EVALUATION OF SUITABILITY OF SELECTED HARDWOOD IN CIVIL ENGINEERING

VREDNOVANJE PRIKLADNOSTI IZABRANOG TRVDOG DRVETA U GRAĐEVINARSTVU

Eva ŠUHAJDOVÁ
Miloslav NOVOTNÝ
Jan PĚNČÍK
Karel ŠUHAJDA
Pavel SCHMID
Bohumil STRAKA

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1 INTRODUCTION

The use of local hardwood species is a very topical issue not only in Europe, but also worldwide. There is some experience with the production of hardwood bearing elements from Switzerland, where particularly ash and beech is used, as well as oak and locust up to a certain extent [24]. Out of the large number of uses of hardwood for construction in Switzerland, the following examples are mentioned: Sports Centre in Sargans, built

in 2011, Tribune Kulm Hotel in St. Moritz (2016/2017), and a parking house Innerarosa with the length of 37 m and width of 42 m in Arosa (2010). The Swiss constructions can be found in other countries as well, e.g. roofing of a courtyard Porta Nuova Garibaldi in Piazza GaeAulenti in Milano (2012) and new courtyards of a language school St'Clares School in Oxford (2015) [24]. Hardwood bearing elements were often used in historical constructions [31]. Properties of long-term in-built wood are important for analyses of the existing structures as well [26].

In order to use hardwood in practice in constructions, it is necessary to have theoretical knowledge of its behaviour, e.g. discussed by Ammann in [1], where he examines adhesion in order to describe the delamination behaviour of glue joints. Tran et al. in [32] and [33] presented experimental research of glue beech and oak timber beams. Hunger et al. in [14] describes experimental research of glued-in rods in hardwood glulam elements (ash, beech). Miklečičin [21] examines properties of thermally modified beech wood. Moosavi et al. [23] focused on hornbeam wood and effects of altitude on bending creep behaviour.

More viewpoints influence the suitability of use of specific wood. The dominant viewpoint is the resource availability, which reflects the most important criterion – material price. In addition, it is necessary to take into account mechanical and physical properties of selected wood. Solutions to complicated decision-making situations, when a large number of often contradictory criteria are frequently dealt with by multiple criteria analyses, are described by Ginevičius[15], Liu [19], Maityand Chakraborty [20], Montajabiha [22] and others.

Ing. Eva ŠUHAJDOVÁ, Corresponding author, Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology, Address: Veveří 95, 602 00, Brno, Czech Republic. E-mail: suhajdova.e@fce.vutbr.cz.

prof. Ing. Miloslav NOVOTNÝ, CSc., Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology, Address: Veveří 95, 602 00, Brno, Czech Republic. E-mail: novotny.m@fce.vutbr.cz. Phone

doc. Ing. Jan PĚNČÍK, Ph.D., Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology, Address: Veveří 95, 602 00, Brno, Czech Republic. E-mail: pencik.j@fce.vutbr.cz.

doc. Ing. Karel ŠUHAJDA, Ph.D., Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology, Address: Veveří 95, 602 00, Brno, Czech Republic. E-mail: suhajda.k@fce.vutbr.cz.

doc. Ing. Bohumil STRAKA, CSc., Institute of Metal and Timber Structures, Faculty of Civil Engineering, Brno University of Technology, Address: Veveří 95, 602 00, Brno, Czech Republic. E-mail: straka.b@fce.vutbr.cz. Phone

doc. Ing. Pavel SCHMID, Ph.D., Institute of Building Testing, Faculty of Civil Engineering, Brno University of Technology, Address: Veveří 95, 602 00, Brno, Czech Republic. E-mail: schmid.p@fce.vutbr.cz.

Regarding the needs of the evaluation of the most suitable hardwood for constructions, the climate-tolerant hardwood species with the largest share in the recommended forest tree species composition in the Czech Republic were selected. According to [16], the area of broadleaf forests in the Czech Republic should reach 35.6 % of the total forest area in contrast to the current 25.6 %. The increase in hardwood timber stock in Europe is also mentioned in [1], [29] and others. Forests in the Czech Republic are currently formed by predominantly coniferous forest land areas, with spruce occupying more than 50 % of coniferous forest land areas. However, spruce areas are gradually decreasing. According to [16], broadleaf forests are predominantly formed by beech with 7.7 % and oak with 7 % of the total broadleaf forest land area.

According to [16], the largest areas in the recommended forest tree species composition concerning broadleaf forests will be occupied by beech (18 %), oak (9 %), lime (3.2 %), maple (1.5 %), and hornbeam (0.9 %). The highest increase is expected for beech. Lime was excluded from the whole group, since its wood is soft and fragile and is unsuitable for construction purposes.

