieter through the development of the wood formation process as a basis to calibrate and interpret the information stored in tree rings. Our PhD students Jožica Gričar and Peter Prislan had the opportunity to develop this area with Dieter's colleagues Uwe Schmitt and Gerald Koch and their teams in Hamburg (e.g. Schmitt et al., 2016 and the literature therein). However, everything reported here is only a small part of Dieter's scientific output and contribution to the development of dendrochronology and wood biology in our country.

Dieter Eckstein was a great scientist and a great personality. Together with his colleagues Walter Liese, Josef Bauch, and others who shared the same values, he helped bring down the Iron Curtain and other barriers so that scientists from around the world could form a true community. Everyone who met Dieter considered him one of the best teachers and scientists. He was a wonderful person with no airs and graces. He lived for science and most of all for people who shared the same values and passions. All of us who were fortunate enough to be his students and colleagues will try to keep his spirit alive in our communities. Dieter's passing has brought his community together and this report has been written based on communication with many who have shared their warm memories of Dieter. We will miss him greatly.

3 SUMMARY

3 POVZETEK

Svetovna dendrokronološka skupnost žaluje, ker nas je zapustil prof. dr. Dieter Eckstein (15. marec 1939 - 10. november 2021), naš učitelj, profesor, mentor, vodja, podpornik, izjemni znanstvenik, motivator, kolega in prijatelj. Skupnost izreka najgloblje sožalje njegovi ženi Ursuli Eckstein, sinu prof. dr. Lutzu Ecksteinu in družini ter vsem drugim sorodnikom in prijateljem.

V tem prispevku se ga želimo spomniti predvsem kot vodilnega znanstvenika, učitelja in vodje ter podpornika dendrokronologije v Sloveniji.

Dieter Eckstein se je rodil v družini, kjer je bil oče gozdar, v kraju Glashütten v Nemčiji (Sass-Klaassen, 2005). Na Univerzi v Hamburgu je diplomiral iz lesarstva. Na začetku svoje kariere se je skupaj s prof. dr. Josefom Bauchom in prof. dr. Walterjem Liesejem ukvarjal s ključnimi vprašanji dendrokronologije in biologije lesa (Bauch et al., 1967; Bauch & Eckstein, 1970). Delo v okviru njegove disertacije "Razvoj in uporaba dendrokronologije za določitev starosti vikinške naselbine Haithabu v Schleswigu v severni Nemčiji" (Eckstein, 1969), kjer je bil njegov mentor Walter Liese, je privedlo do absolutne datacije naselbine Haithabu (Eckstein, 1976) ter do razvoja in široke uporabe dendrokronologije v severni Nemčiji in širši regiji ter kasneje do izuma in široke uporabe metode dendroprovenience.

Dieter je pripomogel k uvedbi digitalnih tehnik v dendrokronologiji (Eckstein & Bauch, 1969) in prispeval k zgodnji uporabi histometričnih tehnik v anatomiji lesa (Liese et al., 1975). To pionirsko delo je bilo le uvod v dolgoletno uspešno znanstveno kariero, v kateri je objavil približno 300 publikacij (Wazny, 2021; Bibliography of dendrochronology, 2021; Scopus, 2021) kar je vplivalo na vsesplošni razvoj anatomije lesa, biologije lesa in dendrokronologije v naslednjih desetletjih.

V sedemdesetih letih prejšnjega stoletja je Inštitut za biologijo lesa na Univerzi v Hamburgu in Zvezni raziskovalni inštitut za gozdarstvo in gozdne proizvode (Bundesforschungsanstalt für Forst- und Holzwirtschaft - BFH) pod vodstvom Walterja Lieseja postal eden vodilnih svetovnih centrov za biologijo lesa. Del te zgodbe je bil tudi dendrokronološki laboratorij, ki ga je vodil Dieter Eckstein. Njegov laboratorij je postal priljubljeno zbirališče številnih mladih znanstvenikov, ki so bili pionirji pri uvajanju dendrokronologije v svojih državah po Evropi in po svetu. Med leti 1994 in 2004 je bil vodja Oddelka za biologijo lesa na Univerzi v Hamburgu, direktor Inštituta za biologijo in zaščito lesa pri Zveznem raziskovalnem centru za gozdarstvo in lesarstvo ter generalni direktor Gozdarskega raziskovalnega centra v Hamburgu. Tudi kot vodja je, kljub bremenu administrativnega dela, ostal znanstvenik, profesor in mentor široki dendrokronološki skupnosti.

Dieter je bil učitelj, mentor številnim doktorskim študentom doma in po svetu. Bil je iskan recenzent in član komisij za doktorske disertacije. Veliko delo je opravil tudi kot urednik in recenzent. Prispeval je k razvoju znanstvenih revij Dendrochronologia, Tree-Ring Bulletin (zdaj Tree-Ring Research) in IAWA Journal.

Dieter Eckstein je sodeloval s svetovno dendrokronološko skupnostjo tudi kot dejaven član društva Tree Ring Society. Podpiral je svetovne dendrokronološke konference, kjer velja omeniti konferenco v Tucsonu v Arizoni leta 1994 (Dean et al., 1996), v Pekingu na Kitajskem leta 2006 (Zhang & Shao, 2007) in leta 2010 v Rovaniemiju na Finskem (Eckstein & Cherubini, 2012).

Dieter Eckstein in Sigrid Wrobel sta bila glavna pobudnika in podpornika konferenc Eurodendro, na katerih se skupnost praviloma zbere vsako leto v drugi državi (npr. Čufar, 2007). Med leti 1989 in 2018 je bilo organiziranih dvajset konferenc Eurodendro. Dieter, Sigrid in sodelavci so v severni Nemčiji organizirali dve konferenci: v kraju Travemünde (1994) in Rendsburg (2004), slednjo ob Dieterjevi upokojitvi, ki so se je udeležili njegovi številni prijatelji in učenci z vsega sveta (Sass-Klaassen, 2005).

Dieter se je uradno upokojil leta 2004, vendar je ostal dejaven in njegov laboratorij je bil še naprej odprt za goste z vsega sveta. Obsežna bibliografija kaže, da je kljub uradni upokojitvi nadaljeval z raziskovalnim delom in samo v obdobju 2005-2020 objavil več kot 53 člankov in poglavij v knjigah (Wazny, 2021; Scopus, 2021). Poleg tega je še naprej vodil doktorske študente, bil iskan urednik, recenzent in član komisij za doktorske disertacije ter pobudnik drugih dogodkov.

Dieterja Ecksteina sem (avtorica tega prispevka) spoznala leta 1985, ko sem bila na izpopolnjevanju v skupini Josefa Baucha na Inštitutu za biologijo lesa v Hamburgu, ki ga je takrat vodil Walter Liese. Pri preučevanju umiranja jelke sem se srečala s pojavom manjkajočih in nepopolnih branik, problemom, ki ga je mogoče rešiti samo s pomočjo dendrokronologije. Ko je Dieter Eckstein na svetlobni mizi pregledal grafe zaporedij širin branik, ki smo jih takrat morali natisniti na dolge zvitke papirja, je potrdil, da imajo naša drevesa številne manjkajoče branike. To je preusmerilo metodologijo dela pri pripravi debelnih analiz za mojo doktorsko disertacijo (Čufar, 1990). Prvo srečanje z dendrokronologijo je bilo težavno in vznemirljivo, saj je bilo treba delo v Sloveniji opraviti brez specializirane strojne in programske opreme, kakršna je bila takrat že na voljo v Dieterjevem laboratoriju. Osebni računalniki in uporabnikom prijazni dendrokronološki programi takrat namreč še niso bili splošno dostopni. Manjkajoče branike so mi omogočile vstop v Dieterjevo skupino z zanimivimi sodelavkami in sodelavci, doktorskimi študentkami in študenti ter številnimi gostjami in gosti iz vsega sveta, od katerih so mnogi postali vodilni na področju lesarstva in dendrokronologije.

Leta 1993, ko so slovenski strokovnjaki s področja arheologije, restavratorstva in kulturne dediščine spoznali, da Slovenija potrebuje dendrokronologijo tudi za raziskave na področju kulturne dediščine, sem bila kot mlada doktorica znanosti povabljena k ustanovitvi dendrokronološkega laboratorija na Oddelku za lesarstvo Biotehniške fakultete Univerze v Ljubljani. Pri reševanju osnovnih vprašanj ob uvajanju dendrokronologije v Sloveniji je Dieter Eckstein nudil vsestransko pomoč. Leta 1994 je obiskal nastajajoči dendrokronološki laboratorij v Ljubljani, ki je medtem pridobil novega mladega raziskovalca Toma Levaniča.

S Tomom Levaničem ne bova nikoli pozabila prve udeležbe na konferenci Eurodendro 1994 v kraju Travemünde v Nemčiji, ki sta jo organizirala Dieter Eckstein in Sigrid Wrobel. Tam sva spoznala skupnost, ki se je ukvarjala s podobnimi vprašanji, reševala podobne težave in si delila navdušenje nad dendrokronologijo. Po konferenci je veliko udeležencev želelo obiskati laboratorij v Hamburgu in mnogi izmed njih so bili povabljeni, da so se za nekaj dni nastanili v hiši Dieterja in Ursule Eckstein ter tako postali člani dendrokronološke družine. Večina od nas se je v naslednjih letih redno udeleževala Eurodendro konferenc, mnogi pa smo jih tudi organizirali.

Mnogi med nami smo postali tudi redni gostje v Dieterjevem laboratoriju in pogosto tudi v družini Dieterja in Ursule v legendarni hiši na Husumerstrasse v Reinbeku. Spoznali smo Dieterjeve doktorske študentke in študente, kot so Ute Sass, Constantin Sander, Nathsuda Pumijumnong, in številne goste z vsega sveta.

