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APPLICATION OF WOODEN MODULAR CONSTRUCTION FOR THE NEEDS OF THE ELDERLY

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Research paper

Abstract: *In recent years, changes in demographic structure have been observed worldwide. To sustain the growing population of elderly people with special needs, homes need a radical rethink both in designing new houses and in retrofitting new solutions to existing houses. Designs that facilitate aging in place, designs that maintain thermal comfort, and designs that have net-zero energy demands and low to zero to negative carbon footprints are needed. The article discusses the issues of construction for the elderly. The trends in the demographic development of society in selected countries are presented. Additionally, information on the housing stock for elderly people in Poland is provided. The carbon dioxide emission limits to mitigate climate change make it necessary to find an alternative to concrete and steel, traditional construction materials. In this context, Cross Laminated Timber (CLT) fulfills the sustainability requirements. However, to select the suitable panel a detailed analysis of timber characteristics is required. It is necessary to evaluate mechanical properties in bending, tension, compression, and shear. Since the mechanical properties of certain types of wood differ, their proper selection is challenging. The multi-criteria analysis could address this. In this article, four wood species, spruce, oak, ash, and beech, were evaluated using the Analytic Hierarchy Process (AHP) analysis. Based on the type of construction elements and their functions, analyses were using six mechanical properties as criteria. The optimal type of wood was indicated.*

Key words: *Cross Laminated Timber, modular construction, elderly people, optimization, AHP.*

1. Introduction

The studies on demographic change (Pašalić et. al. 2020) reveal a relatively rapid increase in the growth of the elderly population. It is expected that in the next 30 years the ratio of elderly people (aged 65 and above) to the whole population will increase from 7% in the first decade of the 21st century to 16% in 2050 (Cohen,

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2003; WHO, 2021). This trend is observed especially in the developed countries and results in a high reduction of the percentage of the population of working age. The life expectancy has increased in recent decades (Roser et al., 2013). The reason for that is mainly related to the improvement of living and social conditions (Nicał, 2016). Although demographic changes occur worldwide, their extent and timing differ significantly in the developing countries in Latin America and Africa from the western European countries and Japan (Krueger & Ludwig, 2007; Bloom & Williamson, 1998; United Nations, 2002). Due to health issues, the majority of elderly people spend most of their time at home and very often depend on other's people with housework. The solution for these people can be robotic support systems in everyday activities at home (ADLs - Activities of Daily Living) (Bock et al., 2012; Nicał, 2017). These systems are part of a research and development program AAL (Active and Assisted Living Programme) supporting projects that use information and communication technologies (ICT) to improve the quality of life of older people. The implementation of the AAL program usually entails the need to reconstruct the apartments where elderly people live. In many European countries (e.g. Poland), elderly people live in buildings erected in the 1960s, 1970s, and 1980s. A large proportion of these buildings are made in standardized large-block and large-panel systems. Figure 1. presents the share of each of these technologies in residential buildings in Poland in the period between 1970-1985 (Nicał, 2017; Dzierżewicz & Starosolski, 2010).

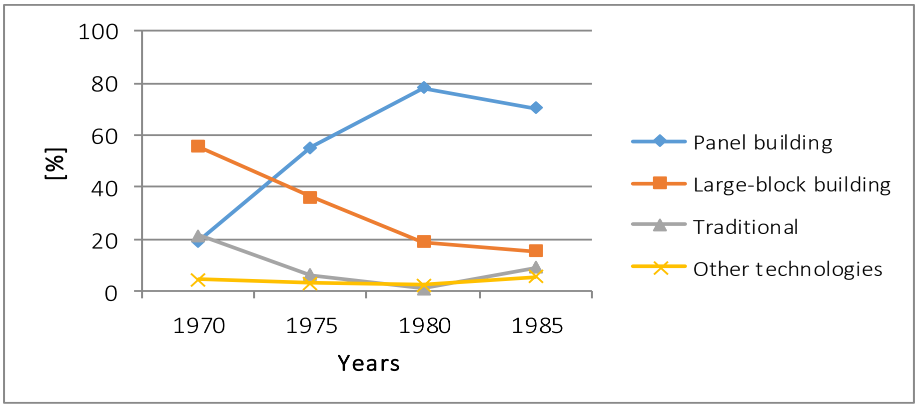

Figure 1. Share of the various technologies in residential buildings in Poland in the period between 1970-1985 (Nicał, 2017; Dzierżewicz & Starosolski, 2010).