The following species of hardwood were evaluated for their use in building constructions for bearing elements: (i) European beech (*Fagus silvatica*), (ii) common oak (*Quercus robur*), (iii) common hornbeam (*Carpinus betulus*), and (iv) Norway maple (*Acer platanoides*).

2 MATERIAL AND METHODS

The aim of the decision-making process is to find the most suitable species of hardwood for the use in building constructions. Good properties of wood in comparison with other materials particularly include low density, easy workability and connectability, and strength. Price, which is closely related to the supply of specific wood on the market, plays an important role as well. Regarding the use for bearing elements, the shape stability, which is generally worse for hardwood than for coniferous wood, needs to be taken into account [13], [18]. However, this property can well be eliminated by laminating, i.e. using construction elements from glue laminated (GL), or cross

laminated timber (CLT), as mentioned e. g. in [30], [34] and others.

The evaluation criteria are selected so that individual variants can be well assessed, i.e. to find properties with the highest effect on the price of timber, building structures from a given material and its physical and mechanical properties.

The following evaluation criteria were selected: bending strength, elasticity modulus, compression strength, density, shrinkage, occurrence of knots and straight grains, workability and increase in forest land area.

2.1 Criteria input values

The values of some properties were experimentally tested on the samples of evaluated wood (bending strength, elasticity modulus, compression strength, occurrence of knots and faults), the others were taken over from specialized literature.

The values specified by specialized publications for the same wood differ considerably, e.g. according to [28] density of oak and hornbeam differ marginally (by 0.1 %), while according to [18], they differ by 17.7 %. Therefore, the properties with a high variance of values needed to be determined with the use of specialized literature and their validity verified. The samples of all experimentally tested wood were taken from a single supplier, who received them from more localities from the Czech Republic. The supplier arranged the preparation of all testing samples for the use of the same production procedures.

2.1.1 Bending strength

Bending strength was experimentally determined on samples with dimensions of $25 \times 25 \times 475$ mm. In total, 30 samples from each wood were tested; the test complied with standard ČSN EN 408[4], see Fig. 1. Loading was applied with constant speed until the failure. Maximum effective force F_{max} was determined and loading F and deformation w over time for the calculation of elasticity modulus, see section 2.1.2., were continuously recorded.

Fig. 1 Scheme of strength and elasticity modulus tests by four-point bending method

Fig. 2 Strength testing values by four-point bending method expressed in a box chart

Regarding the results of the experimental bending tests (see Fig. 2), beech wood has the highest average bending strength with the value of 108.4 N/mm², oak wood has the lowest value reaching 91.7 N/mm². The resulting values of bending strength are compared to literature in Tab. 1.

2.1.2 Elasticity modulus

Tests for elasticity modulus were performed simultaneously together with bending strength tests, i.e. on the same samples. The experiment is described in section 2.1.1.

Fig. 3(left) shows behaviour of compared hardwood in load-deflection curve, formed by average values of

deflection $\bar{w}$ in relation to average force $\bar{F}$. The curves show that in order to reach the same value of deflection w , it is necessary to use the biggest force F for beech and the lowest for maple. In contrast, maple reaches the biggest deflection at the use of the identical force. Oak and hornbeam wood behaved similarly in the experiment; however, oak wood bending occurred at the lower force than hornbeam wood bending.

The highest value of elasticity modulus (see Fig. 3 right) was found for beech with the value of 19 947 N/mm², while the lowest was for maple with the value of 13 996 N/mm². The results of tested bending strength are compared with specialized literature in Tab. 2.

Tab. 1 Bending strength according to test results in comparison with specialized literature; ¹American beech (*Fagus grandifolia*), ²Red oak (*Quercus rubra*), ³Bigleaf maple (*Acer Macrophyllum*).

$f_{m,12}$ N/mm ²		beech	oak	hornbeam	maple
test results	average $\bar{F}$	108.4	91.7	101.7	94.1
	median $\tilde{F}$	107.8	93.9	103.7	96.5
	Standard deviations	5.06	10.50	21.41	11.64
values from specialized literature	[28]	124	85.2	130.7	114
	[13]	103 ¹	96 ²	-	74 ³
	[18](to the value for 12% moisture converted from the value for 15% moisture according to [8])	115	97	143	129

Fig. 3 Compared of behaviour of individual wood species in load displacement diagram ($F - w$), average values (left), Results of experimental determination of elasticity modulus expressed in a box chart (right)

Tab. 2 Elasticity modulus according to test results in comparison with specialized literature; ¹American beech (*Fagus grandifolia*), ²Red oak (*Quercus rubra*), ³Bigleaf maple (*Acer Macrophyllum*).

