Abstract

The evolving landscape of environmental and economic challenges in the construction sector underscores the need for innovative material solutions. Wood is increasingly considered a viable alternative, offering a potential path forward. With its renewable nature, carbon sequestration potential, and favourable mechanical properties for its relatively low weight, wood differentiates itself from conventional materials. However, environmental crises and evolving climate conditions threaten the long-term stability of wood resources, underscoring the need for proactive and diversified strategies in resource management.

To address these challenges, this study presents *TUP4C* (Timber Utilisation Potential for Construction), a decision-support approach designed to assist multiple stakeholders in selecting suitable wood species for construction. The tool integrates economic, environmental, social and technical criteria within a holistic, multi-criteria decision-making framework. Its adaptable design allows for customisation to various stakeholder profiles, aligning with their priorities, targeted product categories, and strategic timeframes. In the preliminary phase of a project, the tool reveals diversification opportunities by considering new wood species aligned with a defined product and vision. An application in Wallonia (Belgium) demonstrates its ability to highlight lesser-known hardwoods while confirming spruce's industrial predominance for structural and exterior joinery applications.

By promoting the use of diversified wood species, *TUP4C* contributes to a more resilient and adaptive forestry-wood-construction sector, fostering sustainable resource management and strategic decision-making.

Keywords

- → Sustainable building materials
- → Wood species selection
- → Forest resource management
- → Multi-criteria decision analysis (MCDA)
- → Holistic selection methods

Article

Timber Species Selection for Sustainable Construction: A Holistic Approach to Species Assessment and Decision Support

1. INTRODUCTION

1.1 Wood Construction Sector

In recent years, the wooden building sector has generated increasing interest, driven by its potential role in mitigating climate change [1]. There has been a notable rise in scientific production in the field [2], [3]. This momentum aligns with the context of pressing environmental concerns. The buildings construction industry, driven by concrete, aluminium, and steel, is particularly energy-intensive and responsible for 6% of global CO_2 emissions in 2021 [4], [5]. In this context, wood stands out as a favoured material. It is a renewable resource that stores carbon, on average, 50% of a weight-to-weight basis [6] and plays a crucial role in substitution, reducing overall emissions by replacing carbon-intensive materials. In addition to its environmental benefits, wood presents attractive properties for construction, including good mechanical properties, the potential for prefabrication, and advantageous characteristics related to thermal comfort, aesthetics and lightness. [1], [7].

From an economic point of view, although the construction of wooden high-rise buildings is growing [8], the market share of wooden construction has remained at around 8 to 10% on average in Europe over the last few decades [9]. Although widely used in the Nordic countries, this method of construction remains relatively minor in several European countries [9], [10], [11], [12]. In Belgium, for instance, new wooden housing construction represented 6.75% of residential building construction in 2022, and the sector's growth seems to be slowing, with the share of wooden constructions stagnating in recent years [13]. Several factors may explain this phenomenon, including the COVID-19 pandemic and the net increase in energy prices during this period [13]. However, if current interest in scientific research is followed by the construction market and public policies promoting the use of renewable materials are implemented, an increase in demand for wood in the construction sector can be expected [14], [15], [16], [17], [18].

1.2 Contemporary Challenges

The forest-based sector currently faces numerous challenges, with pressures likely to intensify as the market evolves and environmental conditions change. One of the sector's critical challenges concerns the role of forest carbon sinks in mitigating climate change [19], [20], [21]. Forest carbon sink represents the difference between stored and emitted CO_2 flux from forest resources. Maintaining a positive sink is crucial for absorbing fossil carbon emissions and regulating atmospheric greenhouse gases [21]. However, balancing production and conservation is complex due to increasing wood demand [22] and external pressures from decarbonisation strategies, including carbon offset systems and substitution [23], [24].

Besides, climate change has complex effects on forests. While increased temperatures and CO_2 levels could enhance forest productivity in coming years [19], [20], [22], [25] , more frequent extreme weather events and exotic pathogens threaten forest health [19], [25], [26]. The slow migration rates of tree species can hardly match the pace of climate change [26], endangering forest ecosystem sustainability. Although diversified silvicultural practices could strengthen forest resilience [27], [28], [29], [30], [31], [32], current monoculture systems and intensive softwood species exploitation increase vulnerability to disturbances [32], [33], [34].

Environmental crises complicate wood industry supply chains [35]. Climate events and biological disturbances cause resource availability fluctuations, while recent health (COVID-19) [36] and geopolitical [37] crises have highlighted regional supply dependencies.

Raw material supply instability generates high volatility in wood resource prices and directly affects construction stakeholders [38], [39]. It also creates a risk of wood losing competitiveness against materials with more stable prices or produced by better-capitalised industries, whether foreign wood products or other construction materials. Competition between wood uses (construction, furniture, packaging, energy) intensifies resource pressure [40], [41]. This competition is exacerbated by specific dynamics, such as the strong competitiveness of wood energy in terms of processing and potential incentives provided by public policies promoting renewable energy use in line with EU objectives. This competition necessitates usage prioritisation for optimal carbon and material conservation [42], [43], [44].

These considerations highlight, namely, the importance of local resource production and consumption [45]. However, the forest-wood industry's fragmented structure hinders sector-wide strategy implementation [18]. Additionally, forests' multifunctional nature providing various ecosystem services (economic, ecological, recreational, cultural) [46] requires careful balance of local forestry activities with public perception, demanding clear communication about sustainable forest management.

1.3 Proactive Resource Management

The forest-wood sector requires proactive resource management to address current and future crises. Several techniques have been developed at the European level to promote sustainable forest management, including dynamic silviculture methods based on species diversity and forest cover maintenance such as continuous cover forestry (CCF) [33], [47], or assisted migration to help species occupy more appropriate environments [48]. At the regional level, in Belgium, these innovative practices have been implemented in projects such as *Pro Silva* [49] and *Trees For Future* [50]. The development of new value chains for certain underutilised broadleaf species [51] or the establishment of micro and mobile-sawmills to process marginal species in peri-urban areas [52] are also projects attempting to develop alternatives to traditional exploitation methods in Belgium.

Given the growing interest in wood and the need to prioritise sustainable resource management, the forest-wood-construction sector require comprehensive shared tools to support collective and coherent decision-making. Aligning the strategies of diverse stakeholders—such as forest managers, architects, builders, and policymakers—is essential to address future challenges. I Such considerations outline the interest for decision-support tools promoting wood species diversification, namely allowing reducing pressure on softwood species such as spruce, which is suffering from bark beetles in Belgium [53].

This paper proposes a decision-support tool designed to evaluate the suitability of wood species for the construction sector. It evaluates the relevance of these species based on sustainability criteria and their technical performance for specific applications. The tool is designed to accommodate the diverse contexts and decision-making needs of stakeholders across the forest-wood-construction value chain. The structure of the article is as follows. First, the issue of material selection is introduced, with a focus on existing tools for selecting wood species in relation to the previously outlined challenges. Next, a holistic framework is presented, detailing the hierarchical structure of the approach and the indicators identified as relevant for analysis. This theoretical section is intentionally separated from the practical evaluation methods, which are addressed in Chapter 4, including the multi-criteria assessment approach and weighting principles. Chapter 5 provides an application of the tool in Wallonia (Belgium), using two user profiles to illustrate its versatility. Finally, the conclusion summarises the tool's contributions and limitations and suggests potential improvements. Key insights from the case studies are also highlighted.

2. WOOD SELECTION PROBLEM

2.1 Generalities

Material selection in the construction sector aims at identifying optimal materials for specific applications based on predefined criteria. Traditional tools for selecting construction material currently range from technical datasheets to sophisticated systems. While manufacturer databases provide foundational information, their analysis can be time-consuming and require extensive expertise [54]. More advanced systems include multicriteria decision-making (MCDM) for evaluating different aspects, such as cost or technical performance [55], [56], [57], [58], [59], [60], [61], [62]. Life cycle analyses (LCA) assess the environmental impact of materials across the various stages of their life cycle [63]. Emerging AI-based tools offer new perspectives in decision-support by processing large amounts of material data to help identify optimal materials [64], [65].

Most of these tools are primarily aimed at engineers, architects and project designers. They are used to compare different materials for use in a project (concrete, steel, timber) but are not intended to develop strategies at the sectoral level. Furthermore, wood's unique properties - including anisotropy and moisture behaviour - distinguish it from homogeneous materials [66], [67], [68], complicating its integration into traditional selection strategies.

2.2 Specifics of Wood Species Selection Tools

Existing wood species selection tools primarily concern silvicultural decisions. Implementing appropriate agroforestry practises requires considering numerous parameters (biophysical, economic and social) that these tools attempt to translate to help users choosing tree species or silvicultural methods suitable for their specific objectives and contexts [69], [70], [71], [72], [73]. Other tools assess ecological contributions of wood species, such as flood management or urban air pollution reduction [74], [75], [76], [77].

Species selection tools based on properties and uses have also been developed. *The Wood Database* is an extensive database that allows exploration of technical characteristics for hundreds of species [78]. The book *Timber Selection by Properties: The Species for the Job* by C. Webster provides a methodology for assessing the suitability of species for specific uses, particularly in interior joinery and furniture [79], [80]. In the construction field, Özşahin et al. [81] developed a decision-support tool to evaluate a range of softwood species and identify optimal alternatives for structural and non-structural uses. This tool relies on *AHP* (Analytic Hierarchy Process) and MOORA (Multi-Objective Optimisation on the basis of Ratio Analysis) methods. Oum Lissouck & al. [82] designed a tool for valorising tropical species from the Congo Basin in glued-laminated timber applications. Using the ELECTRE TRI-B (ÉLimination Et Choix Traduisant la RÉalité) method, this tool categorises species into three levels of consensus (High, Moderate, or Insufficient) for potential applications. Finally, Šuhajdová & al. [83] developed an evaluation tool for assessing the suitability of four hardwood species for construction applications, using the PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) method [84].

2.3 Limitations Regarding Challenges

An analysis of existing tools reveals significant gaps concerning the sustainability objectives. First, existing tools [78], [79], [80], [81], [82] lack a holistic perspective, focusing on economic and technical aspects while neglecting environmental sustainability and social impacts. Furthermore, none specifically addresses both softwood and hardwood species for Western European construction. Existing tools are typically designed for specific user groups or decision contexts and do not aim to support the diverse needs and priorities of multiple stakeholders across the forest-wood-construction value chain.

These gaps highlight the interest for a comprehensive wood selection tool for construction that integrates environmental, economic and social sustainability while ensuring technical performance with the intended applications. The tool aims to support multiple wood-construction stakeholders in developing strategies and selecting appropriate species aligned with their economic and environmental objectives. The tool enables sustainable wood to be selected by revealing its potential for use and its interest in construction, hence the abbreviation "*TUP4C*" for "Timber Utilisation Potential for Construction".

3. HOLISTIC APPROACH FOR SELECTING TIMBER SPECIES IN CONSTRUCTION

3.1 Approach Principle

The proposed holistic approach integrates multiple criteria based on the three pillars of sustainable development (social, economic and environmental) [85], [86], [87], supplemented by a fourth pillar for technical aspects. It structures decision-making by categorising influential factors.

From each of these four pillars, the proposed approach establishes three hierarchical levels of criteria (primary criteria, sub-criteria and indicators) which are illustrated in Figure 1 and will be discussed in the following sections. Each indicator is specified as either beneficial or non-beneficial, depending on whether higher or lower values are associated with better performance.

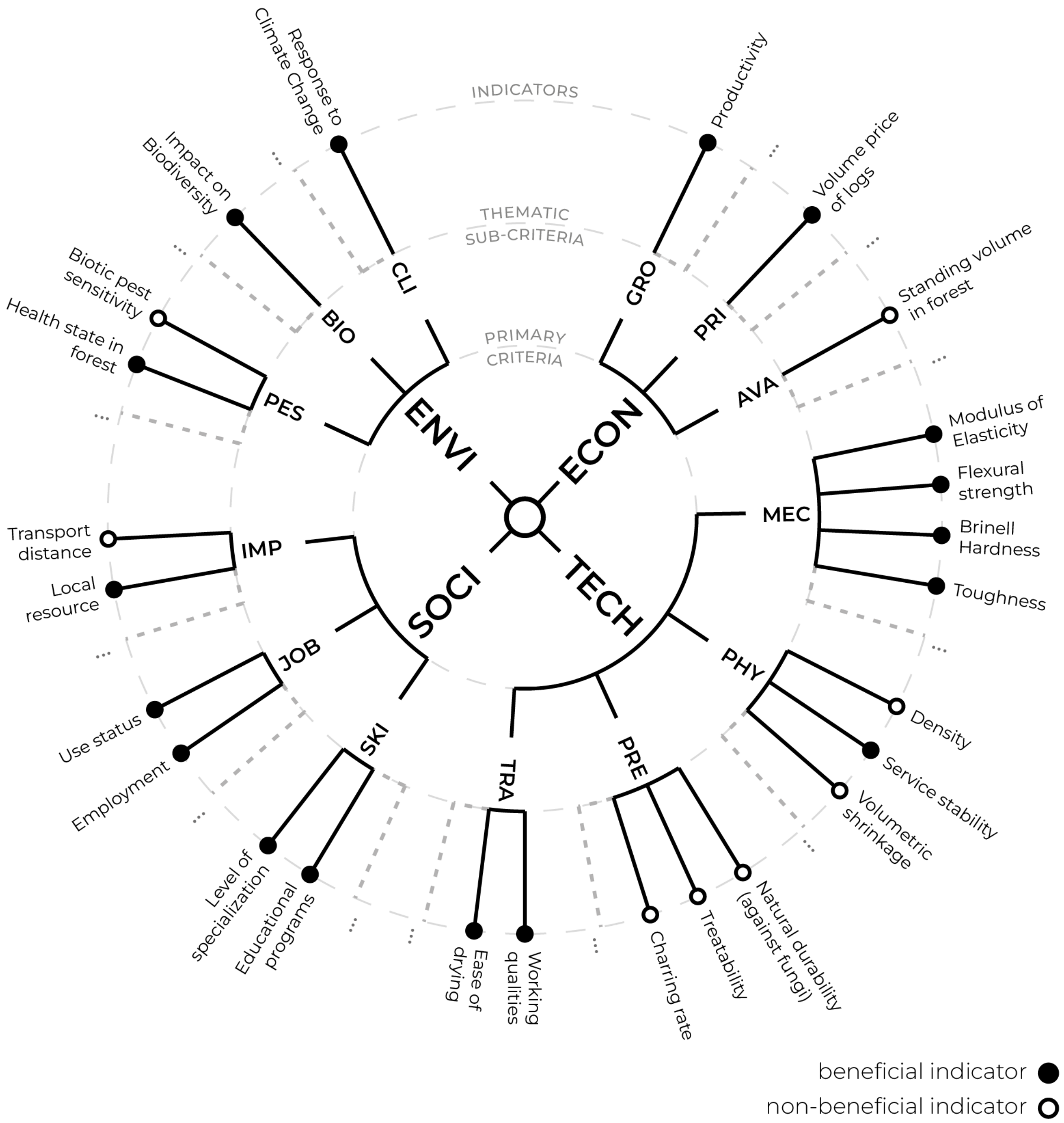


Figure 1 - Flowchart of primary criteria, their thematic sub-criteria, and associated indicators for a holistic view of the choice of wood species in the construction sector (beneficial indicator = to be maximised; non-beneficial indicator = to be minimised).

