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POTENTIALS OF THE EVALUATION OF THE WOOD QUALITY IN LIVING TREES BY USING SEMI- AND NON-DESTRUCTIVE METHODS IN ORDER TO REDUCE WOOD-PROCESSING COSTS

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Abstract: *Being a natural, ecological and renewable resource, wood is increasingly replacing artificial and toxic materials in the manufacture of various types of packaging and other products; thus, its proper and economically justified use has become necessary. The best utilization of wood raw materials has been sought both in practice and theory, which led to the development of a number of non-destructive and semi-destructive methods for the wood quality assessments in various stages of wood exploitation. In this paper, two instruments for the inspection of the internal condition of standing trees were analyzed. The resistograph was designed for the detection of internal defects. In addition to assessing the condition of living trees of different species, the instrument is used to assess the wood density in various materials. The observed resistance during drilling is proportional to the change in the wood density or the relative mass of the element analyzed. The results of drilling in different spots or directions, through the cross-section and along the element, can be used to map the properties of the element. The fractometer is a device designed to measure the strength and other mechanical properties of on a core sample extracted by using an increment borer from a certain part of the tree or branch examined. The fractometer can determine the maximum fracture force and bending and pressure strength of wood. It is also possible to identify the stage of decay. Due to its heterogeneous structure and anisotropy, the wood compressive and bending strengths differ between different anatomical directions even within a single species. The results of previous research in the literature indicate that there is a significant positive correlation between the radial bending strength and the longitudinal compressive strength of wood. This*

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actualizes the need for the use of different tree species in construction, depending on the load that the wood element will be exposed to. These devices provide high precision and quality in measurement and can achieve a good correlation between the measured values and the mechanical properties of wood. This way, science and practice could be provided by significant data on the properties and quality of wood, while its consumption is minimized.

Keywords: fractometer, resistograph, wood quality determination and evaluation, wood consumption, wood-processing costs

MOGUĆNOSTI PROCENE KVALITETA DRVETA ŽIVIH STABALA POLUDESTRUKTIVNIM I NEDESTRUKTIVNIM METODAMA U CILJU SMANJENJA TROŠKOVA PRERADE

Izvod: *Drvo, kao prirodni, ekološki i obnovljiv resurs, sve više zamenjuje veštačke i toksične materijale u izradi različitih vrsta ambalaže i drugih proizvoda, te je njegovo pravilno i ekonomski opravdano korišćenje postalo nužno. U praksi i u teoriji se teži što boljem iskorišćenju drvne sirovine, stoga je razvijen veliki broj nedestruktivnih i poludestruktivnih metoda analize kvaliteta drveta u raznim fazama eksploatacije. U radu su analizirana dva uređaja za procenu stanja dubećih stabala na licu mesta – rezistograf i fraktometar. Rezistograf je razvijen sa ciljem detekcije unutrašnjih defekata u drvetu. Osim za procenu stanja živih stabala različitih vrsta drveća, ovaj instrument se koristi za procenu gustine drveta u različitim drvnim materijalima (kompoziti, razne konstrukcije). Posmatrani otpor u toku bušenja proporcionalan je promeni gustine drveta ili relativne mase elementa koji se ispituje. Rezultati bušenja na više mesta u različitim pravcima, kroz poprečni presek i duž elementa, mogu se složiti i organizovati u mapu stanja elementa. Fraktometar je uređaj za merenje čvrstoće i ostalih mehaničkih osobina drveta na izvrtku uzetom Preslerovim svrdlom sa određenog dela stabla ili grane koja se ispituje. Fraktometrom se mogu odrediti vrednosti sile loma i čvrstoće pri savijanju i(li) pritisku. Takođe, moguće je identifikovati fazu štete prouzrokovane truljenjem. Zbog heterogene strukture i anizotropnosti drveta, čvrstoće na pritisak i savijanje se razlikuju za istu vrstu u različitim anatomskim pravcima. Rezultati dosadašnjih istraživanja u literaturi ukazuju na značajnu i pozitivnu korelaciju između radijalne čvrstoće na savijanje i uzdužne pritisne čvrstoće drveta. Ovo aktuelizuje potrebu za korišćenjem različitih vrsta drveća u građevinarstvu u odnosu na opterećenje kojem će element od drveta biti izložen. Ovi uređaji pružaju veliku preciznost i kvalitet pri merenju i mogu postići dobru korelaciju između merenih vrednosti i mehaničkih svojstava drveta. Na taj način nauka i praksa mogu dobiti značajne podatke o svojstvima i kvalitetu drveta, a utrošak materijala se minimalizuje.*