$E_{m,l}$ v N/mm^2		beech	oak	hornbeam	maple
test results	average $\bar{x}$	19 947	18155	17925	13996
	median $\tilde{x}$	19 968	17821	17573	14134
	standard deviation s	730	1549	2782	1563
values from specialized literature	[28] pro $\omega = 10 - 12 \%$	12 966	-	13 417	9 582
	[13]	11900	11300	-	10000
	[18](to the value for 12% moisture converted from the value for 15% moisture according to [9])	16 495	12 100	16 700	11 650

2.1.3 Compression strength parallel to grains

Destructive tests to determine compression strength parallel to grains. Tests were performed in compliance with standard ČSN EN 408[4], see scheme in Fig. 5 left. Samples were produced with dimensions of $25 \times 25 \times 300$ mm in the number of 30 pcs for each wood species, loading surfaces were adjusted so that their parallel relationship and perpendicularity to the axis of the sample were maintained.

Hornbeam wood reached the highest compression strength values (Fig. 4 right) of $58.8 N/mm^2$, while maple wood reached the lowest compression strength values of $41.6 N/mm^2$. The results of tested compression strength parallel to grains are compared with values in specialized literature in Tab. 3.

Fig. 4 Tests for compression strength parallel to grains, scheme (left) and test results expressed in box chart (right)

Tab. 3 Compression strength parallel to grains according to test results in comparison with specialized literature; ¹American beech (*Fagus grandifolia*), ²Red oak (*Quercus rubra*), ³Bigleaf maple (*Acer Macrophyllum*).

$f_{c,0,12}$, v $N \cdot mm^{-2}$		beech	oak	hornbeam	maple
test results	average $\bar{x}$	53.8	46.7	58.8	41.6
	median $\tilde{x}$	53.6	47.4	59.3	43.9
	standard deviation s	1.93	2.88	4.53	5.45
values from specialized literature	[28]	56.7	59.8	62.5	59
	[13]	50.3	45	-	41
	[18](to the value for 12% moisture converted from the value for 15% moisture according to [7])	58	57	73	58

2.1.4 Density

Wood density is based on the content of water. For better handling with construction elements it is generally preferable to use the elements of lower weight. On the other hand, higher density leads to better mechanical properties of wood (strength, elasticity moduli). Wood of higher density has higher biological resistance as well [17], [27].

Density was determined in compliance with standard ČSN 49 0108 [6] on the samples for tests of bending strength and elasticity modulus parallel to grains. Moisture of the samples was determined by the weight method in compliance with EN 13183-1 [11].

Final values of bending strength are compared with the values available in specialized literature in Table 4. Based on the experimental test results, maple has the lowest density of 556 kg/m³ from the examined wood at the moisture of 0 %, while hornbeam has the highest density of 667 kg/m³.

2.1.5 Shrinking

According to ČSN EN 844-4 [5], shrinking is defined as a reduction of wood dimensions caused by decrease in moisture. Due to anisotropic wood structure, considerable differences in shrinking and swelling occur particularly in tangential and radial directions. They cause changes in the shape of wooden elements. According to [17], shrinking leads to occurrence of surface cracks, particularly with large elements.

The values of shrinking of individual wood species were taken from specialized literature [18]. Tab. 5 provides illustrative comparisons with specialized literature [13], which shows American, not European wood species evaluation. According to [18], hornbeam shows the highest shrinkage values of 19.7 %. Maple and oak have the lowest shrinking values of 12.5 and 12.6 %.

2.1.6 Occurrence of knots and straight grains

This criterion was evaluated qualitatively, based on the occurrence of knots and course of grains within the whole set of samples for testing of bending strength and compression strength parallel to grains. A scale for the evaluation was set from 1 (straight grained wood, low occurrence of knots) to 10 (grains twist and turn, high occurrence of knots).

2.1.7 Workability

Workability can be expressed, according to [35], as a difficulty rate to work the wood including the effect on tool wear. This category was evaluated qualitatively and a scale from 1 to 10 was used for the evaluation. Value 1 was assigned to wood with excellent workability, while the value 10 was assigned to wood that is very hard to work with.

Tab 4 Density of the samples of individual wood species in kg/m³ including a comparison with specialized literature; ¹American beech (*Fagus grandifolia*), ²Red oak (*Quercus rubra*), ³Bigleaf maple (*Acer Macrophyllum*).