Depending on the system, these buildings were erected in spatial arrangements in which most of the walls serve as load-bearing. Therefore, it is not possible to move or demolish such walls. This circumstance causes many inconveniences in terms of adapting apartments for elderly people such as widening corridors or door openings (Nicał et al., 2019). Therefore, it is necessary to build facilities adapted to the needs of the elderly. Moreover, these buildings should be erected as quickly as possible by the implementation of advanced technologies (Xing et al., 2020). Panel buildings, usually made in concrete technology, are not environmentally friendly. Research in this area has been carried out, inter alia, by (Pierobon et al., 2019). Results showed that an average of 26.5% reduction in the global warming potential is achieved in the hybrid CLT building compared to the concrete building. CLT compared to other wood-based materials such as glued laminated timber (GLT), has lower: emissions in Global warming potential (GWP), Terrestrial Ecotoxicity (TE), Land Use (LUP), and Ozone layer depletion (OLD) (Balasbaneh & Sher, 2021). In addition, taking into account the trends in the field of environmental protection and reduction of CO_2 emissions, it is necessary to use the material with the lowest carbon footprint. The material that meets these criteria is cross-laminated timber (CLT). When choosing wood for CLT, the decision-makers are faced with the dilemma of choosing the wood species that compose it. Thus, a research gap exists at the interface between timber engineering and the decision-making process of selecting the leading parameters when selecting it. The purpose of this paper and its contribution to the field of construction for the elderly is to establish a methodology for selecting the most optimal timber spieces taking into account their six main mechanical criteria.

2. Cross Laminated Timber (CLT)

2.1. General information

CLT constitutes a plate-like engineered timber product, optimized for bearing loads in and out of plane and is composed of an uneven number of layers. As defined in the Standard PN-EN 16351 (PN-EN 16351:2015), CLT is structural construction timber consisting of at least three layers of wood or wood-based materials, of which at least three layers are perpendicular to each other. Figure 2. below presents an example of a CLT 160 L5s (40L-20W-40L-20W-40L). A detailed explanation of the individual symbols is provided below (Fig. 3).

Figure 2. An example of CLT 160 L5s (40l-20w-40l-20w-40l).

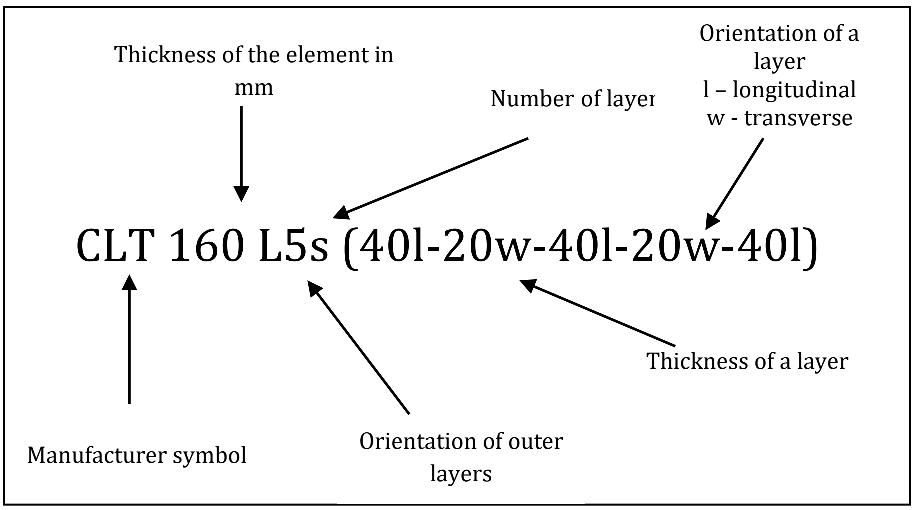

Figure 3. A detailed explanation of the individual symbols in the CLT labeling.