Ključne reči: fraktometar, rezistograf, ispitivanje i procena kvaliteta drveta, iskorišćavanje drveta, troškovi prerade drveta

1. INTRODUCTION

Forests are a very valuable national resource. They represent habitats of wild animals and plants, and they also serve as a renewable source of raw materials for wood and wood fiber products.

Forests may be able to produce sufficient wood but production costs will rise and so too will the cost of wood products (Rajković and Tabaković-Tošić, 2007). Natural genetic engineering has created wide variation in the structure of wood, causing numerous difficulties in the wood processing industry, i.e. in the use of wood as a material. Wood is sometimes difficult to process into quality products due to the large range of its mechanical and chemical properties. Due to its organic origin and renewability, wood is one of the most sought-after natural materials. Its rapid exploitation stemmed from the high demand and development of new products has led to the lack of good-quality raw wood materials.

Development of the wood processing industry is causing growing demand for high-quality wood raw materials (Marković *et al.*, 2015). Therefore, attention must be paid to the rational use of this material. In each technological process, it is necessary to determine the quality of wood assortments, because it significantly influences further processing and use of wood. Wood properties are mainly determined by its structure, biological and organic origin, but also by the conditions in which the wood is used and exploited. Being a natural, ecological and renewable resource, wood is increasingly replacing artificial and toxic materials in the manufacture of various types of packaging and other products; thus, its proper and economically justified use has become necessary. As practice and theory strive to make the best use of wood raw materials, a large number of non-destructive and semi-destructive methods for analyzing the quality of wood in various phases of its exploitation have been developed.

Most methods determine properties of wood in an indirect way; therefore, suitable devices have been constructed to determine the characteristics of the material analyzed based on the drilling resistance, sound propagation or velocity, radiation absorption, etc. Using statistical methods, the measured parameters are transformed into the required properties of wood. Finally, the accuracy of the method used is checked, by establishing a correlation between the properties of wood, determined by the non-destructive method and those measured experimentally (Todorović, 2014).

Non-destructive methods can determine properties of wood in situ, without destruction. This way, science and practice are provided by significant data on the properties and quality of wood, while its consumption is minimized (Todorović, 2014). In developed countries, most of these methods are standardized and applied successfully in both science and practice. There are mechanical methods, acoustic methods and methods of radiation.

In this paper, two devices for the assessment of wood quality in standing trees were analyzed – the resistograph and the fractometer, as tools for the evaluation of the effects of decay on wood.

The resistograph was patented in 1990 (Rinntech, Heidelberg, Germany[2]). It is a device that measures drilling resistance on site, determining certain properties of wood. The resistograph was developed as an easy to use and precise measuring system for detecting internal defects in wood. The energy consumption of the device is measured electronically. The results are immediately stored in the

[2] www.rinntech.com

internal memory of the device (Rinn *et al.*, 1996). Besides the assessment of wood quality in standing trees of different species, the instrument is also used for the determination of the density of wood in various wood materials, such as wood composites and various types of timber products. Drills vary in price, applicability, weight, drilling depth, and particularly in technical characteristics, such as precision and resolution (Kasal and Tannert, 2011).

The fractometer (Lat. frango, frangere = to break) is a device for measuring the strength and other mechanical properties of wood on a core sample extracted by using an increment borer from a certain part of the tree or branch being examined. Two versions of the device have been developed, Fractometer 1 which measures the maximum force and fracture angle in the bending load and Fractometer 2 which, in addition, measures the properties of compressed wood. Depending on the device used, the fracture strength and bending strength and/or compression can be determined. Moreover, it is possible to identify the stage of decay (2017).