Density in kg/m ³ / Wood			beech	oak	hornbeam	maple
experimentally determined	At moisture, [%]:		8.40	9.40	8.50	9.10
			672	609	677	726
	At moisture 0 %		620	556	624	667
values from specialized literature	[28]	At moisture 0 %	684	526	696	697
	[18]	At moisture 0 %	680	620	650	790
	[13]	At moisture 12%	640 ¹	610 ²	480 ³	-

Tab. 5 Shrinking of individual wood species in % according to [18] and [13]; ¹American beech (*Fagus grandifolia*), ²Red oak (*Quercus rubra*), ³Bigleaf maple (*Acer Macrophyllum*)

		according to	beech	oak	maple	hornbeam
Shrinking along grains α_l	[18]		0.3	0.4	0.5	0.5
	[13]		-	-	-	-
Radial shrinking α_r	[18]		5	4.0	3.2	6.8
	[13]		5.5 ¹	4.4 ²	3.7 ³	-
Tangential shrinking α_t	[18]		11.8	7.8	8.4	11.5
	[13]		11.9 ¹	11.1 ²	7.1 ³	-
Volume shrinking α_v	[18]		17.5	12.6	12.5	19.7
	[13]		17.2 ¹	15.1 ²	11.6 ³	-

According to [35], beech and maple are well workable out of the examined wood, oak workability is sufficient, while hornbeam has poor workability properties.

2.1.8 Increase of individual species representation in forest composition

The input values for this criterion were determined through subtracting the current forest land area from the recommended forest land area in % specified in [16]. Recommended forest tree species compositions in the Czech Republic are based on an optimized compromise between the natural composition and the most economically suitable forest tree species composition. Selected values and considered increase in forest land area are shown in Tab. 6.

2.2 Evaluation of individual species suitability

PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) methods were used to find suitability of individual hardwood species for reconstructions of building structures. These methods are used for solutions to general decision-making issues. Basic PROMETHEE method elements were introduced by Brans [2]. The calculation using this method consists of five steps, as described in [19]. This method evaluation results are based on a selected preferential function $p(d)$ for each criterion describing the tested subject and on parameters of the function.

Input values for evaluation of individual variants are summarized in Tab. 7.

Individual variants can be compared in a spider chart, which shows values of each criterion on a separate axis (Fig. 5). Individual values were converted into percentages, where 0 % stands for the worst and 100 % for the best value. The most suitable variant is then the one which occupies the largest area on the graph. Fig. 5 shows that beech occupies the largest area, while hornbeam occupies the smallest area. This evaluation method is just illustrative, since it fails to take into account the gravity of individual criteria.

Fig. 5 Simplified comparison of variants using a spider chart; area of beech 34.5 %, oak 14.9 %, hornbeam 12.4 %, maple 14.6 %.

Tab. 6 Selected values from Table Reconstructed natural, current and recommended forest tree species composition in the Czech Republic[16]

Forest tree species composition in %	Natural	Current	Recommended	Forest land area increase
oak	19.4	7.0	9.0	2.0
beech	40.2	7.7	18.0	10.3
hornbeam	1.6	1.3	0.9	0
maple	0.7	1.3	1.5	0.2

Tab. 7 Input values for multiple criteria analysis; min = minimization criterion, max = maximization criterion (Source: authors)

i	criterion	species		a ₁	a ₂	a ₃	a ₄
				beech	oak	hornbeam	maple
1	Bending strength	N/mm ²	max	108.4	91.7	101.7	94.1
2	Elasticity modulus	N/mm ²	max	19 947	18 155	17 925	13 996
3	Compression strength	N/mm ²	max	53.8	46.7	58.8	41.6
4	Density	kg/m ³	min	620	624	667	556
5	Shrinking	%	min	17.5	12.6	19.7	12.5
6	Workability	-	min	6	8	9	6
7	Occurrence of knots, straight grains	-	min	1	6	9	4
8	Increase in forest land area	%	max	10.3	2.0	0	0.2

$$R = \begin{matrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{matrix} \begin{bmatrix} 108 & 19947 & 54 & 620 & 17,5 & 6 & 1 & 10,3 \\ 92 & 18155 & 47 & 624 & 12,6 & 8 & 6 & 2 \\ 102 & 17925 & 59 & 667 & 19,7 & 9 & 9 & 0 \\ 94 & 13996 & 42 & 556 & 12,5 & 6 & 4 & 0,2 \end{bmatrix} \quad (1)$$

$$R_M = \begin{matrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{matrix} \begin{bmatrix} 108 & 19947 & 54 & 47 & 2,2 & 3 & 8 & 10,3 \\ 92 & 18155 & 47 & 43 & 7,1 & 1 & 3 & 2 \\ 102 & 17925 & 59 & 0 & 0 & 0 & 0 & 0 \\ 94 & 13996 & 42 & 111 & 7,2 & 3 & 5 & 0,2 \end{bmatrix} \quad (2)$$

2.2.1 Criteria matrix

Individual criteria have different units, some are maximizing criteria (yields), some are minimizing criteria (costs) (see Tab. 7).

A basic criteria matrix **R** can be created on the basis of Tab. 7 and written in the form of (1). The basic criteria matrix **R** is modified into a form of a modified criteria matrix **R_M** with all maximizing criteria by subtracting the criterion value from the worst minimization criterion option, i.e. for evaluation how much a given variant is better than the worst option [12]. The modified criteria matrix **R_M** is shown in the form of (2).