3.2 Technical Criterion (TECH)

This criterion assesses a wood species' ability to meet technical and functional construction requirements based on properties and intended applications [88], [89], [90]. It could be divided into four thematic sub-criteria:

- Mechanical (MEC): evaluates load-bearing capacity of the species.
- Physical (PHY): considers properties such as density, stability and moisture-related behaviour.
- Preservation (PRE): assesses the natural or acquired durability to biological degradation and the fire resistance behaviour.
- Transformation (TRA): examines the ease of processing, machining and drying characteristics.

Table 1 lists the indicators for each sub-thematic criterion.

TECH	INDICATOR	ID	UNIT	TYPE	DEFINITION	COMMENTS
MEC	Modulus of Elasticity *(MOE)*	i_1	[MPa]	B	Capacity to resist deformation.	*Mechanical properties are affected by factors like moisture content and defects such as knots and cracks. While most data in the literature come from small, clear wood specimens, defects in larger pieces can significantly impact species selection for construction* [66], [67], [68].
	Flexural strength *(f_m)*	i_2	[MPa]	B	Capacity to resist stress.	
	Hardness Brinell *(HBW)*	i_3	[MPa]	B	Capacity to resist penetration.	
	Toughness *(Th)*	i_4	[J/cm²]	B	Capacity to resist cracking under impact.	
PHY	Density *($\rho_{12\%}$)*	i_5	[kg/m³]	N-B	Generates higher loads and greater difficulty in handling.	*Physical properties are influenced by many factors. Service Stability depends on multiple interrelated factors such as shrinkage and porosity. Stability is typically classified from "Not stable" to "Very stable" in the literature, though the criteria for these classifications remain unclear* [91].
	Service Stability	i_6	[class]	B	Capacity to maintain dimensions throughout product lifecycle.	
	Volumetric shrinkage *($\beta_{V,tot}$)*	i_7	[%]	N-B	Volume variation based on moisture content.	
PRE	Natural durability against fungi *($DC_{heart,fungi}$)*	i_8	[class]	N-B	Resistance to fungal agents over time (EN 350 [92]).	*Other durability indicators like insect resistance* [92] *exist but were excluded due to limited differentiation among species. Durability classes should not be confused with use classes, which define exposure conditions without considering service life* [93].. *Charring rate is influenced by many factors such as density, moisture content, etc* [94].
	Treatability *($Treat._{sap.}$)*	i_9	[class]	N-B	Ease of penetration by treatment liquids during impregnation (EN 350 [92]).	
	Charring rate (*V*)	i_{10}	[mm/min]	N-B	Depth and speed that material burns on exposure to fire [95], [96].	
TRA	Working qualities *($W_{qual.}$)*	i_{11}	[class]	B	Capacity to be easily worked. Indicator based on gluing, machining, finishing and sawing properties [91], [97].	*In literature, workability and drying ease indicators are often evaluated qualitatively based on empirical knowledge, limiting the precision of data and the comparability between sources* [91], [98].
	Ease of drying *($E_{dry.}$)*	i_{12}	[class]	B	Capacity to be dried efficiently without defects. Indicator considers drying speed, cracking, deformation, collapse, or case-hardening [99].	

Table 1 - Sub-Thematic criteria and indicators for technical properties (TECH). B = Beneficial; N-B = Non-Beneficial.

3.3 Economic Criterion (ECON)

The economic criterion plays a crucial role in the selection of wood species for construction, as it directly affects profitability. It assesses the economic viability of species based on decision-makers' contexts and objectives. It could be divided into three thematic sub-criteria:

- Price (PRI): evaluates the market price of the species.
- Availability (AVA): assesses the supply consistency of the species.
- Growth and Productivity (GRO): considers the growth rate of the species.

The Table 2 lists the indicators for each sub-thematic criterion.

ECON	INDICATOR	ID	UNIT	TYPE	DEFINITION	COMMENTS
AVA	Standing volume in forest	i_{13}	[m³]	B	Estimation of the total volume of a species in forests.	*Available data covers common species. Estimates for rare species remain highly variable due to extrapolated inventory methods* [100], [101]. *Additionally, recording species by genus rather than individually reduces precision, as species within the same genus may have distinct mechanical and physical properties.*
PRI	Volume price of logs	i_{14}	[€/m³]	N-B	Commercial price of logs after forest cutting. Price varies according to the tree diameter.	*Price data for many wood species is unreliable, restricting analysis to commercially exploited species. Moreover, the price indicator reflects only post-harvest log costs, while actual expenses depend on processing needs, creating interdependencies with transformation indicators (*Technical Criterion *in 3.2) and economic value.*
GRO	Productivity	i_{15}	[m³ha⁻¹yr⁻¹]	B	Annual wood production per hectare for a given species.	*Productivity is influenced by stand composition, tree density, climatic and soil conditions and exploitation duration, making it difficult to determine precise values for each species.*

Table 2 - Sub-Thematic criteria and indicators for economic properties (ECON). B = Beneficial; N-B = Non-Beneficial.

3.4 Environmental Criterion (ENVI)

The environmental criterion evaluates the ecological impact of wood species, focusing on resilience to disturbances and contributions to forest health. It could be divided into four thematic sub-criteria:

- Resistance to Climate Change (CLI): assesses the adaptability of the species to changing climatic conditions.
- Biodiversity (BIO): evaluates the role of the species in maintaining ecosystem diversity.
- Biotic Pathogens (PES): examines the susceptibility of the species to pests and diseases.

The Table 3 lists the indicators for each sub-thematic criterion.

ENVI	INDICATOR	ID	UNIT	TYPE	DEFINITION	COMMENTS
CLI	Climate change resistance	i_{16}	[class]	B	Ability of species to withstand climate events (drought, heatwaves, temperature rise, late frost, root waterlogging, water deficit, etc.).	*Species responses to changing conditions remain unpredictable* [19]. *This indicator relies on qualitative assessments by silvicultural experts* [102], [103] *and is context-dependent (Western Europe).*
BIO	Impact on biodiversity	i_{17}	[pts]	B	Positive impact of the species on biodiversity. Indicator considers litter decomposition, ecological potential, root systems, species-specific associations and melliferous	*Traditional biodiversity indicators assess habitat suitability through forest structure rather than the direct impact of a species. The current expert-based indicator offers a simplified evaluation but does not fully capture complex species-environment interactions*

					characteristics. Invasive species negatively impact biodiversity [102], [103].	*or local context variations* [102], [103].
PES	Biotic pest sensitivity (insects, fungi)	i_{18}	[pts]	N-B	Susceptibility to known main pathogens (insects and fungi) based on their impact and frequency [102], [103], [104].	*Species health status is influenced by regional conditions, while globalisation and climate change introduce new threats, making long-term resilience predictions uncertain* [19].
	Health state in forest	i_{19}	[class]	B	Current health status of species in forests facing various pests [105].	

Table 3 - Sub-Thematic criteria and indicators for environmental properties (ENVI). B = Beneficial; N-B = Non-Beneficial.

3.5 Social Criterion (SOCI)

The social criterion assesses the impact of wood species selection on local communities, employment and local expertise [106], [107], [108], [109], [110], [111]. It could be divided into three thematic sub-criteria:

- Skill Development (SKI): evaluates how the use of a species promotes local expertise.
- Job Creation (JOB): measures the potential of a species to generate employment.
- Wood Origin (IMP): examines the geographical sourcing of wood.

The Table 4 lists the indicators for each sub-thematic criterion.

SOCI	INDICATOR	ID	UNIT	TYPE	DEFINITION	COMMENTS
SKI	Educational programs	i_{20}	[/]	B	Number of training courses or educational programs related to the species.	*Complex data to collect or do not exist at the wood species level. They also depend on regional policies or private sector initiatives and are linked to the final application produced.*
	Level of specialisation	i_{21}	[/]	B	Level of specialisation required to process the species (industrial or artisanal quality).	
JOB	Employment	i_{22}	[/]	N-B	Employment ratio created per m³ harvested/processed.	*Complex data to collect or do not exist at the wood species level. They are linked to the final application produced.*
	Use status	i_{23}	[/]	B	Number of local businesses using the species in question.	
IMP	Local resource	i_{24}	[%]	N-B	Percentage of wood sourced from local forests.	*Complex data to collect or do not exist at the wood species level. Import and export data for species are frequently aggregated with other forest products, complicating specific analyses in the construction sector* [112].
	Transport distance	i_{25}	[km]	N-B	Average distance between source and end users.	

Table 4 - Sub-Thematic criteria and indicators for social properties (SOCI). B = Beneficial; N-B = Non-Beneficial.

3.6 Key issues and limitations

3.6.1 Category of Products and Properties

Technical indicators (TECH) vary by construction product categories. For instance, exterior joinery requires good durability, while structural applications prioritise mechanical performance. Therefore, defining the product is an essential step in determining the indicators and their importance.

As wood is a natural and complex material, its technical properties often demonstrate significant correlations, such as density influencing mechanical strength [66]. Simultaneous inclusion of several strongly correlated indicators in an analysis can lead to overweighting certain characteristics and bias the species evaluation process for a specific application. To limit this risk, it is essential to restrict the number of selected indicators. However, some species exhibit unique property combinations that justify deeper analysis for specific applications.

3.6.2 Temporality of Strategies

Economic indicators (ECON) vary by temporality of strategies. Decision-makers can develop strategies adapted to different timeframes through indicator choice. In the short term, the price indicator allows quick identification of economically accessible and commercially available species. In the medium term, forest availability and productivity indicators highlight species with interesting economic potential, although factors such as logistical accessibility must also be considered. A long-term approach could include prospective scenarios considering climate change effects on species availability. Mauri & al. [113] has developed a dataset on the future distribution of European tree species which could be integrated into this approach.

3.6.3 Normative Requirements

Construction wood has to meet specific safety and performance standards. These requirements include, for instance, mechanical grading procedures that define strength classes [114]. Specific properties of wood species, such as knots, density, fibre inclination and geographical origin, can influence the grading of various species [115], [116]. These normative requirements were excluded from the study as they limit the study's scope by favouring established species while excluding underutilised or emerging alternatives.

3.6.4 Silvicultural and Environmental Interactions

Silvicultural practices play a crucial role in shaping wood characteristics, influencing yield, mechanical properties and resilience to climate change and pests [27], [117], [118]. Techniques such as selective thinning and pruning improve trunk straightness and reduce knot formation, enhancing overall wood quality [117].

Besides, the environmental relevance of a species is closely tied to its natural context. Isolating wood species from its ecosystem may overlook critical interactions with its environment. A species deemed beneficial according to the considered criteria could prove problematic in specific situations that had never been encountered before.

Despite their importance, methodological constraints hinder the inclusion of silvicultural and environmental factors. First, reliable data on species-specific silvicultural effects are lacking, making it difficult to establish explicit indicators for comparative analysis. Secondly, the complexity and uncertainty of species interactions necessitate cautious interpretation of results. The proposed approach, therefore, relies on currently available data and conventional forest management knowledge.

3.6.5 Social Considerations and Data Challenges

Social aspects are fundamental to sustainable resource management. However, their quantification presents significant challenges (cf. Table 4). Considering the importance of promoting local resources (cf. 1.2), a potential approach is to indirectly account social considerations by focusing on wood resources that are locally available. Future research should focus on developing robust and standardised metrics to accurately assess social impacts, enabling their integration into comprehensive decision-support frameworks.

4. PROPOSED METHOD AND DATA SOURCING

4.1 Method

4.1.1 Multi-criteria Approach

Multi-criteria evaluation was chosen to enable structured and objective decision-making. This approach calculates a global score for different alternatives based on multiple criteria. Alternatives are potential solutions to a multi-criteria problem. In this study, they correspond to wood species. Instead of identifying a single optimal choice, the method presents a top X species (e.g., a top 5) to provide a more nuanced perspective.

4.1.2 Evaluation Method: *TOPSIS*

The *TOPSIS* method (Technique for Order Preference by Similarity to Ideal Solution) [119] was selected for species evaluation due to its conceptual relevance and practical advantages. *TOPSIS* represents each alternative as points in n-dimensional space, where n corresponds to the number of considered indicators. Each point's coordinates correspond to criteria-specific characteristic values. The method identifies optimal alternatives by measuring their geometric proximity to an ideal solution (maximising beneficial indicators, minimising non-beneficial indicators) while maximising the distance from an anti-ideal solution. A single score is calculated for each alternative, enabling a ranking between the alternatives.

Besides the fact that *TOPSIS* is widely recognised [120], several factors support the choice of this method. Its simplicity and ease of interpretation ensure transparency for users. The ability to synthesise multiple criteria into a single score facilitates the communication of results. The method is flexible and easily applied to indicators of various natures (beneficial or non-beneficial) [121], [122], [123]. Unlike

ELECTRE [124] or *PROMETHEE* [84], it does not require predefined ranking thresholds, allowing for greater freedom in interpretation and preventing potentially relevant alternatives from being prematurely excluded.

The different steps of the *TOPSIS* method are detailed below.

The decision matrix is named X(1). Its dimensions $m \times n$ represent the number of alternatives (m) and the number of criteria (n). A is the set of alternatives and Q is the set of criteria. x_{ij} represents the performance of alternative A_i according to criterion Q_j with $i = 1, \dots, m$ and $j = 1, \dots, n$.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

The decision matrix is then normalised to ensure comparability between different criteria. R is the normalised matrix (2). A vector normalisation is used in (3).

$$R = (r_{ij})_{m \times n} \quad (2)$$

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}} \quad with \quad i = 1, \dots, m \quad et \quad j = 1, \dots, n \quad (3)$$

Each criterion has relative importance given by a weight defined using the *AHP* method (in 4.1.3). The weighted matrix is obtained by multiplying the normalised matrix by each criterion's weight. The weight vector is $W = (w_1, \dots, w_n)$ and must satisfy equation (4):

$$\sum_{j=1}^{n} w_j = 1 \quad (4)$$

The normalised and weighted matrix is R_W (5)&(6).

$$R_W = (r_{W,ij})_{m \times n} \quad (5)$$

$$r_{W,ij} = r_{ij} \cdot w_j \quad with \quad i = 1, \dots, m \quad et \quad j = 1, \dots, n \quad (6)$$

The ideal solution V^+ is determined using the maximum (beneficial) or minimum (non-beneficial) value for each criterion (7).

The anti-ideal solution V^- is defined by the minimum (beneficial) or maximum (non-beneficial) value for each criterion (8).

$$V^+ = \{v_1^+, \dots, v_n^+\} = \{\langle \min(r_{w,ij} \mid i = 1, \dots, m) \mid j \in J_-\rangle, \langle \max(r_{w,ij} \mid i = 1, \dots, m) \mid j \in J_+\rangle, \} \quad (7)$$

$$V^- = \{v_1^-, \dots, v_n^-\} = \{\langle \max(r_{w,ij} \mid i = 1, \dots, m) \mid j \in J_-\rangle, \langle \min(r_{w,ij} \mid i = 1, \dots, m) \mid j \in J_+\rangle, \} \quad (8)$$

$$J_+ = \{j = 1, \dots, n \mid j\} \; associated \; to \; beneficial \; criteria \quad (9)$$

$$J_- = \{j = 1, \dots, n \mid j\} \; associated \; to \; non-beneficial \; criteria \quad (10)$$

Euclidean distance is used to calculate the distance between each alternative and both the ideal V^+ and anti-ideal V^- solutions (11)&(12).