Reference books on wood properties have very limited importance in assessing individual trees. A tree that is examined is usually not the best representative of the species and deviates from the average values of the mechanical properties in comparison to the surrounding trees in the habitat, and is often damaged by fungi or insects. If the symptoms of internal defects are detected, it is necessary to examine the tree in more detail, especially in public areas. A tree can collapse due to its poor mechanical properties. However, a tree can also break easily if its strength is reduced due to the destruction of its structure by fungus activity. In tree safety assessment, using the Visual Tree Assessment (VTA) method, tree characteristics are first visually checked. VTA helps in making the difference between trees where there is a potential risk of collapse and those that are really dangerous to the environment. VTA provides information on the physical characteristics of a tree and its mechanical properties and indicates the correct use of measuring instruments.

2. MATERIAL AND METHODS

The analytic-synthetic method was used as a basic method in the paper. Prior to the analytical procedure, it was necessary to collect, evaluate, select, systematize and update information about the two devices studied. The evaluation of data was based on simple, practical, but also some complex indicators. It was necessary to make a full review of the results obtained in numerous papers.

The collected literature sources, related to the potentials for applying the resistograph and the fractometer in forest evaluation have been carefully studied and classified in several groups:

1. Literature related to the historical development of the devices studied;
2. Literature related to the theoretical definitions, purpose and practical applications of the devices;
3. Literature comprising comparative tests with other non-destructive methods for quality evaluation of living trees;
4. Literature comprising the result of the same methods applied to different tree species.

3. RESULTS AND DISCUSSION

A number of studies deal with the problem of determining the characteristics of wood using the resistograph. In addition, numerous papers have compared this method with various other non-destructive and semi-destructive methods. The results of the most notable studies are presented in Table 1.

Resistance drilling has been used to inspect trees and timber since 1987 (Rinn, 2013). Rinn *et al.* (1996) have compared the tree-ring density obtained by using the drilling resistance method with X-rays densiometry in several different species. The results show that the resistance from the drilled profiles correlates to the density of dry wood (r^2>0.8). Changes in the density within and between tree rings and the density variations caused by decay were discovered using the resistance profile.

Table 1. *The most notable wood property investigations conducted using semi- and non-destructive methods*

Nº	Method used	Tree species	Correlation (r^2)	Property analyzed	Reference
1.	Drilling resistance, X-rays densiometry	Several	>0.80	Dry wood density	Rinn *et al.* (1996)
2.	Resistograph, Micro-densitometry	Several	0.93–0.97	Quality, wood density	Chantre and Rozenberg (1997)
3.	Resistograph	*Eucalyptus globulus, Ulmus glabra*	Strong	Density	Costello and Quarles (1999)
4.	Resistograph	*Pinus taeda*	0.29–0.65	Wood density	Isik and Li (2003)
5.	Resistograph	*Pinus echinata*	0.23–0.47	Wood density, drilling resistance	Gwaze and Stevenson (2008)
6.	Fractometer	25 tropical species	Strong	Radial bending strength, radial bending angle, longitudinal compressive strength	Tang *et al.* 2005
7.	Fractometer, Static testing	*Agathis* sp., *Pinus merkusii, Acacia mangium, Swietenia* sp., *Tectona grandis*	Strong	Compressive strength, basic density	Matsumoto *et al.* (2010)

Chantre and Rozenberg (1997) made recordings using the resistograph and micro-densitometry on the same trees. The results of comparing the two types of profiles showed excellent correlations (from 0.93 to 0.97). They concluded that the resistograph provides better correlations for the evaluation of the whole trunk parameters and that a single value can be summarized. It also provides an evaluation of wood quality.

Costello and Quarles (1999) compared decayed and sound wood assessments made using the resistograph and the portable drill with laboratory measurements of wood density. They made field evaluations of sixteen trees of *Eucalyptus globulus* Labill. and five trees of *Ulmus glabra* Huds., cut, sectioned along the resistograph, drilled in test paths and measured for density. Density measurements and resistograph measurements show strong relations of soundwood depth in 85.5% of all cases for *Eucalyptus globulus* and in 100% of all cases for

Ulmus glabra. Portable drill measurements provided a close connection with the density measurements in 73% of the cases for *Eucalyptus globulus* and 81% for *Ulmus glabra*. Drill evaluations were noticeably diverse among operators. The resistograph provided a higher level of uniformity and accuracy than the portable drill. Both methods showed that the knowledge of mechanical patterns of wood properties is critical for evaluation.

