Selection of Softwood Species for Structural and Non-Structural Timber Construction by Using the Analytic Hierarchy Process (AHP) and the Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA)

ŞÜKRÜ ÖZŞAHIN[1], HILAL SINGER[2], ALI TEMIZ[3] AND İBRAHIM YİLDİRİM[3*]
[1] *Karadeniz Technical University, Department of Industrial Engineering, 61080, Trabzon, Turkey*
[2] *Bolu Abant Izzet Baysal University, Department of Industrial Engineering, 14030, Bolu, Turkey*
[3] *Karadeniz Technical University, Department of Forest Industrial Engineering, 61080, Trabzon, Turkey*
** Corresponding author: ibrahim@ktu.edu.tr, Phone: + 90 462 3771512, Fax: + 90 462 3257499*

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Abstract

In this study, the hybrid approach of the analytic hierarchy process (AHP) and the multi-objective optimization on the basis of ratio analysis (MOORA) was used in order to select the most suitable softwood timber for construction. Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus concorta*), red pine (*Pinus resinosa*), redwood (*Sequoia sempervirens*), Engelmann spruce (*Picea engelmannii*), eastern hemlock (*Tsuga canadensis*), western larch (*Larix occidentalis*) and western red cedar (*Thuja plicata*) were evaluated in terms of economic, physical, mechanical, thermal and durability properties. According to the results, the most suitable timbers for structural and non-structural applications were determined to be western larch and redwood, respectively.

Keywords: AHP, MOORA, Softwoods, Timber construction

Introduction

Timber construction provides reduced waste, lower costs and short period of installation and in addition saves on embodied carbon and energy comparing with other traditional construction materials. Therefore, use of wood in construction for structural and non-structural applications has been increased. Multi-storey wooden building with solid-sawn timber and engineered wood products such as glulam, laminated veneer lumber (LVL), cross-laminated timber (CLT) has growing demand. The fourteen storey wooden building in Bergen, Norway seems to be tallest in the world of its kind (Malo et al. 2016). Each wood species has different physical, mechanical, thermal properties and these properties restrict their design and construction (Ramage et al. 2017). Which timber should be used in outdoor conditions? To answer this question, multiple wood properties should be considered include physical, mechanical strength, thermal properties, decay resistance, purchasing cost, etc.

Multi-criteria decision making (MCDM) is used to make preference decision over the available alternatives. It provides qualitative/quantitative assessments to identify the value of each alternative with respect to each criterion, in addition the relative importance of the criteria in terms of the overall objective of the problems (Ma et al. 2010, Dalalah et al. 2011). Several methods exist for MCDM. Among these methods, the most popular ones are analytical hierarchy process (AHP), preference ranking organisation method for enrichment evaluation (PROMETHEE), elimination and choice translating reality (ELECTRE), technique for order reference by similarity to ideal solution (TOPSIS) (Pohekar and Ramachandran 2004, Pires et al. 2011). Multi-objective optimization on the basis of ratio analysis (MOORA), one of the MCDM methods, was developed by Brauers and Zavadskas

(2006). This method has been successfully employed to evaluate decision alternatives by researchers (Brauers et al. 2008, Kalibatas and Turskis 2008, Chakraborty 2011, Karande and Chakraborty 2012, Gadakh et al. 2018). It was reported that MOORA is more stronger in many aspects than some popular MCDM methods such as AHP, TOPSIS, VIKOR, ELECTRE, and PROMETHEE (Brauers and Zavadskas 2012).

The AHP (Saaty 1977, Saaty 1980) is a known multi-attribute weighting method for decision support (Vidal et al. 2010). This method has been widely employed to solve various decision problems such as evaluation of mobile phone alternatives (Işıklar and Büyüközkan 2007), assessment of criteria and farming activities for tobacco diversification (Chavez et al. 2012), evaluation of mobile services and substantial adoption factors (Nikou and Mezei 2013), evaluation of reallocation criteria in land consolidation studies (Cay and Uyan 2013), the selection of the most appropriate package of Solar Home System (Ahammed and Azeem 2013), the selection of a small run-of-river hydropower plant (Fuentes-Bargues and Ferrer-Gisbert 2015), and determination of the strategies and ethics of sustainability in agriculture and food systems (Veisi et al. 2016). However, the number of studies regarding the multi-criteria analysis of decision problems in the field of wood science is very limited. Smith et al. (1995) employed the AHP to analyze factors affecting the adoption of timber as a bridge material. Azizi (2008) determined the best option to supply poplar wood by applying the analytic network process (ANP) and BOCR's (benefits, opportunities, costs and risks) structures. Lipuščck et al. (2010) employed the AHP method for classifying wood products in terms of their impact on the environment. Azizi and Modarres (2011) selected the best construction panel by using the AHP and ANP methods. Azizi et al. (2012) selected the best imported medium density fiberboard (MDF) product using the AHP. Kuzman and Grošelj (2012) compared different construction types by the AHP method. Sarfi et al. (2013) used the AHP to analyze factors influencing markets of particleboard and MDF. Karakuş et al. (2017) predicted optimum properties of the nanocomposites by TOPSIS, multiple attribute utility theory (MAUT) and compromise programming (CP) methods.