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \tag{11}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \tag{12}$$

The proximity score P_i^+, defined in (13), is between 0 and 1. If an alternative has a proximity score of 1, it means that the positive ideal is exactly defined by that alternative. Conversely, if the proximity score is 0, the negative ideal (anti-ideal) is exactly defined by that alternative.

$$P_i^+ = \frac{D_i^-}{D_i^+ + D_i^-} \tag{13}$$

Finally, alternatives are ranked in descending order to their final score. The alternative with the highest score is considered as the best solution.

4.1.3 Weighting Method: *AHP*

The *AHP* (Analytic Hierarchy Process) method is used to define weightings. This method is widely recognised for its clarity, accessibility, and suitability for structuring complex decision-making problems. *AHP* was chosen for its simplicity and transparency, which make it appropriate for a wide range of stakeholders [121]. It relies on pairwise comparisons of all indicators or criteria [123]. A value is assigned to each preference according to a scale from 1 (*Criterion A is equivalent to criterion B*) to 9 (*Criterion A is extremely more important than criterion B*). If the comparison is reversed, the value is also inverted. For example, when comparing criterion A which is *strongly more important than* criterion B with a preference value of 5, if comparing criterion B, which is *strongly less important than* criterion A, then the preference value is 1/5.

Once all possible comparisons between criteria or indicators have been made, the pairwise comparison matrix C is created (14). Its dimensions are $n \times n$, where n represents the number of criteria. The element c_{ij} is the preference value for the comparison between criterion Q_i and criterion Q_j, with $i = 1, \dots, n$ and $j = 1, \dots, n$.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix} \tag{14}$$

The matrix is then normalised (15). A linear normalisation process is used, dividing each criterion's preference values by the sum of those values (16).

$$C_N = (c_{N,ij})_{n \times n} \tag{15}$$

$$c_{N,ij} = \frac{c_{ij}}{\sum_{k=1}^{n} c_{kj}} \quad with \quad i = 1, \dots, n \quad et \quad j = 1, \dots, n \tag{16}$$

The weight vector $W = (w_1, \dots, w_n)$ is calculated based on the arithmetic mean of normalised values (17).

$$w_k = \frac{1}{n}\sum_{j=1}^{n} c_{N,kj} \quad with \quad k = 1, \dots, n \tag{17}$$

Finally, the consistency of obtained weights is verified using the consistency ratio CR (18). If $CR < 0{,}1$, the calculated weights are considered consistent.

$$CR = \frac{CI}{RI} \tag{18}$$

With CI being the consistency index (19) and RI a random index.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{19}$$

$$\lambda_{max} = \frac{1}{n}\sum_{k=1}^{n} \frac{\sum_{j=1}^{n} c_{W,kj}}{w_k} \tag{20}$$

The element $c_{W,ij}$ in (20) represents the values of the normalised and weighted matrix C_W (21)&(22).

$$C_W = (c_{W,ij})_{m\times n} \tag{21}$$

$$c_{W,ij} = c_{N,ij} \cdot w_j \quad with \quad i = 1, \dots, n \quad et \quad j = 1, \dots, n \tag{22}$$

The random index RI depends on the number of evaluated criteria n as shown in Table 5.

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

Table 5 - Average random index (RI) based on the number of evaluated criteria (n)

4.1.4 Strategical Profiles Personalisation

To allow the efficient usage of the *TUP4C* tool by diverse stakeholders in the forest-construction sector with regards to their own vision and needs, it is crucial to understand and model their specific profiles and priorities. To this end, our approach is based on three dimensions of personalisation. First, the user's vision is assessed regarding the four pillars (TECH, ECON, ENVI, SOCI). While industrial may prioritise the economic dimension, political actors might give greater importance to social or environmental aspects. Second, the type of targeted category product is considered, enabling project designers to identify the wood species that best meets the requirements for specific applications. Third, the decision-maker's temporal vision is taken into consideration, distinguishing between immediate solutions (short-term strategies) and planning for future projects or medium-term strategic adjustments. By allowing the setup of these three dimensions, our tool aims to accurately model the decision-makers needs and provide a flexible, context-sensitive decision support system.

4.1.5 Practical Implementation of the Tool and its Results

4.1.5.1 Preliminary Inputs

Users play a key role in shaping the *TUP4C* tool's outcomes. Their vision and priorities are reflected by the weightings assigned to primary criteria. Their selection of a product category influences the relative weightings of sub-criteria and indicators within the technical criterion. In the same way, the choice of a short- or medium-term strategy influences weightings of sub-criteria and economic indicators.

4.1.5.2 TUP4C *Tool Architecture*

The final score is based on the aggregation of the primary criteria scores (level 1) according to their importance to the user. Primary criteria scores are calculated based on the associated sub-criteria (level 2) and indicators (level 3). Sub-criteria group indicators into thematic categories for clarity. Indicators are quantitative and qualitative data used to assess wood species.

Figure 2 presents the global structure of the *TUP4C* tool and shows the overall structure of the tool while Figure 3 focuses on the definition of the score for primary criteria.

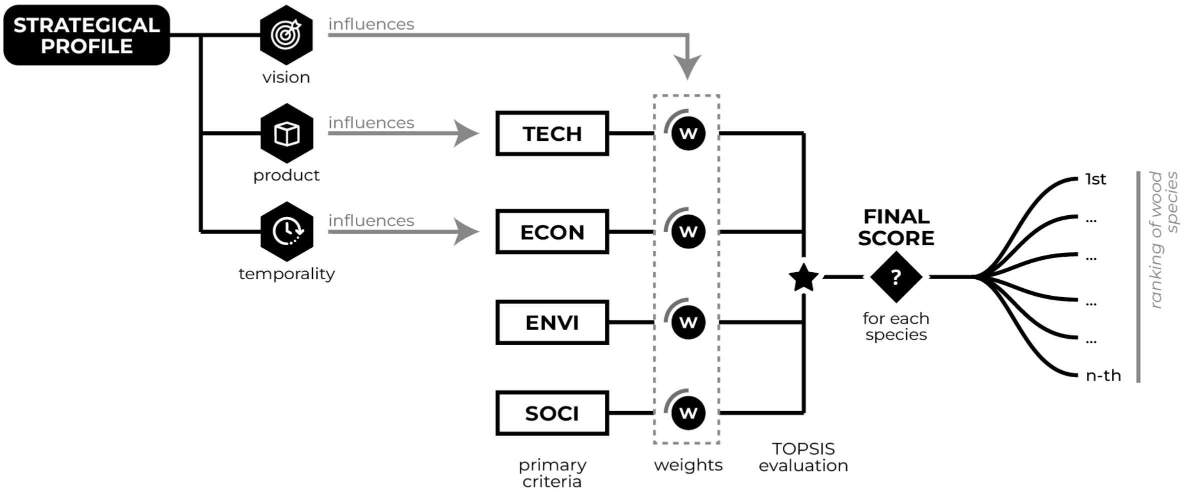


Figure 2 - Flowchart of the tool structure showing the effects of strategical profiles on final scores and wood species rankings. In this case, equivalent weights are assigned to each primary criterion (25%).

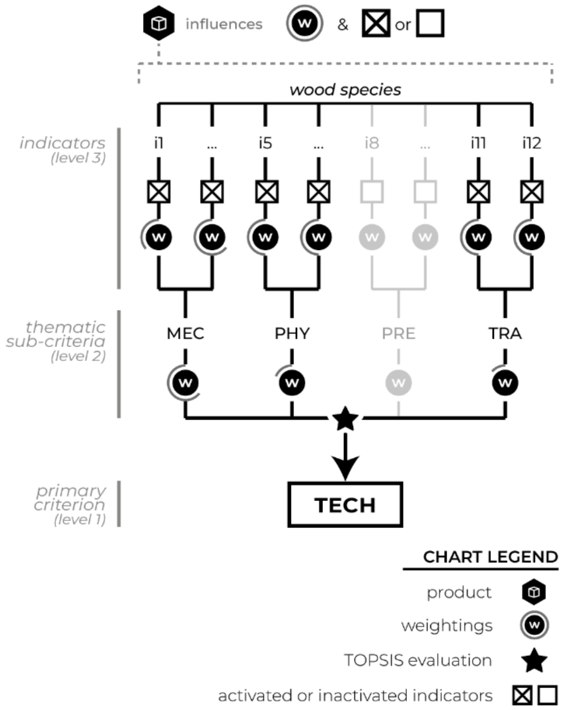


Figure 3 - Flowchart showing the hierarchy of criteria and indicators and the effects of the user's choice on the weighting and activation or non-activation of the criteria. In this case, the technical criterion (TECH), influenced by the product's choice, is shown.

4.1.5.3 Overall Ranking (Top X)

This result format identifies the most suitable species. This ranking focuses on the top X and is accompanied by detailed scores for each primary criterion.

4.1.5.4 Robustness Diagnostic

The robustness diagnostic enables a sensitivity analysis by evaluating the stability of species rankings under varying assumptions. To facilitate understanding and adoption by stakeholders in the forestry and construction sectors, three robustness indices were developed with a focus on interpretability. Each index yields a single value between 0 and 1, reflecting the frequency with which a species appears among the top X alternatives when weights and input data are arbitrarily varied. This approach helps estimate the reliability of the overall ranking and highlights species that are potentially sensitive to fluctuations in initial assumptions.

4.1.5.4.1 Robustness Index Based on Weightings:

Different scenarios of variation are applied to initial weights (before normalisation) and all possible combinations are studied (50% increase or 50% decrease). Note that in the case of many indicators, this analysis may favour species performing well in the most heavily weighted indicators. A large proportion of generated scenarios concerns small variations on indicators with low initial weight and these variations have a low impact on the final ranking.

4.1.5.4.2 Robustness Index Based on Input Data:

Different scenarios of input data, i.e., species characteristics for different indicators are created through *Monte Carlo* simulations (normal distribution). A coefficient of variation (COV) is defined for each indicator. The COV is based on ISO 3129 standard [125] or is equal to 20% if no data is available. Many simulations (min. 1000) are performed. Note that assuming normality can be problematic, as studies indicate that several wood properties follow a log-normal distribution instead [126]. Moreover, applying a uniform COV for all species has the effect of stabilising the final score of species with low mean values. Indeed, the variability of these characteristics is limited by a low initial mean value, which ultimately generates less variation in the final score for these species.

4.1.5.4.3 Robustness Index Based on Key Alternative Removal:

Different scenarios are created where key alternatives, defining positive or negative ideals in the *TOPSIS* method, are removed. Indeed, positive and negative ideals directly influence distance calculations and thus ranking. It calculates the proportion of times a species remains in the top X relative to scenarios where it is still eligible (i.e., not removed). Note that although this index is interesting from the perspective of *TOPSIS* method verification, it often has little relevance when numerous species are studied.

4.2 Data Sourcing

4.2.1 Wood Species Data Integration

Indicator values describing each wood species are sourced from scientific and technical literature. Quantitative indicators are used directly, while qualitative indicators require numerical transposition. Most follow a linear scale, but properties such as natural durability and treatability follow a non-linear approach to reflect real-world preferences. This ensures that species with moderate performance in both do not receive the same score as those excelling in one, as practical applications favour either high durability or easy treatability.

4.2.2 Use of Data from the Wood Literature

Literature values are typically reported as means, often without dispersion measures, whereas construction codes typically rely on characteristic values (e.g., 5th percentile) [127]. This discrepancy may overestimate the performance of species with high variability. In addition, many data originate from ideal laboratory samples, which do not reflect the properties of timber in terms of construction quality and size. As such, results based on these datasets should be interpreted as indicative rather than prescriptive, especially for structural uses.

4.3 Discussion on biases reduction

This section aims to identify potential sources of bias inherent in the method and data used in the *TUP4C* tool. The discussion is structured by type of bias, each addressed with mitigation methods applied in the study and supplemented with alternative solutions drawn from decision science literature [128].

4.3.1 Alternative Selection Biases

A key concern in multicriteria evaluation is the representativeness of the alternatives under analysis. In this study, two primary risks were identified: *(i) omitted variable bias*, resulting from the exclusion of lesser-known or underrepresented species [129], [130], and *(ii) data-related biases*, due to the unavailability or variability of data for certain species, which may limit the comprehensiveness and comparability of the analysis space [131].

To mitigate these risks, a contextual framing approach was adopted, restricting the scope to a well-defined geographical region where species identification is more exhaustive. Species with missing values were excluded via listwise deletion. Although this ensures methodological consistency, it reduces the coverage of potential alternatives. To assess the effect of data variability on results, a sensitivity analysis was performed using a robustness index, evaluating the stability of species rankings under input variations (cf. 4.1.5.5.2).

Additional methods could further address these biases, such as data imputation, provided the substituted values are validated through consistency checks or expert input [131].

4.3.2 Indicator Selection Biases

Bias may also arise from the choice of indicators, notably through the omission of key decision criteria or the inclusion of redundant, correlated indicators, which could distort the relative importance of certain properties [121], [129], [132], [133], [134].

To reduce such bias, an initial literature review guided the selection of indicators relevant to wood species evaluation in construction. Moreover, sensitivity analyses were conducted to identify and assess the collinearity among indicators.

Other techniques could enhance indicator selection, such as the use of a *Delphi* panel to iteratively validate indicator relevance through expert consensus [135], or applying dimensionality reduction methods, such as *Principal Component Analysis (PCA)* [136], to aggregate strongly correlated indicators into composite variables. Alternatively, the *CRITIC method* could be used to assign objective weights to indicators based on their variability and correlations, reducing redundancy in a data-driven way [137], [138].

4.3.3 Weighting Biases

The subjectivity inherent in expert-based weighting of indicators constitutes a critical source of bias. To address this, consistency ratio (CR) (cf.4.1.3) were calculated for all pairwise comparison matrices to ensure logical coherence in judgments [139]. In parallel, a sensitivity analysis was performed using a robustness index, evaluating the stability of species rankings under different weighting scenarios (cf. 4.1.5.5.1). Furthermore, *Shapley Value* analysis was employed to quantify the actual contribution of each indicator to the final *TOPSIS* scores and compare them with the initial *AHP* weightings [140], [141].

Alternative methods for reducing weighting bias include *Delphi*-based iterative expert consultations to achieve a stable consensus [135], as well as the application of inter-rater reliability metrics such as *Krippendorff's alpha*, *Cohen's kappa*, or the *Intraclass Correlation Coefficient (ICC)* to quantify agreement among experts [142].

4.3.4 Methodological Biases

The use of multicriteria methods such as *TOPSIS* and *AHP* may introduce structural biases due to their intrinsic assumptions and simplifications [121]. To limit such effects, the study prioritized transparent and interpretable methods, enabling critical review of the results. A sensitivity analysis was also performed using a robustness index to test the stability of rankings after the removal of key alternatives in the *TOPSIS* method (cf. 4.1.5.5.3). Cross-comparison with other published studies using distinct approaches further supported the reliability of outcomes.

Future work could incorporate methodological benchmarking, by applying alternative multicriteria decision methods (e.g., *PROMETHEE*, *ELECTRE*, *VIKOR*) to assess the consistency and convergence of rankings across models.

5. APPLICATION

5.1 Context and Objectives of Proposed Exploitation

This case study is presented for illustrative purposes to demonstrate the potential of the *TUP4C* tool and explore its usefulness for stakeholders in the forestry and construction sectors. It aims to demonstrate the method's ability to support species selection while providing initial insights based on current data.