Z Dieterjem in Univerzo v Hamburgu smo vzpostavili pedagoško sodelovanje in izmenjave študentk in študentov. Na Inštitutu za biologijo lesa v Hamburgu so se izobraževali naši Tom Levanič, Franc Ferlin, Primož Oven, Jožica Gričar, Peter Prislan in številne ERASMUS študentke in študenti. Dieter je bil član doktorskih komisij Toma Levaniča in Jožice Gričar v Ljubljani, sama pa sem imela možnost sodelovati pri diplomah Birgit Schichler (Schichler et al., 1997) in v komisijah doktorskih disertacij, ki so jih pripravili Micha Beuting, Jeong Wook Seo in Claus Frankenstein, če naštejem samo nekaj skupnih aktivnosti.

Eden glavnih ciljev slovenske dendrokronologije je bil razviti dolgo referenčno kronologijo širin branik hrasta. Prvi poskusi sestave kronologije niso bili spodbudni. Ovire, kot je poseben dendrokronološki signal in pomanjkanje telekonekcije, so bile podobne tistim, na katere je Dieter naletel med svojim pionirskim delom v severni Nemčiji. V Sloveniji smo potrebovali skoraj 15 let, da smo iz kronologij dreves in zgodovinskih objektov sestavili 548-letno kronologijo širin branik hrasta, članki o tem pa so bili pripravljeni med mojim zadnjim daljšim bivanjem v Hamburgu leta 2006 (Čufar et al., 2008a, b, 2009). Za vzpostavitev kronologije za prazgodovinske koliščarske naselbine in njihovo datiranje s pomočjo telekonekcije s kombinirano švicarsko-južnonemško kronologijo pa smo potrebovali še dodatnih 7 let (Čufar et al., 2015). Ob vsem tem nam veliko izzivov ostaja tudi za prihodnost.

Z Dieterjem Ecksteinom nas je povezovala skupna temeljna izobrazba, lesarstvo, s koreninami v anatomiji in biologiji lesa, zato smo sodelovali tudi pri proučevanju nastajanja lesa kot osnove za kalibracijo in interpretacijo informacij, shranjenih v branikah. Jožica Gričar in Peter Prislan sta kot doktorska študentka in študent imela priložnost razvijati to področje z Dieterjevima kolegoma Uwejem Schmittom in Geraldom Kochom ter njunimi ekipami v Hamburgu (npr. Schmitt et al., 2016 in tam navedena literatura). Vse to pa je le majhen del Dieterjevega znanstvenega dela in prispevka k razvoju dendrokronologije in biologije lesa v Sloveniji.

Dieter Eckstein je bil velik znanstvenik in velika osebnost. Skupaj s kolegi Walterjem Liesejem, Josefom Bauchom in drugimi raziskovalci iz Hamburga, ki so delili iste vrednote, je pripomogel, da je padla železna zavesa in druge ovire, tako da so znanstveniki z vsega sveta lahko zgradili pravo skupnost. Vsi, ki so Dieterja spoznali, so ga imeli za enega najboljših učiteljev in znanstvenikov. Bil je čudovit človek, ki je bil izredno skromen in preprost in se ni nikoli boril za lastno slavo in interese. Živel je za znanost in predvsem za ljudi, ki so delili iste vrednote in predanost znanosti. Vsi, ki smo imeli to srečo, da smo bili njegove učenke in učenci ter sodelavke in sodelavci, skušamo ohranjati in širiti to, kar nas je s svojim zgledom naučil. Novica, da se je Dieter Eckstein od nas za vedno poslovil, je ponovno povezala njegovo skupnost, to poročilo pa je nastalo ob pomoči številnih kolegic in kolegov, s katerimi delimo skupne spomine nanj. Zelo ga bomo pogrešali.

ACKNOWLEDGEMENTS
ZAHVALA

This report has been written based on communication with many who have shared their memories of Dieter. Many thanks to Sigrid Wrobel, Gerald Koch, Ute Sass Klaassen, Tomasz Wazny, Constantin Sander, Eryuan Liang, and Kevin Smith, who also helped with editing of the English text.

REFERENCES
VIRI

Bauch, J., Liese, W., & Eckstein, D. (1967). Über die Altersbestimmung von Eichenholz in Norddeutschland mit Hilfe der Dendrochronologie. Holz als Roh und Werkstoff, 25, 285-291.

Bauch, J., & Eckstein, D. (1970). Dendrochronological dating of oak panels of Dutch seventeenth-century paintings. Studies in Conservation, 15, 45-50.

Čufar, K. (1990). Električna upornost tkiv, prirastne značilnosti in odziv na poškodbe pri zdravih in obolelih jelkah = Electrical resistance of tissues, increment characteristics and response to injuries in healthy and diseased silver firs : doktorska disertacija. Ljubljana

Čufar, K., De Luis, M., Zupancic, M., & Eckstein, D. (2008a). A 548-year tree-ring chronology of oak (*Quercus* spp.) for southeast Slovenia and its significance as a dating tool and climate archive. Tree-Ring Research, 64 (1), 3-15.

Čufar, K., De Luis, M., Eckstein, D., & Kajfež-Bogataj, L. (2008b). Reconstructing dry and wet summers in SE Slovenia from oak tree-ring series. International Journal of Biometeorology, 52(7), 607-615.

Čufar, K., Zupančič, M., Krže, L., de Luis, M., & Eckstein, D. (2009). Dendrochronology of oak (*Quercus* spp.) in Slovenia – an interim report. Pages 132-135 In: T. Levanič, J. Gričar, P. Hafner, R. Kranjnc, S. Jagodic, H. Gartner, I. Heinrich, and G. Helle, eds., Tree Rings in Archaeology, Climatology and Ecology, Volume 8. Proceedings of the Dendrosymposium 2009. GFZ German Research Centre for Geosciences: Potsdam, Germany. Scientific Technical Report STR10/05.

Čufar, K., Tegel, W., Merela, M., Kromer, B., & Velušček, A. (2015). Eneolithic pile dwellings south of the Alps precisely dated with tree-ring chronologies from the north. Dendrochronologia 35: 91–98.

Čufar, K. (2007). Dendrochronology and past human activity—A review of advances since 2000. Tree-Ring Research, 63(1), 47-60.

Dean, J. S., Meko, D. M., & Swetnam, T. W. eds. (1996). Tree Rings, Environment, and Humanity: Proceedings of the International Conference, Tucson, Arizona, 17-21 May 1994, Radiocarbon, Department of Geosciences, University of Arizona, 1996 - 889 pp.

Eckstein, D. (1969). Entwicklung und Anwendung der Dendrochronologie zur Alterbestimmung der Siedlung Haithabu. Ph.D. dissertation, University of Hamburg, Germany, Hamburg, Germany. 113 pp.

Eckstein, D., & Bauch, J. (1969). Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. Forstwissenschaftliches Centralblatt, 88 (4), 230-250.

Eckstein, D. (1976). Die absolute Datierung der wikingerzeitlichen Siedlung Haithabu/Schleswig mit Hilfe der Dendrochronologie. Naturwissenschaftliche Rundschau, 29 (3), 81-84.

Eckstein, D., & Wrobel, S. (1983). Dendrochronologie in Europa. Dendrochronologia, 1, 9-20.

Eckstein, D. (2006). Human time in tree rings. In: K. Cufar, M. Romagnoli, and U. Sass-Klaassen, eds., EuroDendro 2005: Humans and Environment. Dendrochronologia, 24 (2-3), 53-60.

Eckstein, D., & Cherubini, P. (2012). The "dendrochronological community" at Rovaniemi, Finland, 2010: Lessons learned from the past and perspectives for the future. Dendrochronologia, 30 (2): 195-197.

Garcia Gonzalez, I., & Eckstein, D. (2003). Climatic signal of earlywood vessels of oak on a maritime site. Tree Physiology, 23(7), 497-504.

Liang, E., & Eckstein, D. (2006). Light rings in Chinese pine (*Pinus tabulaeformis*) in semiarid areas of north China and their palaeo-climatological potential. New Phytologyst, 171 (4), 783-791.

Liang, E., Liu., W., Ren, P., Dawadi, B., & Eckstein, D. (2014). The alpine dwarf shrub *Cassiope fastigiata* in the Himalayas: does it reflect site-specific climatic signals in its annual growth rings? Trees, 29 (1), 79-86.

Liese, W., Schneider, M., & Eckstein, D. (1975). Histometrische Untersuchungen am Holz einer rauchgeschädigten Fichte. European Journal of Forest Pathology, 5, 152-161.

Sander, C., Stiller, B., & Eckstein, D. (1996). A practical test of a new computer program for cell recognition. Dendrochronologia, 14, 241-245.

Sass, U., & Eckstein, D. (1994). Preparation of large thin sections and surfaces of wood for automatic image analysis. Holzforschung, 48(2), 117-118.

Sass, U., & Eckstein, D. (1995). The variability of vessel size in beech (*Fagus sylvatica* L.) and its ecophysiological interpretation. Trees, 9(5), 247-252.

Sass-Klaassen, U. (2005). Tribute to Dieter Eckstein at Eurodendro 2004. Dendrochronologia 22, 71–73.

Schichler, B., Levanič, T., Čufar, K., & Eckstein, D. (1997). Climate-growth relationship of fir in the Dinaric Mountains in Slovenia using different standardizations and response function calculations. Dendrochronologia, 15, 207-214.

Schmitt, U., Koch, G., Eckstein, D., Seo, J. W., Prislan, P., Gričar, J., Čufar, K., Stobbe, H., & Jalkanen, R. (2016). The vascular cambium of trees and its involvement in defining xylem anatomy. In: Kim, Y. S., Funada, R., P. Singh, A. P. Eds. Secondary Xylem Biology, Origins, Functions, and Applications. Academic Press, Elsevier, pp 3-24.

Seo, J.-W., Eckstein, D., Olbrich, A., Jalkanen, R., Salminen, H., Schmitt, U., & Fromm, J. (2013). Climate control of wood formation : illustrated for Scots Pine at its northern distribution limit. Plant Cell Monographs 20, 159-185.

Wazny, T., & Eckstein, D. (1987). Der Holzhandel von Danzig/Gdansk - Geschichte, Umfang, und Reichweite. Holz als Roh und Werkstoff, 45, 509-513.

Wazny, T., & Eckstein, D. (1991). The dendrochronological signal of oak (*Quercus* spp.) in Poland. Dendrochronologia, 9, 35-49.

