Modeling the environmental sustainability of timber structures: a case study.

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Abstract:

A revival in timber buildings and the appreciation of their positive physical and mechanical properties can be explained by the unique environmental credentials of timber products and their versatility. Heightened public awareness of sustainability in the construction sector places timber among the most preferential sustainable materials. There is plenty of previous research on sustainability assessments for complete buildings, although far less on the sustainability assessment of specific parts of the buildings, such as the case of timber structures. The objective of this study is to present an evaluation model, based on MIVES methodology, specifically designed for timber structures, which can be used to enhance the environmental sustainability and to reduce the impacts that are generated, in those areas where it has been awarded a lower score. The application of the model to the largest multi-storey residential timber building in south-western Europe clearly shows that changes to the material, such as its background and environmental certification, generate significant changes to the overall results of the assessment. A sensitivity analysis is then used to verify the analysis of the results and both the validity and the stability of the proposed model.

Keywords: environmental sustainability; assessment; model; timber structures; MIVES

1. INTRODUCTION

Timber is among the first construction materials and its structural use can be found throughout the existence of humankind. One example is the well of Altscherbitz, near Leipzig, which has been identified as the oldest existing timber construction (Woodard and Milner, 2016), built more than 7,000 years ago (around 5600–4900 BC). Another example might be the Horyuji Temple in Nara, Japan, where timber from trees felled 1400 years ago (approximately 594 AD) were used for its construction (Woodard and Milner, 2016).

Throughout history, timber has gradually been integrated with brick and mortar construction materials and more recently replaced by concrete and steel, due to their greater strength, inflammability, and resistance to biotic and abiotic agents. However, timber and especially tall-timber constructions are now undergoing a revival in two different areas (Moya et al., 2017): on the one hand, the development of new Engineered Wood Products (EWPs) and, on the other, architectural and designer innovation in the fight against global CO_2 emissions through the use of low carbon footprint materials (Woodard and Milner, 2016, Stocchero et al., 2017, Balasbaneh and Bin Marsono, 2018, Balasbaneh et al., 2018).

In this regard, the construction sector has a lot to answer for, because it is one of the largest consumers of natural resources and energy (Lu et al., 2016). As a major contributor, it is responsible for one third of global greenhouse gases (Gan et al., 2017) and the consumption of up to 40% of all energy (Liu et al., 2018). The sector is also responsible for the consumption of 3 billion tons of natural raw materials (40%–50% of the total flow in the global economy) and for 12% of existing water resources (Martin and Perry, 2019).

Global shifts towards a future with CO_2 emission limitations bring deeper analysis of timber as a building material, due to its unique environmental credentials, beauty, and versatility (Gold and Rubik, 2009). Timber is sourced from trees that depend on solar energy, and like all plant life, convert CO_2 into carbon and release oxygen into the atmosphere (Newell and Vos, 2012). It is therefore a renewable, recyclable, and biodegradable material; its production and processing are energetically efficient; and, its use in construction contributes to the fight against the greenhouse-gas effect (Balasbaneh and Bin Marsono, 2017). In this sense, the promotion of timber in the construction sector is a central public policy objective, which is needed to boost the Bioeconomy, aiming to move towards a new paradigm based on renewable energies and raw biological materials (Purkus et al., 2018). The use of timber in the construction sector can play an important role in achieving those objectives (Bin Marsono and Balasbaneh, 2015).

In addition, increasing demand for sustainable and healthy indoor environments has been accompanied by new, reusable, and recyclable materials with low-embodied energy, such as timber products (Liblik and Just, 2016). According to several authors (Woodard and Milner, 2016, Bin Marsono and Balasbaneh, 2015), “timber from sustainably managed forests is one of the most environmentally friendly materials available”. In addition, from a technical point of view, the positive physical and mechanical properties of timber as a structural material mean that it is ideal for the construction of building structures, except when exposed to flooding (Balasbaneh et al., 2019). Timber has a high strength-to-weight ratio (Zerpa et al., 2017), is characterized by low deadweight, and timber construction elements, such as Cross-Laminated Timber (CLT) (Baño et al., 2016), are nowadays highly durable products with low maintenance expenses, insulating both heat and sound, and are prefabricated in the factor for high quality and precision. Furthermore, construction structures made of CLT are lighter than concrete-steel structures, permitting a high degree of offsite manufacture and rapid assembly of factory quality construction units. In addition, this type of construction acts as a carbon sink.