Proposed exploitation focuses on the Walloon Region in Belgium, analysing locally produced or available species (cf. 4.3.1). The data (TECH, ENVI, ECON) reflect regional environmental, economic and silvicultural conditions. Social aspects (SOCI) are indirectly included by promoting local production, which reduces import dependency and supports the regional economy.

All input data correspond to 2024 (and earlier) and are compiled from scientific and technical literature. Given the evolving nature of forest management, markets, and environmental pressures, regular updates are recommended. The full dataset, including the species list, is detailed in Appendices B to E (cf. 7.2, 7.3, 7.4 and 7.5) and accessible through the following database: https://doi.org/10.5281/zenodo.15038880 [143]. Genus-level data were used where species-specific values were missing, especially for economic indicators.

Indicator weightings were defined arbitrarily by the research team, based on a review of relevant literature and their disciplinary expertise in timber structural mechanics and forestry. The methodology followed is detailed in Appendix A (cf. 7.1). As discussed in 4.3.3, these are preliminary and should ideally be refined through broader expert consultation.

5.2 Profiles as an Analytical Framework

The *TUP4C* methodology is designed to accommodate the diverse needs of stakeholders in the wood construction sector. To illustrate its versatility and provide a comprehensive understanding of its potential, two user profiles were developed. Each reflects distinct priorities and product applications, enabling different combinations of technical, economic, and environmental criteria. The first profile represents an industrial sawmill operator focused on short- to medium-term decision-making in a high-volume structural timber market. The second reflects a forest manager engaged in long-term planning to produce joinery-grade timber. This profile prioritises the selection of resilient species that can withstand climate change and enhance biodiversity, responding to more specific market demands. These profiles were selected for their representativeness and their capacity to illustrate the breadth of challenges in the wood construction industry—from industrial productivity to ecological resilience.

5.2.1 Profile 1 – Industrial Sawyer

This first profile focuses on technical aspects and profitability (50% TECH and 50% ECON). It represents a traditional sawmill manager specialising in processing softwood used in interior structural products. They seek to develop short and medium-term strategies regarding wood species to use.

Figure 4 shows the different weights attributed to each criterion and indicator. They were calculated using the *AHP* method (cf. 4.1.3) with simple hypotheses according to the methodology presented in Appendix A (cf. 7.1).

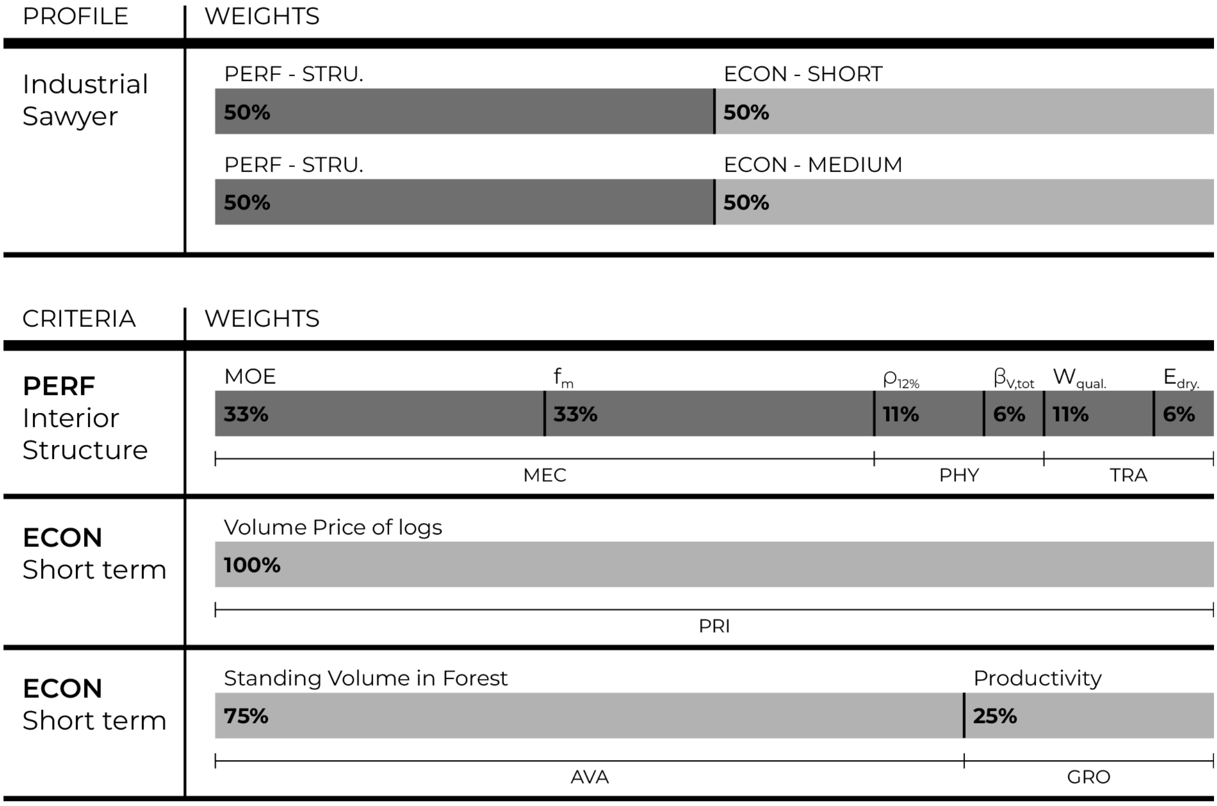


Figure 4 - Summary of the weightings assigned to the primary criteria, thematic sub-criteria and indicators according to user profiles (Industrial Sawyer), product categories (Interior Structure) end strategy timeframes (Short and Medium term).

5.2.1.1 Technical Criterion

The product category covered is interior structures (TECH - STRU). For these products, mechanical properties are essential. The strength and rigidity of the species must ensure the element's viability concerning ultimate or serviceability limit states [98]. It is also important to limit density, as it increases structural load and complicates handling. Volumetric shrinkage should also be minimised, as it directly impacts dimensional variations due to fluctuations in moisture content in the building. Finally, the wood used should have good workability and, whenever possible, be easy to dry.

5.2.1.2 Economic Criterion

Economic assessment considers short- and medium-term strategies (cf. 3.6.2.). The long-term strategy was not integrated into the *TUP4C* tool. This exclusion is based on the complexity such analysis implies, particularly due to the high number of necessary hypotheses and scenario creation considering factors such as future climate change impacts on construction market evolution, etc.

5.2.1.2.1 Short-term Strategy

It focuses exclusively on wood resource price. This choice is based on the hypothesis that price integrates immediate, even instantaneous, issues related to species availability and market pressure.

The retained price indicator is the price of a log with a circumference of 250 mm or more measured at 1.50m height.

5.2.1.2.2 Medium-term Strategy

It aims to evaluate wood species' economic interest through two factors, species availability in forest and productivity. Availability is defined as the volume of standing wood present in forest. Productivity is the volume of wood produced per hectare per year.

5.2.2 Profile 2 – Forest Manager

This second profile emphasises plantation diversification and cultivation of target trees for exterior joinery products. The manager uses the tool to select species adapted to end-user needs while ensuring their resilience to future environmental crises and positive contribution to biodiversity (50% TECH and 50% ENVI).

Figure 5 shows the different weights attributed to each criterion and indicator. They were calculated using the *AHP* method (cf. 4.1.3) with simple hypotheses according to the methodology presented in Appendix A (cf. 7.1).

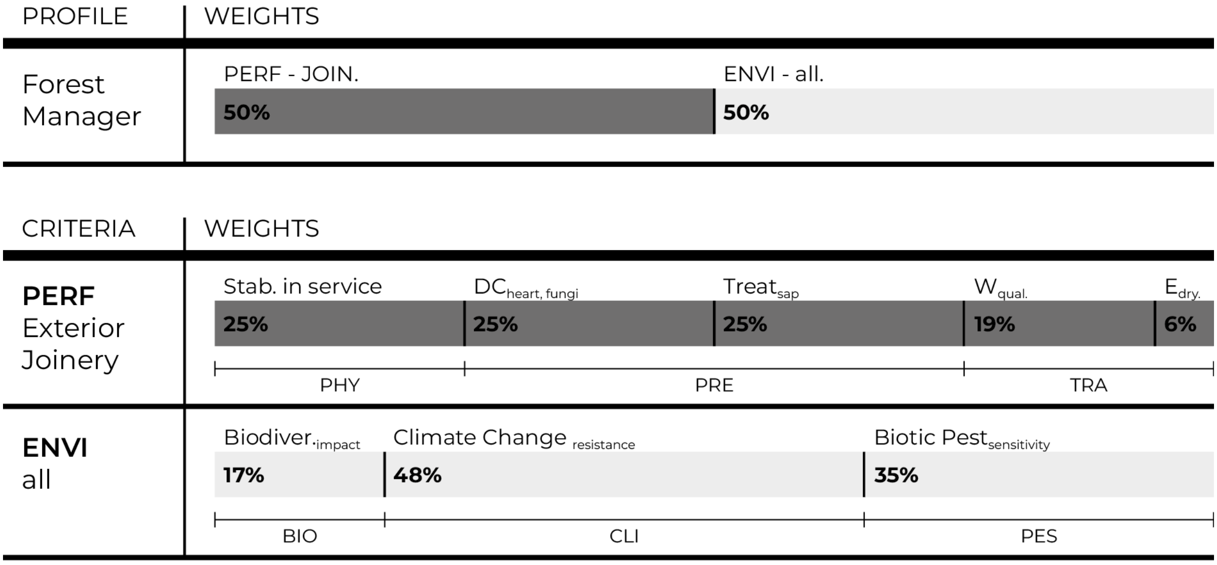


Figure 5 - Summary of the weightings assigned to the primary criteria, thematic sub-criteria and indicators according to user profiles (Forest Manager), product categories (Exterior Joinery) and for the environmental criterion (ENVI-all).

5.2.2.1 Technical criterion

The product category covered is exterior joinery (TECH - JOIN). These profiled products, exposed to weather, must present good durability (natural or acquired) and dimensional stability. The wood must also present good workability and proper drying ease [90], [98].

5.2.2.2 Environmental Criterion

The environmental criterion (ECON – all) remains constant across applications and timeframe strategy. It is based on three main indicators reflecting key ecological issues. The first indicator evaluates species resistance to climate change, a determining factor for their sustainability in the face of increasing environmental disturbances. The second indicator assesses susceptibility to biological pests. Finally, the third indicator measures the impact of species on biodiversity.

5.3 Results & Discussion

5.3.1 Profile 1 – Industrial Sawyer

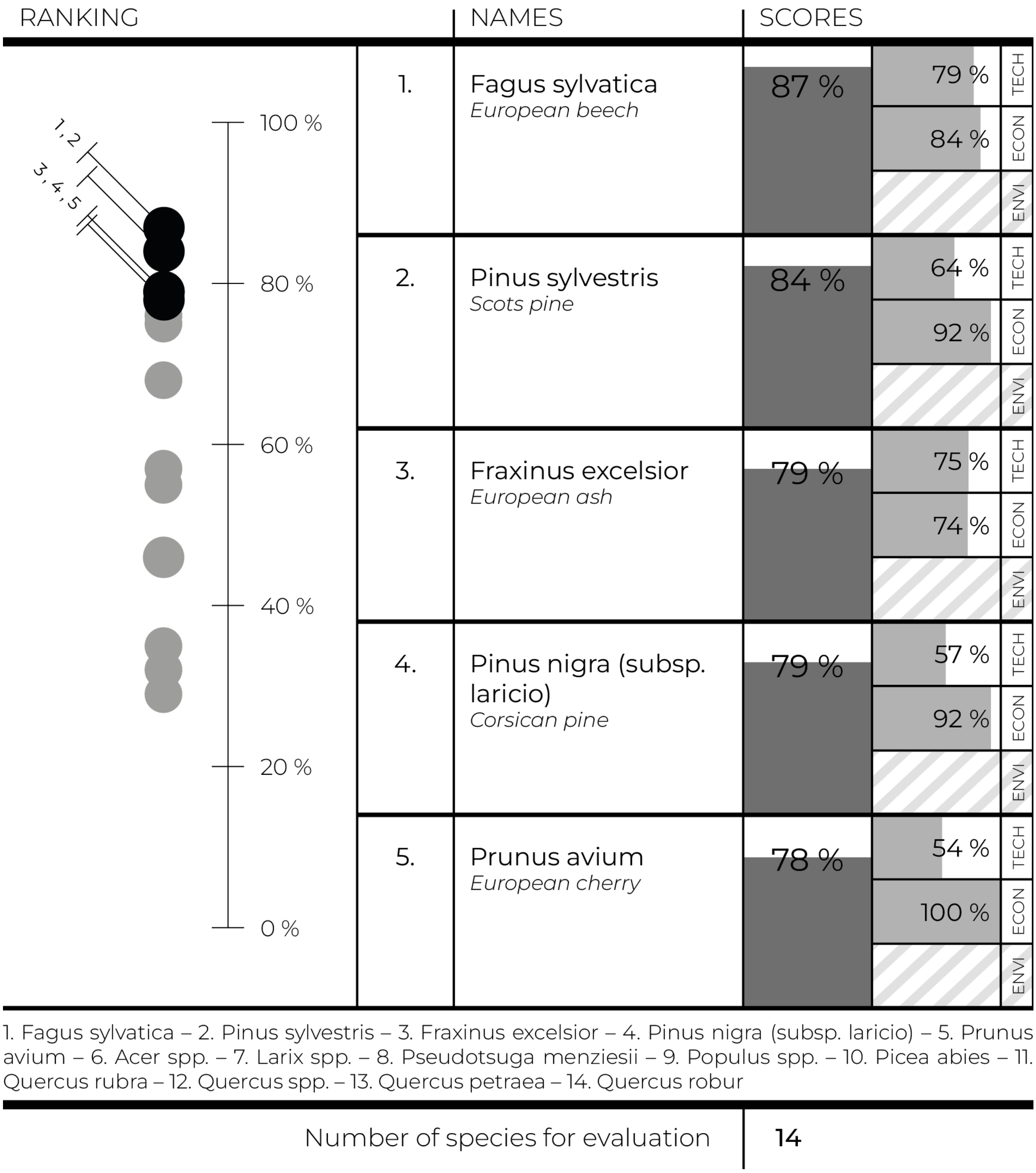
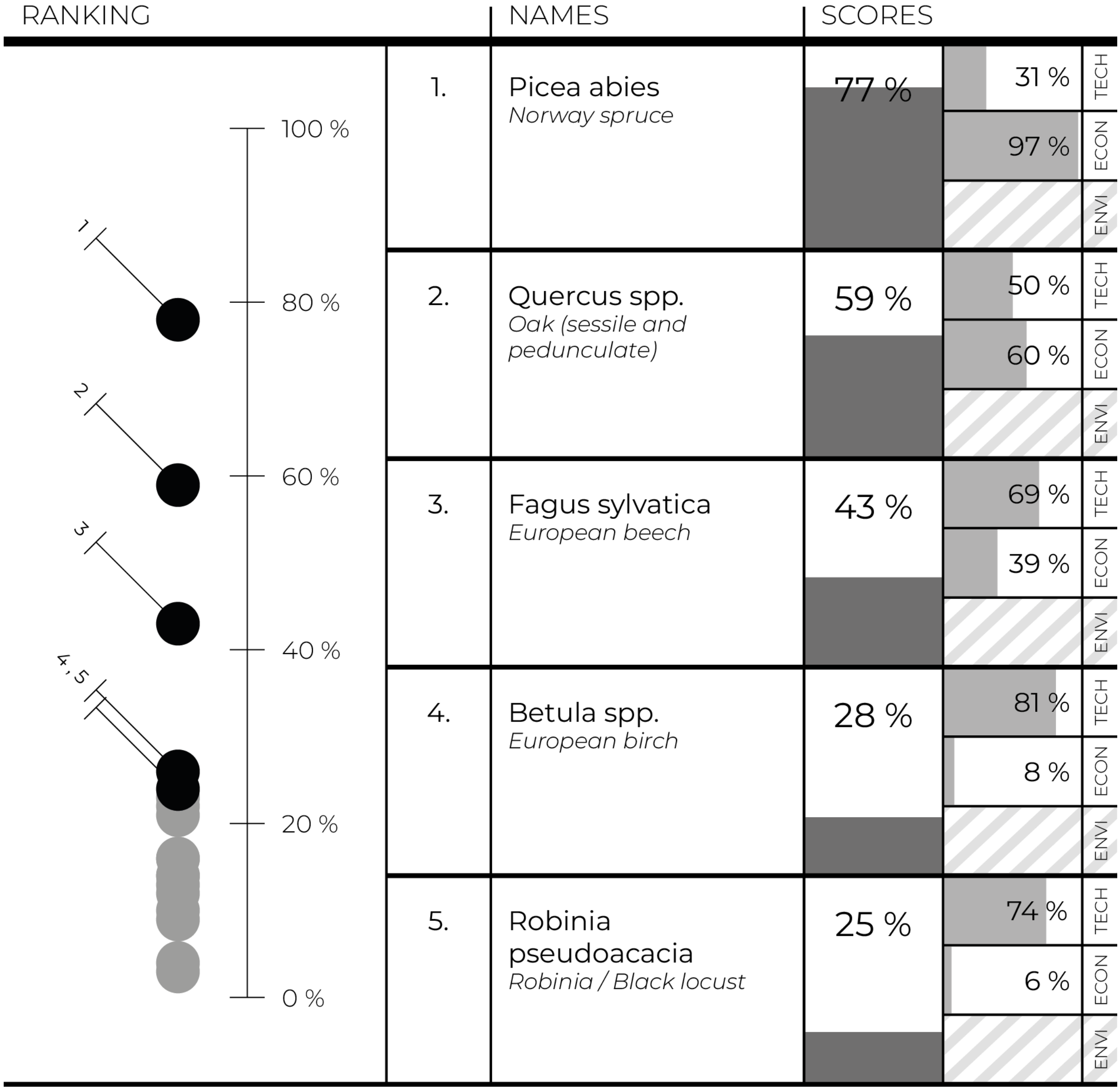