The purpose of this study is to select the most suitable softwood timber for structural and non-structural applications in outdoor conditions in terms of economic, physical, mechanical, thermal and durability properties of wood. Therefore, this study presents the hybrid approach of AHP and MOORA. At first, a hierarchical structure of the decision problem was constructed. Then, the AHP method was used to obtain the weights of the criteria. Finally, the MOORA method was employed to select the best softwood alternatives.

Materials and Methods

Materials

In this study, softwood species such as Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus concorta*), red pine (*Pinus resinosa*), redwood (*Sequoia sempervirens*), Engelmann spruce (*Picea engelmannii*), eastern hemlock (*Tsuga canadensis*), western larch (*Larix occidentalis*), and western red cedar (*Thuja plicata*) were chosen. Softwood species are primarily wood species used in structural and non-structural applications in outdoor due to they are cheap, plentiful, and available in different dimensions, easily convert into engineered timber products.

In light of the aim, five main criteria and fifteen sub-criteria were defined. The criteria used in this study were as follows:

1. Economic values
    1.1. Purchasing cost
    1.2. Paintability
2. Physical properties
    2.1. Dimensional change
    2.2. Wood density
3. Mechanical properties
    3.1. Modulus of rupture
    3.2. Modulus of elasticity
    3.3. Compression strength perpendicular to grain
    3.4. Compression strength parallel to grain
    3.5. Impact bending strength
    3.6. Work to maximum load in bending
    3.7. Shear strength parallel to grain
4. Thermal properties
    4.1. Thermal conductivity
    4.2. Flame spread
5. Durability properties
    5.1. Decay resistance
    5.2. Impregnability

The data required for purchasing cost, flame spread and decay resistance were obtained from a sales office, Janssens and Douglas (2004), and Scheffer and Morrell (1998), respectively. The data required for the other sub-criteria were taken from Forest Products Laboratory (2010).

The analytic hierarchy process (AHP) method

The AHP employs a hierarchical structure of goal, criteria, sub-criteria, and alternatives in order to obtain a solution. This method is composed of four main steps: (1) construction of a hierarchy by breaking down the problem into sub-problems, (2) pair-wise comparison of the elements (criteria and decision alternatives), (3) consistency check and (4) synthesis of priorities (Nikou and Mezei 2013).

As mentioned above, the first step of the AHP is to break down the MCDM problem into a hierarchy of the elements. This hierarchy has different levels: goal of the problem at the top, criteria and sub-criteria in the intermediate levels, and decision alternatives at the bottom (Işıklar and Büyüközkan 2007).

The comparisons of criteria and decision alternatives are carried out based on the Saaty's nine point scale (see Table 1). All of the elements in the same level of the hierarchy are compared pair-wise with respect to the element at the higher level (Veisi et al. 2016). With the help of the expert judgment, a_{ij}, a pair-wise comparison matrix, *D,* is formed for each level.

$$D = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \tag{1}$$

where $a_{ji} = 1/a_{ij}$; $i, j = 1, 2, \ldots, n$ (Aragonés-Beltrán et al. 2014).

Table 1. AHP evaluation scale (Fuentes-Bargues and Ferrer-Gisbert 2015)

Numerical value	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance of one element over another	Experience and judgment moderately favour one element over another
5	Strong importance of one element over another	One element is strongly favoured
7	Very strong importance of one element over another	One element is very dominant
9	Extreme importance of one element over another	One element is favoured by at least a difference of one order of magnitude
2,4,6,8	Intermediate values between two adjacent judgments	Used as a compromise between two judgments

According to Saaty (1990), the consistency of judgments can be checked using the following equation:

$$\text{CR (Consistency ratio)} = \frac{\text{CI}}{\text{RC}} \tag{2}$$

The CI (consistency index) value can be computed using Eq. (3). The RC (random consistency index) value can be obtained from Table 2. If the CR value is less than 0.10, the comparisons can be thought of as being acceptable. If it exceeds 0.10, the comparisons must be revised by the decision maker.

$$\text{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix and n is the matrix size ($n \times n$).

