Multicriteria Evaluation of Structural Composite Lumber Products

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Abstract: In this study, laminated veneer lumber, parallel strand lumber, and laminated strand lumber were evaluated via multicriteria decision-making methods. Within the model, nine evaluation criteria were defined: moisture content, density, bending strength, modulus of elasticity, compression strength parallel to grain, dynamic bending strength, tensile strength parallel to surface, tensile strength perpendicular to surface, and screw holding capacity. The weights of the criteria were computed using the fuzzy analytic hierarchy process (FAHP). The evaluation based on distance from an average solution (EDAS) and the technique for order preference by similarity to an ideal solution (TOPSIS) were employed to determine the ranking of the alternatives. After the borda count method was used, an integrated ranking was obtained. According to the results, the first three important subcriteria were density, bending strength, and modulus of elasticity. Furthermore, laminated veneer lumber was determined as the best alternative. Consequently, this study can present a road map to evaluate wooden materials.

Keywords: EDAS, FAHP, multicriteria decision-making, structural composite lumber, TOPSIS.

INTRODUCTION

Structural composite lumber (SCL) is a family of engineered wood products. It includes laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL) (Bayatkashkoli and Faegh, 2014). LVL is manufactured from wood veneers that are rotary peeled, dried, and laminated together with parallelly oriented grains under heat and pressure with an adhesive (Çolak et al., 2007). PSL is manufactured by adhesively bonding long, thin, and narrow strands of wood under high pressure (Arwade et al., 2010). LSL consists of oriented wood flakes that are glued and compressed to form panels up to 90 mm thick (Moses et al., 2003). OSL is similar to LSL. The SCL products are commonly used for rafters, headers, beams, joists, studs,
and columns (APA, 2016). The advantages of SCL are high strength, flexibility, high stiffness, and excellent preservative treatability (Yazdani et al., 2004).

A large number of experimental studies have been conducted to evaluate the various properties of the SCL products (Ahmad & Kamke, 2011; Arwade et al., 2010; Bal, 2016; Bayatkashkoli & Faegh, 2014; Colak et al., 2007; Çolak et al., 2019; Moses et al., 2003; Yazdani et al., 2004). In light of the experimental studies, it can be said that there are many factors that must be carefully evaluated. Therefore, it is important to use methods providing supportive and logical results in the evaluation process. Multicriteria decision-making (MCDM) methods can be used to evaluate decision elements. The fuzzy analytic hierarchy process (FAHP), the evaluation based on distance from an average solution (EDAS), and the technique for order preference by similarity to an ideal solution (TOPSIS) have been widely used to deal with decision-making problems and obtain quite reliable results (Chauhan & Singh, 2016; Ecer, 2018; Karakuş et al., 2017). Therefore, in this study, these methods are used to evaluate the SCL products.

The MCDM methods have been efficiently applied to the various fields of wood science. Smith et al. (1995) employed the AHP method to analyze factors affecting the adoption of timber as a bridge material. Azizi (2008) selected the best wood supply alternative by employing the analytic network process (ANP) and the BOCR approach. Lipušček et al. (2010) employed the AHP method to classify 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) used the AHP method to select the best medium density fiberboard (MDF) product. Kuzman and Grošelj (2012) compared different construction types by utilizing the AHP method. Sarif et al. (2013) used the AHP method to analyze factors influencing the markets of particleboard and MDF. Karakuş et al. (2017) employed the TOPSIS method, the multiple attribute utility theory, and the compromise programing to predict the optimum properties of some nanocomposites. Singer and Özşahin (2018, 2020a, 2020b) prioritized some factors influencing the surface roughness of wood and wood-based materials in sawing, planing, and CNC machining. Özşahin et al. (2019) employed AHP and MOORA to select the best softwood species for construction.

Consequently, the literature review has demonstrated that there are many attempts on the use of MCDM methods for solving various decision-making problems in wood science. However, the literature has a gap in evaluating the SCL products by MCDM methods. Therefore, the objective of this study is to evaluate LVL, PSL, and LSL by the MCDM analysis. In order to determine the priorities of the alternatives, an evaluation model containing FAHP, EDAS, and TOPSIS is proposed.