Figure 6 - Evaluation results for the profile of industrial sawyer (50% TECH and 50% ECON) with a short-term strategy for an interior structure product.



1. Picea abies – 2. Quercus spp. – 3. Fagus sylvatica – 4. Betula spp. – 5. Robinia pseudoacacia – 6. Carpinus betulus – 7. Pseudotsuga menziesii – 8. Fraxinus excelsior – 9. Quercus rubra – 10. Pinus sylvestris – 11. Acer spp. – 12. Larix spp. – 13. Pinus nigra (subsp. laricio) – 14. Prunus avium – 15. Alnus spp. – 16. Picea sitchensis – 17. Populus spp. – 18. Castanea sativa

Number of species for evaluation	18

Figure 7 - Evaluation results for the profile of an industrial sawyer (50% TECH and 50% ECON) with a medium-term strategy for an interior structure product.

The analysis for traditional sawyers producing interior structural timber reveals several key findings. Figure 6 presents the short-term results and Figure 7 the medium-term results. The result format provides the following information. The graph displays the position of wood species according to their overall score. Black dots indicate the scores of the species appearing in the top five. Next, the species name is given, followed by the overall score and the scores for each primary criterion. For example, in Figure 6, beech (*Fagus sylvatica*) ranks first with an overall score of 87%. Its score in the technical criterion is 79%, while the economic criterion score is 84%. As previously explained in 5.2.1, the environmental score is not considered for this profile.

In the short term, spruce (*Picea abies*), despite its dominant status in traditional sawmills, ranks only 10th due to low technical performance and high demand-driven cost. However, it leads medium-term rankings due to its exceptional availability in Walloon forests, reflecting an established silvicultural system producing user-adapted trees. Choosing to turn to other species raises questions regarding accessibility, tree quality, and other factors.

Hardwood species dominate both short- and medium-term rankings, suggesting benefits in diversifying sawmill production. In the short term, ash (*Fraxinus excelsior*) and beech (*Fagus sylvatica*) stand out for their excellent balance between technical performance and economic competitiveness. In the medium term, oak (*Quercus spp.*) and beech show favourable positioning due to high availability and moderate technical and economic scores. Emerging species like birch (*Betula spp.*) and black locust (*Robinia pseudoacacia*) demonstrate high technical performance despite lower availability.

For sawmills unable to diversify towards hardwoods, Scots pine (*Pinus sylvestris*) and Corsican pine (*Pinus nigra subsp. laricio*) offer better technical performance and price competitiveness than spruce.

Score graph analysis reveals additional insights. In the short-term, a competitive group including maple (*Acer spp.*), larch (*Larix spp.*) and Douglas fir (P*seudotsuga menziesii*) shows comparable scores to the top-ranked 5 species. In the medium-term, the economic factor becomes dominant, with spruce leading due to its availability. Secondary contenders with strong technical performance include hornbeam (*Carpinus betulus*), Douglas fir and ash.

5.3.2 Profile 2 – Forest Manager

For forest managers aiming to diversify species for exterior joinery, the results are presented in Figure 8. Black locust (*Robinia pseudoacacia*) and Atlas cedar (*Cedrus atlantica*) stand out for their strong technical and environmental properties. However, black locust, despite its resilience to climate change and pests, may be considered as invasive [144], requiring careful management.

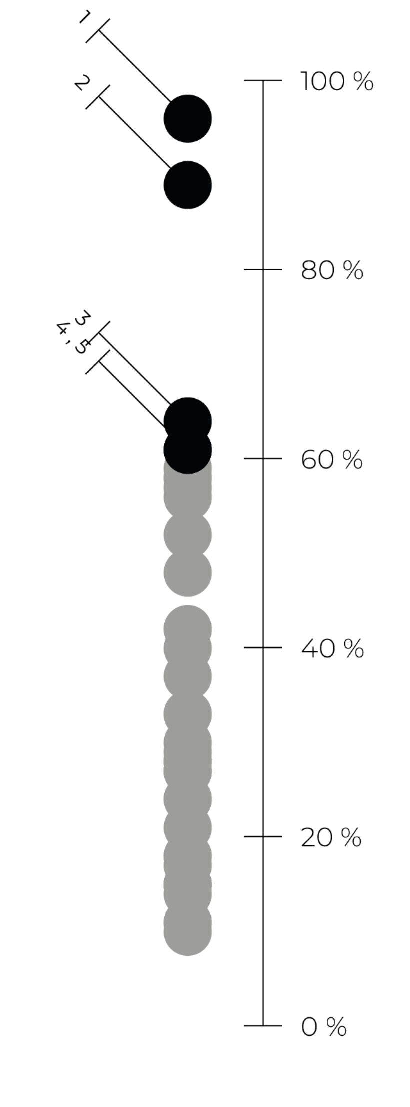
Sweet chestnut (*Castanea sativa*), yew (*Taxus baccata*) and small-leaved lime (*Tilia cordata*) ranked next, offering balanced technical and environmental performance. Yew's excellent properties are notable, though its toxicity demands specific processing precautions.

The analysis of the score chart also highlights other species with comparable scores. It includes lime (*Tilia spp.*, *Tilia platyphyllos*), black walnut (*Juglans nigra*), alder (*Alnus spp.*, *Alnus glutinosa*), hornbeam (*Carpinus betulus*) and Norway maple (*Acer platanoides*).

Technical performance scores are moderate, rarely exceeding 50%. This stems from the *TOPSIS* evaluation method and use of indicators such as natural durability and treatability. The ideal theoretical, highly durable and easy to treat doesn't exist in natural state. The best alternative cannot therefore achieve a score of 100%. The recalibrated 65% maximum in the combined technical-environmental assessment significantly influenced rankings, as demonstrated by the yew's favourable position despite lower environmental scores.

Comparing both profiles, the industrial sawyer evaluates fewer species than the forest manager, due to limited economic data on lesser-known species. Strengthening silvicultural research on availability, resource quality, tree maturity and accessibility are crucial for informed diversification strategies. The emergence of lesser-known species in Profile 2 confirms their potential value.

RANKING	NAMES	SCORES	TECH	ENVI	ECON
1.	Robinia pseudoacacia *Robinia / Black locust*	96 %	63 %	89 %	
2.	Cedrus atlantica *Atlas cedar*	89 %	65 %	73 %	
3.	Castanea sativa *Sweet chestnut*	64 %	41 %	85 %	
4.	Taxus baccata *Yew*	61 %	42 %	66 %	
5.	Tilia cordata *Small-leaved lime*	61 %	39 %	86 %	



1. Robinia pseudoacacia – 2. Cedrus atlantica – 3. Castanea sativa – 4. Taxus baccata – 5. Tilia cordata – 5. Tilia platyphyllos – 5. Tilia spp. – 6. Juglans nigra – 7. Alnus glutinosa – 7. Alnus spp. – 8. Carpinus betulus – 9. Acer platanoides – 10. Thuja plicata – 11. Fagus sylvatica – 12. Betula pendula – 12. Betula spp. – 13. Betula pubescens – 14. Acer spp. – 15. Acer pseudoplatanus – 16. Prunus avium – 17. Quercus petraea – 18. Larix spp. – 19. Larix decidua – 20. Quercus robur – 21. Salix alba – 22. Ulmus minor – 23. Ulmus spp. – 24. Juglans regia – 24. Juglans spp. – 25. Fraxinus excelsior – 26. Pseudotsuga menziesii – 27. Tsuga heterophylla – 28. Populus spp. – 29. Populus nigra – 30. Abies alba – 31. Picea sitchensis – 32. Picea abies – 33. Picea spp. – 34. Abies spp. – 35. Quercus rubra – 36. Quercus spp. – 37. Pinus spp. – 38. Pinus nigra (subsp. laricio) – 39. Pinus sylvestris

Number of species for evaluation	44

Figure 8 - Evaluation results for the profile of forest manager (50% TECH and 50% ENVI) for an exterior joinery product.

5.3.3 Key Findings from Analysis

The proposed application of the tool to Walloon forests reveals distinct priorities between industrial actors and forest managers. For the industrial sawyer profile, species such as spruce (*Picea abies*) ranked highly due to their strong market alignment and exceptional availability, despite lower technical performance. Other species like ash (*Fraxinus excelsior*), beech (*Fagus sylvatica*), and Scots pine (*Pinus sylvestris*) also emerged as viable alternatives. For the forest manager profile, the rankings emphasised species such as black locust (Robinia pseudoacacia) and Atlas cedar (Cedrus atlantica), which combine technical suitability with environmental benefits for specific uses such as exterior joinery.

Across both profiles, the emergence of lesser-known species highlights opportunities for diversification and adaptation to future challenges. However, this potential remains limited by data gaps. Enhancing silvicultural research and improving data availability for these underutilised species is essential to support more robust selection strategies and foster a resilient, diversified forest-wood value chain.

5.3.4 In-depth Analysis

The objective of this section is to present more advanced analytical approaches that serve two main purposes. First, to address potential methodological biases discussed in Section 4.3. Second, to provide a deeper understanding of the *TUP4C* results and to uncover additional insights that are not immediately apparent through standard result interpretation. Four complementary analyses are proposed:

- A comparison of results obtained from the profiles.
- A detailed examination of robustness indices.
- An investigation of feature importance through *Shapley Values* and indicator correlations.
- A statistical comparison of species scores across categorical groups (hardwoods vs. softwoods).

5.3.4.1 Profiles Comparison

To assess whether distinct profiles yield to different results, the *TUP4C* method was applied to a reduced set of species with complete data across both profiles. Rankings were compared using *Spearman's correlation*. As shown in Figure 9, the scatterplot displays no correlation ($Spearman's\ \rho = -0{,}05056$; $p\ value = 0{,}84$), indicating no significant relationship between rankings. This supports the relevance of defining separate profiles to capture varying stakeholder priorities.

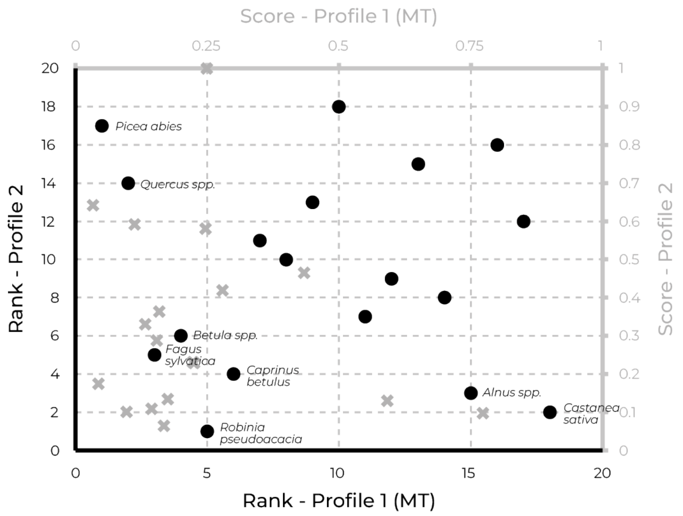


Figure 9 - Scatter plot comparing species rankings and scores between profile 1 (medium term) and profile 2. Each point represents a species. The primary axes indicate the rankings and the secondary axes the scores. Species in the top five of either profile are highlighted by name.

5.3.4.2 Robustness indices

RANK	NAMES	$ROB_{Weights}$	ROB_{Data}	$ROB_{Alt. deleted}$
1.	Betula spp. *European birch*	100 %	58 %	100 %
2.	Betula pendula *European white birch*	94 %	55 %	100 %
3.	Carya tomentosa *Mockernut hickory*	76 %	52 %	100 %
4.	Carpinus betulus *European hornbeam*	66 %	52 %	100 %
5.	Robinia pseudoacacia *Robinia / Black locust*	41 %	37 %	100 %
6.	Carya spp. *Hickory*	42 %	47 %	36 %
7.	Fagus sylvatica *European beech*	29 %	38 %	0 %
8.	Juglans regia *European walnut*	33 %	28 %	0 %
9.	Fraxinus excelsior *European ash*	0 %	19 %	0 %
10.	Juglans spp. *Walnut*	8 %	16 %	0 %

1. Betula spp. – 2. Betula pendula – 3. Carya tomentosa – 4. Carpinus betulus – 5. Robinia pseudoacacia – 6. Carya spp. – 7. Fagus sylvatica – 8. Juglans regia – 9. Fraxinus excelsior – 10. Juglans spp. – 11. Betula pubescens – 12. Sorbus aucuparia – 13. Sorbus spp. – 14. Quercus rubra – 15. Acer platanoides – 16. Sorbus torminalis – 17. Quercus petraea – 18. Pinus sylvestris – 19. Juglans nigra – 20. Quercus spp. – 21. Larix decidua – 22. Taxus baccata – 23. Acer spp. – 24. Larix spp. – 25. Quercus robur – 26. Pseudotsuga menziesii – 27. Acer pseudoplatanus – 28. Pinus nigra (subsp. laricio) – 29. Pinus palustris – 30. Prunus avium – 31. Alnus spp. – 32. Alnus glutinosa – 33. Tilia platyphyllos – 34. Tilia cordata – 35. Platanus x hispanica – 36. Tilia spp. – 37. Pinus spp. – 38. Pinus radiata – 39. Abies alba – 40. Abies spp. – 41. Tsuga heterophylla – 42. Cedrus atlantica – 43. Liriodendron tulipifera – 44. Picea spp. – 45. Picea abies – 46. Picea sitchensis – 47. Platanus occidentalis – 48. Platanus spp. – 49. Pyrus communis – 50. Ulmus spp. – 51. Pinus strobus – 52. Abies grandis – 53. Ulmus minor – 54. Pinus pinaster – 55. Castanea sativa – 56. Populus tremula – 57. Pinus cembra – 58. Populus spp. – 59. Thuja plicata – 60. Populus nigra – 61. Sequoia sempervirens – 62. Salix alba – 63. Aesculus hippocastanum

Number of species for evaluation	**63**

Figure 10 – Ranking and robustness indices as part of an exclusive evaluation of the primary technical criterion for an interior structure product.