Zhang, Q.-B., & Shao, X. (2007). Tree Rings and Ecology: The 7th International Conference on Dendrochronology. Journal of Integrative Plant Biology, 49, 129-130.

INTERNET SOURCES / INTERNETNI VIRI

Bibliography of dendrochronology WSL, https://www.wsl.ch/dendro/products/dendro_bibliography/index_EN (4 Dec. 2021)

Scopus, Bibliography Dieter Eckstein, https://www.scopus.com (4 Dec. 2021)

Thuenen institute, Bibliography Dieter Eckstein, https://www.thuenen.de/index.php?id=609&L=0&keywords=eckstein&ACT&S=Jahr&p=1 (4 Dec. 2021)

Wazny, T. (2021). [ITRDBFOR] Dieter Eckstein 1939-2021, International dendrochronology discussion list - arc – itrdbfor
https://itrdbfor.org/wws/info/itrdbfor (10 Nov. 2021)

Prof. Dr. Leon Oblak received the WoodEMA International Association Annual Award

Prof. dr. Leon Oblak – prejemnik priznanja mednarodne asociacije WoodEMA

Denis Jelačić

The Association for Economics and Management in Wood Processing and Furniture Manufacturing, WoodEMA, i.a., is an international, non-political, non-profit and open scientific association. The aim of the association is to promote science and the results of the scientific and professional work of its members, mutual scientific cooperation, as well as to support science and professional development in the areas of work of the association. WoodEMA, i.a. was founded in 2007, and nowadays it has members whose fields of interest cover a wide range of economic and management aspects in relation to forestry, wood processing and furniture manufacturing. The association has members on three continents, from the USA to India and Malaysia, and in Europe from Spain to Russia and from Finland to North Macedonia.

Each year, WoodEMA, i.a. awards a “Roy Damary Scholarship” to young scientists and, in accordance with the statutes of the association, may also give special recognition to outstanding members who have contributed to the scientific and professional development of the association. In the fourteen years since WoodEMA’s inception, this recognition has only been given once. This year, however, the second recipient was named as Prof. Dr. Leon Oblak.

Prof. Dr. Oblak is a distinguished member of WoodEMA, i.a., he is one of the founders of the association and he has been a very active member from the very beginning, starting in 2007. The Executive Board and the General Assembly of the association unanimously elected him as the first president of the association for a two-year term (2007-2009) due to his outstanding scientific and professional work, due to many highly recognized articles in journals and at many scientific conferences worldwide, and due to his pedagogical work in the subject areas of the association at the Department of Wood Science and Technology of the Biotechnical Faculty at the University of Ljubljana. His outstanding work in the association was recognized by the members, who elected him as a member of WoodEMA Executive Board for four consecutive mandates (2009-2015). Since January 1, 2020 he has been one of the three members of the newly established Supervisory Board of WoodEMA i.a., a post he gained by election.

Prof. Dr. Oblak has actively participated in every kind of activity engaged in by WoodEMA, i.a. (conferences, general assembly meetings, executive board meetings, supervisory board meetings, informal meetings, promotional activities of the association, recruitment of new members for the association), and is one of the few members who has attended all fourteen WoodEMA conferences. He was one of the first members of the association from Slovenia, and he attracted other scientists from the Biotechnical Faculty to become full members. In addition to actively participating with articles and presentations in every WoodEMA annual international scientific conference, Prof. Dr. Oblak has also contributed chapters to scientific books published by WoodEMA, i.a.

Prof. Dr. Oblak suggested on two occasions that the scientific conference WoodEMA should be organized in Slovenia, and the association's general assembly accepted his proposals both times. Thus he was the head of the organizing committees for the WoodEMA conference in 2011, which was held in Kozina under the title "Wood processing and furniture manufacturing: present conditions, opportunities and new challenges", and the WoodEMA conference in 2021, which was held in Koper under the title "The response of the forest-based sector to changes in the global economy". Prof. Dr. Oblak and his team from the Department of Wood Science and Technology of the Biotechnical Faculty received high marks for their work on both occasions.

For all the above reasons and many others, for all his efforts and dedicated work for the benefit of the association, the International Association for Economics and Management in Wood Processing and Furniture Manufacturing presented the WoodEMA, i.a. Annual Award for significant contributions to the development of the association to Prof. Dr. Leon Oblak.

Združenje za ekonomiko in management v predelavi lesa in pohištvu WoodEMA, je mednarodna, nepolitična, neprofitna in odprta znanstvena asociacija. Cilj združenja je promocija znanosti in rezultatov znanstvenega in strokovnega dela svojih članov, medsebojno znanstveno sodelovanje ter podpora znanosti in strokovnemu razvoju na področju dela asociacije. Združenje WoodEMA je bilo ustanovljeno leta 2007, danes pa ima člane, ki delujejo na širokem spektru ekonomskih in managerskih področij v gozdarstvu, predelavi lesa in proizvodnji pohištva. Združenje ima člane na treh celinah, od ZDA do Indije in Malezije ter v Evropi od Španije do Rusije ter od Finske do Severne Makedonije.

Vsako leto združenje WoodEMA podeli "štipendijo Roy Damary" za mlajše raziskovalce, v skladu s svojim statutom pa lahko podeli tudi posebno priznanje asociacije uglednim članom, ki so pomembno prispevali k znanstvenemu in strokovnemu razvoju združenja. V štirinajstih letih, odkar je bilo združenje WoodEMA ustanovljeno, je bilo to priznanje podeljeno samo enkrat. Letos pa je drugi prejemnik tega priznanja postal prof. dr. Leon Oblak.

Prof. dr. Leon Oblak je ugleden član združenja WoodEMA, je eden od ustanoviteljev združenja in zelo aktiven član od samega začetka, od leta 2007. Člani Upravnega odbora in Generalne skupščine združenja so ga leta 2007, ob ustanovitvi, soglasno izvolili za prvega predsednika za dveletni mandat (2007-2009), zaradi izjemnega znanstvenega in strokovnega dela, zaradi številnih člankov v uglednih revijah in sodelovanja na mnogih znanstvenih konferencah po vsem svetu ter zaradi pedagoškega dela na tem področju, ki ga opravlja na Oddelku za lesarstvo Biotehniške fakultete Univerze v Ljubljani. Njegovo izjemno delo v združenju so člani prepoznali in ga po izteku te funkcije trikrat zapovrstjo izvolili za člana Upravnega odbora združenja WoodEMA (2009-2015). Od 1. januarja 2020 je eden od treh članov novoustanovljenega Nadzornega sveta združenja WoodEMA.

Prof. dr. Leon Oblak aktivno sodeluje pri vseh dejavnostih združenja (konferencah, sejah Generalne skupščine, sejah Upravnega odbora, sejah Nadzornega sveta, neformalnih sejah, promocijskih dejavnostih društva, novačenju novih članov za združenje) in je eden redkih članov, ki so se udeležili vseh štirinajstih dosedanjih konferenc WoodEMA. Bil je eden prvih članov združenja iz Slovenije in nagovoril je še druge znanstvenike iz Biotehniške fakultete, da so postali polnopravni člani združenja WoodEMA. Poleg aktivnega sodelovanja s članki in predstavitvami na vseh znanstvenih mednarodnih konferencah združenja je prof. dr. Leon Oblak sodeloval tudi s poglavji v znanstvenih knjigah, ki jih izdaja združenje.

Prof. dr. Leon Oblak je dvakrat predlagal, da bi v Sloveniji organizirati znanstveno konferenco WoodEMA. Generalna skupščina je oba predloga sprejela. Tako je bil vodja organizacijskega odbora konference WoodEMA leta 2011, ki je bila v Kozini pod naslovom "Predelava lesa in proizvodnja pohištva: sedanji pogoji, priložnosti in novi izzivi" in konference WoodEMA leta 2021, ki je bila v Kopru pod naslovom "Odziv lesnega sektorja na spremembe v svetovnem gospodarstvu". Prof. dr. Leon Oblak je s svojo ekipo z Oddelka za lesarstvo Biotehniške fakultete obakrat prejel visoko oceno za svoje delo.

Zaradi vseh zgoraj navedenih in številnih drugih razlogov, zaradi vseh njegovih prizadevanj in predanega dela v korist združenja je mednarodno Združenje za ekonomiko in management v predelavi lesa in pohištvu prof. dr. Leonu Oblaku podelilo priznanje asociacije WoodEMA za pomemben prispevek k razvoju združenja.

Interview with Dr. Arnaud Maxime Cheumani Yona

Intervju - dr. Arnaud Maxime Cheumani Yona

Katarina Čufar

Dr. Arnaud Maxime Cheumani Yona* worked at our Department of Wood Science and Technology (DWST), Biotechnical Faculty (BF), University of Ljubljana (UL) from 1st February 2020 to 31st July 2021. In September 2018, he applied for Marie Skłodowska Curie (MSC) European Individual Fellowship with the proposal "SilWoodCoat". The project was awarded the seal of excellence in March 2019 and in September 2019 the Slovenian National Research Agency (ARRS) supported the fellowship so that research work could be conducted in Ljubljana, Slovenia. We have interviewed Dr. Arnaud Maxime Cheumani Yona in November 2021.

Figure 1. Dr. Arnaud Maxime Cheumani Yona in the office at the Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Slovenia.

Slika 1. Dr. Arnaud Maxime Cheumani Yona v pisarni na Oddelku za lesarstvo Biotehniške fakultete, Univerze v Ljubljani.

* Dr. Arnaud Maxime Cheumani Yona, Department of Chemistry, **École** Normale Supérieure, University of Yaoundé 1, P.O. Box 47 Yaoundé, Cameroon
Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, SI-1000 Ljubljana, Slovenia
email: acheumani@gmail.com

1. **Dr. Arnaud Maxime Cheumani Yona, can you please briefly present yourself and your professional development?**
I hold a PhD in physical sciences and engineering, speciality Wood Science, completed in 2009 at Bordeaux 1 University in France with the support of the international French-speaking university network AUF, "Agence Universitaire de la Francophonie". I am a chemist by training. I have a Bachelor of Science in chemistry and a master's degree in physical chemistry. I teach chemistry at the Faculty of Science of the University of Yaounde 1 in Yaounde, Cameroon, and since 2012 I perform my research activities in the macromolecular team in the Laboratory of Applied Inorganic Chemistry. I have supervised a dozen master's theses. Currently I am involved in the supervision of five PhDs, three of the five jointly with research groups in France, Belgium, and India. I have expertise in wood coatings, the preparation and characterization of composite materials from wood and other lignocellulosic residues, organic, and inorganic polymers, and biopolymers' extraction and characterization.