Isik and Li (2003) used the resistograph as a tool for quick assessment of wood density of living trees in progeny trials. They examined 1477 trees from fourteen full-sib loblolly pine tree families. The resistograph amplitude had weak (0.29) to moderate (0.65) phenotypic correlations with wood density on an individual-tree basis. They gave an opinion that the resistograph is more reliable for measuring the relative wood density of living trees than other instruments.

The resistograph was also used by Gantz (2002) to estimate genetic parameters of wood in two softwood and two hardwood species and compare them to x-ray densitometry. The conclusion was that the resistograph provides good results in genetic tests for wood density.

Gwaze and Stevenson (2008) searched for high correlations between wood density and drill resistance obtained by the resistograph. At the individual tree level, the linear relationship between wood density and drill resistance (amplitude) was weak and positive (r^2=0.23), but at the family mean level the relationship was stronger (r^2=0.47).

Kahl *et al.* (2009) did quick, quantitative, field estimation and made a comparison with conventional methods of wood density for logs of Norway spruce in four different decay stages. They noticed the predicting model of wood density but that predictor explained 65% of the differences in wood density. The relationship between the drill resistance and gravimetric wood density depended on decay status.

The first presentation of fractometar examination was given by Mattheck *et al.* (1995) as a new method that included visual tree assessment on a biomechanical basis, as well as fractometer examination. Numerous field studies suggested that radial strength decreases in the same way as longitudinal strength because of decay action. The authors pointed out that "all the equipment, including the Fractometer, is only able to measure and quantify what one has already seen before. Most important of all is the experience of the arborist, and this will never change in the future since it cannot be substituted by any kind of measuring device.'' (*Mattheck et al.*, 1995).

Schwarze *et al.* (1995) tested two devices, ''Metriguard'' (stress wave timers for detecting decay) and the fractometer, for the measurements of the loss of strength. Metriguard failed to detect the first fungal stages, but it detected decays of white and brown rot in further stages. The fractometer indicated a great loss of strength for all stages of fungal attack [for *Ustulina deusta* (Hoffm.) Lind., even in an early stage of decay].

Zipse *et al.* (1998) investigated the effects of wind on the mechanical properties of 14 wind exposed living trees of *Fagus sylvatica* L. using a fractometar. They concluded that the wind exposed trees develop wood which is stronger and allows larger stresses before a failure.

Matheny *et al.* (1999) evaluated the fracture moment and the fracture angle of core samples from the lower trunk of 25 tree species using the fractometer. They found that the results varied with species, core segment, and location of the tree. Some of these differences might be related to the examination of different species within a genus. Also, there was some major variation in fractometer results due to location, so they suggested that habitat factors could be the cause of such differences. They concluded that when using the fractometer, researchers must pay special attention to the samples taken from individual trees rather than tables of standardized results. In evaluating the strength loss associated with decay, fractometer results must be compared to the values from clear samples of the same tree.

On the other hand, Gruber and Hagermann (2000) explored the bending solidity of 24 (1 m long) stem samples of *Fagus sylvatica*, *Populus* spp., *Picea abies* (L.) H. Karst. and *Pseudotsuga menziesii* (Mirb.) Franco, using DIN 52-186 and the fractometry method. They did not find any correlation between the DIN bending solidity and the fractometer measurements. Still, their suggestion is that fractometry method can be highly recommended for evaluating tree strength.

Lin *et al.* (2003) analyzed radial changes of living trees in *Taiwania cryptomerioides* Hay. using the fractometer. The differences in crushing strength in the transverse direction increased from the pith to the bark. The analysis of variance and correlation showed that the value of the radial difference in crushing strength was lower than the tree-to-tree variation.