Layers are quasi rigidly connected by adhesive bonding (Brandner, 2013). Thanks to the multilayer, alternating arrangement of layers, the significance of the natural imperfections like knots of a single wooden board are reduced and a rigid wall or a floor slab is obtained (Kotarski & Przepiórka, 2020).

The advantages of CLT as a large-sized and panel-like solid timber construction element for the construction are mostly related to its outstanding degree of prefabrication, the dry and clean construction technique, and the short erection times on site (e.g. roughly one to two days per family house) (Brandner, 2013). CLT is characterized by high dimensional accuracy and easy adjustment. It can also transfer loads in two dimensions. Together with its low self-weight, it is particularly suitable for the conversion and modernization of existing buildings, but also for resisting exceptional loads (e.g. earthquakes). CLT offers, in contrast to the lightweight timber structures (e.g. framing, post, and beam system), a clear separation of load-bearing from insulation and installation layers. Additionally, CLT is characterized by the low air permeability, the distinctive specific storage capacity for humidity and temperature, the independence of modular dimensions in arranging window and door openings as well as in fastening of furniture.

2.2. Production and processing of CLT

The first stage of CLT production is not much different from the production process of glued laminated timber and consists of the following activities (Figure 4) (Brandner, 2013):

- strength or stiffness grading of already (kiln) dried boards;
- cutting out of local growth characteristics which do not meet the requirements of the strength class and finger jointing of the residual board segments to endless lamellas;
- division and cutting of lamellas for later use in longitudinal and transverse layers of CLT.

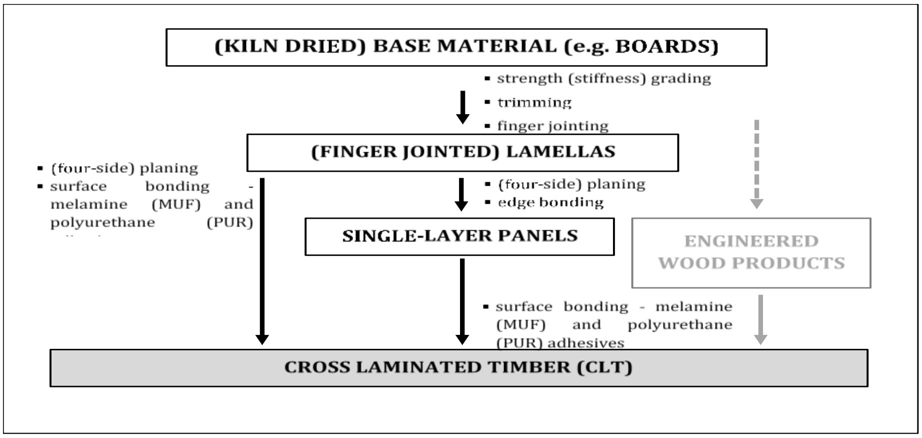

Figure 4. Overview of CLT production process (Brandner, 2013).

Usually, CLT is composed of boards with thickness t_B = (12 ÷ 45) mm (PN-EN 16351:2015). There is no upper limit for the board width but due to rolling shear stresses in-between the CLT layers a minimum width of $w_B \geq 4 \cdot tB$ (Brandner, 2013). The reference board width is proposed with $w_{B,ref}$ = 150 mm, as given in PN-EN 338 (PN-EN 338:2016-06) and PN-EN 384 (PN-EN 384+A1:2018-12). Currently, mainly softwood species are used for CLT. Material moisture tolerance is 12 +/- 2% (Kotarski & Przepiórka, 2020). Each of the CLT layers must be made of sawn timber of the same strength class determined in accordance with PN-EN 14081-1 (PN-EN 14081-1+A1:2019-11), however, it is allowed to use different types of wood provided that the same technical parameters are maintained, especially swelling and shrinkage. It is also possible to use bent cross-laminated timber elements, the thickness of which depends primarily on the bend radius of the elements. The demand for bent CLTs is very small on the market, and the cost of setting up the production is incomparably higher than for simple elements, hence few manufacturers decided to offer this type of product. However, it is a future-proof product, offering an even greater range of design options for architects (Brandner, 2013). The second stage of CLT production consists of the following activities (PN-EN 16351:2015) (Figure 4):

- adhesive bonding of lamellas to single-layer panels (optional);
- assembling and adhesive bonding of lamellas or single-layer panels to CLT;
- cutting and joining to structural elements (customizing).