**MATERIALS AND METHODS**

**Sample Preparation:** The experimental data used in this study were obtained from the literature ( Özçiftçi et al., 2010; Sizüçen, 2008). The experimental process could be briefly explained as follows. Poplar (Populus tremula L.) veneers with the thickness of 3 mm were used to produce LVLs. Poplar (Populus tremula L.) strands were used to produce PSLs and LSLs. The size of strands in PSLs was 3 mm thick by 20 mm wide by 600 mm long. The size of strands in LSLs was 1.2 mm thick by 20 mm wide by 300 mm long. The veneers and strands were conditioned at a temperature of 55±2 °C and a relative humidity of 6±1% until they reached an average moisture content of 3%. Phenol formaldehyde was chosen as the adhesive. It has density, viscosity, and pH value of 1.195-1.205 kg/m$^3$, 250-500 MPa s, and 10.5-13, respectively. The materials were pressed for 7 minutes at a temperature of 180±3 °C and a pressure of 30 kg/cm$^2$ (ASTM D 5456, 1996). After pressing, the samples were conditioned at a temperature of 20±2 °C and a relative humidity of 65±5% (TS 642/ISO 554, 1997). The moisture content and density values of the samples were determined according to TS 2471 (1976) and TS 2472 (1976). The bending strength and modulus of elasticity tests were carried out according to the procedure of TS EN 310 (1999). The compression strength parallel to grain, dynamic bending strength, screw withdrawal, and tensile strength tests were carried out according to TS 2595 (1977), TS 2477 (1976), ASTM D 1761 (2000), and ASTM D 1037-06a (2006), respectively.

**Fuzzy Sets and Fuzzy Numbers:** The fuzzy set theory was developed by Zadeh (1965) in order to represent the uncertainty, vagueness, and ambiguity of judgments (Chauhan & Singh, 2016). In the classical set theory, an element belongs or does not belong to a set. The element of a fuzzy set naturally belongs to the set with a membership value from the interval [0,1] (Kahraman & Kaya, 2010). The most commonly utilized fuzzy numbers are triangular and trapezoidal fuzzy numbers. In this study, triangular fuzzy numbers (TFNs) will be employed owing to their ease of use. The following equation is the membership function of a TFN denoted as $(l, m, u)$:

$$
\mu_{\alpha}(x) = \begin{cases} 
0, & x < l \text{ or } x > u \\
(x - l)/(m - l), & l \leq x \leq m \\
(u - x)/(u - m), & m \leq x \leq u 
\end{cases} 
$$

(1)

$l, m, u$ indicate the lower value, the mid-value, and the upper value, respectively. The main arithmetic operations for two TFNs are as follows:
\[ \tilde{M}_1 \otimes \tilde{M}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (2) \]
\[ \tilde{M}_1 \otimes \tilde{M}_2 = (l_1 l_2, m_1 m_2, u_1 u_2) \quad (3) \]
\[ \tilde{M}_1^{-1} = (1/u_1, 1/m_1, 1/l_1) \quad (4) \]

**The FAHP Method:** AHP is a useful method to solve complex MCDM problems (Saaty, 1980). In the AHP method, the elements of the same level are compared in pairs with respect to an element located at the higher level. However, AHP is based on crisp judgments. In reality, it is very hard to acquire precise data owing to uncertainties on the judgments of decision-makers. Each decision-maker prefers natural language expressions rather than crisp numbers (Heo et al., 2010). Therefore, FAHP will be used to obtain the weights of the criteria. The steps of the FAHP method used in this study can be summarized as follows (Chang, 1996; Somsuk & Laosirihongthong, 2014):

Step 1: The value of fuzzy synthetic extent with respect to the jth object is computed.

\[ S_j = \sum_{i=1}^{m} M_{ij} \otimes \left( \sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij} \right)^{-1} \quad (5) \]

Step 2: The degree of possibility of \( S_j = (l_j, m_j, u_j) \geq S_j = (l_j, m_j, u_j) \) is calculated using the following equation:

\[ V(S_j \geq S_j) = \begin{cases} 
1, & m_i \geq m_j \\
0, & l_j \geq u_i \\
\frac{l_j - u_i}{(m_i - u_i) - (m_j - u_j)}, & \text{otherwise} 
\end{cases} \quad (6) \]

where \( i = 1, 2, \ldots, n \), \( j = 1, 2, \ldots, m \), and \( i \neq j \).