The weights are obtained from pair-wise comparison matrices. The first step in determining weights is to normalize a matrix. Therefore, each column is divided by the sum of entries of the corresponding column. Then, the resulting rows are averaged. The averaged numbers correspond weights (Ahammed and Azeem 2013).

The multi-objective optimization on the basis of ratio analysis (MOORA) method

The main parts of MOORA are the ratio system and the reference point approach (Brauers and Zavadskas 2012). In this method, first, the decision matrix, *D,* of *m* alternatives and *n* criteria is formed as below (Karande and Chakraborty 2012).

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{4}$$

where x_{ij} is the performance value of i^{th} alternative ($i = 1,2,\ldots,m$), respecting to the j^{th} criterion ($j = 1, 2,\ldots, n$).

Data in an initial decision matrix is normalized in each method. To do this, the following equation is used.

$$x_{ij}^{*} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}} \tag{5}$$

where x_{ij} is the normalized performance value of i^{th} alternative on j^{th} criterion.

The ratio system

In the ratio system, the normalized values are added in case of maximization (for beneficial criteria) and subtracted in case of minimization (for non-beneficial criteria). Then, the optimization problem becomes:

$$y_i^{*} = \sum_{j=1}^{g} x_{ij}^{*} - \sum_{j=g+1}^{n} x_{ij}^{*} \tag{6}$$

where g is the number of criteria to be maximized, (n–g) is the number of criteria to be minimized, and is the normalized assessment value of i^{th} alternative with respect to all the criteria (Chakraborty 2011).

The criteria used in decision-making can be weighted using the following equation (Gadakh et al. 2018):

$$y_i^{*} = \sum_{j=1}^{g} w_j x_{ij}^{*} - \sum_{j=g+1}^{n} w_j x_{ij}^{*} \tag{7}$$

where w_j is the weight of j^{th} criterion.

Once the value of each alternative is determined, alternatives are ranked depending on these values. The best alternative has the highest value.

The reference point approach

In the reference point approach, reference points are established for each criterion. The j^{th} coordinate of

Table 2. RC index

n	1	2	3	4	5	6	7	8	9	10
RC	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

the reference point can be described as $r_j = \max_i x^*_{ij}$ in case of maximization. Every element of the normalized response matrix is recalculated and final rank is given according to deviation from the reference point and the Min-Max Metric of Tchebycheff (Streimikiene et al. 2012):

$$\min_{(i)}(\max|r_j - x^*_{ij}|_{(j)}) \tag{8}$$

The criteria used in decision-making can be weighted using the following equation (Adalı and Işık 2017):

$$\min_{(i)}\left(\max\left|w_j r_j - w_j x^*_{ij}\right|_{(j)}\right) \tag{9}$$

Evaluation of alternatives

In the present study, the aim is to select the most suitable timber for structural and non-structural applications such as decking, pergola, siding, and fence in outdoor conditions. Therefore, a hierarchical structure of the decision problem that consists of four levels (goal, main criteria, sub-criteria and alternatives) was constructed.

The first level of the hierarchy represents the goal of the decision problem. This goal was divided into five main criteria, which are economic values (C_1), physical properties (C_2), mechanical properties (C_3), thermal properties (C_4), and durability properties (C_5). The third level includes sub-criteria. The sub-criteria of the criterion economic values are purchasing cost (C_{11}) (in dollar) and paintability (C_{12}) (value judgment on a scale of 1–3; 1: difficult, 3: easy). The sub-criteria of the criterion physical properties are dimensional change (C_{21}) (in coefficients) and wood density (C_{22}) (in kg/m^3). The sub-criteria of the criterion mechanical properties are modulus of rupture (C_{31}) (in kPa), modulus of elasticity (C_{32}) (in MPa), compression strength perpendicular to grain (C_{33}) (in kPa), compression strength parallel to grain (C_{34}) (in kPa), impact bending strength (C_{35}) (in mm), work to maximum load in bending (C_{36}) (in kJ m^{-3}) and shear strength parallel to grain (C_{37}) (in kPa). The sub-criteria of the criterion thermal properties are thermal conductivity (C_{41}) (in W m^{-1}K^{-1}) and flame spread (C_{42}) (in index). The sub-criteria of the criterion durability properties are decay resistance (C_{51}) (value judgment on a scale of 1–4; 1: non-resistant, 2: moderately resistant, 3: resistant, 4: very resistant) and impregnability (C_{52}) (value judgment on a scale of 1–4; 1: very difficult, 2: difficult, 3: moderately difficult, 4: least difficult). Lastly, the last level consists of eight alternatives: Douglas fir, lodgepole pine, red pine, redwood, Engelmann spruce, eastern hemlock, western larch, and western red cedar. Figure 1 shows the structuring of the decision hierarchy.