Melamine (MUF) and polyurethane (PUR) adhesives are most often used to connect the individual layers. They meet stringent standards in terms of formaldehyde emissions and are safe for health during production, use, and also during fire. The application of the adhesive to surface bonding is usually carried out mechanically and without contact on single lamellas in a continuous through-feed device or on CLT layers already pre-positioned in a positioning or press bed. A line-wise discrete application of adhesive is preferred (Brandner, 2013). The lamellas do not have to be glued on the side surfaces and it is allowed to arrange them with a spacing of up to 6 mm. Cross-glued timber is glued in hydraulic or vacuum presses (Kotarski & Przepiórka, 2020). In both cases, under the gluing technology, adequate pressure of the joined elements is required, which enables a permanent adhesive bond. In the case of hydraulic presses, it is from 0.1 to 1.0 N/mm^2, and in the case of vacuum gluing, from 0.05 to 0.1 N/mm^2 (Kotarski & Przepiórka, 2020), with 0.4 N/mm^2 being already sufficient for most typical configurations (Sikora et al., 2015). Clamps, pins, and nails are very rarely used in the production of CLT, this is acceptable (Kotarski & Przepiórka, 2020). After pressing, standard CLT elements are normally trimmed on their edges. The surface of the elements after pressing is treated differently, without further processing by planning or sanding (Brandner, 2013). Application of additional non-load-bearing layers like OSB, acoustic panels, gypsum plasterboards, or three-layered solid wood panels is possible. The additional layers are primarily connected by surface bonding (Brandner, 2013).

To ensure the appropriate quality of products, it is necessary to maintain the following parameters during production (Brandner, 2013):

- during bonding: temperature ≥ 15°C and relative humidity (40 ÷ 75) %;
- during curing: temperature ≥ 18°C and relative humidity ≥ 30 %;

- moisture content of adherents u = (6 ÷ 15) % (≤ 18 % in case of preservative treatment);
- the maximum difference in moisture content between two parallel layers Δu ≤ 5 %.

2.3. Selected properties of CLT

Mechanical properties of CLT panels are determined mainly by destructive testing i.a. bending, rolling shear, compression, tension (He et al., 2020). Among the conducted research, it is necessary to mention the i.a. bending and compressive properties of CLT panels made from Canadian hemlock that calibrated the theoretical bending stiffness using the experimental values (He, 2018), and the bending and shear properties of three- and five-layer CLT panels fabricated with Irish Sitka spruce (Sikora et al., 2016, O'Ceallaigh et al., 2018). Moreover, testing of rolling shear properties of CLT fabricated with New Zealand Radiata pine and correlation between lamination thickness and its influence on rolling shear strength has been developed (Li, 2017). The test results for the properties of the 3-layer and the 5-layer CLT (He et al., 2020) panels show, inter alia, that 3-layer panels have about 11.3% higher stiffness parallel-to-grain direction and over 15.8% higher stiffness perpendicular-to-grain direction. In addition, the average global modulus of elasticity of 3-layer panels is over 19.2% higher than 5-layer panels. 5-layer panels are characterized by, among others 11.4% higher strength parallel-to-grain direction and 9.7% higher strength perpendicular-to-grain direction. The average local bending stiffness by the 5-layer panel is 243.9% larger than for the 3-layer panel, and the average global bending stiffness by 252.5%, respectively. The average shear strength by the 5-layer panel is 3.8% higher than for the 3-layer panel, while the bending strength is 4.3% higher than for the 3-layer panel. Both the 3-layer and the 5-layer CLT panels were manufactured with a width of 310 mm, using the Canadian black spruce lumber (No 2-grade) with the following material properties (NLGA, 2010):

- stiffness parallel-to-grain direction ($E_{l,0}$) = 10925.0 MPa;
- stiffness perpendicular-to-grain direction ($E_{l,90}$) = 993.2 MPa;
- strength parallel-to-grain direction ($f_{lc,0}$) = 28.7 MPa;
- strength parallel-to-grain direction ($f_{lc,90}$) = 5.8 MPa.