2. **What is your current position at your home university?**
I've been a senior lecturer at my home University of Yaounde 1 since 2013. It is the second grade in our university hierarchy. The first is assistant professor, and above there are associate professor and the highest full professor.

3. **What stimulated your co-operation with Prof. Dr. Marko Petrič and University of Ljubljana?**
Prof. Dr. Petrič and I met in France in 2010 after the defence of my PhD doctorate. He was an invited researcher in the laboratory of Prof. Dr. Philippe Girardin at the University of Nancy-France, which was one of the reviewers of my PhD thesis. I can say that at that time I had poor knowledge of Central European countries and Slovenia. But we discussed research opportunities at UL and living in Slovenia. His scientific knowledge, general skills and expertise, and human qualities convinced me, so I joined the UL in 2011 for a post-doctoral position in collaboration with the former Institute of Wood Science of Technology. The research stay was successful and led to several research articles in peer-reviewed journals and conferences papers. We remained in contact since that period looking for research collaboration opportunities, and I'm happy to be here at BF-UL working on this new research project.

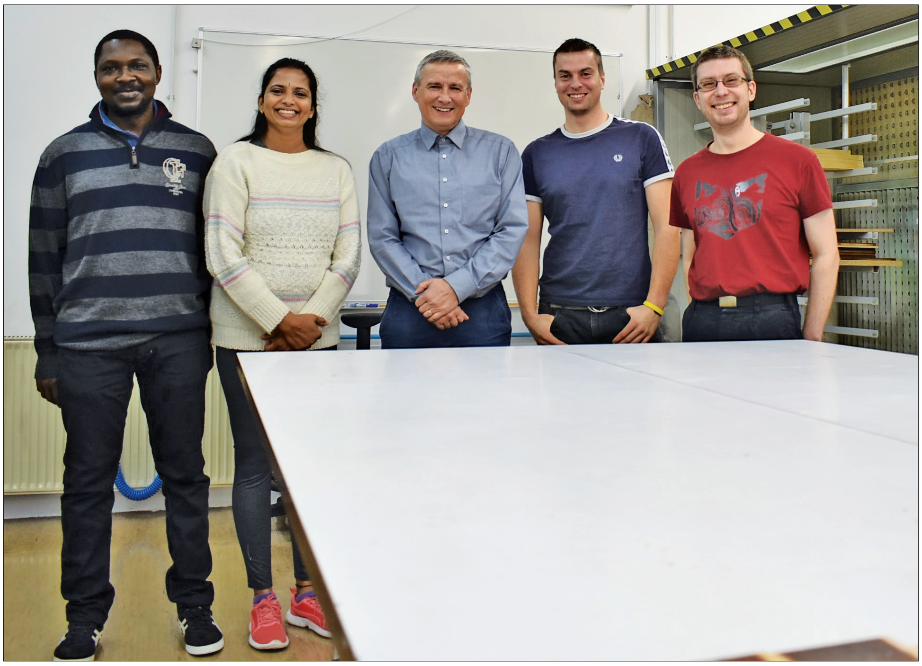


Figure 2. Group members with the supervisor; from left to right Arnaud Maxime Cheumani Yona, Kavyashree Srinivasa, Marko Petrič, Jure Žigon and Sebastian Dahle in spring of 2021.
Slika 2. Skupina raziskovalcev z mentorjem prof. dr. Markom Petričem, od leve proti desni Arnaud Maxime Cheumani Yona, Kavyashree Srinivasa, Marko Petrič, Jure Žigon in Sebastian Dahle spomladi 2021.

4. **Which program supported your stay in Ljubljana in the recent period?**
   We applied for the Marie Skłodowska Curie (MSC) European Individual Fellowship with the proposal "SilWoodCoat". The project was awarded the seal of excellence, but the available funds were not enough for the financial support of the project at the European level. As it is common in many European countries to fund MSC seal of excellence projects through the national research agency, our project is supported by ARRS, the Slovenian Research Agency.

5. **What are the main challenges and achievements of your stay?**
   The objective of the project is the development of mineral silicate-based coatings that could perform durably on wood without primer. The binder for such coatings is a water glass (especially potassium) or a silicate sol (mixture of water glass and colloidal silica). Silicate coatings have been used for concrete and masonry, and the corrosion protection of steel, and have proved to be able to provide UV light and biological resistance, fire resistance, and durable finishes at the surface of these materials. Wood is a material with different structures and chemistries, and is dimensionally less stable than concrete and steel. It undergoes significant swelling and shrinkage when exposed to moisture which leads to important mechanical stresses on the coating layers and results in progressive cracking and debonding of the coatings. The durability of a coating at the surface of wood depends on its ability to prevent moisture uptake or to accommodate the ensuing mechanical stresses, and to protect wood against other damaging agents (UV light, fungi, and insects). This ability can be estimated through measurements of the coating's properties, such as adhesion strength, flexibility, scratch and impact resistances, and water resistance. However, the literature on the performances of silicate coatings on wood substrates remains limited. A technology using a mineralized primer based on an alkyd resin or drying oil and silicate coatings as a top layer has been developed by some companies, such as Keimfarben® and Beeck®. A coating without a primer or with a low-cost water-based primer could reduce the cost of the protection. We have formulated silicate coatings with different mass ratios between the components and chemical additives to study their adhesion, surface morphology, and water resistance at the surface of the wood. This work has led to the publication of two research arti-

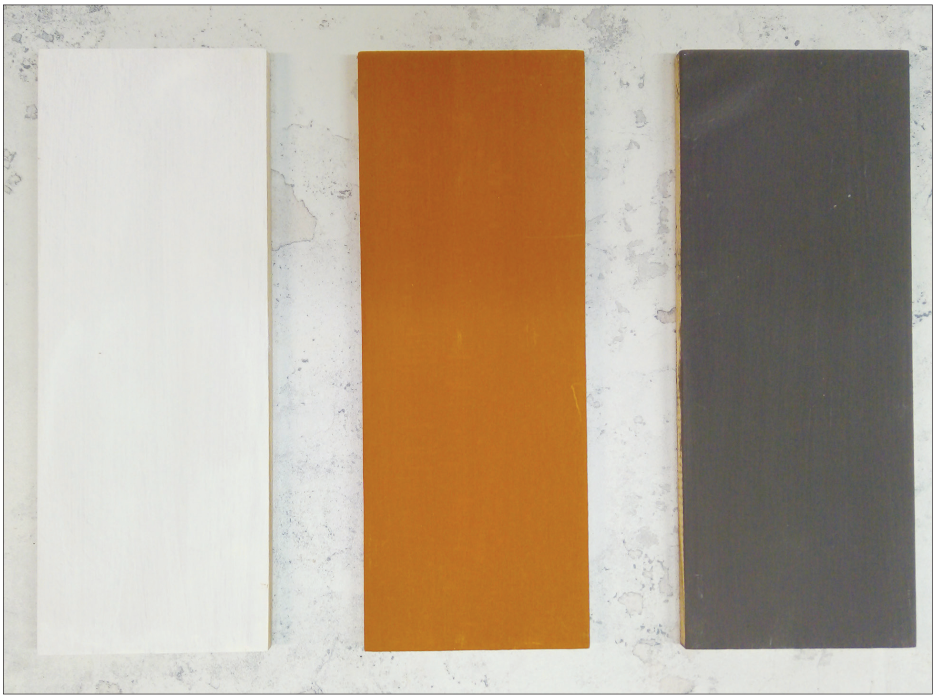


Figure 3. Beech wood samples coated with silicate coatings containing different mineral pigments. From left to right white (titanium dioxide), brown (iron(III) oxide) and deep blue (copper (II) oxide).
Slika 3. Vzorci bukovega lesa, prevlečeni s silikatnimi premazi, ki vsebujejo različne mineralne pigmente. Od leve proti desni bela (titanov dioksid), rjava (železov(III) oksid) in temno modra (bakrov(II) oksid).

cles in peer reviewed journals. A review article was also prepared and published in the *Journal of Wood Science and Technology*.

6. **What are the main professional challenges of your home university and country, and in global sense?**
In Cameroon, with an area of 475,442 km^2 and 24 million inhabitants, the forest covers approx. 22 million hectares, i.e., 46% of the total land area. The wood production is estimated around 2.3 million m^3 per year and the forestry sector represents 30% of the national economy, with a contribution between 2 and 4% to GDP. This contribution can be increased by a reduction of unprocessed and semi-processed log exports, production of value-added timbers and reconstituted wood fibre or particle composites. Indeed, wood exploitation provides a significant volume of residues, including upper parts of the trunk and branches (about 40% of the cut trees), and the residues from the first and second transformations. These residues are currently partially used for mainly domestic heating, but a great part is abandoned and non-valorized. Moreover, Cameroon has approximately three hundred (300) tree species, but only about twenty are commercialized. Fortunately, there is a growing awareness at the national level of the need to strengthen the technical know-how and solutions in the wood industry through appropriate training programmes in wood timber construction, wood fibres or particle boards and valorization of wood in biorefining processes. The University Institute of Wood Technology Mbalmayo, almost entirely focused on wood technology, has recently been opened at the University of Yaounde 1, in addition to other wood training program at the University of Dschang in Dschang, West Cameroon, and the University of Douala, Douala, in the coastal region of Cameroon. I am collaborating with these institutes for the training of students, and several of them have already had a research stay in our laboratory. I think if we believe in our potential, we can rapidly gain expertise in the field of wood timber and reconstituted wood panels for construction and furniture.