Robustness indices were employed to critically evaluate the *TUP4C* tool's results and verify the coherence of identified species of interest. Figure 9 presents the top ten species and their technical performance scores, alongside three robustness indices related to:

1. **Weighting Sensitivity:** The first index evaluated species stability in the top 5 under modified indicator weightings. Birch (*Betula pendula*, *Betula spp.*) demonstrated exceptional stability, maintaining top 5 placement in over 90% of the weighting scenarios, indicating balanced cross-criteria technical performance. In contrast, black locust (*Robinia pseudoacacia*) showed lower stability at 40%, suggesting its ranking heavily depends on specific criterion weightings.

2. **Input Data Variability**: This index, examining input data variations reflecting natural wood characteristics, revealed multiple species could achieve top 5 ranking with over 15% occurrence. Black locust again showed less stability compared to others like hickory (*Carya spp.*), ranked sixth. This can be explained by its higher mean values leading to increased dispersion.
3. **Key Species Removal**: This index, analysing ranking changes after key species removal, confirmed the stability of top 5 rankings and highlighted hickory's potential significance in this scenario.

5.3.4.3 Shapley Value and Indicator Correlations

This analysis aims to assess the effective contribution of each indicator on the *TOPSIS* score and evaluate its consistency with the predefined weighting scheme. *Shapley Values*, computed from a linear regression model using the *TOPSIS* scores as target variables, were employed to estimate each indicator's marginal contribution. While the linear model assumes additive relationships—unlike the geometric nature of *TOPSIS*—it provides interpretable approximations of the direction and magnitude of each feature's influence. This analysis was conducted for the technical criterion only, but the approach is replicable across all primary criteria.

The summary plot highlights bending strength and modulus of elasticity as the most impactful variables, followed by working properties and volumetric shrinkage. Density and drying ease contribute less. Negative Shapley values for non-beneficial indicators (e.g., high density or shrinkage) confirm alignment with the methodological intent.

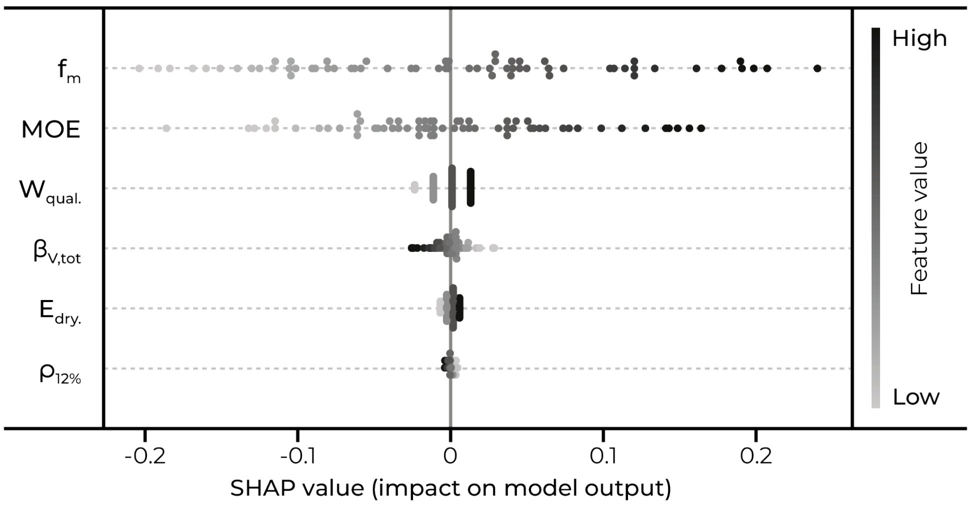


Figure 11 - SHAP Summary Plot: Influence of each feature on the final TUP4C score for the technical criterion (TECH). A linear regression model was used to approximate the TOPSIS score based on input indicators (Score ≈ 3.86E-05 · MOE + 5.16E-03 · fm – 2.10E-05 · $\rho_{12\%}$ – 4.77E-03 · $\beta_{v,tot}$ + 8.43E-03 · E_{dry} + 2.45E-02 · $W_{qual.}$). Points represent species; colour indicates feature value. Features are ordered by average absolute SHAP value (fm = 0.092, MOE = 0.060, $W_{qual.}$ = 0.009, $\beta_{v,tot}$ = 0.008, $E_{dry.}$ = 0.003, $\rho_{12\%}$ = 0.002).

However, a heatmap reveals strong correlations among several indicators (particularly density, strength, stiffness, and shrinkage) suggesting potential redundancy and overemphasis of some features. These interactions may also explain inconsistent results observed with tree-based models, such as misleading positive effects for high shrinkage correlated with high flexural strength.

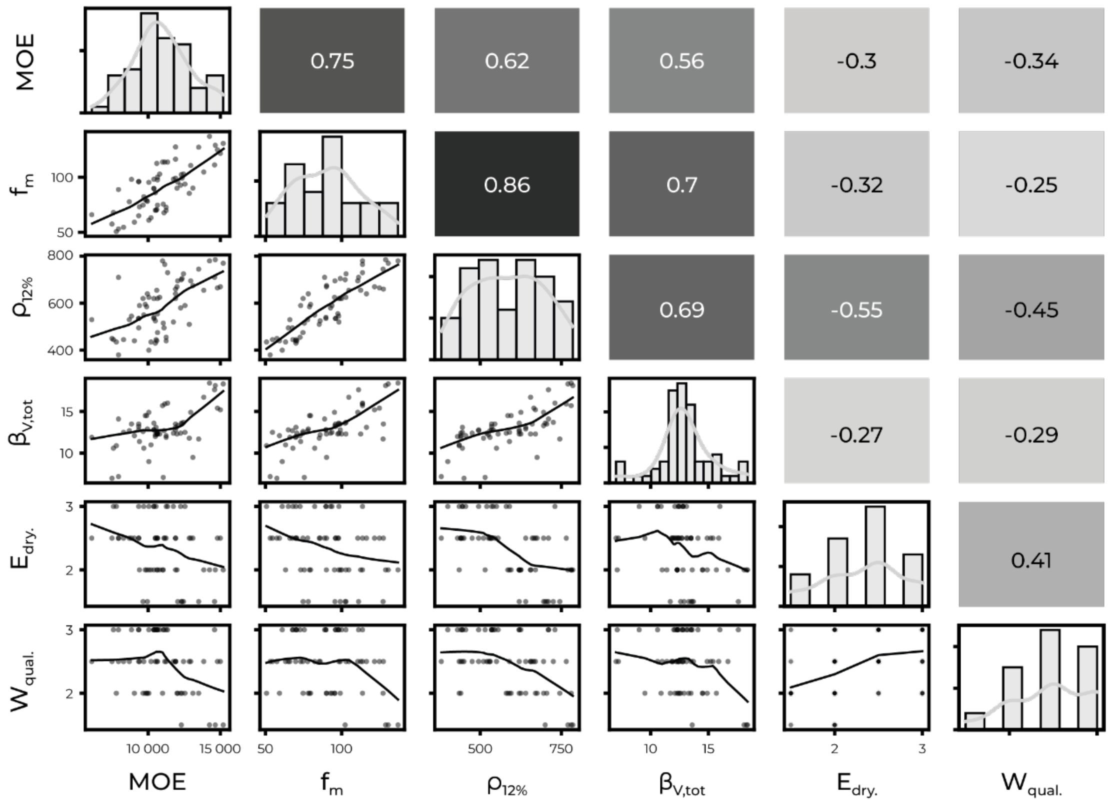


Figure 12 - Scatterplot matrix with Pearson's correlation coefficients for all indicators used in TUP4C analysis for the technical criterion. Units: MOE [MPa]; f_m [MPa]; $\rho_{12\%}$ [kg/m³]; $\beta_{v,tot}$ [%]; $E_{dry.}$ [class]; $W_{qual.}$ [class].

5.3.4.4 Score Comparison between Hardwoods and Softwoods

A comparative analysis was conducted to assess whether species type (hardwood vs. softwood) significantly affects technical scores. Normality was confirmed via the Shapiro-Wilk test, while Levene's test indicated unequal variances. Consequently, Welch's t-test was used. Results in Table 6 show that hardwoods have significantly higher mean scores than softwoods, which display lower variability. This suggests that the current indicator selection and weighting in the *TUP4C* framework tend to favour hardwood species.

TYPE	SCORES				SHAPIRO WILK (α = 0.05)		LEVENE (α = 0.05)		WELCH (α = 0.05)	
	n	Mean	SD	CV	Stat W	p-value	Stat L	p-value	Stat We	p-value
Hardwood	41	0.532	0.176	33.1%	0.964	0.211	6.346	0.014	2.914	0.005
Softwood	22	0.427	0.107	25.2%	0.942	0.221				

Table 6 - Descriptive statistics, normality test (Shapiro Wilk), variance homogeneity test (Levene) and unequal variance t-test (Welch) on scores by species type (α = 0.05).

5.3.5 Comparison with Previous Studies

This section compares the methodology and results of the *TUP4C* tool with two previous studies that share similarities in terms of species considered and evaluation criteria (cf.2.2).

5.3.5.1 Study 1 – Šuhajdová et al. [83]:

This study evaluates the suitability of four hardwood species for construction applications in the Czech Republic: European beech (*Fagus sylvatica*), common oak (*Quercus robur*), Norway maple (*Acer platanoides*), and common hornbeam (*Carpinus betulus*). The ranking order is as follows: 1st – beech, 2nd – oak, 3rd – maple, and 4th – hornbeam. These species were selected based on their local abundance. The assessment is based on eight indicators grouped into three thematic criteria:

- Mechanical properties: bending strength (12.6%), modulus of elasticity (12.6%), and compression strength (6.3%).
- Physical properties: density (3.8%), shrinkage (15%), and workability (7.5%).
- Price: knot occurrence, grain straightness (7%), and forest area expansion (35%).

These indicators and their weightings are comparable to those used in Profile 1 of *TUP4C*. Except for Norway maple (excluded from *TUP4C* due to insufficient data), all species appear in the *TUP4C* top 10 ranking. Notably, oak ranks higher than beech in *TUP4C*, which can be explained by the higher regional availability of oak in Wallonia. Hornbeam, which Šuhajdová ranks lowest due to its poor workability and high knot occurrence, is rated more favourably by *TUP4C* due to its strong mechanical performance. This highlights the importance of interpreting results with caution when criteria diverge.

5.3.5.2 Study 2 – Özşahin et al. [81]

This study assesses the suitability of softwood species for structural and non-structural exterior applications. The species evaluated and their rankings are provided in Table 7.

SPECIES	RANKING Structural Construction (S)	RANKING Non-Structural Construction (NS)
Douglas fir (*Pseudotsuga menziesii*)	3	3
Lodgepole pine (*Pinus concorta*)	5	4
Red pine (*Pinus resinosa*)	4	6
Redwood (*Sequoia sempervirens*)	2	1
Engelmann spruce (*Picea engelmannii*)	7	7
Eastern hemlock (*Tsuga canadensis*)	6	8
Western larch (*Larix occidentalis*)	1	2
Western red cedar (*Thuja plicata*)	8	5
	Number of species	**8**

Table 7 - S. Özşahin et al. (2019) - Results of the analysis for the selection of softwood species for structural and non-structural timber construction.

The method considers 15 indicators grouped into five thematic categories with distinct weightings for structural and non-structural applications.

- Economic values: purchasing cost, paintability.
- Physical properties: dimensional change, density.
- Mechanical properties: modulus of rupture, modulus of elasticity, compression strength perpendicular to grain, compression strength parallel to grain, impact bending strength, work to maximum load in bending, shear strength parallel to grain.
- Thermal properties: thermal conductivity, flame spread.
- Durability properties: decay resistance, impregnability.

Direct comparison with *TUP4C* is limited due to differences in criteria and weightings. Nonetheless, both studies identify *Larix spp.* (Western larch and European larch) and *Pseudotsuga menziesii* (Douglas fir) among the top softwood candidates across profiles.

An interesting secondary observation concerns *Thuja plicata* (Western red cedar), which ranks fifth in Özşahin's study but is one of the few softwood species to appear in the top 10 of *TUP4C*'s Profile 2 (non-structural). The discrepancy in rankings can likely be attributed to the inclusion of purchasing cost in Özşahin's evaluation, where *Thuja plicata* performed particularly poorly.

A notable feature of Özşahin's method is the inclusion of a large number of indicators, many of which are assigned relatively low weights (around 5%). This approach raises questions about potential redundancy resulting from correlations between indicators. Further analysis of this aspect could provide valuable insights into the robustness and efficiency of such multi-criteria evaluation frameworks.

5.3.5.3 Key Differences and Contributions of TUP4C

Compared to these studies, *TUP4C* introduces several differences:

- Inclusion of an environmental criterion, absent in the two other studies.
- Consideration of a broader range of species, including both hardwoods and softwoods.
- Adaptability of the tool to various user objectives and regional contexts through profile-based evaluations.

6. CONCLUSION

This study presents a decision-support tool designed to assist in the selection of wood species suitable for construction applications (*TUP4C* - Timber Utilisation Potential for Construction). Unlike many existing material selection tools that are primarily focused on industrial or economic performance, the proposed tool relies on the holistic integration of economic, environmental and technical performance dimensions.

TUP4C was designed to reflect the diverse priorities of stakeholders throughout the forest-wood-construction value chain. It offers an accessible and transparent structure, employing a multi-criteria methodology with modifiable indicators and weightings. To enhance usability across professional profiles, the tool produces intuitive outputs, such as aggregated scores, ranking visualisations, and robustness indices, facilitating interpretation and communication of results.

However, several limitations must be acknowledged. First, the validity of rankings depends heavily on data availability and quality, particularly for lesser-known or emerging species. Second, finding the appropriate balance in the number and nature of indicators is a persistent challenge: too many indicators can generate redundancy and obscure key trade-offs, while too few risks oversimplifying the decision space. Third, the simplified weighting system, while promoting clarity and flexibility, may oversimplify the complexity of decision-making contexts involving multiple stakeholders.