Another study (Tang *et al.*, 2005) was done by evaluating the wood strength properties of 25 tree species in Hong Kong using Fractometer II. Radial bending strength was tested on 2656 samples and longitudinal compressive strength and fracture angle on 4779 samples. Meaningful and positive correlations between radial bending strength and longitudinal compressive strength were established, showing a strong connection between radial and longitudinal mechanical strengths. Hierarchical clustering and multidimensional scaling analysis revealed a clear grouping of tree species into different types of wood properties.

Chiu *et al.* (2006) used the fractometer to measure the crushing strength, aiming to mark the line between juvenile and mature wood. They used segmented regression and variance component analysis for this purpose and discovered that the crushing strength of core wood increases with the tree age. Differences between trees were more significant than within tree variations and the line between juvenile and mature wood at the age of 18–20 was found at an approximate distance of 10.8–13.2 cm from the pith.

Matsumoto *et al.* (2008) examined two Japanese softwoods. *Cryptomeria japonica* (L.f.) D. Don and *Pinus densiflora* Siebold & Zucc. were tested by measuring radial changes of bending and compression strength of core samples using the fractometer. They also tested small clear specimens of juvenile wood for static bending properties and static compression strength parallel to grain at juvenile stage. However, they did not find a meaningful relationship between the bending strength of core samples and static bending strength of small clear specimens. A significant positive correlation was found between the compression strength obtained with the fractometer and the static test. They concluded that wood properties, mostly the compression strength of wood, can be assessed by the compression strength of core samples measured with the fractometer.

Matsumoto *et al.* (2010) did another experiment with living trees. They examined wood properties of five Indonesian species using the fractometer. They concluded that the compressive strength measured with the fractometer could be applied for living tree properties and they noticed a high coefficient of determination between this compressive strength and density. Therefore, they concluded that the fractometer is a good tool for the determination of wood properties *in situ*.

Ganesan and Hamid (2010) did research on 25 urban tree species in Singapore. They used the fractometer to assess the radial bending strength, longitudinal compression strength and fracture angle and made some tables of standard values for the tested species. They found that the readings for the fracture moment and fracture angles can be obtained with confidence. Speaking of the longitudinal compressive strength, they had difficulty in determining the first spot of failure when wood fibers are kinked.

Due to its heterogeneous structure and anisotropy, the wood compressive and bending strengths differ between different anatomical directions even within a single species. The results of previous research in the literature indicate that there is a significant positive correlation between the radial bending strength and the longitudinal compressive strength of wood. This actualizes the need for the use of different tree species in construction, depending on the load that the wood element will be exposed to. These devices provide high precision and quality in measurement and can achieve a good correlation between the measured values and the mechanical properties of wood.

4. CONCLUSIONS

The purpose of this paper was to show the significance of two apparatuses (the resistograph and the fractometer) as tools for the evaluation of the effects of decay on wood. The strength of wood determines the stability and safety of a tree. The devices in question are suggested for measuring the strength properties of wood directly. Studies discussed in this paper have shown that the transverse strength decreases in the same way as the axial strength, as a result of wood decay. Basic comprehension of the method used and the knowledge of technical properties of the devices employed is required for the proper selection of a suitable device. Besides the resolution and precision of the profile, when the use of the resistograph is considered, there are many other details to be considered before a final decision is made what device to choose and how to use it.

Studies discussed in the paper revealed high correlations between the measured properties and the actual wood quality. That means that the quality of wood can be estimated *in situ*, and the devices in question can help us make the right decision. These estimates make wood processing much less expensive because trees can be selected according to the quality tests before they are cut. This way, science and practice could be provided by significant data on the properties and quality of wood, while its consumption is minimized.

Finally, it must be pointed out that all the devices used, including the resistograph and the fractometer, are only measuring and quantifying tools of what has already been seen by man. Therefore, the most important of all is the practical experience of the researcher. It will not change in the future because the human expertise cannot be replaced by any measuring tools.