Dr. Arnaud Maxime Cheumani Yona je od 1. februarja 2020 do 31. julija 2021 delal na Oddelku za lesarstvo (OL) Biotehniške fakultete (BF) Univerze v Ljubljani (UL). Septembra 2018 se je s predlogom projekta "SilWoodCoat" prijavil za evropsko individualno štipendijo Marie Skłodowska Curie (MSC). Projekt je marca 2019 prejel znak odličnosti, Javna agencija za raziskovalno dejavnost Republike Slovenije (ARRS) pa ga je septembra 2019 podprla s štipendijo za izvajanje raziskovalnega dela v Ljubljani. Razgovor z njim smo opravili novembra 2021.

1. **Dr. Arnaud Maxime Cheumani Yona, ali lahko na kratko predstavite sebe in svoj poklicni razvoj?**
Imam doktorat iz fizikalnih znanosti in tehnike, specialnost Lesarstvo, ki sem ga zaključil leta 2009 na Univerzi Bordeaux 1 v Franciji s podporo mednarodne francosko govoreče univerzitetne mreže AUF "Agence Universitaire de la Francophonie". Po izobrazbi sem kemik. Imam diplomo iz kemije in magisterij iz fizikalne kemije. Od leta 2012 poučujem kemijo na Fakulteti za naravoslovje Univerze Yaounde 1, raziskovalno dejavnost pa opravljam v makromolekularni skupini v Laboratoriju za uporabno anorgansko kemijo. Vodil sem vrsto magistrskih nalog. Sodelujem kot mentor ali somentor pri petih doktorandih, od tega pri treh sodelujem z raziskovalnimi skupinami v Franciji, Belgiji in Indiji. Imam strokovno znanje na področju premazov za les, priprave in karakterizacije kompozitnih materialov iz lesa in drugih lignoceluloznih ostankov, organskih in anorganskih polimerov ter ekstrakcije in karakterizacije biopolimerov.
Od leta 2013 sem višji predavatelj na domači univerzi. S prof. dr. Petričem sva se srečala v Franciji leta 2010 po zagovoru mojega doktorata. Bil je vabljeni raziskovalec v laboratoriju prof. dr. Philippa Girardina na Univerzi v Nancy-Francija in je bil eden od recenzentov moje doktorske disertacije. Lahko rečem, da sem takrat slabo poznal srednjeevropske države in Slovenijo. Razpravljali pa smo o raziskovalnih možnostih na UL in bivanju v Sloveniji. Njegovo znanstveno delo, splošne veščine in strokovnost ter človeške lastnosti so me prepričali, da sem se leta 2011 pridružil UL na podoktorskem projektu v sodelovanju s takratnim Tehnološkim inštitutom za lesarstvo. Raziskovalno bivanje je bilo uspešno

in je privedlo do številnih znanstvenih člankov v strokovnih revijah. Pripravili smo tudi prispevke na konferencah. Od takrat ostajamo v stiku in iščemo priložnosti za raziskovalno sodelovanje. Vesel sem, da lahko delujem na BF-UL na raziskovalnem projektu.

V letu 2018 sem se prijavil za evropsko individualno štipendijo Marie Skłodowska Curie (MSC) s projektom »SilWoodCoat«. Projekt je prejel pečat odličnosti, a razpoložljiva sredstva niso zadostovala za finančno podporo projekta na evropski ravni. Kot je v mnogih evropskih državah običajno, da financirajo projekte s pečatom odličnosti MSC prek nacionalne raziskovalne agencije, je tudi naš projekt podprla ARRS.

Cilj projekta je razvoj premazov na osnovi mineralnih silikatov, ki bi se dobro obnesli brez temeljnega premaza. Vezivo za takšne premaze je vodno steklo (zlasti kalijevo) ali silikatna sol (mešanica vodnega stekla in koloidnega silicijevega dioksida). Silikatne premaze uporabljajo za beton in zidove, protikorozijsko zaščito jekla. Lahko zagotovijo zaščito pred ultravijolično svetlobo in povečajo biološko odpornost, požarno odpornost in so zelo trajni. Les je material s posebno zgradbo in kemizmom, ter je dimenzijsko manj stabilen od betona in jekla. Ko je izpostavljen vlagi, je podvržen znatnemu nabrekanju in krčenju, kar vodi do pomembnih mehanskih obremenitev na slojih premaza in povzroči postopen nastanek razpok in ločevanje premazov od podlage. Obstojnost premaza na površini lesa je odvisna od njegove sposobnosti preprečevanja vdora vlage ali prilagajanja posledičnim mehanskim obremenitvam ter zaščite lesa pred drugimi škodljivimi vplivi (ultravijolična svetloba, glive in insekti). To sposobnost je mogoče oceniti z meritvami lastnosti premaza, kot so oprijemna trdnost, fleksibilnost, odpornost proti razenju in udarcem ter vodoodpornost. Literatura o delovanju silikatnih premazov na lesnih podlagah je bila doslej redka. Nekatera podjetja, kot sta Keimfarben® in Beeck®, so razvila tehnologijo z uporabo mineraliziranega temeljnega premaza na osnovi alkidne smole ali sušečega se olja in silikatnih premazov kot zgornje plasti. Premaz brez temelja ali z nizkocenovnim temeljnim premazom na vodni osnovi bi lahko znižal stroške zaščite. Zasnovali smo silikatne premaze z različnimi masnimi razmerji med komponentami in kemičnimi dodatki, da bi preučili njihovo oprijemnost, morfologijo površine ter vodoodpornost na površini lesa. Raziskave so privedle do objave dveh člankov v znanstvenih revijah. Objavili smo tudi pregledni članek, ki je bil objavljen v Journal of Wood Science and Technology.

2. Kateri so vaši glavni raziskovalni izzivi?

V Kamerunu s površino 475 442 km² in 24 milijoni prebivalcev gozd pokriva pribl. 22 milijonov hektarjev, to je 46 % celotne površine. Proizvodnja lesa je ocenjena na okoli 2,3 miliјona m^3 na leto, gozdarski sektor pa predstavlja 30 % nacionalnega gospodarstva s prispevkom med 2 do 4 % k bruto domačemu proizvodu (BDP). Prispevek lesnega sektorja k BDP bi se lahko povečal z zmanjšanjem izvoza nepredelane in delno predelane hlodovine. Povečati bi morali predelavo lesa v izdelke z visoko dodano vrednostjo in s proizvodnjo lesnih vlaken ali kompozitov. Izkoriščanje lesa zagotavlja pomembno količino ostankov, vključno z zgornjim delom debla in vejami (približno 40 % volumna posekanih dreves), nastajajo tudi ostanki iz primarne in sekundarne predelave. Ostanki se trenutno delno uporabljajo predvsem za ogrevanje gospodinjstev, velik del pa ostane neizkoriščen. Poleg tega ima Kamerun približno tristo (300) različnih drevesnih vrst, približno dvajset pa jih ima komercialni pomen. Na srečo se na nacionalni ravni krepi zavedanje o potrebi po krepitvi tehničnega znanja in rešitev v lesni industriji z ustreznimi izobraževalnimi programi na področju lesene gradnje, lesnih vlaken ali ivernih plošč in uporabe lesa v biorafinerijah. Univerzitetni inštitut za tehnologijo lesa Mbalmayo, ki je skoraj v celoti osredotočen na lesnopredelovalno tehnologijo, je bil nedavno ustanovljen na Univerzi Yaounde 1, poleg drugih obstoječih programov usposabljanja za les na Univerzi Dschang in Univerzi v Douali. S temi inštituti sodelujem pri usposabljanju študentov in nekaj jih je že zaključilo raziskovalno delo v našem laboratoriju. Mislim, da lahko, če verjamemo v svoje potenciale, hitro pridobimo strokovno znanje na področju masivnega lesa in lesnih plošč za gradbeništvo in pohištvo.

Interview with Dr. Kavyashree Srinivasa

Intervju z dr. Kavyashree Srinivasa

Katarina Čufar

Dr. Kavyashree Srinivasa* has worked at our Department of Wood Science and Technology (DWST), Biotechnical Faculty (BF), University of Ljubljana (UL) since February 2020. In September 2018 she applied for a Marie Skłodowska Curie (MSCA) individual fellowship from the European Commission. The proposal "Enhancement of UV stability of thermally modified wood through envelope impregnation with nano-based stabilisers" (NewSiest 867451) was awarded with a Seal of Excellence and funding was approved under the Widening fellowship scheme, and Kavyashree Srinivasa became a postdoctoral researcher at BF UL for the period from February 2020 to 2022. We interviewed her in November 2021.

Figure 1. Dr. Kavyashree Srinivasa during her stay in Ljubljana, Slovenia.
Slika 1. Dr. Kavyashree Srinivasa med svojim bivanjem v Ljubljani.

1. **Can you briefly present yourself and your professional development?**
   I am Kavyashree Srinivasa, born in India, a multicultural and diverse country, and the largest democracy in the world. I received my master's degree in chemistry (analytical chemistry) from the University of Mysore. Then I joined the Institute of Wood Science & Technology, Bengaluru as a junior research fellow under a project, and then enrolled myself for a doctoral degree in Forestry (Wood Science & Technology) at the Forest Research Institute Deemed University, Dehradun. This four years of work experience at the research institute was life-changing, and transformed my views on the importance of sustainability, preservation and durability of wood and its products.

2. **What stimulated your co-operation with Prof. Dr. Marko Petrič and the University of Ljubljana.**
   Initially I met Prof. Dr. Marko Petrič in person during IRG-WP (IRG44), Stockholm, Sweden, and I had been following his work during my doctoral studies. After completing my doctoral degree, I approached Prof. Petrič with regard to hosting a nationally funded overseas post-doctoral fellowship (DST-OPDF). The application time frame was not suitable, so he suggested that I apply for a Marie Sklodowska Curie fellowship, and I succeeded in obtaining an MSCA Widening fellowship from the European Commission.