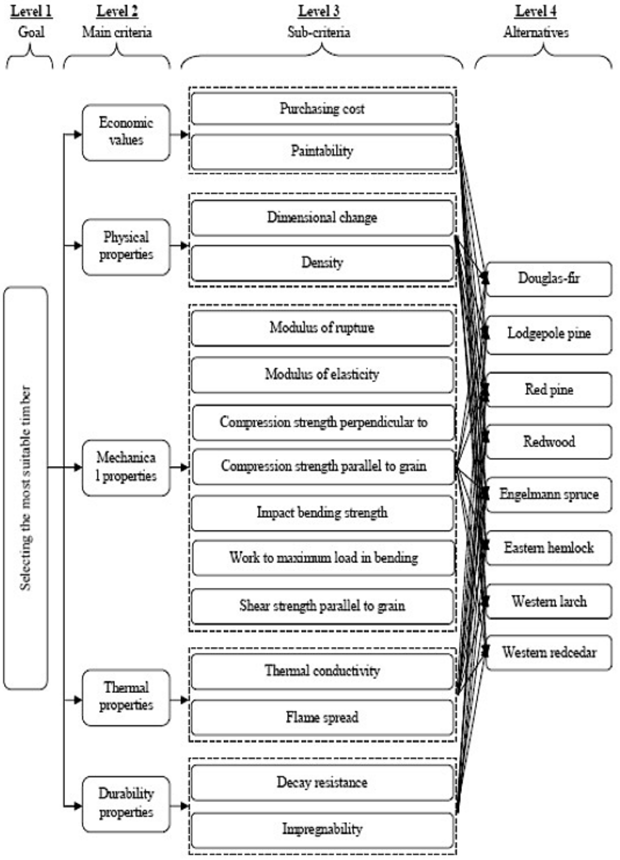

Figure 1. The hierarchical structure of the decision problem

After the construction of the hierarchy, the weights of each criterion were computed using the AHP. A decision-making team including three experts (one professor, one associate professor and one assistant professor) from the Wood Science Departments in Turkey, was gathered to make pair-wise comparisons of the criteria. The wood science experts in the team were asked to make pair-wise comparisons for all the criteria by using the scale given in Table 1. Then, the pair-wise comparison matrices were formed with the help of the data obtained from the experts. There was a consistency among expert judgments. The evaluation matrices can be seen from Tables 3–8.

In the next step, the consistency ratios were calculated using Eq. (2). For economic values, physical properties, thermal properties and durability properties main

Table 3. The pair-wise comparison matrices of the main criteria

Main criterion	C_1	C_2	C_3	C_4	C_5	Weight
		Pair-wise comparison matrix for structural construction				
C_1	1	4	1/5	7	1/3	0.1644
C_2		1	1/7	2	1/4	0.0605
C_3			1	8	3	0.4953
C_4				1	1/6	0.0383
C_5					1	0.2415
		Pair-wise comparison matrix for non-structural construction				
C_1	1	5	2	7	1/6	0.2154
C_2		1	1/2	3	1/7	0.0721
C_3			1	5	1/5	0.1280
C_4				1	1/8	0.0362
C_5					1	0.5483

Table 4. The pair-wise comparison matrices of the sub-criteria within economic properties

Sub-criterion	C_{21}	C_{22}	Weight
Pair-wise comparison matrix for structural construction			
C_{21}	1	5	0.8333
C_{22}		1	0.1667
Pair-wise comparison matrix for non-structural construction			
C_{21}	1	3	0.7500
C_{22}		1	0.2500

Table 5. The pair-wise comparison matrices of the sub-criteria within physical properties

Sub-criterion	C_{21}	C_{22}	Weight
Pair-wise comparison matrix for structural construction			
C_{21}	1	1/6	0.1429
C_{22}		1	0.8571
Pair-wise comparison matrix for non-structural construction			
C_{21}	1	1/3	0.2500
C_{22}		1	0.7500