Based on the presented results, it can be concluded that both the 3-layer and the 5-layer CLT panels fabricated with the No.2-grade black spruce can provide ideal bending or shear properties. The properties can be comparable to those of the CLT fabricated with other commonly used wood species (He et al., 2018).

3. Housing for the elderly

3.1. General assumptions

Buildings intended for the stay of elderly people should meet several criteria, such as:

- the building and its surroundings must not have architectural barriers;

- a multi-storey building must have a lift adapted to the needs of disabled and elderly people;
- the building must be equipped with a call and alarm system and a fire alarm system.

Other requirements include the need to construct wide corridors, larger areas of rooms, dining rooms, guest rooms, and other technical rooms to meet the sanitary needs of residents. It is also important to remember to provide adequate conditions in the bathrooms. These are the place where a lot of accidents happen. While designing it is important to take into account the necessity of ensuring an adequate maneuver space for a wheelchair that should not be smaller than 150x150 cm (Nicał, 2016), (Budny, 2009). Providing large living and communication areas entails the necessity to construct facilities with the use of construction elements with significant spans. Additionally, the construction elements should be light and slender to ensure the largest possible cubic capacity. Buildings intended for the stay of elderly people should also be made of prefabricated elements, to ensure a short construction time. In this respect, the use of CLT seems to perfectly meet the expectations.

3.2. Selection of wood for construction

Hardwood shows a higher natural strength potential than softwood, see Figure 5 (Franke, 2013). Additionally, hardwood, with its good mechanical properties, perfectly fits for long-spanned and high stressed timber constructions.

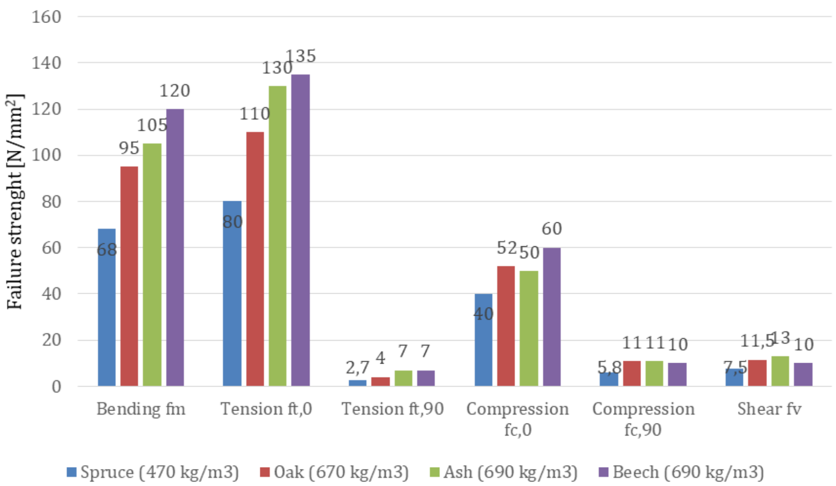

Figure 5. Comparison of mechanical properties of hardwood and softwood species (Franke, 2016).

The tensile strength perpendicular to the grain for hardwood can reach up to 260% of the softwood strength values (Franke, 2016). Regarding bending and compression parallel to the grain, the strength values are up to 175% and 150% higher, respectively (Franke, 2016). As a result, the use of hardwood allows larger spans and smaller cross-sections. These numbers indicate that structural elements for buildings intended for the stay of elderly people could be erected of hardwood.