Step 3: The degree of possibility of \( S_j \geq S_j \) over all the other fuzzy numbers is calculated.

\[ V(S_j \geq S_j) = \min V(S_j \geq S_j | i = 1, 2, \ldots, m; i \neq j) \quad (7) \]

Step 4: Compute the weight vector of a fuzzy matrix. Assume that \( w_j = \min V(S_j \geq S_j | i = 1, 2, \ldots, m; i \neq j) \).

\[ w_j = \frac{w_j}{\sum_{j=1}^{n} w_j} \quad (8) \]

Here, \( w_j \) is a non-fuzzy value. The evaluation scale used in this study is given in Table 1.

| Linguistic Scale | Triangular Fuzzy Scale |
|------------------|------------------------|
| Equal            | (1.1, 2)               |
| Moderate         | (2.3, 4)               |
| Strong           | (4.5, 6)               |
| Very strong      | (6.7, 8)               |
| Extremely preferred | (8.9, 10)          |

**The EDAS Method:** EDAS is a MCDM method that uses distances from average solutions (AV). The evaluation of alternatives is carried out according to the higher values of the positive distance from the average (PDA) and the lower values of the negative distance from the average (NDA). The EDAS procedure consists of the following steps (Keshavarz Ghorabaee et al., 2015):

Step 1: The decision matrix \( D \) of \( n \) alternatives and \( m \) criteria is formed.

\[ D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \quad (9) \]

Step 2: AV values are calculated.

\[ AV_j = \frac{\sum_{i=1}^{n} x_{ij}}{n} \quad (10) \]

Step 3: The values of PDA and NDA are computed.

\[ PDA_{ij} = \begin{cases} 
\frac{\max(0, (x_{ij} - AV_j))}{AV_j}, & \text{if } j \in B \\
\frac{\max(0, (AV_j - x_{ij}))}{AV_j}, & \text{if } j \in NB 
\end{cases} \quad (11) \]

\[ NDA_{ij} = \begin{cases} 
\frac{\max(0, (x_{ij} - AV_j))}{AV_j}, & \text{if } j \in B \\
\frac{\max(0, (AV_j - x_{ij}))}{AV_j}, & \text{if } j \in NB 
\end{cases} \quad (12) \]

\( B \) and \( NB \) are associated with benefit criteria and non-benefit criteria, respectively.

Step 4: The weighted sums of PDA and NDA are calculated with Equations (13) and (14).

\[ SP_i = \sum_{j=1}^{m} (w_j PDA_{ij}) \quad (13) \]

\[ SN_i = \sum_{j=1}^{m} (w_j NDA_{ij}) \quad (14) \]

Here, \( w_j \) is the weight of the \( j \)th criterion.

Step 5: The normalized values of SP and SN are determined as follows:

\[ NSP_i = \frac{SP_i}{\max(SP_i)} \quad (15) \]

\[ NSN_i = 1 - \frac{SN_i}{\max(SN_i)} \quad (16) \]

Step 6: The appraisal score (AS) is calculated.
The TOPSIS Method: TOPSIS is a MCDM method that obtains a solution which is closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS). The TOPSIS procedure consists of the following steps (Hwang & Yoon, 1981):

Step 1: The decision matrix is formed (see Equation (9)).

Step 2: The normalized decision matrix is obtained.

\[
r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}, \quad i = 1,2,\ldots,n; \quad j = 1,2,\ldots,m
\]  

(18)

Step 3: The weighted normalized decision matrix is obtained according to Equation (19).

\[
V_{ij} = w_j r_{ij}
\]

(19)

Step 4: PIS and NIS are determined using Equations (20) and (21), respectively.

\[
A^+ = \{v_1^+, v_2^+, \ldots, v_n^+\} = \{(\max v_{ij} | j \in B), (\min v_{ij} | j \in NB)\}
\]

(20)

\[
A^- = \{v_1^-, v_2^-, \ldots, v_n^-\} = \{(\min v_{ij} | j \in B), (\max v_{ij} | j \in NB)\}
\]

(21)

Step 5: Calculate the distance of alternatives from PIS and NIS.

\[
d_i^+ = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_{ij}^+)^2}
\]

(22)

\[
d_i^- = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_{ij}^-)^2}
\]

(23)

Step 6: The relative closeness to the ideal solution (C_i) is computed.

\[
C_i = \frac{d_i^-}{d_i^- + d_i^+}
\]

(24)

The Borda Count Method: The borda count method can be employed to incorporate different ranking results. An alternative gets m votes for the first-ranked criterion, m–1 votes for the second-ranked criterion, and 1 vote for the last-ranked criterion. The alternative with the largest sum of scores is the winner (Laukkanen et al., 2005).