Table 6. The pair-wise comparison matrices of the sub-criteria within mechanical properties

Sub-criterion	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	Weight
Pair-wise comparison matrix for structural construction								
C_{31}	1	2	1	1/4	4	1/3	1/3	0.0916
C_{32}		1	1/2	1/5	3	1/3	1/4	0.0633
C_{33}			1	1/3	5	1/3	1/4	0.0970
C_{34}				1	5	1/3	1/2	0.1977
C_{35}					1	1/4	1/3	0.0383
C_{36}						1	3	0.3009
C_{37}							1	0.2112
Pair-wise comparison matrix for non-structural construction								
C_{31}	1	2	1	3	1/4	1/3	3	0.1246
C_{32}		1	1/2	1	1/3	1/3	4	0.0916
C_{33}			1	3	1/3	1/3	4	0.1360
C_{34}				1	1/4	1/3	1	0.0601
C_{35}					1	2	3	0.3055
C_{36}						1	3	0.2281
C_{37}							1	0.0541

Table 7. The pair-wise comparison matrices of the sub-criteria within thermal properties

Sub-criterion	C_{41}	C_{42}	Weight
Pair-wise comparison matrix for structural construction			
C_{41}	1	1/5	0.1667
C_{42}		1	0.8333
Pair-wise comparison matrix for non-structural construction			
C_{41}	1	1/5	0.1667
C_{42}		1	0.8333

Table 8. The pair-wise comparison matrices of the sub-criteria within durability properties

Sub-criterion	C_{51}	C_{52}	Weight
Pair-wise comparison matrix for structural construction			
C_{51}	1	4	0.8000
C_{52}		1	0.2000
Pair-wise comparison matrix for non-structural construction			
C_{51}	1	4	0.8000
C_{52}		1	0.2000

criteria, the consistency ratio cannot be computed because they have two sub-criteria. The consistency ratio for the main criteria and mechanical properties matrices was found to be lower than 0.10. Therefore, all of the weights were used in the selection process.

The resulting weights of the criteria were the local weights. The global weight of each sub-criterion was computed by multiplying its local weight with its corresponding weight. The results (local weights and global weights) are summarized in Table 9. From these obtained results, it can be concluded that decay resistance is the most important evaluation criterion.

Table 9. Summary of the weights

	Criterion	Structural c.		Non-structural c.	
		Local weight	Global weight	Local weight	Global weight
C_1	*Economic properties*	0.1644		0.2154	
C_{11}	Purchasing cost	0.8333	0.1370	0.7500	0.1616
C_{12}	Paintability	0.1667	0.0274	0.2500	0.0539
C_2	*Physical properties*	0.0605		0.0721	
C_{21}	Dimensional change	0.1429	0.0086	0.2500	0.0180
C_{22}	Density	0.8571	0.0519	0.7500	0.0541
C_3	*Mechanical properties*	0.4953		0.1280	
C_{31}	Modulus of rupture	0.0916	0.0454	0.1246	0.0159
C_{32}	Modulus of elasticity	0.0633	0.0314	0.0916	0.0117
C_{33}	Compression strength perpendicular to grain	0.0970	0.0480	0.1360	0.0174
C_{34}	Compression strength parallel to grain	0.1977	0.0979	0.0601	0.0077
C_{35}	Impact bending strength	0.0383	0.0190	0.3055	0.0391
C_{36}	Work to maximum load in bending	0.3009	0.1490	0.2281	0.0292
C_{37}	Shear strength parallel to grain	0.2112	0.1046	0.0541	0.0069
C_4	*Thermal properties*	0.0383		0.0362	
C_{41}	Thermal conductivity	0.1667	0.0064	0.1667	0.0060
C_{42}	Flame spread	0.8333	0.0319	0.8333	0.0302
C_5	*Durability properties*	0.2415		0.5483	
C_{51}	Decay resistance	0.8000	0.1932	0.8000	0.4386
C_{52}	Impregnability	0.2000	0.0483	0.2000	0.1097

[a] Local weight is obtained from the pair-wise comparison matrix.
[b] Global weight is derived from multiplication by the weight of the criteria.

After the importance among the criteria was found, the second phase of the evaluation model was carried out. In this phase, first, the decision matrix as in Table 10 was formed with the help of the data obtained from Forest Products Laboratory (2010), Janssens and Douglas (2004) and Scheffer and Morrell (1998). Next step is to obtain normalized decision matrices. Employing the weights computed by the AHP, the weighted normalized decision matrices formed (Table 11 for structural construction and Table 12 for non-structural construction). Lastly, performance values were computed using Eqs. (7) and (9) in order to rank the alternatives. According to the results, it is possible to say that western larch can be used for structural applications and redwood can be used for non-structural applications.