2.2.2 Weight of criteria

Regarding the large number of criteria, the analytic hierarchy process was used. First, the criteria were put into partial groups based on their mutual relationships. Every criteria group was assigned with a standardized criterion weight. Subsequently, every criterion was assigned with a standardized criterion weight. The resulting criterion weight is then the product of the standardized weight of the group and standardized weight of the criterion.

A method of quantitative pair wise comparison (Saaty's method) was used for an assignment of group

standardized weight and standardized criteria weights in groups. According to [19], apart from selecting a preferred criterion, the method determines the size of this preference for every pair of criteria. The preference receives values from 1 (criteria are of the same significance) up to 9 (the first criterion is absolutely more significant than the other one). The size of preferences of the *i*-th criterion against *j*-th one are arranged in a Saaty's matrix **S**= (*s_{ij}*). The elements *s_{ij}* stand for estimates of criteria weights ratios. The matrix is square and reciprocal. If the matrix **S** is at least partially consistent, the criteria weights can be calculated with the use of standardized geometric average of matrix **S** lines[10]:

$$\omega_i = \frac{\left[\prod_{j=1}^n s_{ij} \right]^{\frac{1}{n}}}{\sum_{k=1}^n \left[\prod_{j=1}^n s_{kj} \right]^{\frac{1}{n}}}, i=1,2,\dots,n, \quad (3)$$

where *s_{ij}* or *s_{kj}* is an element of Saaty's matrix; *i, j, k* are criteria numbers; *n* is number of criteria.

The calculation of criteria weights is summarized in Tab. 8. Criteria group I – price is considered slightly more significant than criterion II – physical properties.

Tab. 8 Weight values of *i*-th criterion

Group number	Criteria group	Group weight ω_g	i	Criterion	Crit. weight in group ω_c	Final criterion weight ω_i
I	Mechanical properties	0.316	1	bending strength	0.4	0.126
			2	elasticity modulus	0.4	0.126
			3	compression strength	0.2	0.063
II	Physical properties	0.263	4	density	0.143	0.038
			5	shrinking	0.571	0.150
			6	workability	0.286	0.075
III	Price	0.421	7	occurrence of knots, straight grains	0.167	0.070
			8	Increase in forest land area	0.833	0.351
			Σ			1.000

2.2.3 Calculation by PROMETHEE methods

PROMETHEE methods compare all alternatives *A_j* and *A_k*, by determining preferential relation $\pi(A_j, A_k)$. The calculation procedure is described in details in the literature [3],[15], [22] and [25].

PROMETHEE method contains 6 basic types of preferential functions. For the needs of the evaluation of suitability of the use of hardwood, the preferential function V was selected for all criteria. The function V was described by Ginevičius in [15] and Montajabiha in [22]:

$$p(d) = \begin{cases} 0, & \text{if } d \leq q^* \\ \frac{d - q^*}{p^* - q^*}, & \text{if } q^* < d < p^* \\ 1, & \text{if } d > p^* \end{cases} \quad (4)$$

where $p(d)$ is the preferential function, q^* is a preference threshold, q^* was chosen with 60 % of the maximum difference d , and p^* indifference threshold, where $p^* = -q^*$.

3 RESULTS AND DISCUSSION

According to [15], the ranking of alternatives, or wood species, respectively, a_1, a_2, a_3, a_4 (Tab. 7) is based on the difference between the values F_j^+ and F_j^- . The bigger the difference, the more suitable variant. The values of $\pi(A_j, A_k)$, sum of all positive (output) relationships F_j^+ and negative (input) relationships F_j^- , difference between them $F_j = F_j^+ - F_j^-$ ($j = 1, 2, \dots, n$), and ranking of all variants evaluated by PROMETHEE 2 method are summarized in Tab. 9.

Tab. 9 The results obtained by calculation of suitability of evaluated hardwood by PROMETHEE method (Source: authors)

Hardwood (alternatives)	Hardwood (alternatives)			
	a_1	a_2	a_3	a_4
a_1 (beech)	0	0.74	0.84	0.70
a_2 (oak)	0.21	0	0.42	0.35
a_3 (hornbeam)	0.14	0.27	0	0.30
a_4 (maple)	0.20	0.33	0.35	0
F_j^+	2.29	0.97	0.71	0.88
F_j^-	0.55	1.34	1.61	1.35
F_j	1.74	-0.37	-0.91	-0.47
Ranking	1	2	4	3

Correct selection of criteria and determination of weights are important factors to objectively evaluate the variants with the use of PROMETHEE method. The presented study places a great stress on percentage increase in forest land area, since there is a high likelihood of its influence on the price of timber.