A preliminary application in the Walloon region highlighted the tool's capacity to reveal strategic trade-offs and to identify underutilised but promising species, supporting the broader goal of forest resource diversification. Yet, due to the above-mentioned limitations, the tool should be interpreted as a support for exploration and stakeholder dialogue, not as a deterministic or prescriptive solution.

Looking ahead, several research directions could help strengthen both the tool and the broader field of wood species selection for construction. These include:

- Integrating dynamic features to account for changing market conditions, climate scenarios, and forest ecosystem responses, including long-term projections of price, availability, and suitability.
- Establishing transparent rating systems for data quality and source reliability.

- Expanding the scope of analysis beyond single-species approaches to include forest stand typologies or mixed-species dynamics, better reflecting ecosystem realities.
- Further developing social and territorial indicators, such as employment generation or regional economic impact, to better align selection strategies with sustainability goals.
- Finally, incorporating feedback mechanisms could support more adaptive forest management, balancing ecological constraints with long-term resource availability. For example, penalising overexploited species or prioritising climate-resilient ones.

7. APPENDIX

7.1 Appendix A – Indicators Selection and Weighting Methodology

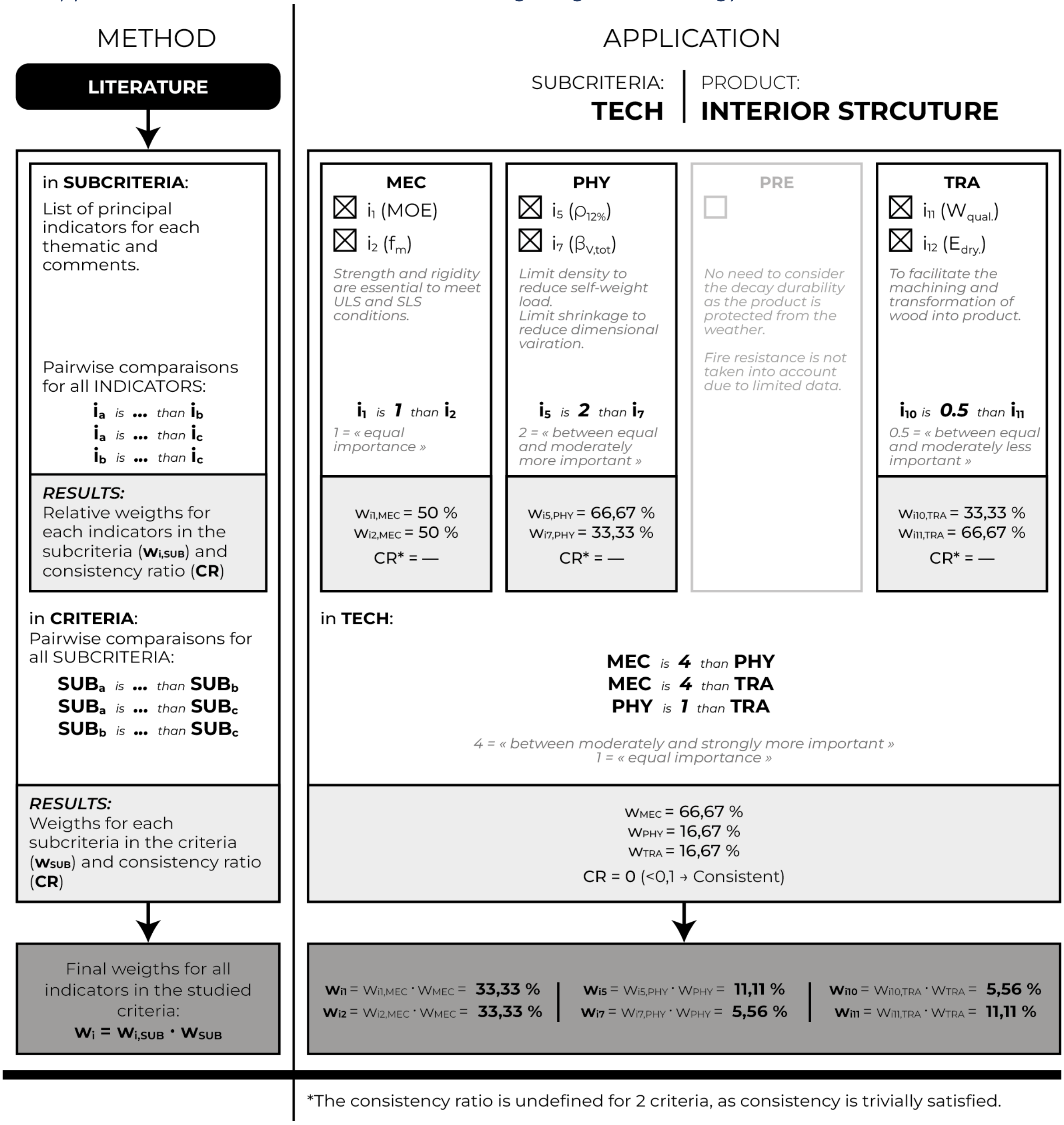


Figure 13 - Indicators Selection and Weighting Methodology - Application on technical indicators for an interior structure product.

As shown in Figure 10, the selection and weighting of indicators followed a structured multi-step process. First, relevant indicators were identified to represent each primary criterion, based on the specialist literature. This led to the establishment of a list of relevant indicators for each thematic criterion, depending on the product category (cf. 3.6.1) or the temporality of the strategy (cf. 3.6.2) chosen.

The weighting process was then carried out in two stages, both employing the Analytic Hierarchy Process (*AHP*) based on pairwise comparisons (cf. 4.1.3). In the first stage, the relative weights of the individual indicators $w_{i,SUB}$ were established within each thematic sub-criterion. In the second stage, the weights of thematic sub-criteria w_{SUB} were determined within each primary criterion. The final weight of each indicator w_i was obtained by multiplying its relative weight by the weight of its parent sub-criterion (23).

$$w_i = w_{i,SUB} \cdot w_{SUB} \tag{23}$$

This hierarchical approach effectively reduces the total number of pairwise comparisons required in the *AHP* method.

As mentioned in 4.1.3, all pairwise comparisons were carried out by the research team. However, to enhance the relevance and accuracy of weightings, it would be valuable to incorporate input from multiple domain experts.

7.2 Appendix B – Tree Species and Data Sources

NAME	REFS – TECH	REFS – ECON	REFS – ENVI
Acer campestre	e, h, q	s	s, w, ac
Acer platanoides	b, d, h, q	s	s, w, ac
Acer pseudoplatanus	a, b, c, d, e, f, g, h, j, n, p, q	n, s, u, x, z	s, w, ac
Acer spp.	a, b, c, d, e, f, g, h, j, n, p, q	n, r, s, t, v, x	s, w, aa, ac
Aesculus hippocastanum	b, d, f, h, j, n, p, q	n	
Alnus glutinosa	a, b, d, e, f, h, j, n, p, q	n, s, u	s, w, ac
Alnus incana	h		
Alnus spp.	a, b, d, e, f, h, j, n, p, q	n, s, t, z	s, w, ac
Betula pendula	b, d, e, f, h, j, k, l, m, n, q	n, s	s, w, ac
Betula pubescens	b, f, h, j, k, l, m, o, q	s	s, w, ac
Betula spp.	b, d, e, f, h, j, k, l, m, n, o, q	n, s, t, u, z	s, w, ac
Buxus sempervirens	d, h, j, n	n	
Carpinus betulus	b, c, d, e, h, j, n, q	n, s, x, y	s, w, aa, ac
Carya cordiformis	i, q	s	s, ac
Carya glabra	b, i, q	s	s, ac
Carya spp.	b, d, e, f, i, j, n, q	n, s	s, w, ac
Carya tomentosa	b, e, i, n, q	n, s	s, ac
Castanea sativa	a, b, c, d, e, f, g, h, j, n, p, q	n, s, u, x, y	s, w, aa, ac
Fagus sylvatica	a, b, c, d, e, f, g, h, j, n, p, q	n, r, s, t, u, v, x, y, z	s, w, aa, ac
Fraxinus excelsior	a, b, c, d, e, f, g, h, j, n, q	n, r, s, t, u, v, y, z	s, w, aa, ac
Ilex aquifolium	h, j, q		
Juglans nigra	b, c, d, f, h, i, j, n, q	n, s, x	s, w, ac
Juglans regia	a, b, d, e, f, g, h, j, n, p, q	n, s	s, w, ac
Juglans spp.	a, b, c, d, e, f, g, h, i, j, n, p, q	n, s, x	s, w, ac
Laburnum anagyroides	h, j	n	
Liriodendron tulipifera	b, f, h, i, j, n, q	s	s, w, ac
Malus sylvestris	b, h, q	n, s	s, w, ac
Olea europaea	h, q	n	
Platanus occidentalis	d, e, f, h, i, q		
Platanus spp.	b, d, e, f, h, i, j, n, p, q	n	
Platanus x hispanica	b, d, f, h, j, n, q	n, x	
Populus balsamifera	i, q		
Populus nigra	b, d, h, n, q	n, s	s, w, ac
Populus spp.	a, b, d, e, f, g, h, i, j, n, p, q	n, s, u, v, x, z	s, w, aa, ac
Populus tremula	e, h, n, q	n, s	s, w, ac
Populus trichocarpa	i, q	n, s	s, w, ac
Populus x canescens	b, d, h, q	s	s, w, ac
Populus x euramericana	b, d, e, p	s, x	s, w, ac
Prunus avium	a, b, c, d, f, g, h, j, n, q	n, r, s, u, v	s, w, ac
Pyrus communis	b, c, d, j, n, q	n, s	s, w, ac
Quercus petraea	a, b, c, d, e, f, g, h, j, n, q	n, s, v, y	s, w, ac
Quercus robur	a, b, c, d, e, f, g, h, j, n, q	n, s, v, y	s, w, ac
Quercus rubra	a, b, c, d, e, f, h, i, j, n, q	n, s, u, v, z	s, w, ac
Quercus spp.	a, b, c, d, e, f, g, h, i, j, n, q	n, r, s, t, u, v, z	w, aa, ac
Robinia pseudoacacia	b, c, d, e, f, g, h, i, j, n, q	n, s, x	s, w, ac
Salix alba	d, e, f, h, j, n, p, q	n, s, u, z	s, w, ac
Sorbus aria	h	n	
Sorbus aucuparia	h, n, q	n, s	s, w, ac

Sorbus spp.	h, n, q	n, s	s, w, ac
Sorbus torminalis	h, n, q	n, s	s, w, ac
Tilia cordata	b, d, h, n, p, q	n, s, x	s, w, ac
Tilia platyphyllos	b, d, h, n, q	n, s	s, w, ac
Tilia spp.	b, c, d, e, f, h, n, p, q	n, s, x	s, w, ac
Ulmus minor	a, b, c, e, f, h, j, n, q	n, w	w, ac
Ulmus spp.	a, b, c, d, e, f, h, j, n, p, q	n, w	w, ac
Quercus Ilex		y	
Quercus pubescent		y	
		Number of hardwood species	**57**

Table 8 - List of hardwood species and data sources for different properties

NAMES	REFS – TECH	REFS – ECON	REFS – ENVI
Abies alba	a, b, c, d, e, f, g, h, n, q	n, s, x, y	s, w, ac
Abies grandis	b, h, i, n, q	n, s, x	s, w, ac
Abies procera	b, h, i, q	s, x	s, w, ac
Abies spp.	a, b, c, d, e, f, g, h, i, n, p, q	n, s, t, x	s, w, aa, ac
Cedrus atlantica	b, d, f, g, h, j, n, q	n, s, x	s, w, ac
Chamaecyparis lawsoniana	h, i, j, q	s, x	s, ac
Larix decidua	a, b, c, d, e, f, g, h, j, n, q	n, s, x	s, w, aa, ac
Larix kaempferi	b, f, h, q	s, x	s, w, ac
Larix spp.	a, b, c, d, e, f, g, h, j, n, q	n, r, s, t, u, v, x, z	s, w, aa, ac
Larix x eurolepis	b, h	s	s, w, ac
Picea abies	a, b, c, d, e, f, g, h, j, n, p, q	n, r, s, u, v, y, z	s, w, aa, ac
Picea sitchensis	a, b, c, d, f, h, i, j, q	s	s, w, ac
Picea spp.	a, b, c, d, e, f, g, h, i, j, n, p, q	n, s, t	s, w, aa, ac
Pinus cembra	d, h, n		
Pinus nigra (subsp. laricio)	b, d, e, f, h	s, u, v, x, z	s, w, ac
Pinus nigra (subsp. nigra)	e, h, p, q	s, x, z	s, w, ac
Pinus palustris	n	n	
Pinus pinaster	a, b, c, d, e, f, g, h, q	u, x, y	
Pinus pinea	b, d, h		
Pinus radiata	n	n, x	
Pinus spp.	a, b, c, d, e, f, g, h, j, n, p, q	n, r, s, t, x	s, w, aa, ac
Pinus strobus	n	n, x	
Pinus sylvestris	a, b, c, d, e, f, g, h, j, n, q	n, s, u, v, x, y, z	s, w, ac
Pseudotsuga menziesii	a, b, c, d, e, f, g, h, i, j, n, q	n, r, s, t, u, v, x, y, z	s, w, aa, ac
Taxus baccata	b, d, f, h, j, n, q	n, w	w, ac
Thuja plicata	a, b, c, d, e, f, g, h, i, j, n, q	n, s, x	s, w, ac
Tsuga heterophylla	a, b, c, d, e, f, h, i, j, n, q	n, s, x	s, w, ac
Sequoia sempervirens	n	n, x	
		Number of softwood species	**28**

Table 9 - List of softwood species and data sources for different properties

ID	REFERENCES
a	Y. Benoit, 2008. *Le guide des essences de bois*
b	CEN, 2016. *EN 350: Durability of wood and wood-based products*
c	J. F. Rijsdijk, 1994. *Physical and related properties of 145 timbers*
d	J. Sell & F. Kropf, 1990. *Propriétés et caractéristiques des essences de bois*
e	G. Tsoumis, 1991. *Science and technology of wood: structure, properties, utilisation*

f	BM TRADA, 2021. *WIS 2/3-10 : Timbers – their properties and uses*
g	J. Gérard & al., 2011. *Tropix 7*
h	J. M. Leban et al., 2022. *XyloDensMap - Wood Basic Density for 156 tree forest species*
i	R. Ross, 2021. *Wood handbook: Wood as an engineering material*
j	B. J. Rendle, 1969. *World Timbers: Europe and Africa*
k	H. Heräjärvi, 2024. *Properties of birch (Betula pendula, B. pubescens) for sawmilling and further processing in Finland*
l	M. Boedts, 2016. *Effet du traitement thermique sur les propriétés physico-mécaniques et la durabilité du bois de bouleau*
m	H. Dubois, 2022. *Le bouleau, (Betula pendula ROTH et B. pubescens EHRH.) essence d'avenir en Europe occidentale ?*
n	R. Wagenführ & A. Wagenführ, 2022. *Holzatlas*
o	D. Vedernikov & al., 2022. *Chemical composition and mechanical properties of various parts of birch wood*
p	J. A. Kakaras & J. L. Philippou, 1996. *Treatability of several Greek wood species with the water soluble preservative CCB*
q	E. Meier, 20244. *The Wood Database*
r	B. Nailis & al., 2024. *Panorabois Wallonie*
s	S. Petit & al., 2017. *Fichier écologique des essences*
t	Thünen-Institut, 2022. *Fourth National Forest Inventory (Germany)*
u	L. Govaere and A. Leyman, 2022. *Vlaamse bosinventarisatie*
v	Fédération Nationale des Experts Forestiers (FNEF), 2024. *Mercuriales (Prix bois sur pied)*
w	S. Petit & al., 2020. *Fichier écologique des essences du Grand-Duché de Luxembourg*
x	C. Dixon & al., 2013. *The CABI encyclopedia of forest trees*
y	IGN, 2024. *Mémento 2024 - Inventaire forestier national*
z	M. J. Schelhaas & al., 2022. *Zevende Nederlandse Bosinventarisatie: Methoden en resultaten*
aa	A. André & al., 2023. *La lettre d'info de l'OWSF n°11*
ab	DSF & INRAE, n.d. *Ephytia - Santé des Forêts*
Number of references	28

Table 10 - List of data sources for wood properties

7.3 Appendix C – Tree Species Data – Profile 1

Data for all the tree species used in the assessment for profile 1 (cf. 5.3.1) are presented in Table 10 (Short Term Strategy) and in Table 11 (Medium Term Strategy).