Results

The priorities of the main criteria and sub-criteria were determined based on the calculation procedure of

Table 10. The decision matrix

	C_{11}	C_{12}^{a}	C_{21}^{a}	C_{22}^{a}	C_{31}^{a}	C_{32}^{a}	C_{33}^{a}	C_{34}^{a}	C_{35}^{a}	C_{36}^{a}	C_{37}^{a}	C_{41}^{a}	C_{42}^{b}	C_{51}^{c}	C_{52}^{a}
	min.	max.	min.	max.	max.	max.	max.	max.	max.	max.	max.	min.	min.	max.	max.
Douglas fir	645	1	0.00267	0.48	85000	13400	5500	49900	790	68	7800	0.14	85	2	3
Lodgepole pine	370	2	0.00234	0.41	65000	9200	4200	37000	510	47	6100	0.12	98	2	2
Red pine	300	1	0.00252	0.46	76000	11200	4100	41900	660	68	8400	0.13	142	1	3
Redwood	260	3	0.00229	0.35	54000	7600	3600	36000	380	36	7600	0.11	70	3	4
Engelmann spruce	485	3	0.00248	0.35	64000	8900	2800	30900	460	44	8300	0.11	55	1	2
Eastern hemlock	495	2	0.00237	0.40	61000	8300	4500	37300	530	47	7300	0.12	67.5	1	2
Western larch	400	2	0.00323	0.52	90000	12900	6400	52500	890	87	9400	0.15	45	2	2
Western red cedar	1175	3	0.00234	0.32	51700	7700	3200	31400	430	40	6800	0.10	70	3	1

Sources: [a] Forest Products Laboratory (2010), [b] Janssens and Douglas (2004), [c] Scheffer and Morrell (1998).

Table 11. The weighted normalized decision matrix for structural construction

	C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{41}	C_{42}	C_{51}	C_{52}
	min.	max.	min.	max.	max.	max.	max.	max.	max.	max.	max.	min.	min.	max.	max.
Douglas-fir	0.0535	0.0043	0.0032	0.0211	0.0196	0.0147	0.0211	0.0428	0.0088	0.0628	0.0371	0.0026	0.0114	0.0673	0.0203
Lodgepole pine	0.0307	0.0086	0.0028	0.0181	0.0150	0.0101	0.0161	0.0318	0.0057	0.0434	0.0290	0.0022	0.0132	0.0673	0.0135
Red pine	0.0249	0.0043	0.0030	0.0203	0.0175	0.0123	0.0157	0.0360	0.0073	0.0628	0.0400	0.0024	0.0191	0.0336	0.0203
Redwood	0.0216	0.0128	0.0027	0.0154	0.0125	0.0083	0.0138	0.0309	0.0042	0.0332	0.0362	0.0020	0.0094	0.1009	0.0271
Engelmann spruce	0.0402	0.0128	0.0030	0.0154	0.0148	0.0098	0.0107	0.0265	0.0051	0.0406	0.0395	0.0020	0.0074	0.0336	0.0135
Eastern hemlock	0.0410	0.0086	0.0028	0.0176	0.0141	0.0091	0.0172	0.0320	0.0059	0.0434	0.0347	0.0022	0.0091	0.0336	0.0135
Western larch	0.0332	0.0086	0.0039	0.0229	0.0208	0.0141	0.0245	0.0451	0.0099	0.0803	0.0447	0.0027	0.0060	0.0673	0.0135
Western red cedar	0.0974	0.0128	0.0028	0.0141	0.0119	0.0084	0.0123	0.0270	0.0048	0.0369	0.0324	0.0018	0.0094	0.1009	0.0068

Table 12. The weighted normalized decision matrix for non-structural construction