As a comparison, the same calculation was made, but this time with the same weight for all criteria. Still, variant a_1 – beech was found the most suitable and variant a_3 – hornbeam the least suitable. However, there was a change in the second and third position, where variant a_4 – maple was evaluated as the second most suitable. The effect of criterion 4 – density is clearly visible; maple has the lowest density of the evaluated hardwood. In addition, maple, together with oak, shows the lowest volume changes due to moisture (criterion 5); its workability (criterion 7) is comparable to beech.

The calculation could include other criteria as well, while some criteria could be omitted. That particularly holds for strengths, which are included in two criteria. Nevertheless, omitting a single strength would not affect the final ranking. Calculations with modified input conditions were made: placing more stress on mechanical properties (in the step criteria selection

3.1 Discussion

Based on the results of multiple criteria analysis by PROMETHEE 2 method, the most suitable hardwood from the group (beech, oak, hornbeam, maple) is variant a_1 – beech. The highest increase in forest land area is expected for beech, which would lead to the decrease in the price for beech timber. In contrast to other evaluated hardwood, beech has straight grains with low occurrence of knots, on the other hand, it has relatively poor properties in terms of shape stability (shrinking). Regarding mechanical properties and density, beech is comparable to oak. It has the best workability properties, together with maple.

The second in the ranking was variant a_2 – oak, the third was a_4 maple, and variant a_3 hornbeam was considered the least suitable. Hornbeam is the hardest wood grown in the Czech Republic and even though its mechanical properties easily surpass the other evaluated hardwood species, its other unsuitable properties placed this variant in the last position. Hornbeam has the worst workability properties of all the evaluated hardwood species, turning irregular grains, frequent occurrence of knots, and its volume stability is the worst of all the evaluated hardwood due to moisture.

Group I – mechanical properties were assigned with slight superiority) was without an effect on the final ranking. Subsequent more significant changes in criteria weights led to changes in positions 2 and 3, potentially 4, but with all tested modifications variant a_1 – beech still kept the best ranking in all results. No significant changes occurred with a change of the preferential function to function type I or VI.

4 CONCLUSION

Although the evaluation by PROMETHEE method is influenced by the attitude of decision makers and their preferences, i.e. it is individual up to a certain extent, the evaluation revealed that the use of beech wood is considered the most suitable of all the evaluated variants even under different modifications of the input conditions.

The advantages of using beech wood are significant, its drawbacks can be relatively easily eliminated by its use in glued and cross laminated elements. Therefore, it is very probable that beech wood will become natural heavy duty material used in the future for designing and building structures from wood.