Application: In the present study, a MCDM model is proposed to evaluate LVL, PSL, and LSL. This model consists of the following main phases: (1) prioritization of the criteria by FAHP, (2) prioritization of the alternatives by EDAS and TOPSIS, and (3) determination of the final ranking of the alternatives by Borda. The evaluation model is shown in Figure 1.

In order to evaluate the alternatives, two main criteria are defined as physical properties (PP) and mechanical properties (MP). The subcriteria of physical properties are moisture content (PP1) and density (PP2). The subcriteria of mechanical properties are bending strength (MP1), modulus of elasticity (MP2), compression strength parallel to grain (MP3), dynamic bending strength (MP4), tensile strength parallel to surface (MP5), tensile strength perpendicular to surface (MP6), and screw holding capacity (MP7). The hierarchical structure of the problem is portrayed in Figure 2.

A decision-making team consisting of five experts who have experience with the research topic is constructed to evaluate each criterion. The experts use the linguistic terms (see Table 1) to compare the criteria. The linguistic terms are then converted to TFNs. The geometric means of
the fuzzy values are computed to obtain the overall results of each evaluation matrix.

RESULTS AND DISCUSSION

The importance of each criterion is determined using FAHP. The comparison matrices can be seen from Tables 2-4.

Table 2. The comparison matrix of the main criteria.

| Criterion | PP | MP |
|-----------|----|----|
| PP        | (1.000, 1.000, 1.000) | (0.608, 0.730, 0.944) |
| MP        | (1.059, 1.332, 1.644) | (1.000, 1.000, 1.000) |

Table 3. The comparison matrix of the subcriteria within physical properties.

| Criterion | PP1 | PP2 |
|-----------|-----|-----|
| PP1       | (1.000, 1.000, 1.000) | (0.758, 0.933, 1.217) |
| PP2       | (0.822, 1.108, 1.320) | (1.000, 1.000, 1.000) |

Table 4. The comparison matrix of the subcriteria within mechanical properties.

| Criterion | MP1 | MP2 | MP3 | MP4 | MP5 | MP6 | MP7 |
|-----------|-----|-----|-----|-----|-----|-----|-----|
| MP1       | (1.000, 1.084, 1.149, 1.084, 1.081, 0.871, 0.871) | (1.320, 1.000, 0.699, 0.699, 0.699, 1.000, 1.000) |
| MP2       | (0.500, 1.000, 1.246, 0.922, 1.059, 1.059, 1.059) | (0.725, 1.000, 1.000, 1.000, 1.000, 1.000, 1.000) |
| MP3       | (0.844, 1.000, 1.000, 1.246, 1.246, 1.246, 1.246) | (0.922, 1.000, 1.000, 1.000, 1.000, 1.000, 1.000) |
| MP4       | (0.461, 0.435, 0.100, 0.803, 0.699, 0.699, 0.699) | (0.461, 0.435, 0.100, 0.803, 0.699, 0.699, 0.699) |
| MP5       | (0.725, 0.678, 1.000, 0.966, 0.903, 0.903, 1.380) | (0.725, 0.803, 1.000, 1.000, 1.000, 1.000, 1.000) |
| MP6       | (0.871, 0.803, 1.000, 1.000, 1.000, 1.000, 1.000) | (0.871, 0.803, 1.000, 1.000, 1.000, 1.000, 1.000) |
| MP7       | (0.574, 0.608, 0.758, 0.758, 0.758, 0.758, 1.320) | (0.574, 0.608, 0.758, 0.758, 0.758, 0.758, 1.320) |

The weights are presented in Table 5. As seen in Table 5, mechanical properties (0.734) are more important than physical properties (0.266). The most significant subcriterion is density (0.147). Other important subcriteria are ranked as follows: bending strength (0.132), modulus of elasticity (0.132), moisture content (0.119), tensile strength parallel to surface (0.114), and tensile strength perpendicular to surface (0.112). The lowest priority value belongs to screw holding capacity (0.040). It is followed by compression strength parallel to grain (0.093).