Even so, timber must as with all construction materials comply with a series of standards, so that it is used as efficiently as possible from an environmental point of view.

Over recent decades, different models have been developed to analyze the sustainability of buildings and the different materials and components that compose them (Armengou, et al., 2012, Kim and Todorovic, 2013, Raslanas et al., 2016, Kalutara et al., 2018, de la Fuente et al., 2016, Pons et al., 2016, de la Fuente et al., 2017, Haapio and Viitaniemi, 2008, Pons et al., 2012). Some of these evaluation models take the 3 basic pillars of sustainability into account: economic and social components (Sierra et al., 2018), and environmental impact (San-José and Cuadrado, 2010, Cuadrado et al., 2016, Cuadrado et al., 2015). The aforementioned models have expanded the body of knowledge on sustainability evaluation at the level of a complete conventional building, built using different materials, such as concrete, steel, etc. Nevertheless, research that specifically evaluates the sustainability of timber buildings is scarce. Some examples of the studies that have analyzed the sustainability evaluation of hybrid or mixed structures, in which timber is a further component (Rodrigues et al., 2017, Hein et al., 2015), are the comparative study by Maxineasa et al. (Maxineasa et al., 2018) on the environmental performance of different timber structures, in the specific case of roofs, and the research conducted by Kovacic et al (Kovacic et al., 2016), in which they analyzed the environmental impacts of three different façade systems, one of which formed by a system of cross-laminated timber panels. It may therefore be concluded that the evaluation of sustainability at the level of complete timber structure represents a "knowledge gap" in this field of study.

In this paper, the development of an environmental sustainability evaluation model for timber structures is described. The model assigns a numeric value, (between 0 and 1) to different structural solutions. The proposed model generates a value that reflects the degree to which the timber structure under evaluation is adapted to environmental sustainability criteria and may serve to enhance the environmental sustainability of a structural solution in the design phase, through the definition of different scenarios.

In the present study, the sustainability model was applied to the largest and tallest multi-story residential building built mainly of timber in south-western Europe. The building was constructed out of 2,200 m3 of cross-laminated radiata pine timber and it houses 65 apartments. An Environmental Sustainability Index value of this specific building is therefore analyzed. The remainder of the paper is organized as follows. Following this introduction, the proposed research method will be described. Then, the conclusions of both the literature review on sustainability assessment in construction and best the way to approach its evaluation will be presented. Afterwards, the development of the environmental sustainability evaluation model and the results of the application of the final model to a real project, together with the global results of the sensitivity analysis, will be described. In the Conclusions section, the main contributions of the research will be set out, as well as their limitations and directions for future work.

2. RESEARCH METHOD

The present research will be organized, as shown in Fig. 1, into 4 parts. The first part presents the conclusions of the review of the scientific literature on sustainability assessment in construction. In the second, the MIVES methodology is first presented, with the mathematical method that generates an evaluation index. Having presented the theoretical framework, an environmental sustainability assessment model for timber structures is developed. To do so, a Delphi process involving a panel of 11 experts from the construction sector is followed, to select the indicators and criteria, together with their corresponding relative weights. In a third phase, a real residential building is selected to which the developed model is applied, in order to test its response capacity and behavior. In the last part, a One-at-a-time (OAT) sensitivity analysis is carried out, in order to demonstrate the validity, stability, and robustness of the results, once the weights of each criterion have been varied.