3. **Which program supported your stay in Ljubljana in the recent period**.
   I am currently working as part of an EU funded project titled "Enhancement of UV stability of thermally modified wood through envelope impregnation with nano-based stabilisers"

* Kavyashree Srinivasa, Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, SI-1000 Ljubljana, Slovenia
e-mail: Kavyashree.Srinivasa@bf.uni-lj.si,
kavyashree15@gmail.com

(NewSiest 867451) as a postdoctoral researcher from Feb 2020-2022.

4. **What are the main challenges and achievements of your stay?**
There were a few challenges initially when I started my work here, since this was my first stay outside my country and, like everyone, I had to get accustomed to new climatic conditions, work culture, language, food, and social life, and then the COVID-19 outbreak started and forced us to a new way of life. The support from my team members and family gave me courage to overcome all such challenges. Due to the pandemic, attending conferences and networking could not happen as planned, but being a part of the project team has given me a great opportunity to develop interpersonal and professional skills.

5. **What are the main professional challenges of your home university, country and in global sense.**
India being a tropical country with a population of around 1.4 billion is among the largest importers as well as producers of wood and wood-based products. It has committed to creating a carbon sink of 2.5-3 billion MT of CO_2 by 2030 through additional tree and forest cover (UNFCCC, Paris Agreement, 2015). However, in the past few decades the majority of India's forest cover has been degraded by the construction of dams and highways, along with mining and industrial work, or inhabited to accommodate increasing population or displaced into sanctuaries and national parks to improve tourism. The sustainable management of forest resources is still rare, and the related policies and accomplishments are in a contradictory stage. There is a huge gap between the policymakers and professionals working on the ground in fields related to R&D, industry and the involvement of general public. Scientists working in the wood sector have few international collaborations and little experience working abroad, as there is less support from national funding. In this regard, I would like to share my experiences, educate and encourage people around me to pursue higher education in forestry and utilize the available resources to develop and gain expertise, leading to the development of skills.

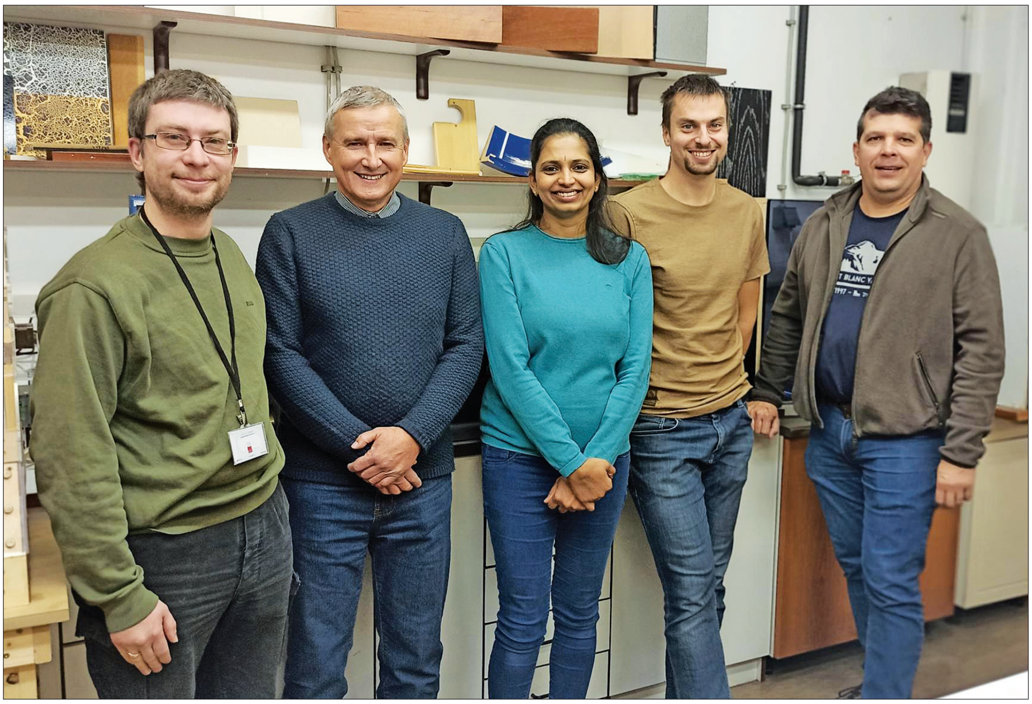


Figure 2. In the laboratory with her supervisor and colleagues.
Slika 2. V laboratoriju z mentorjem in kolegi

Dr. Kavyashree Srinivasa je od februarja 2020 zaposlena na Oddelku za lesarstvo (OL) Biotehniške fakultete (BF) Univerze v Ljubljani (UL). Septembra 2018 se je prijavila na razpis za individualno štipendijo Marie Skłodowska Curie (MSCA) Evropske komisije. Predlog projekta "Enhancement of UV stability of thermally modified wood through envelope impregnation with nanobased stabilisers" (NewSiest 867451) je bil nagrajen s Pečatom odličnosti, sredstva so bila odobrena v okviru programa »Widening fellowship scheme« in Kavyashree Srinivasa je postala podoktorska raziskovalka na BF UL za obdobje februar 2020-2022. Razgovor z njo smo opravili novembra 2021.

1. **Ali lahko na kratko predstavite sebe in svojo poklicno pot?**
   Sem Kavyashree Srinivasa, rojena v Indiji, večkulturni, raznoliki in največji demokratični državi. Magistrirala sem iz kemije (analizna kemija) na Univerzi Mysore. Nato sem se kot mlajša raziskovalka v okviru projekta pridružila Inštitutu za znanost in tehnologijo lesa v Bengaluruju, nato pa sem se vpisala na doktorski študij gozdarstva (znanost in tehnologija lesa) na Forest Research Institute Deemed University v Dehradunu. Te štiriletne delovne izkušnje na raziskovalnem inštitutu so mi spremenile življenje in pogled na pomen trajnosti, ohranjanja in trajnosti lesa ter izdelkov iz lesa.

2. **Kaj (in kdaj) je spodbudilo vaše sodelovanje s prof. dr. Markom Petričem in Univerzo v Ljubljani?**
   Prof. dr. Marka Petriča sem spoznala na konferenci IRG-WP (IRG44) v Stockholmu na Švedskem. Njegovo delo sem spremljala že med doktorskim študijem. Po končanem doktoratu sem se obrnila na profesorja Petriča s predlogom za gostovanje v okviru podoktorske štipendije v tujini, financirane iz nacionalnih sredstev (DST-OPDF). Časovni okvir prijave se ni ujemal, zato mi je predlagal, naj se prijavim za štipendijo Marie Sklodowska Curie, in uspela sem pridobiti razširitveno štipendijo MSCA Evropske komisije.
   Od februarja 2020 do predvidoma 2022 delujem kot podoktorska raziskovalka pri projektu, ki ga financira EU, z naslovom "Enhancement of UV stability of thermally modified wood through envelope impregnation with nanobased stabilisers" (NewSiest 867451).

4. **Kateri so glavni izzivi in dosežki vašega bivanja v Sloveniji?**
   Na začetku, ko sem začela delati v Sloveniji, je bilo nekaj izzivov, saj je bilo to moje prvo bivanje zunaj moje države. Tako sem se morala kot vsi navaditi na nove podnebne razmere, delovno kulturo, jezik, hrano, družabno življenje. Izbruh Covid 19 mi je tako kot vsem dodatno zapletel življenje. Podpora članov ekipe in družine mi je dajala pogum, da sem premagala vse težave. Zaradi pandemije udeležba na konferencah in mreženje žal ne moreta normalno potekati. Biti del projektne skupine mi je hkrati dalo odlično priložnost za razvoj medosebnih in strokovnih veščin.

5. **Kateri so vaši glavni poklicni izzivi?**
   Indija kot tropska država s približno 1,4 milijarde prebivalcev je med največjimi uvozniki in tudi proizvajalci lesa in lesnih izdelkov. Zavezala se je, da bo do leta 2030 izboljšala pokritost države z drevesi in gozdovi ter tako omogočila ponor ogljika v višini 2,5-3 milijard MT CO_2 (UNFCCC, Pariški sporazum, 2015). Žal je bila v zadnjih nekaj desetletjih večina indijskih gozdnih površin degradirana zaradi gradnje jezov, avtocest, rudarjenja, industrijskih del ali poselitve zaradi prilagajanja naraščajočemu številu prebivalstva ali spremenjena v rezervate in nacionalne parke zaradi izboljšanja turizma. Trajnostno gospodarjenje z gozdnimi viri je še vedno redko. Politike in dosežki so si nasprotujoči. Obstaja velik razkorak med oblikovalci politik in strokovnjaki, ki delujejo na terenu na področjih, povezanih z raziskavami in razvojem, industrijo in vključevanjem splošne javnosti. Znanstveniki, ki delajo v lesnem sektorju, imajo manj mednarodnih sodelovanj in izkušenj z delom v tujini, saj je podpora z nacionalnimi viri manjša. V zvezi s tem bi si želela deliti svoje izkušnje, izobraževati in spodbujati ljudi okoli sebe, da nadaljujejo visokošolsko izobraževanje na področju gozdarstva in lesarstva, da bi bolje izkoristili razpoložljive vire za razvoj in pridobivanje strokovnega znanja, ki vodi k splošnem razvoju.

Z delavnico Zaščita, vgradnja in uporaba lesa na prostem se krepi usposobljenost zaposlenih na področju gradnje z lesom

Tina Drolc, Miha Humar, Davor Kržišnik, Boštjan Lesar

V četrtek, 16. septembra 2021, je bila v okviru aktivnosti za vzpostavitev Kompetenčnega centra za razvoj kadrov v lesarstvu KOCles 3.0 organizirana spletna delavnica. Raziskovalci Biotehniške fakultete, prof. dr. Miha Humar, doc. dr. Boštjan Lesar ter doc. dr. Davor Kržišnik s Katedre za lesne škodljivce, zaščito in modifikacijo lesa na Oddelku za lesarstvo Biotehniške fakultete Univerze v Ljubljani so za tehnologe, projektante in konstruktorje organizirali spletno delavnico z naslovom Zaščita, vgradnja in uporaba lesa na prostem. Delavnica z naslovom Zaščita, vgradnja in uporaba lesa na prostem je bila sestavljena iz treh delov, najprej je prof. dr. Miha Humar predstavil Vpliv podnebnih sprememb na dinamiko razkroja lesa v Sloveniji. Sledilo je predavanje doc. dr. Davorja Kržišnika z naslovom Nevarnosti novih lesnih škodljivcev za leseno gradnjo v Evropi in Sloveniji. Delavnica se je zaključila s predstavitvijo doc. dr. Boštjana Lesarja z naslovom Študij primerov – lesni škodljivci v lesenih stavbah. Na delavnici, ki je potekala od 10.00 do 16.00, je sodelovalo več kot 15 udeležencev.