4. Methodology

4.1. AHP multicriteria assessment method for the selection of wood for construction materials

One of the most difficult problems in construction, as well as, in CLT material selection is to take objective decisions, especially for the selection of technology and material solutions (Książek et al., 2014). Construction projects planning requires a proper materials selection process that should be assessed in terms of their long-term cost (Rosłon et al., 2020), durability, quality (Nicał & Anysz, 2020), expected construction time (Ibadov, 2019), and mechanical properties. The utilization of AHP (Analytic Hierarchy Process) multicriteria assessment method (Hwang & Yoon, 1981), (Alosta, et al. 2021) can be beneficial. Among many proven and recognized methods of multi-criteria evaluation, such as e.g. FUCOM (Bozanic et al, 2021) or Decision Making Trial and Evaluation Laboratory Model (DEMATEL) technique, integrated with Analytic Network Process (ANP) (Osintsev et al. 2021), as well as, Fuzzy AHP and Fuzzy MARCOS Approach (Bakir et al. 2021), it was decided to use the AHP method. It is broadly spread in engineering and is very usable method that separates the problem into litter steps.

The AHP is a four-step method with the following steps (Saaty, 1980), (Saaty, 2008), (Trzaskalik, 2006). The steps are the following:

- Step I – hierarchy of the problem;
- Step II – definition of preferences by the decision-maker;
- Step III – preference matrix consistency testing;
- Step IV – creating a summary ranking.

In step I, it is necessary to define: the problem faced by the decision-maker, available options of a solution, criteria against which the available options will be assessed, and possibly further sub-criteria. The hierarchical structure results from the decomposition of the problem into the main goal, main factors, and side factors (Anysz et al., 2021). In step II the decision-maker using numerical values from 1 to 9 (less often from 1 to 7) has to define the preferences. Table 1. shows the values of the comparative assessment against each other. Values not listed in Table 2 (2, 4, 6, 8) characterize intermediate values (Anysz et al., 2021).

Table 1. Comparative assessment in the AHP method (Anysz et al., 2021).

COMPARATIVE, PAIRWISE ASSESSMENT OF A AGAINST B	VALUE
Just as good or important	1
A little better or more important	3
Definitely better or more important	5
Much better or more important	7
Extremely better or more important	9

Preferences are specified for each level within the defined hierarchical structure (Anysz et al., 2021). Objects that are only at one level of the hierarchy can be assessed against each other. The comparative assessment is subjective and is made by the decision-maker (Grzegorzewski, 2019). The result of step II is a square matrix A in which the terms a_{ij} concerns the preferences of the decision-maker. The digits 1 are on the diagonal of the matrix A, there is also the reciprocal of the adopted preferences, i.e.:

$$a_{ij} = \frac{1}{a_{ji}} \tag{1}$$

The following sub-step is to normalize matrix A to matrix B using the dependence below:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{2}$$

The value b_{ij} is expressed as the quotient of the term a_{ij} to the sum of the terms in the j-th column of matrix A (Anysz et al., 2021). Weights of the examined elements (w_i) are the arithmetic means of the rows of the matrix B according to the following formula (Saaty, 1980; Anysz et al., 2021; Książek et al., 2014; Tułecki & Król, 2007).

$$w_i = \frac{1}{n}\sum_{j=1}^{n} b_{ij} \tag{3}$$

In step III only one pair of criteria is assessed by the decision-maker each time. The preference relationship between the criteria is asymmetric (Anysz et al., 2021). Potential inconsistencies in the assessments of the decision-maker can be avoided, with the introduction of the following control coefficients: Consistency Index (CI) and Consistency Ratio (CR)

$$CI = \frac{\lambda_{max} - n}{(n-1)} \tag{4}$$

$$CR = \frac{\lambda_{max} - n}{RI \cdot (n-1)} \tag{5}$$

where:

λ_{max} - the maximum eigenvalue of the matrix,

RI - the value of the average random consistency index CI according to the table below (Table 2).

Table 2. The values of the average random index of RI.

Matrix dimension n	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

If $CR \leq 0.10$, then the preference matrix is considered consistent. When $CR > 0.150$, the assumptions from step II should be changed (Saaty, 1980; Saaty, 2008).

In the last step IV, a ranking of the available solutions in terms of their suitability to meet the main goal is created. The order from the best to the worst needs to be kept. The total score of a single variant can be calculated according to the following formula (Anysz et al., 2021):

$$P = \sum_{i=1}^{n} w_i \cdot k_i \tag{6}$$

where:

P - final score for a given solution variant,

w_i - criterion weight according to the formula (3),

k_i - evaluation of a given criterion.