	C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{41}	C_{42}	C_{51}	C_{52}
	min.	max.	min.	max.	max.	max.	max.	max.	max.	max.	max.	min.	min.	max.	max.
Douglas-fir	0.0631	0.0084	0.0067	0.0220	0.0069	0.0055	0.0076	0.0034	0.0180	0.0123	0.0024	0.0024	0.0108	0.1527	0.0461
Lodgepole pine	0.0362	0.0168	0.0058	0.0188	0.0053	0.0038	0.0058	0.0025	0.0116	0.0085	0.0019	0.0021	0.0125	0.1527	0.0307
Red pine	0.0293	0.0084	0.0063	0.0211	0.0061	0.0046	0.0057	0.0028	0.0151	0.0123	0.0026	0.0022	0.0181	0.0764	0.0461
Redwood	0.0254	0.0253	0.0057	0.0161	0.0044	0.0031	0.0050	0.0024	0.0087	0.0065	0.0024	0.0019	0.0089	0.2291	0.0614
Engelmann spruce	0.0474	0.0253	0.0062	0.0161	0.0052	0.0036	0.0039	0.0021	0.0105	0.0080	0.0026	0.0019	0.0070	0.0764	0.0307
Eastern hemlock	0.0484	0.0168	0.0059	0.0184	0.0049	0.0034	0.0063	0.0025	0.0121	0.0085	0.0023	0.0021	0.0086	0.0764	0.0307
Western larch	0.0391	0.0168	0.0081	0.0239	0.0073	0.0053	0.0089	0.0035	0.0203	0.0157	0.0030	0.0026	0.0057	0.1527	0.0307
Western red cedar	0.1149	0.0253	0.0058	0.0147	0.0042	0.0031	0.0044	0.0021	0.0098	0.0072	0.0021	0.0017	0.0089	0.2291	0.0154

Table 13. Results of the ratio system

	For structural construction				For non-structural construction			
	$\sum_{j=1}^{n} w_j x_{ij}^*$	$\sum_{j=g+1}^{n} w_j x_{ij}^*$	y	Ranking	$\sum_{j=1}^{n} w_j x_{ij}^*$	$\sum_{j=g+1}^{n} w_j x_{ij}^*$	y	Ranking
Douglas-fir	0.3198	0.0706	0.2492	3	0.2854	0.0830	0.2024	3
Lodgepole pine	0.2584	0.0488	0.2096	5	0.2585	0.0566	0.2019	4
Red pine	0.2700	0.0493	0.2207	4	0.2012	0.0559	0.1453	6
Redwood	0.2953	0.0357	0.2596	2	0.3643	0.0419	0.3224	1
Engelmann spruce	0.2224	0.0526	0.1698	7	0.1842	0.0625	0.1217	7
Eastern hemlock	0.2298	0.0551	0.1746	6	0.1823	0.0650	0.1173	8
Western larch	0.3516	0.0458	0.3058	1	0.2881	0.0555	0.2326	2
Western red cedar	0.2682	0.1114	0.1568	8	0.3174	0.1314	0.1861	5

Table 14. Deviations from the reference points for structural construction

	C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{41}	C_{42}	C_{51}	C_{52}	Score	Ranking
	min.	max.	min.	max.	max.	max.	max.	max.	max.	max.	max.	min.	min.	max.	max.		
Douglas-fir	0.0319	0.0086	0.0005	0.0018	0.0012	0.0000	0.0034	0.0022	0.0011	0.0175	0.0076	0.0007	0.0054	0.0336	0.0068	0.0336	1
Lodgepole pine	0.0091	0.0043	0.0001	0.0048	0.0058	0.0046	0.0084	0.0133	0.0042	0.0369	0.0157	0.0004	0.0071	0.0336	0.0135	0.0369	2
Red pine	0.0033	0.0086	0.0003	0.0026	0.0032	0.0024	0.0088	0.0091	0.0026	0.0175	0.0048	0.0005	0.0130	0.0673	0.0068	0.0673	4
Redwood	0.0000	0.0000	0.0000	0.0075	0.0083	0.0064	0.0107	0.0142	0.0057	0.0471	0.0086	0.0002	0.0034	0.0000	0.0000	0.0471	3
Engelmann spruce	0.0187	0.0000	0.0002	0.0075	0.0060	0.0049	0.0138	0.0185	0.0048	0.0397	0.0052	0.0002	0.0013	0.0673	0.0135	0.0673	4
Eastern hemlock	0.0195	0.0043	0.0001	0.0053	0.0067	0.0056	0.0073	0.0131	0.0040	0.0369	0.0100	0.0004	0.0030	0.0673	0.0135	0.0673	4
Western larch	0.0116	0.0043	0.0011	0.0000	0.0000	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0009	0.0000	0.0336	0.0135	0.0336	1
Western redcedar	0.0758	0.0000	0.0001	0.0088	0.0088	0.0062	0.0123	0.0181	0.0051	0.0434	0.0124	0.0000	0.0034	0.0000	0.0203	0.0758	5
r_j	0.0216	0.0128	0.0027	0.0229	0.0208	0.0147	0.0245	0.0451	0.0099	0.0803	0.0447	0.0018	0.0060	0.1009	0.0271		