SPECIES	TECH						ECON
	MOE	f_m	$\rho_{12\%}$	$\beta_{V,tot}$	$W_{qual.}$	$E_{dry.}$	Volume $Price_{Logs}$
	[MPa]	[MPa]	[kg/m³]	[%]	[class]	[class]	[€/m³]
Acer spp.	10800	102.8	625	12.3	2	3	70
Fagus sylvatica	14600	111.1	710	17.6	1.5	3	65
Fraxinus excelsior	12950	110.6	695	14.9	2.5	2.5	85
Populus spp.	9050	59.2	440	12.1	2.5	2	52.5
Prunus avium	10400	98.1	620	13.6	2	3	35
Quercus petraea	12300	102.3	700	13.6	1.5	1.5	225
Quercus robur	12050	95.6	695	13.3	1.5	2	225
Quercus rubra	12450	102.9	725	13.7	1.5	2.5	170
Quercus spp.	12350	99.1	705	13.5	1.5	2	206.5
Larix spp.	12250	92.7	580	12.4	3	2	75
Picea abies	10550	70	445	13.1	3	3	95
Pinus nigra (subsp. laricio)	10650	97.5	555	12.3	2.5	3	50
Pinus sylvestris	11750	98.2	520	12.4	3	2.5	50
Pseudotsuga menziesii	12850	85.3	510	11.8	2.5	2.5	95
						Number of species	**14**

Table 11 - Tree species data used in the evaluation for the profile of industrial sawyer (50% TECH and 50% ECON) with a short-term strategy for an interior structure product.

SPECIES	TECH						ECON	
	MOE	f_m	$\rho_{12\%}$	$\beta_{V,tot}$	$W_{qual.}$	$E_{dry.}$	Standing volume in Forest (Wallonia)	Productivity
	[MPa]	[MPa]	[kg/m³]	[%]	[class]	[class]	[m³]	[$m^3ha^{-1}yr^{-1}$]
Acer spp.	10800	102.8	625	12.3	2	3	2280793	4
Alnus spp.	10400	89.7	535	12.8	3	3	874600	7
Betula spp.	14800	124.8	665	15.4	2.5	2.5	3560334	5
Carpinus betulus	14250	137	780	18.4	2	1.5	1308012	5
Castanea sativa	9400	73.1	590	11.4	2	2.5	456119	9.5
Fagus sylvatica	14600	111.1	710	17.6	1.5	3	16305039	8.5
Fraxinus excelsior	12950	110.6	695	14.9	2.5	2.5	3342693	7.5
Populus spp.	9050	59.2	440	12.1	2.5	2	1137936	11
Prunus avium	10400	98.1	620	13.6	2	3	692725	7
Quercus rubra	12450	102.9	725	13.7	1.5	2.5	907743	8.5
Quercus spp.	12350	99.1	705	13.5	1.5	2	25354406	6.5
Robinia pseudoacacia	13500	127.2	745	11.7	1.5	2	209808	10
Larix spp.	12250	92.7	580	12.4	3	2	2800490	9.5
Picea abies	10550	70	445	13.1	3	3	41930427	13
Picea sitchensis	10500	70	430	12	2.5	3	462634	15
Pinus nigra (subsp. laricio)	10650	97.5	555	12.3	2.5	3	457816	9.5
Pinus sylvestris	11750	98.2	520	12.4	3	2.5	2462903	8.5
Pseudotsuga menziesii	12850	85.3	510	11.8	2.5	2.5	7351547	16
							Number of species	**16**

Table 12 - Tree species data used in the evaluation for the profile of industrial sawyer (50% TECH and 50% ECON) with a medium-term strategy for an interior structure product

7.4 Appendix D – Tree Species Data – Profile 2

Data for all the tree species used in the assessment for profile 2 (cf. 5.3.2) are presented in Table 12.

SPECIES	TECH					ENVI		
	$Stab_{serv.}$	$DC_{heart,fungi}$	$Treat._{sap.}$	$W_{qual.}$	$E_{dry.}$	$Biodiver._{impact}$	Climate Change Resistance	Biotic Pest Sensitivity
	[class]	[pts]	[pts]	[class]	[class]	[pts]	[class]	[pts]
Acer platanoides	2.5	1	64	2	2.5	8	3	36
Acer pseudoplatanus	1.5	1	32	2	3	8	2	32
Acer spp.	1.5	1	32	2	3	8	3	33
Alnus glutinosa	2.5	1	64	3	3	9	3	25
Alnus spp.	2.5	1	64	3	3	9	3	25
Betula pendula	2.5	1	32	2.5	2.5	10	3	17
Betula pubescens	3	1	32	2	2.5	10	2	17
Betula spp.	2.5	1	32	2.5	2.5	10	3	17
Carpinus betulus	2.5	1	64	2	1.5	4	3	9
Castanea sativa	2.5	64	1	2	2.5	7	4	22
Fagus sylvatica	1	1	64	1.5	3	3	1	36
Fraxinus excelsior	2	1	16	2.5	2.5	10	2	33
Juglans nigra	3	64	2	2	2.5	4	2	26
Juglans regia	2.5	16	4	2.5	2.5	4	2	26
Juglans spp.	2.5	16	4	2.5	2.5	4	2	26
Populus nigra	2	1	4	2.5	2.5	8	2	43
Populus spp.	2	1	8	2.5	2	8	2	42
Prunus avium	2.5	4	1	2	3	10	3	19
Quercus petraea	2	32	1	1.5	1.5	7	3	55
Quercus robur	2	32	1	1.5	2	7	2	50
Quercus rubra	2	4	4	1.5	2.5	5	2	50
Quercus spp.	2	8	2	1.5	2	6	2	52
Robinia pseudoacacia	2	128	1	1.5	2	6	4	9
Salix alba	3	1	4	3	2	10	3	45
Tilia cordata	3	1	64	2.5	3	6	4	18
Tilia platyphyllos	3	1	64	2.5	3	6	4	18
Tilia spp.	3	1	64	2.5	3	6	4	18
Ulmus minor	1	2	8	1.5	2	5	3	9
Ulmus spp.	1.5	2	4	1.5	2	5	3	9
Abies alba	2.5	2	8	3	3	4	1	57
Abies spp.	2.5	2	8	2.5	2.5	3	1	56
Cedrus atlantica	3	128	4	3	2.5	3	4	33
Larix decidua	2.5	16	1	3	2	5	3	37
Larix spp.	2.5	16	1	3	2	5	3	35
Picea abies	2.5	4	2	3	3	1	1	64
Picea sitchensis	2.5	4	4	2.5	3	2	1	61
Picea spp.	2.5	4	2	2.5	3	2	1	63

Pinus nigra (subsp. laricio)	1.5	4	2	2.5	3	5	4	103
Pinus spp.	2	4	2	2.5	2.5	6	4	103
Pinus sylvestris	2	8	2	3	2.5	7	3	102
Pseudotsuga menziesii	2.5	16	1	2.5	2.5	3	3	53
Taxus baccata	3	64	4	2.5	2	3	2	6
Thuja plicata	2.5	64	2	2.5	2.5	1	1	46
Tsuga heterophylla	2.5	2	4	2.5	2.5	1	1	12
							Number of species	**44**

Table 13 - Tree species data used in the evaluation for the profile of forest manager (50% TECH and 50% ENVI) for an exterior joinery product.

Units for natural durability ($DC_{heart,fungi}$) and treatability ($Teat._{sap.}$) of wood are $[pts]$. A non-linear scale has been used to translate classes into the form of points and reflect real-world preferences (cf. 0).

Unit of biotic pest sensitivity is $[pts]$. This data is obtained by adding together all the sensitivity scores for each insect and fungal pest known for a wood species. The pest sensitivity score is obtained by multiplying the impact class (1 = low risk to 3 = high risk) and the frequency (1 = rare to 3 = common) of the pest in the studied region [102], [103], [104].

7.5 Appendix E – Tree Species Data – Technical Criterion

Data for all the tree species used in the assessment for technical criterion for an interior structure product (cf. 5.3.3.2, 5.3.3.3, 5.3.3.4) and results from *TUP4C* analysis are presented in Table 13.

SPECIES	TECH						*TUP4C* ANALYSIS	
	MOE	f_m	$\rho_{12\%}$	$\beta_{V,tot}$	$W_{qual.}$	$E_{dry.}$	Rank	Score
	[MPa]	[MPa]	[kg/m³]	[%]	[class]	[class]	[/]	[%]
Acer platanoides	10600	112.5	655	12.3	2	2.5	15	60
Acer pseudoplatanus	10650	100	620	12.3	2	3	27	54
Acer spp.	10800	102.8	625	12.3	2	3	23	57
Aesculus hippocastanum	6100	66	530	11.9	2.5	2.5	63	20
Alnus glutinosa	10400	89.7	540	12.8	3	3	32	48
Alnus spp.	10400	89.7	535	12.8	3	3	31	48
Betula pendula	15000	121.6	670	15.2	2.5	2.5	2	81
Betula pubescens	13850	104.7	655	16.7	2	2.5	11	68
Betula spp.	14800	124.8	665	15.4	2.5	2.5	1	82
Carpinus betulus	14250	137	780	18.4	2	1.5	4	77
Carya spp.	14650	128.9	785	18.1	2	1.5	6	76
Carya tomentosa	15200	130.6	770	18.3	2	1.5	3	78
Castanea sativa	9400	73.1	590	11.4	2	2.5	55	33
Fagus sylvatica	14600	111.1	710	17.6	1.5	3	7	73
Fraxinus excelsior	12950	110.6	695	14.9	2.5	2.5	9	69
Juglans nigra	11900	99.1	620	12.8	2	2.5	19	59
Juglans regia	11900	127.4	660	13.5	2.5	2.5	8	73
Juglans spp.	11900	116.3	640	13.1	2.5	2.5	10	68
Liriodendron tulipifera	11100	67.7	495	12.7	2.5	3	43	40
Platanus occidentalis	9900	78.9	585	14.5	2	2	47	37
Platanus spp.	9800	79.6	595	14.5	2	2	48	37
Platanus x hispanica	10050	95.3	625	14.9	2	2	35	47
Populus nigra	8300	54.6	445	12.5	2.5	2.5	60	23
Populus spp.	9050	59.2	440	12.1	2.5	2	58	26
Populus tremula	9350	65	495	12.8	3	2.5	56	30
Prunus avium	10400	98.1	620	13.6	2	3	30	52
Pyrus communis	7950	88.8	710	14.1	2.5	3	49	37
Quercus petraea	12300	102.3	700	13.6	1.5	1.5	17	59
Quercus robur	12050	95.6	695	13.3	1.5	2	25	55
Quercus rubra	12450	102.9	725	13.7	1.5	2.5	14	62
Quercus spp.	12350	99.1	705	13.5	1.5	2	20	59
Robinia pseudoacacia	13500	127.2	745	11.7	1.5	2	5	76
Salix alba	7800	50.7	435	10.9	3	2	62	20
Sorbus aucuparia	11350	113.7	730	16	3	3	12	64
Sorbus spp.	11150	113.7	765	15.9	2.5	2.5	13	62
Sorbus torminalis	11000	113.7	780	15.7	2	2	16	60
Tilia cordata	9350	96	535	13.5	2.5	3	34	47
Tilia platyphyllos	9350	96	535	13.2	2.5	3	33	47
Tilia spp.	8850	98	545	13.5	2.5	3	36	46
Ulmus minor	9650	74.7	620	12.6	1.5	2	53	33
Ulmus spp.	9950	78.1	640	12.9	1.5	2	50	36
Abies alba	11250	72.7	455	12.1	3	3	39	43
Abies grandis	10200	63.2	435	11	2	2.5	52	34
Abies spp.	11250	69.8	440	11.9	2.5	2.5	40	41
Cedrus atlantica	9700	82.3	550	10.6	3	2.5	42	40
Larix decidua	12550	93.7	590	12.5	3	2	21	58
Larix spp.	12250	92.7	580	12.4	3	2	24	56

Picea abies	10550	70	445	13.1	3	3	45	39
Picea sitchensis	10500	70	430	12	2.5	3	46	39
Picea spp.	10600	70.6	440	12.4	2.5	3	44	40
Pinus cembra	7600	68	445	10.6	3	3	57	28
Pinus nigra (subsp. laricio)	10650	97.5	555	12.3	2.5	3	28	54
Pinus palustris	12000	90	670	12.3	2	2	29	52
Pinus pinaster	8700	77.7	530	12.7	2.5	2.5	54	33
Pinus radiata	11050	75.5	515	7.1	2	3	38	44
Pinus spp.	10500	85.9	525	12.2	2.5	2.5	37	46
Pinus strobus	10050	61	400	9	3	3	51	35
Pinus sylvestris	11750	98.2	520	12.4	3	2.5	18	59
Pseudotsuga menziesii	12850	85.3	510	11.8	2.5	2.5	26	55
Taxus baccata	13100	90.1	675	9.5	2.5	2	22	57
Thuja plicata	7950	53.1	380	7.2	2.5	2.5	59	24
Tsuga heterophylla	10650	74.6	475	12.4	2.5	2.5	41	40
Sequoia sempervirens	7500	57.5	450	7	2.5	2.5	61	22
						Number of species	63	

Table 14 - Tree species data used in the evaluation for the technical criterion for an interior structure product.

7.6 Appendix F – Trees species scores for comparison of profile 1 and 2

SPECIES	PROFILE 1 (medium-term)		PROFILE 2	
	Rank	Score	Rank	Score
	[/]	[%]	[/]	[%]
Picea abies	1	77	17	10
Quercus spp.	2	59	14	13
Fagus sylvatica	3	43	5	46
Betula spp.	4	28	6	42
Robinia pseudoacacia	5	25	1	100
Carpinus betulus	6	25	4	58
Pseudotsuga menziesii	7	22	11	23
Fraxinus excelsior	8	22	10	23
Quercus rubra	9	18	13	13
Pinus sylvestris	10	17	18	6
Acer spp.	11	16	7	36
Larix spp.	12	15	9	29
Pinus nigra (subsp. laricio)	13	14	15	11
Prunus avium	14	13	8	33
Alnus spp.	15	11	3	59
Picea sitchensis	16	10	16	10
Populus spp.	17	4	12	18
Castanea sativa	18	3	2	64
		Number of species	18	

Table 15 - Tree species scores of a reduced set for which complete data were available across profiles 1 (medium term) and 2.

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