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5 REFERENCES

- [1] Ammann, S., Schlegel, S., Beyer, M., Aehlig, K., Lehmann, M., Jung, H., Niemz, P. Quality assessment of glue dash wood for construction engineering. *European Journal of Wood and Wood Products*, 2016. 74(1), 67-74. ISSN 0018-3768. In: <http://link.springer.com/10.1007/s00107-015-0981-2>. DOI: 10.1007/s00107-015-0981-2.
- [2] Brans, J.P. L'ingénierie de la décision; Elaboration d'instruments d'aide à la décision. La méthode PROMETHEE. In R. Nadeau and M. Landry, editors, *L'aide à la décision: Nature, Instruments et Perspectives d'Avenir*, 1982. p. 183-213, Presses de l'Université Laval. Québec, Canada.
- [3] Brožová, H., Houška, M., Šubrt, T., Modely pro vícekritériální rozhodování. 2003. Credit, 178 p. Prague. ISBN 80-213-1019-7.
- [4] ČSN EN 408(73 1741) + A1. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. Prague: Czech Office for Standards, Metrology and Testing. 12.2012.
- [5] ČSN EN 844-4 (49 0016). Round and sawn timber – Terminology – Part 4: Terms relating to moisture content. Prague: Czech Office for Standards, Metrology and Testing. 6.1998
- [6] ČSN 49 0108. Wood. Determination of the density of the physical and mechanical testing. Prague: Czech Office for Standards, Metrology and Testing. 2.1993.
- [7] ČSN 49 0110. Wood. Compression strength limits parallel to the grain. Prague: Czech Office for Standards, Metrology and Testing. 1.1980.
- [8] ČSN 49 0115. Wood. Determination of ultimate strength in flexure tests. Prague: Czech Office for Standards, Metrology and Testing. 12.1979.
- [9] ČSN 49 0116, 1986. Wood. Determination of the modulus of elasticity in static bending. Prague: Czech Office for Standards, Metrology and Testing. 7.1986.
- [10] Doubravová, H. Vícekritériální analýza variant a její aplikace v praxi, thesis. 2009. University of South Bohemia in České Budějovice, Faculty of Economics. [online]. České Budějovice. [cit. 20.12.2015]
- [11] EN 13183-1 (49 1016) Moisture content of a piece of sawn timber – Part 1: Determination by oven dry method. Prague, Czech office for Standards, Metrology and Testing. 3.2004.
- [12] Fiala, P.; Jablonský, J.; Mañas, M. Vícekritériální rozhodování: Určeno pro studenty všech fakult. University of Economics, Prague. 1994. 316 p. Prague. ISBN: 80-7079-748-7
- [13] Wood handbook—Wood as an engineering material. Forest Products Laboratory, 2010. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, 508 p.
- [14] Hunger, F., Stepinac, M., Rajčić, V. a G. van de Kuilen, J. Pull-compression tests on glued-in metric three rods parallel to grain in glulam and laminate veneer lumber of different timber species. *European Journal of Wood and Wood Products*, 2016. 74(3), p. 379-391. ISSN 0018-3768. In: <http://link.springer.com/10.1007/s00107-015-1001-2>. DOI: 10.1007/s00107-015-1001-2.
- [15] Ginevičius, R.; Podvesko, V.; Novotny, M. Evaluating Lithuanian banks from the perspective of their reliability to customers by Promethee method. In: *Business and Management 2010*, 2010. Vilnius, Lithuania: Technika Vilnius, Galtijoskopija, 7 p. ISSN 2029-4441.
- [16] Information on Forests and Forestry in the Czech Republic by 2012. Ministry of Agriculture of the Czech Republic, 2013. [online]. Prague. ISBN 978-80-7434-112-0 [cit. 15.6.2014] p. 54. In: http://eagri.cz/public/web/file/263114/Zprava_o_stavu_lesa_2012.pdf
- [17] Kuklík, P. Dřevěné konstrukce I. ČKAIT, Prague, 2005. 171 p. ISBN 80-86769-72-0.
- [18] Lexa, J. Mechanické a fyzikální vlastnosti dřeva. Práca, Bratislava. 1952. Technologie dřeva. 432 p.
- [19] Liu, Y.; Fan, Z.; Zhang, X. A method for large group decision-making based on evaluation information provided by participators from multiple groups. In: Elsevier B.V., 2016. p. 132 - 141, 2016. In: <http://dx.doi.org/10.1016/j.inffus.2015.08.002>. DOI 10.1016/j.inffus.2015.08.002.
- [20] Maity, S.; Chakraborty, S. Tool steel material selection using PROMETHEE II method. In: Springer-Verlag London, 2015, p. 1537-1547. In: <http://dx.doi.org/10.1007/s00170-014-6760-0>. DOI 10.1007/s00170-014-6760-0.
- [21] Miklečić, J., Jirouš-Rajković, V. Influence of Thermal Modification on Surface Properties and Chemical Composition of Beech Wood (*Fagus sylvatica* L.). *Drvna Industrija*, 2016, 67 (1), p. 65-71. ISSN 1847-1153. In: <https://hrcak.srce.hr/154664>. DOI: 10.5552/drind.2016.1520.
- [22] Montajabiha, M. An Extended PROMETHEE II Multi-Criteria Group Decision Making Technique Based on Intuitionistic Fuzzy Logic for Sustainable Energy Planning. In: Springer Science+Business Media Dordrecht, 2015. p. 221-244. DOI 10.1007/s10726-015-9440-z.
- [23] Moosavi, V., Eslam, H. K., Bazayr, B., Najafi, A., Taleeepoor, M. Bending Creep Behavior of Hornbeam Wood. *Drvna industrija*, 2016, 76 (4), p. 341-350. ISSN 1847-1153. In: <https://hrcak.srce.hr/172563>. DOI: 10.5552/drind.2016.1609.
- [24] Neue Holzbau AG, 2016. Glulamhardwood. [online] Website of the Company Neue Holzbau AG. Lungern, Switzerland [cit. 21.4.2016] In: <http://www.neueholzbau.ch/en/category/referenz/laubholz-projekte/>
- [25] Novotný, M.; Šuhajda, K.; Kučera, R.; Šuhajdová, E. Selection of heating system based on