Table 5. Summary of the weights.

| Main criterion | Local weight | Subcriterion | Local weight | Global weight |
|----------------|--------------|--------------|--------------|---------------|
| Physical properties | 0.266 | Moisture content | 0.044 | 0.044 |
|               |               | Density      | 0.552        | 0.552        |
| Mechanical properties | 0.734 | Bending strength | 0.180        | 0.180        |
|               |               | Modulus of elasticity | 0.180          | 0.180          |
|               |               | Compression strength parallel to grain | 0.127        | 0.127        |
|               |               | Dynamic bending strength | 0.151        | 0.151        |
|               |               | Tensile strength parallel to surface | 0.156        | 0.156        |
|               |               | Tensile strength perpendicular to surface | 0.152        | 0.152        |
|               |               | Screw holding capacity | 0.054        | 0.054        |

The decision matrix is given in Table 6. The physical and mechanical properties of the alternatives are evaluated by EDAS and TOPSIS. The results are presented in Tables 7 and 8. According to the results obtained by using the FAHP-EDAS approach, the best SCL product is LVL with an AS of 0.693. PSL with an AS of 0.597 is positioned at the second rank, while LSL with an AS of 0.491 is placed at the third rank. According to the results of the equal weighted EDAS analysis, the ASs of LVL, PSL, and LSL are 0.776, 0.474 and 0.328, respectively. These values show that the best SCL product is LVL.

Table 6. The decision matrix

| PP1 | PP2 | PP3 | PP4 | PP5 | PP6 | PP7 |
|-----|-----|-----|-----|-----|-----|-----|
| LVL | 8.81 | 0.40 | 64.51 | 7907.2 | 49.87 | 0.46 |
| PSL | 0.00 | 0.44 | 60.23 | 7864.6 | 43.85 | 0.50 |
| LSL | 8.34 | 0.50 | 61.83 | 8022.5 | 41.91 | 0.40 |

Table 7. The EDAS results

| FAHP-EDAS | Equal weighted EDAS |
|-----------|---------------------|
| SP | NSP | SNN | NSN | AS | SP | NSP | SNN | NSN | AS |
| LVL | 0.020 | 1.000 | 0.016 | 0.385 | 0.693 | 0.012 | 0.552 | 0.276 | 1 |
| PSL | 0.014 | 0.705 | 0.015 | 0.490 | 0.597 | 0.017 | 0.377 | 0.474 | 2 |
| LSL | 0.018 | 0.982 | 0.026 | 0.000 | 0.491 | 0.016 | 0.656 | 0.027 | 0.328 | 3 |

Table 8. The TOPSIS results

| FAHP-TOPSIS | Equal weighted TOPSIS |
|-------------|-----------------------|
| d+ | d− | C+ | Ranking | d+ | d− | C+ | Ranking |
| LVL | 0.020 | 0.014 | 0.419 | 5 | 0.015 | 0.017 | 0.518 | 1 |
| PSL | 0.015 | 0.016 | 0.528 | 2 | 0.015 | 0.016 | 0.517 | 2 |
| LSL | 0.018 | 0.019 | 0.520 | 2 | 0.019 | 0.015 | 0.448 | 3 |

When the results of the FAHP-TOPSIS analysis are examined, it is seen that PSL (0.528) is the best alternative. According to the results of the equal weighted TOPSIS analysis, the ranking of the SCL products in descending order with respective weights is LVL (0.518) > PSL (0.517) > LSL (0.448). Borda is employed due to different ranking results. Consequently, the ranking of the alternatives is as follows: [LVL – PSL – LSL]. In light of the results, it can be said that LVL is the best SCL product.

In Sizifine’s work, the experimental results of LVL, PSL, and LSL are reported. However, the ranking of them is not reported. This shortcoming is eliminated by the MCDM analysis.

CONCLUSION

The objective of this study is to evaluate LVL, PSL, and LSL by taking into account their physical and mechanical properties. In order to achieve the objective, an evaluation model containing FAHP, EDAS, and TOPSIS is proposed. FAHP is used to obtain the weights of the criteria. The weights are used in EDAS and TOPSIS to determine the ranking of the alternatives. Borda is employed to incorporate the ranking results. According to the results, the first three important subcriteria are density,
bending strength, and modulus of elasticity. Moreover, it can be said that LVL possesses better properties when compared with PSL and LSL. Consequently, the evaluation model proposed in this study can provide beneficial insights for researchers in terms of the evaluation of wooden materials.

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