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Summary

Optimizing the wood production is one of the major tasks for producers. Wood properties are mainly determined by its structure, biological and organic origin, but also by the conditions in which the wood is used and exploited. As practice and theory strive to make the best use of wood raw materials, a large number of non-destructive and semi-destructive methods for analyzing the quality of wood in various phases of its exploitation have been developed. Most methods determine properties of wood in an indirect way; therefore, suitable devices have been constructed to determine the characteristics of the material analyzed based on the drilling resistance, sound propagation or velocity, radiation absorption, etc. Using statistical methods, the measured parameters are transformed into the required properties of wood. In addition, the accuracy of the method used is checked, by establishing a correlation between the properties of wood, determined by the non-destructive method and those measured experimentally.

The analytic-synthetic method was used as a basic method in the paper. Prior to the analytical procedure, it was necessary to collect, evaluate, select, systematize and update information about the two devices studied. The evaluation of data was based on simple, practical, but also some complex indicators. It was necessary to make a full review of the results obtained in numerous papers.

Studies discussed in the paper revealed high correlations between the measured properties and the actual wood quality. That means that the quality of wood can be estimated in situ, and the devices in question can help us make the right decision. These estimates make wood processing much less expensive because trees can be selected according to the quality tests before they are cut.

Based on the results presented in the analyzed studies, in can be concluded that devices used, including the resistograph and the fractometer, are only measuring and quantifying tools of what has already been seen by man. Therefore, the most important of all is the practical experience of the researcher. It will not change in the future because the human expertise cannot be replaced by any measuring tools.

MOGUĆNOSTI PROCENE KVALITETA DRVETA ŽIVIH STABALA POLUDESTRUKTIVNIM I NEDESTRUKTIVNIM METODAMA U CILJU SMANJENJA TROŠKOVA PRERADE

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Rezime

Optimizacija drvne industrije je jedan od glavnih zadataka proizvođača. Svojstva drveta su uglavnom rezultat njegove strukture, budući da je drvo biološkog i organskog porekla, ali su njegova svojstva takođe posledica uslova u kojima se ono koristi i eksploatiše. Usled nastojanja u praksi i nauci da se postigne najbolja moguća upotreba

drvnih materijala, razvijene su brojne poludestruktivne i nedestruktivne metode za ispitivanje kvaliteta drveta u raznim fazama njegove eksploatacije. Većina metoda utvrđuje svojstva drveta na indirektan način, tako da su konstruisani odgovarajući aparati za utvrđivanje karakteristika ispitivanog materijala, koji se zasnivaju na otporu na bušenje, širenju i brzini zvuka, apsorpciji radijacije, itd. Primenom statističkih metoda, merene vrednosti parametara pretvaraju se u odgovarajuće osobine drveta. Pri tome, tačnost primenjene metode se proverava izračunavanjem korelacija između osobina drveta koje su određene nedestruktivnim metodama i onih dobijenih eksperimentalnim putem.

Osnovni metod ovog rada bio je analitičko-sintetički metod. Pre samog analitičkog postupka, bilo je neophodno prikupiti, razvrstati, proučiti, sistematizovati i dopuniti dostupne informacije o uređajima koji su analizirani – rezistografu i fraktometru. Procena prikupljenih podataka zasnivala se na jednostavnim i praktičnim, ali i složenim pokazateljima kvaliteta drveta. Bilo je nužno načiniti iscrpan pregled rezultata koji su predstavljeni u brojnim naučnim radovima.

Istraživanja o kojima je raspravljano u ovom radu ukazala su na postojanje značajnih zavisnosti između merenih svojstava i stvarnih pokazatelja kvaliteta drveta. To znači da se kvalitet drveta može proceniti *in situ* i da spomenuti uređaji mogu biti od koristi pri donošenju pravih odluka u proizvodnji. Zahvaljujući ovim procenama, obrada drveta je znatno jeftinija, s obzirom da se stabla mogu odabrati shodno ispitivanjima njihovog kvaliteta i pre nego što su ona posečena.

Na osnovu analiziranih literaturnih izvora, može se zaključiti da uređaji koji se koriste, uključujući rezistograf i fraktometar, predstavljaju samo pomagala za merenje i kvantifikaciju onoga što je čovek već uočio. Stoga, praktično iskustvo istraživača je nezamenljivo, što se u budućnosti neće promeniti, jer se stručnost istraživača ne može zameniti nikakvim uređajima za ispitivanje.