4.2. Application of AHP for the selection of wood

The decision problem lies in the selection of the most advantageous type of wood for the structural elements from which the buildings intended for the stay of the elderly will be erected. For this purpose, the study of the data contained in Figure 5, concerning the mechanical characteristics of wood, will be applied. The evaluation criteria, in this case, are the results obtained in the following tests:

- Criterion 1: bending, f_m;
- Criterion 2: tension, $f_{t,0}$;
- Criterion 3: tension, $f_{t,90}$;
- Criterion 4: compression, $f_{c,0}$;
- Criterion 5: compression, $f_{c,90}$;
- Criterion 6: shear, f_v.

The variants are assigned as follows:

- Variant 1: spruce;
- Variant 2: oak;
- Variant 3: ash;
- Variant 4: beech.

4.3. Results

Currently, the natural higher strength can potentially be mostly used for partial reinforcements in timber structures, e.g. for strengthening the lateral compression capacity at supports or loading plates or the tension capacity perpendicular to grain at notches and holes or in tapered and curved beams (Franke, 2013).

According to the calculations in the AHP assessment method, the following criteria weights are obtained (Figure 6).

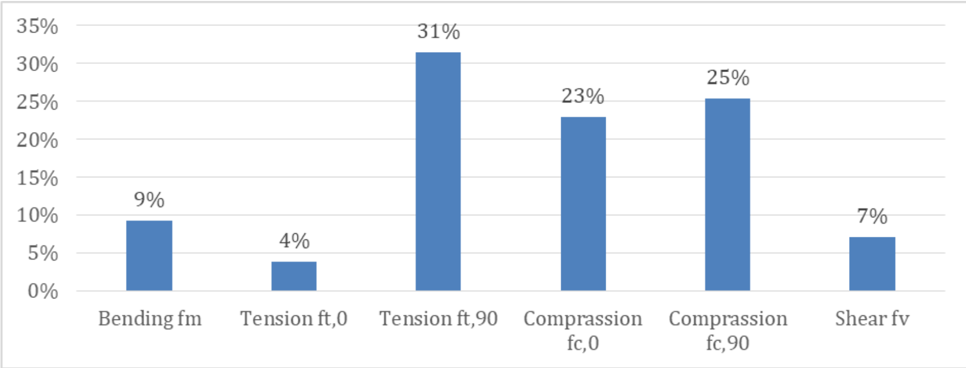

Figure 6. Criteria weights obtained in the AHP method.

Using the criteria weights from Figure 6, the final result and order are as follows (Table 3).

Table 3. Final results and order in the AHP method.

	bending, f_m	tension, $f_{t,0}$	tension, $f_{t,90}$	compression, $f_{c,0}$	compression, $f_{c,90}$	shear, f_v	priority vector	solutions vector	order
Spruce	0.049	0.049	0.124	0.095	0.066	0.064	0.092	0.088	4
Oak	0.131	0.140	0.096	0.258	0.364	0.423	0.038	0.229	3
Ash	0.300	0.308	0.390	0.181	0.364	0.329	0.315	0.320	2
Beech	0.520	0.503	0.390	0.466	0.207	0.185	0.229	**0.363**	**1**
							0.254		
							0.071		

The highest score of 0.363 was obtained for beech. It is followed by ash, oak, and spruce, respectively.

5. Conclusion

AHP analyses ranked timber species taking into account the main mechanical and criteria of main concerns for the elderly population. Results indicated that the most optimum was Beech, followed by Ash, Oak Spruce. However, to provide the selection guidelines that will be generally accepted by the industry further studies should concern aspects of the CLTdurability of the erected facilities and the costs of their long-term operation. It is important to take into account potential limitations in the development of CLT technology, related to, inter alia, access to wood resources with the required strength parameters, and regulations for the silviculture and timber design and utilization as construction material. The aspects of the availability and cost of obtaining wood raw material, which may differ significantly from country to country, are also important. Further studies on CLT optimization should focus on adhesives and bonding parameters, strength, and durability, as well as, on novel fully robotized and highly efficient production technology.

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