Delavnica z naslovom Zaščita, vgradnja in uporaba lesa na prostem je potekala kot notranje usposabljanje v okviru projekta za vzpostavitev Kompetenčnega centra za razvoj kadrov v lesarstvu KOCles 3.0. Namen vzpostavitve kompetenčnega centra je razvoj kadrov v lesarstvu, ki bi omogočal višjo usposobljenost zaposlenih v podjetjih, ki delujejo na področju lesarstva; doseganje večje konkurenčnosti podjetij na področju lesarstva ter podpiral izmenjavo znanja in dobrih praks med partnerji kompetenčnega centra. Prof. dr. Miha Humar, prodekan za kakovost in gospodarske zadeve, je pred delavnico povedal: »Kompetenčni center za razvoj kadrov v lesarstvu KOCles 3.0 je prostor za izmenjavo znanj ter dobrih praks med partnerji kompetenčnega centra in širše na področju lesarstva. Delavnica poteka v sklopu notranjega usposabljanja članov kompetenčnega centra z namenom izboljšati poslovne prakse ter okrepiti uspešnost delovanja slovenskih podjetij na področju lesarstva.«

Prof. dr. Miha Humar je v sklopu predavanja z naslovom Vpliv podnebnih sprememb na dinamiko razkroja lesa v Sloveniji izpostavil: »Intenziteta glivnega razkroja je v največji meri odvisna od vrste lesa, temperature in padavinskih dogodkov. Če želimo oceniti življenjsko dobo in intervale vzdrževanja lesenih objektov, moramo oceniti, kako se bo v določenem okolju les obnašal.« Za ocenjevanje življenjske dobe lesa oziroma intervalov vzdrževanja lesenih objektov so na voljo raznoliki modeli. V praksi se največ uporablja pristop, ki ga je razvil Theodore Scheffer. Scheffer je predlagal klimatski indeks (Schefferjev klimatski indeks - SCI), ki temelji na številu padavinskih dni in povprečni mesečni temperaturi. Na podlagi klimatskih podatkov so na Oddelku za lesarstvo Biotehniške fakultete izračunali Schefferjev klimatski indeks za izbrane lokacije v Sloveniji. Prof. dr. Miha Humar je o izračunanem Schefferjevem klimatskem indeksu za izbrane lokacije v Sloveniji povedal: »Rezultati analize klimatskih razmer kažejo, da je Schefferjev klimatski indeks v večini analiziranih krajev v Sloveniji višji, kot je bil pred desetletji. Intenziteta razkroja se je povečala v vseh analiziranih krajih z izjemo Portoroža. Največje zvišanje Schefferjevega klimatskega indeksa smo zaznali v Ratečah.«

V drugem predavanju z naslovom Nevarnosti novih lesnih škodljivcev za leseno gradnjo v Evropi in Sloveniji je doc. dr. Davor Kržišnik pojasnil, da les kot organski material zaradi delovanja biotskih in abiotskih dejavnikov razkroja razpade v anorgansko snov. Vloga razkrojevalcev lesa je v naravi zaželena in nujno potrebna, saj opravljajo pomemben del kroženja snovi v naravi. Tako na primer poskrbijo, da se odmrla drevesa, debla, panji počasi razkrojijo, razpadejo na majhne delce, ki obogatijo tla z novimi snovmi in jih zato naredijo bolj rodovitne. V svojem predavanju pa je izpostavil: »Za razliko od naravnih procesov, kjer razkroj lesa pomeni kroženje snovi v naravi, pa so takrat, ko les uporabljamo v gospodarske namene, procesi razgradnje nezaželeni in jih želimo čim bolj upočasniti.« Les ogrožajo različni biotski dejavniki razkroja, ki jih imenujemo lesni škodljivci, in so tisti razkrojevalci lesa, ki na različne načine uničujejo uporaben les oziroma nižajo njegovo uporabnost ali kakovost. Tako se na primer z njim prehranjujejo, ga uporabljajo kot življenjski prostor (aktivno delujejo v lesu) ipd. Škodo lahko povzročajo na živih drevesih, na hlodovini in žaganicah, pa tudi na končnih izdelkih. Lesni škodljivci so lahko glive, bakterije, žuželke in morski škodljivci. Med abiotske oziroma nežive dejavnike razkroja lesa uvrščamo visoke in nizke temperature, veter, vodo, vlago, UV svetlobo, kemikalije, ogenj in druge in delujejo na mehanske, kemijske in fizikalne lastnosti lesa relativno počasi.

Doc. dr. Boštjan Lesar je predstavil Študije primerov: lesni škodljivci v lesenih stavbah: »Vzroki za pojav lesnih škodljivcev v lesenih stavbah so različni. Največkrat so težave povezane s povišano vlažnostjo lesa in pojavom gliv razkrojevalk lesa.« V predavanju so si udeleženci pogledali vzroke za povišano vlažnost, ki povzročajo zastajanje vode ali kondenzacijo. V podnebnem pasu, v katerem je tudi Slovenija, največ škode povzročajo glive razkrojevalke. Doc. dr. Boštjan Lesar je izpostavil: »Postopek sanacije je odvisen od tega, katera gliva se pojavi. Poleg gliv težave povzročajo tudi insekti. Predvsem se pojavljajo insekti, ki razkrajajo suh les. Še posebej problematični so pri nas hišni kozlički in trdoglavci.« Poškodbe hišnih kozličkov in trdoglavcev v stavbah največkrat ne povzročajo poškodb, ki bi bile kritične za konstrukcijo, so pa zelo moteče za uporabnike stavb. V predavanju so si udeleženci pogledali nekaj dejanskih primerov stavb, kjer so se pojavile težave z glivami in insekti. Pogledali so si vzroke za nastanek poškodb ter postopke za ustrezno sanacijo in preprečitev nadaljnjih poškodb.

Delavnica se je zaključila z razpravo vseh udeležencev, ki so z raziskovalci delili svoje izkušnje s področja gradnje lesenih objektov.

Resonančna smrekovina s Pokljuke za izdelavo klasične kitare

Klemen Novak, Aleš Straže

V okviru projekta »Analiza kakovosti lesa za izdelke z visoko dodano vrednostjo« raziskujemo različne vrste lesa in njihove lastnosti z namenom doseganja čim boljše rabe lesa in s tem visoke dodane vrednosti.

Med izbranimi drevesnimi vrstami je tudi navadna smreka (*Picea abies*), ki porašča 30 % slovenskih gozdov. Je tipična alpska drevesna vrsta, obstojna na zmrzal in nizke temperature, enostavna za obnovo in gojitev, iglavec z visoko produktivnostjo in s širokim razponom uporabe lesa.

Na rastiščih in gozdnih sestojih, kjer je rast dreves zelo počasna, kjer so branike zelo ozke in homogene, z majhnim deležem kasnega lesa, dosega smrekovina visoko specifično togost, kar pomeni visoko razmerje med togostjo in maso lesa. To so priznane lastnosti resonančne smrekovine, kjer se najboljši in najlepši kosi namenjajo za izdelavo glasbenih inštrumentov, kot so godala in brenkala, tisti manj homogeni pa tudi za izdelavo skodel. Strukturna homogenost resonančnega lesa ima za posledico nizko dušenje zvoka. Ob majhni masi, oz. dovolj nizki gostoti lesa, se z nihanjem strun ter s prenosom akustične energije dosega zadostno mehansko vzbujanje delov glasbenih inštrumentov, tudi v višjih nihajnih načinih. Harmonija, enakomernost ter pestrost vzbujenih frekvenc nihanja pri zvočnicah brenkal in godal v glasbi razumemo kot dobro igranje inštrumenta.

V okviru projekta smo najprej sestavili referenčno kronologijo za smreko na Pokljuki. Sledila je vizualna ocena vzorcev resonančne smrekovine s Pokljuke ter izbira kosov za izdelavo glasbenega inštrumenta. Študenta magistrskega študija lesarstva na Oddelku za lesarstvo Biotehniške fakultete Univerze v Ljubljani, Anže Lopatič in Matija Kunstelj, sta les pridobila za izdelavo delov klasične kitare, kot so zvočnica in rebra. Ostali deli kitare, hrbet in stranici bodo iz ameriškega oreha, vrat z glavo in peto iz mahagonija, ubiralka iz ebenovine in mostiček iz ziricote.

Pomemben del v procesu izdelave kitare je, da smo v okviru projekta »Analiza kakovosti lesa za izdelke z visoko dodano vrednostjo« uporabili resonančno smrekovino iz slovenskih pokljuških gozdov, ter s tem lesu dodali večjo dodano vrednost.

Študenta magistrskega študija lesarstva Anže Lopatič in Matija Kunstelj z izbranima kosoma resonančne smrekovine za izdelavo kitare.

Radialno izrezani deski resonančne smrekovine, debeline 4-5 mm za izdelavo zgornje plošče kitare z zvočnico in rozeto.

Širinsko zrcalno spojeni (zlepljeni) deski zgornje plošče kitare.

Letni sestanek projektne skupine projekta L4-2623: Posvet z naslovom Kaj vemo o ekstraktivih jelove skorje?

Viljem Vek, Ida Poljanšek in Primož Oven

V petek, 24. septembra 2021, je v Podjetniškem inkubatorju Kočevje potekal posvet in letni sestanek projektne skupine L4-2623. Posvet z naslovom Kaj vemo o ekstraktivih jelove skorje? je bil organiziran skladno s terminskim planom projektnih aktivnosti, ki je natančno definiran v projektni prijavi ARRS-RPROJ-JR/929. Kot vodja delovnega sklopa WP7, ki pokriva področje upravljanja projekta in diseminacije, je bil sestanek organiziran na pobudo prof. dr. Primoža Ovna v sodelovanju z izr. prof. dr. Ido Poljanšek in doc. dr. Viljemom Vekom.