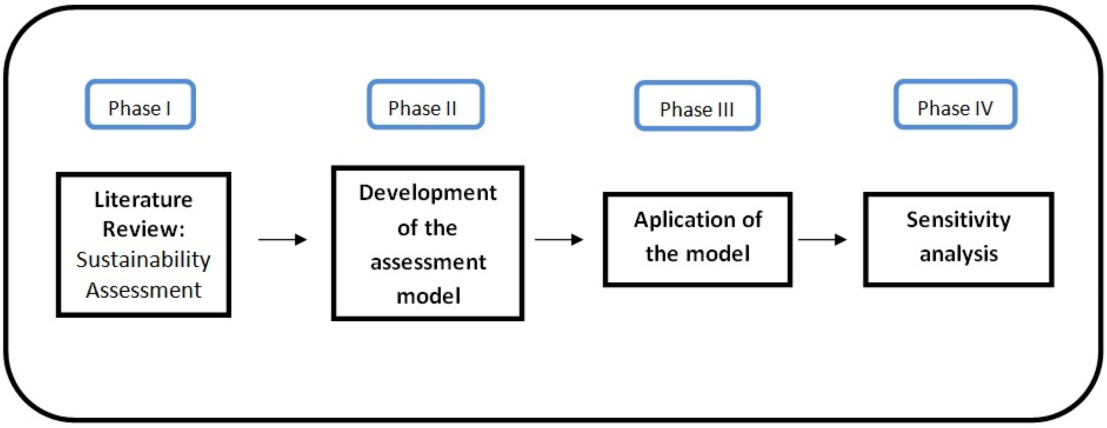

Figure 1. Research Method

3. SUSTAINABILITY ASSESSMENT IN CONSTRUCTION – A REVIEW.

Sustainability assessment in construction has attracted the attention of the scientific community, generating an interest that has led to the development of numerous assessment models and tools (IHOBE, 2010, IHOBE, 2014, Bernardi et al., 2017, Berardi, 2017, Haapio and Viitaniemi, 2008, Sharifi and Murayama, 2013, Castro et al., 2017, Haapio, 2012).

The objective of this section is to review the scientific literature related to the evaluation of sustainability in the construction sector. A number of databases – Web of Science, Sciencedirect, Scopus, Google Scholar, JSTOR, IEEE Xplore and SpringerLink- were searched using the following combination of keywords: “sustainability”; “assessment”; “evaluation”; “construction”, “methodology”; “model” and “tool”. As a result, a total of 27 sustainability assessment models were identified, which are presented in Table 1.

Model	Institution	Country	Website

ATHENA™ Experimental Impact Estimator	ATHENA Sustainable Material Institute	Canada	http://www.athenasmi.org/our-software-data/impact-estimator/
BeCost	VTT	Finland	http://virtual.vtt.fi/virtual/proj6/environ/ohjelmat_e.html
BEES 4.0	U.S. National Institute of Standards and Technology (NIST)	USA	https://www.nist.gov/services-resources/software/bees
BREEAM	BRE Trust	UK	http://www.breeam.org
Casbee	Japan GreenBuild Council (JaGBC) / Japan Sustainable Building Consortium (JSBC)	Japan	http://www.ibec.or.jp/CASBEE/english
DGNB	(DGNB) Deutsche Gesellschaft für nachhaltiges Bauen	Germany	http://www.dgnb.de
EcoEffect	Royal Institute of Technology (KTH)	Sweden	https://www.ecoeffect.se/
EcoProfile	Byggforsk - Norwegian Building Research Institute	Norway	http://www.byggsertifisering.no
Eco-Quantum	IVAM	the Netherlands	http://www.kiesuwlabel.nl/eco-quantum/
EEWH	Taiwan Green Building Council	Taiwan	http://www.taiwangbc.org.tw
Envest 2	Building Research Establishment (BRE)	UK	https://bregroup.com/products/tools/impact-lca/
Green Globes	BOMA Canada; The Green Building Initiative (GBI)	Canada/USA	http://www.greenglobes.com
Green Mark	BCA (Building and Construction Authority)	Singapore	http://www.bca.gov.sg/GreenMark/green_mark_buildings.html
Green Star	Green Building Council of Australia (GBCA)	Australia	http://www.gbca.org.au
Guía Edificación Sostenible	Gobierno Vasco	Basque Country	https://www.ihobe.eus/inicio
HK BEAM	BEAM Society	Hong-Kong	https://www.beamsociety.org.hk/en_index.php
HQE	Association pour la Haute Qualité Environnementale	France	http://www.assohqe.org
LEED	U.S. GBC (Green Building Council)	EEUU	http://www.usgbc.org/LEED
Lider A	-	Portugal	http://www.lidera.info
Minergie	Minergie Building Agency	Switzerland	https://www.minergie.ch/
NABERS	NSW (New South Wales Government)	Australia	https://www.nabers.gov.au/
Nordic Swan	Nordic Council of Ministers	Nordic Countries	http://www.svanen.nu/Default.aspx?tabName=CriteriaDetail&pgr=89
PromisE	Ministerio de Medioambiente (with the support of VTT and others)	Finland	http://www.promiseweb.net

Protocollo ITACA	Istituto per l'Innovazione e Trasparenza degli Appalti e la compatibilita ambientale	Italy	http://www.itaca.org/
SB Tool	iiSBE (International Initiative for a Sustainable Building Environment)	International	http://iisbe.org/about
TEAM™	Ecobilan	France	https://ecobilan.pwc.fr/en/team.html
Verde	GBC España	Spain	http://gbce.es/certificacion-verde/

Table 1. Main sustainability assessment models

The development of these evaluation models has experienced a boom since the application of BREEAM in the United Kingdom, at the beginning of the 90s. Many of the existing national models are also global and are applied in various countries, such as LEED (Leadership in Energy and Environmental Design), and SB Tool. However, other models have an exclusively local scope, and have been designed by adapting their characteristics to the specificities of the country in question, such as DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen, Germany), HQE (Haute Qualité Environnementale, France), and VERDE (Spain) (IHOBE, 2014,IHOBE, L., 2010).