Table 15. Deviations from the reference points for non-structural construction

	C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{41}	C_{42}	C_{51}	C_{52}	Score	Ranking
	min.	max.	min.	max.	max.	max.	max.	max.	max.	max.	max.	min.	min.	max.	max.		
Douglas-fir	0.0376	0.0168	0.0009	0.0018	0.0004	0.0000	0.0013	0.0002	0.0023	0.0034	0.0005	0.0007	0.0051	0.0764	0.0154	0.0764	2
Lodgepole pine	0.0108	0.0084	0.0001	0.0051	0.0020	0.0017	0.0031	0.0010	0.0087	0.0072	0.0010	0.0003	0.0067	0.0764	0.0307	0.0764	2
Red pine	0.0039	0.0168	0.0006	0.0028	0.0011	0.0009	0.0032	0.0007	0.0053	0.0034	0.0003	0.0005	0.0123	0.1527	0.0154	0.1527	4
Redwood	0.0000	0.0000	0.0000	0.0078	0.0029	0.0024	0.0039	0.0011	0.0116	0.0092	0.0006	0.0002	0.0032	0.0000	0.0000	0.0116	1
Engelmann spruce	0.0220	0.0000	0.0005	0.0078	0.0021	0.0018	0.0050	0.0015	0.0098	0.0078	0.0003	0.0002	0.0013	0.1527	0.0307	0.1527	4
Eastern hemlock	0.0230	0.0084	0.0002	0.0055	0.0023	0.0021	0.0026	0.0010	0.0082	0.0072	0.0007	0.0003	0.0029	0.1527	0.0307	0.1527	4
Western larch	0.0137	0.0084	0.0023	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0009	0.0000	0.0764	0.0307	0.0764	2
Western red cedar	0.0895	0.0000	0.0001	0.0092	0.0031	0.0023	0.0044	0.0014	0.0105	0.0085	0.0008	0.0000	0.0032	0.0000	0.0461	0.0895	3
r_j	0.0254	0.0253	0.0057	0.0239	0.0073	0.0055	0.0089	0.0035	0.0203	0.0157	0.0030	0.0017	0.0057	0.2291	0.0614		

the AHP method. The weights are summarized in Table 9.

According to results from structural applications, the ranking of the main criteria in descending order with respective weights are mechanical properties (0.4953) > durability properties (0.2415) > economic values (0.1644) > physical properties (0.0605) > thermal properties (0.0383). From these results, it can be concluded that the most important main criterion is mechanical properties. Furthermore, decay resistance with an overall priority value of 0.1932 was found to be the most important sub-criterion. Other important sub-criteria are ranked as follows: work to maximum load in bending (0.1490), purchasing cost (0.1370), shear strength parallel to grain (0.1046), and compression strength parallel to grain (0.0979). The lowest priority values belong to thermal conductivity (0.0064), followed by dimensional change (0.0086) and paintability (0.0274).

According to results from non-structural applications, the highest weighted main criterion is durability properties (0.5483). As in structural application results, decay resistance was found as the most important sub-criterion. Other considerable sub-criteria are ranked as follows: purchasing cost (0.1616), impregnability (0.1097), density (0.0541), and paintability (0.0539). Thermal conductivity and shear strength parallel to grain sub-criteria have the lowest priority values as 0.0060 and 0.0069, respectively.

After determining the weights, the ratio system and the reference point approach were used to rank the alternatives. When the results obtained for structural application are examined, it is observed that western larch remain the contender for all two of the methods. Therefore, it is possible to say that the most suitable timber for structural construction is western larch. As seen in Tables 13 and 15, redwood timber is the most suitable timber for non-structural applications.

Conclusion

The aim of the study was to employ a hybrid multi-criteria methodology which combines AHP and MOORA to evaluate a set of timber alternatives in order to select the best alternative for structural and non-structural timber constructions.

In the first part of the study, the weights of the criteria were determined using AHP. The results showed that the most important evaluation criterion is decay resistance from the durability properties group. In the second part, the alternatives were evaluated with respect to the criteria. The ratio system and the reference point approach of MOORA were applied to the weighed normalized decision matrices. The results showed that the most suitable timber for structural and non-structural applications were western larch and redwood, respectively.

Consequently, the evaluation model used in this study provides beneficial insights for industries in terms of the selection of a suitable timber for different applications.

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