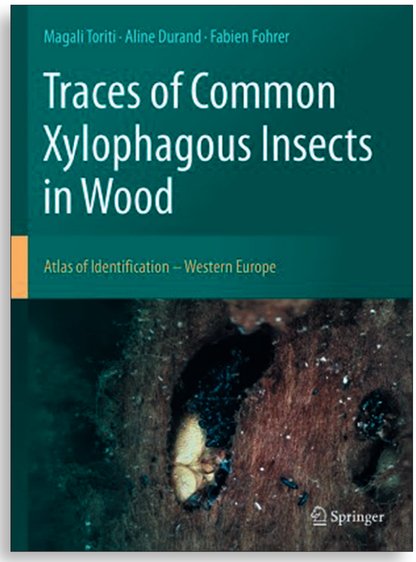
Podjetniški inkubator Kočevje je s svojimi aktivnostmi na kočevskem območju vključen v podjetniško svetovanje in povezovanje, v delo z mladimi, v izobraževanje o novih tehnologijah, predstavlja »sprejemno« pisarno za investitorje, na inkubatorju se vodi projekte, je tudi karierni center za povezovanje podjetij s posamezniki ter center za prototipiranje lesnih izdelkov. Gostitelj dogodka in sestanka projektne skupine je bil gospod Aleš Marolt oziroma podjetje Kočevski les. Ker gre za aplikativen projekt, vse projektne aktivnosti so namreč eksaktno vezane na poslovne cilje sofinancerja projekta, to je podjetja Ars Pharmae, ter zaradi trenutnega neugodnega epidemiološkega stanja v državi, je bil posvet organiziran kot dogodek zaprtega tipa.

Aplikativni projekt z naslovom Pridobivanje ekstraktov grč in skorje z visoko vsebnostjo polifenolov iz manj izkoriščene biomase bele jelke, s šifro L4-2623, financirata Agencija za raziskave in razvoj Republike Slovenije ter podjetje Ars Pharmae. Vse projektne aktivnosti so usmerjene na področje okol-

Posvet in sestanek članov projektne skupine L4-2623 z naslovom Kaj vemo o ekstraktivih jelove skorje? je potekal v konferenčni sobi Podjetniškega inkubatorja Kočevje (foto: Viljem Vek) ju prijaznega pridobivanja bioaktivnih polifenolov iz različnih drevesnih tkiv bele jelke (*Abies alba* Mill.). Na posvetu smo prof. dr. Primož Oven, izr. prof. dr. Ida Poljanšek in doc. dr. Viljem Vek, kot predstavniki članice Univerze v Ljubljani (Biotehniška fakulteta, Oddelek za lesarstvo), predstavili ključne rezultate prvega projektnega obdobja, Marko Domazet in Urška Zaloker sta orisala aktivnosti podjetja Ars Pharmae, Aleš Marolt pa dejavnost podjetja Kočevski les. Pred posvetom je g. Marolt opravil predstavitev oziroma voden ogled prenovljenega objekta Podjetniškega inkubatorja Kočevje.

Posvet je z uvodnim govorom odprl prof. dr. Oven, ki je po formalnem odprtju posveta nadaljeval s predavanjem in navzočim predstavil osnovne podatke o beli jelki, rastiščih bele jelke v Sloveniji ter opisal glavne anatomske značilnosti strukture žive in mrtve skorje. V tem sklopu predavanj so bili predstavljeni tudi rezultati preliminarnih analiz, ki jasno definirajo, kateri sloj skorje predstavlja vir polifenolov. Poleg omenjenega predavanja je Oddelek za lesarstvo na posvetu predstavil še tri prispevke z rezultati raziskovalnih aktivnosti. V drugem prispevku je doc dr. Vek predstavil vpliv letnega časa na količino polifenolov v skorji bele jelke, ob tem pa smo predstavili še rezultate/podatke o longitudinalni variabilnosti ter z njo povezano kvalitativno sestavo ekstraktov, oziroma kako se spreminja delež polifenolov v vodnem ekstraktu z višino vzorčenja. Tretji sklop rezultatov je predstavila izr. prof. dr. Ida Poljanšek, posvetila pa se vplivu različnih ekstrakcijskih tehnik, topil ter deleža vode v organskem topilu na ekstrakcijski donos. V zadnjem sklopu rezultatov je doc. dr. Vek nazorno predstavil vpliv načina in trajanja skladiščenja ter vpliv priprave vzorca na vsebnost vodotopnih ekstraktivov in polifenolov v jelovi skorji. Rezultati aktivnosti, ki so se na Oddelku za lesarstvo odvijale v preteklem projektnem obdobju, predstavljajo originalne in pomembne izsledke, ki bodo Ars Pharmae pomagali pri zagotavljanju večjega in kvalitetnejšega ekstrakcijskega donosa, hkrati pa so raziskave potrdile, da je način oziroma protokol ravnanja in skladiščenja jelove skorje, ki ga trenutno izvajajo v podjetju Ars Pharmae, ustrezen. Po predavanjih je sledil strokovni posvet in diskusija o raziskovalnih aktivnostih, ki projektno skupino čakajo v prihodnjem projektnem obdobju.

Člani projekte skupine so prišli do sklepa, da vse raziskovalne aktivnosti potekajo skladno s terminskim planom projekta L4-2623 ter da so bili v prvem projektnem letu realizirani oziroma doseženi vsi časovni mejniki, torej MS1 in MS9 (Spisek časovnih mejnikov je naveden v opisu projekta na internetni strani Biotehniške fakultete: https://www.bf.uni-lj.si/sl/raziskave/raziskovalni-projekti/). Izbrane rezultate aktivnosti projekta bomo v prihodnje delili tudi s strokovno in znanstveno javnostjo s področja, v obliki člankov in prispevkov na konferencah.



Book review:
Traces of Common Xylophagous Insects in Wood.
Atlas of Identification - Western Europe

Alan Crivellaro[1, 2, *]

Toriti, Magali; Durand, Aline & Fohrer Fabien (2021). Traces of Common Xylophagous Insects in Wood. Atlas of Identification - Western Europe. Springer, Cham. 176 b/w illustrations, 288 illustrations in colour. XVII, 220 pp.
DOI https://doi.org/10.1007/978-3-030-66391-9
Hardcover ISBN 978-3-030-66390-2
Softcover ISBN 978-3-030-66393-3
eBook ISBN 978-3-030-66391-9
Link: https://link.springer.com/book/10.1007/978-3-030-66391-9

This valuable and lavishly illustrated 220-page book, written by Magali Toriti, Aline Durand and Fabien Fohrer, was published by Springer in July 2021.

The three authors constitute a truly interdisciplinary group of subject experts, each with extensive academic and field experience. Dr Magali Toriti is an anthracologist and archaeologist at Le Mans University (FR) and is Associated with the CReAAH - Center for Research in Archaeology, Archeosciences, History in Le Mans (FR). She has been studying preventive archaeological sites. Dr Aline Durand is a historian and anthracologist focusing her research and teaching activities on medieval rural systems at Le Mans University (FR). Her scientific approach interweaves written sources, archaeological data and charcoal analysis to better understand the relationships between societies and the environment. Dr Fabien Fohrer is an entomologist and microbiologist for the CICRP - Interdisciplinary Center of Heritage Conservation and Restoration, in Marseille (FR). He works on preserving cultural heritage and carries out biological diagnoses to prevent and cure pest infestations.

The book, divided into three main chapters, goes beyond the detailed description of and identification keys for 25 xylophagous insect species by providing identification keys and tabulated data for 326 insects. As the idea for the book started after identifying wood-boring insects from archaeological charcoal, frass particles and gallery morphology were examined in detail to design the original identification keys. Four hundred and sixty-four original photographs, microphotographs and drawings offer unique views of insects and rich insights into the structure of galleries and frass characteristics.

Following a short introduction (available online at the book's website), the first chapter introduces the reader to the book's structure. It provides accessible, basic information on both wood composition and the life cycle of a wood-boring beetle. A further description of how to read the atlas ensures each reader gets the most out of it.

The second chapter presents two polytomous identification keys and a key diagram. The first key makes it possible to identify insect species based on galleries and frass characteristics, as explained in figures. The second key is based on frass characteristics only. The key diagrams occupy two spread pages allowing for a summary that facilitates comparisons between groups of insects. While the keys are easy to follow, sometimes the discrimination between proposed leads can be tricky. I practiced the keys using the figures provided for some spe-

[1] Department of Geography, University of Cambridge, Cambridge CB2 3EN, UK.
[2] Forest Biometrics Laboratory, Faculty of Forestry, "Ștefan cel Mare" University of Suceava, 720229 Suceava, Romania.
[*] e-mail: alancrivellaro@gmail.com

cies, and I needed to train myself before knowing how to make the correct choices.

The third chapter, by far the most extensive, describes the origin, geographical distribution, biological cycles, required climatic conditions, and preferred wood species of each xylophagous species. Each description also includes galleries and morphometry of the faecal pellets for xylophagous identification.

The back matter (also available online at the book's website) lists the insect species included in the book. Unfortunately, the index of species only lists those 25 described in extensive detail, and discards about 300 briefly described in the tables. A comprehensive list of about 300 references is classified as general and family-specific. Although some seminal works are missing (e.g., by Cymorec S. and Sama G.), the reference list spans 100 years of scientific research on wood-boring insects.

The book fills an essential niche in entomology, constituting a valuable guide for all working in wood science and related topics. It will be a practical guide for forest managers, heritage conservators, environmental engineers, bioarchaeologists, entomologists, loggers, and wood anatomists. The book opens many possibilities to link wood insect damage with historical, ecological and economic contexts.

The book is for sale in print and e-format on Springer's website: https://link.springer.com/book/10.1007/978-3-030-66391-9