Some of these models have evolved into different versions, including new building typologies in their evaluations. On other occasions, a country has been inspired by the evaluation system used by another country and has adapted it to its own needs (BREEAM, which was born in the United Kingdom, was adapted in Canada and subsequently converted into another independent system, Green Globes). Other evaluation systems, amongst which VERDE, remains attached to their original system, the SB Tool, with adaptations to country specific characteristics (IHOBE, 2014).

Each model addresses the evaluation process in different ways. Some evaluate the impacts that are generated through life-cycle analysis, with great precision, based on the quantification of resource flows and environmental emissions, taking into account all life cycle stages. This type of model requires expert knowledge on the material's origin and their transformation, which involves a lot of data-processing work. Other existing models are simpler when entering data and they base the evaluation on the fulfillment of several requirements that improve the performance of the building, such as LEED and the SB Tool. Finally, others are based on "ecopoint" systems and eco-efficiency concepts, such as CASBEE in Japan.

Kylili and Fokaides (Kylili and Fokaides, 2017) gave another classification of the existing sustainability assessment models, categorizing them as follows:

Level 1 models: models which address the comparative evaluation of simple assemblies, such as BEES 3.0 and TEAM™.

Level 2 models: models that approach the evaluation of the entire building, allowing decision making with respect to specific areas. These are applied from the initial concept through to the detailed design stages, such as ATHENA™, BEAT 2002, BeCost, EcoQuantum, Envest 2, EQUER, LEGEP® and PAPOOSE.

Level 3 models: models which address whole-building assessment systems, approaching the evaluation of sustainability through the combination of social, economic, and environmental aspects. Examples include BRE and the LEED rating system.

Erlandsson and Borg (Erlandsson and Borg, 2003) also analyzed the characteristics of the existing sustainability assessment models, concluding that there are notable differences in relation to the scopes, approaches and methodologies when approaching the whole building assessment. They identified two main approaches, an upward approach that addresses the selection of building materials and a downward approach that considers building improvements as an entity.

Nevertheless, regardless of the evaluation methodology in use, the aspects under evaluation (criteria and indicators) in all the existing models take into account the different building components (façades, roofs and installations), which normally requires different measurement units (surface, energy, weight, etc.) (Cuchí et al., 2003, ASCE - Committee on Sustainability, 2004). So, normally, the sustainability assessment process is based on multi-criteria evaluation methodologies, the final results of which group measurable aspects together with heterogeneous units.

In the case of the Spanish concrete and steel codes (Spanish Ministry of Development, 2008, Spanish Ministry of Development, 2011), an environmental sustainability index was obtained, also based on MIVES methodology. In this way, practitioners can easily understand the analysis without it consuming excessive amounts of time.

The challenge of comparing sustainability assessment models

Comparative studies of the different sustainability assessment models have generated great interest. Their aim is to identify their common characteristics and to identify the key evaluation indicators directly related to the concept of sustainability. All with the ultimate goal of defining an "ideal" sustainability assessment model. However, it is no easy task, due to the difficulties over defining useful and measurable assessment indicators, as sustainability is time- and location-dependent (Berardi, 2017).

Several authors have addressed this issue, such as Ameen et al. (Ameen et al., 2015), who undertook a critical review of existing environmental assessment tools for sustainable urban design. They concluded that the assessment tools showed wide coverage of environmental sustainability issues, although not all were considered. They also identified great disparity in the local and international environments of global sustainability assessment tools, as well as disparities in the scope of the topics covered by the indicators and the sub-indicators of each model, wherein their assessment of global sustainability. In addition, the authors concluded that both economic and cultural aspects are still marginal in the sustainability evaluation tools that were studied. In conclusion, the study concluded that there was no consensus over the optimal number of indicators and their nature, in addition to establishing differences in the importance of the different models. Cabeza et al. (Cabeza et al., 2014) conducted a review of the literature on Life Cycle Assessment (LCA), Life Cycle Energy Analysis (LCEA), and Life Cycle Cost Analysis (LCCA) studies performed for the environmental evaluation of buildings, arriving at the conclusion that it is not easy to compare these studies, due to their specific properties such as construction type, climate, comfort requirements, local regulations, etc. The research moreover highlighted that the functional unit is not mentioned in all studies; and in the studies where it is mentioned, it is not clear which functional unit to consider, greatly complicating any comparison between the studies.