- acquisition and operating cost for family house. In Business and Management 2016. Business and Management. Vilnius, Lithuania: VGTU Press, 2016. s. 1-8. ISBN: 978-609-457-921- 9. ISSN: 2029-4441.
- [26] Partov, D. N., Straka, B., Petkov, M.: Traditional Strengthening Techniques for the Timber Roof Elements, In: Proceedings of the XV-th International Scientific Conference VSU. Sofia, Bulgaria, 2015, Vol. 1., pp 290–301.
- [27] Pavlíková, M., Keppert, M. Chemie, chemie stavebních materiálů. Prague: České vysoké učení technické v Praze. 2009. 195 p. ISBN 978-80-01-04237-3.
- [28] Požgaj, A., Chovanec, D., Kurjatko, S., Babiak, M. Štruktúra a vlastnosti dreva. Bratislava, Príroda, 1997. 485 p. ISBN 8007009604.
- [29] Schlotzhauer, P., Nelis, P. A., Bollmus, S., Gellerich, A., Militz, H., Seim, W., 2017. Effect of size and geometry on strength values and MOE of selected hardwood species. Wood Material Science & Engineering, vol. 12, 2017. In: <https://www.tandfonline.com/doi/full/10.1080/17480272.2015.1073175>. DOI: 10.1080/17480272.2015.1073175.
- [30] Schneider, J., Stierner, S.F., Tesfamariam, S., Karacabeyli, E. and Popovski, M. Damage assessment of cross laminated timber connections subjected to simulated earthquake loads, World Conference on Timber Engineering 2012, WCTE 2012, pp. 398-406.
- [31] Šuhajdová, E. Použití listnatých dřevin v konstrukcích staveb na území ČR v historii a budoucnosti. In Juniorstav 2017. Brno: omega design, s. 1-6. ISBN: 978-80-214-5473- 6.
- [32] Tran, V., Oudjene, M., Méausoone, P., 2014. FE analysis and geometrical optimization of timber beech finger-joint under bending test. International Journal of Adhesion and Adhesives, 52, 40-47. ISSN 01437496. In: <http://linkinghub.elsevier.com/retrieve/pii/S0143749614000761>. DOI: 10.1016/j.ijadhadh.2014.03.007.
- [33] Tran, V., Oudjene, M., Méausoone, P., 2016. Experimental investigation on full-scale glued oak solid timber beams for structural bearing capacity. Construction and Building Materials. 2016, 123, p. 365-371. ISSN 09500618. In: <http://linkinghub.elsevier.com/retrieve/pii/S0950061816311011>. DOI: 10.1016/j.conbuildmat.2016.07.002.
- [34] Tratzmiller, M. Hochwertiges Brettsperrholzausstattet Stammholz. European Journal of Wood and Wood Products, 2010, 68(1), 21-26. ISSN 0018-3768. In: <http://link.springer.com/10.1007/s00107-009-0393-2>. DOI: 10.1007/s00107-009-0393-2.
- [35] Walker, A. Dřevo: velká encyklopedie. Prague: Grada, 2009. ISBN 978-80-247-2858-2.

SUMMARY

EVALUATION OF SUITABILITY OF SELECTED HARDWOOD IN CIVIL ENGINEERING

Eva ŠUHAJDOVÁ
Miloslav NOVOTNÝ
Jan PĚNČÍK
Karel ŠUHAJDA
Pavel SCHMID
Bohumil STRAKA

Apart from gradually disappearing spruce wood, hardwood, particularly beech, oak, hornbeam, and maple, will be among the future local wood sources in the Central Europe. A multiple criteria analysis, PROMETHEE method, was used in order to select the most suitable hardwood for construction purposes. Apart from the forest land area criterion, seven other evaluation criteria were selected including physical and mechanical properties of individual hardwood species. Some of the properties in question were experimentally determined and verified. All alternatives were compared and their ranking was determined based on the use of PROMETHEE II method. The result is a single hardwood species whose use in civil engineering appears to be the most suitable in terms of the selected criteria. In addition, the influence of selected weights of individual criteria on the decision making process is discussed.

Key words: Multiple Criteria Decision Making (MCDM), hardwood species, mechanical properties, physical properties.

REZIME

VREDNOVANJE PRIKLADNOSTI IZABRANOG TRVDOG DRVETA U GRAĐEVINARSTVU

Eva ŠUHAJDOVÁ
Miloslav NOVOTNÝ
Jan PĚNČÍK
Karel ŠUHAJDA
Pavel SCHMID
Bohumil STRAKA

Usled postepenog nestajanja smreke, tvrdo drvo, poput bukve, hrasta, graba i javora, koristiće se kao budući izbor građevinskog materijala u Centralnoj Evropi. U radu je primenjena analiza višestrukih kriterijuma, PROMETHEE metoda, u cilju odabira najprikladnije vrste tvrdog drveta za izgradnju. Osim šumskog zemljišta, utvrđeno je još sedam kriterijuma za ocenjivanje uključujući fizička i mehanička svojstva pojedinačnih vrsta tvrdog drveta. Neke od pomenutih svojstava eksperimentalno su utvrđene i potvrđene. Upoređene su sve alternative, a njihovo rangiranje je određeno na osnovu PROMETHEE 2 metoda. Rezultat je iznalaženje tvrdog drveta čija je upotreba u građevinarstvu najprikladnija u pogledu odabranih kriterijuma. Pored toga, razmatrana je težina pojedinačnih kriterijuma na proces donošenja odluka.

Ključne reči: odlučivanje sa višestrukim kriterijumima (MCDM), vrste tvrdog drveta, mehanička svojstva, fizičke svojstva