Hossain and Ng (Hossain and Ng, 2018) undertook a critical analysis of the building-environmental assessment-related literature in which the LCA technique was applied, with the objective of assessing buildings and the environmental impacts of the built environment. The authors concluded that although these studies provided interesting information on the LCA of buildings, some critical factors were not considered, such as the "materials supply chain and sourcing, identification of low impacts material, whole life assessment of buildings including demolition and the salvage value of materials". In this sense, the authors affirmed that it is still necessary to identify trends and practices in the various approaches to sustainability evaluation and different considerations and investigations along these lines.

Bernardi et al. (Bernardi et al., 2017) conducted a comparative analysis of the 6 most widespread and most cited assessment models (LEED, BREEAM, CASBEE, SBTool, HQE and DGNB) in the scientific literature on sustainability, with the objective of identifying differences between them and any possible implications of those differences. The authors concluded that the different evaluation models had been developed with different objectives, hence the infeasibility of any comparison between their criteria and indicators.

Gil and Duarte (Lopes Gil and Pinto Duarte, 2013) conducted a review of a selection of sustainable urban development evaluation models. They came to similar conclusions that there is a general trend, but that no tool can be identified as the "ideal one". They also concluded that the choice is not easy and that there are still possibilities for improvement in existing tools, as well as the possibility to develop new tools. The authors affirmed that a complete standardization of the different evaluation models is neither possible, nor desirable, because the models can include design principles that cannot be accepted universally. Those models might require data that are neither available in the local scope and can include indicators with no relevance to any one specific context, whether geographic, policy or project-related.

For all these reasons, although there is currently a need for a common language for sustainability assessment, consensus is a long way off (IHOBE, 2014). Additionally, in relation to the present research, it is important to highlight that no model has up until now specifically addressed sustainability evaluation in timber structures. For all these reasons, the objective of our research is to develop an environmental sustainability evaluation model that is specific to timber structures. The development of this model is justified by the fact that a series of criteria on usage and timber sources have to be established, even though timber is in itself a sustainable material with advantages from an environmental point of view. Additionally, it is important to establish criteria on the construction techniques in use, which can also heighten construction sustainability levels.

4. DEVELOPMENT OF THE ASSESSMENT MODEL

The assessment model that is presented is based on MIVES methodology (Alarcon et al., 2011) that is a Multi-Criteria Decision-Making (MCDM) model incorporating AHP (Analytic Hierarchy Process) based value functions (Saaty and Vargas, 2012, Saaty, 2008). AHP decision-making identifies the relative priority of each alternative on a quantifiable scale, emphasizing the importance of the intuitive criteria of decision-makers and the consistency of comparisons between alternatives based on their judgment. The methodology not only shares the principle that decision-makers will always base their judgments on knowledge and experience, but it also systematically organizes both tangible and intangible factors, providing a simple structured solution to their problems. This methodology, as previously mentioned, constitutes a numerical assessment of alternatives based on the systematic assessment of a set of weighted alternatives for clear decision-making (del Caño et al., 2012).

As can be seen in Figure 2, the assessment of environmental sustainability has been subdivided into a series of simpler criteria, in order to evaluate them separately, determining the influence of each on the final objective, as defined in the MIVES methodology. These MIVES-based models are described in different scientific applications in the literature (del Caño and de la Cruz, 2002, Piñero et al., 2017, Zubizarreta et al., 2017, Oses, et al., 2017, Hosseini et al., 2018, Pons et al., 2017, Hosseini, et al., 2016, de la Fuente et al., 2017, Pons et al., 2016, Hosseini et al., 2016) and are based on AHP (Analytic Hierarchy Process) (Saaty and Vargas, 2012, Saaty, 2008).

4.1 Development of the tree

The diagram in Figure 2 represents an analytical framework of sustainable criteria. A criterion can be divided into a series of "indicators", which represent the lowest hierarchical level.

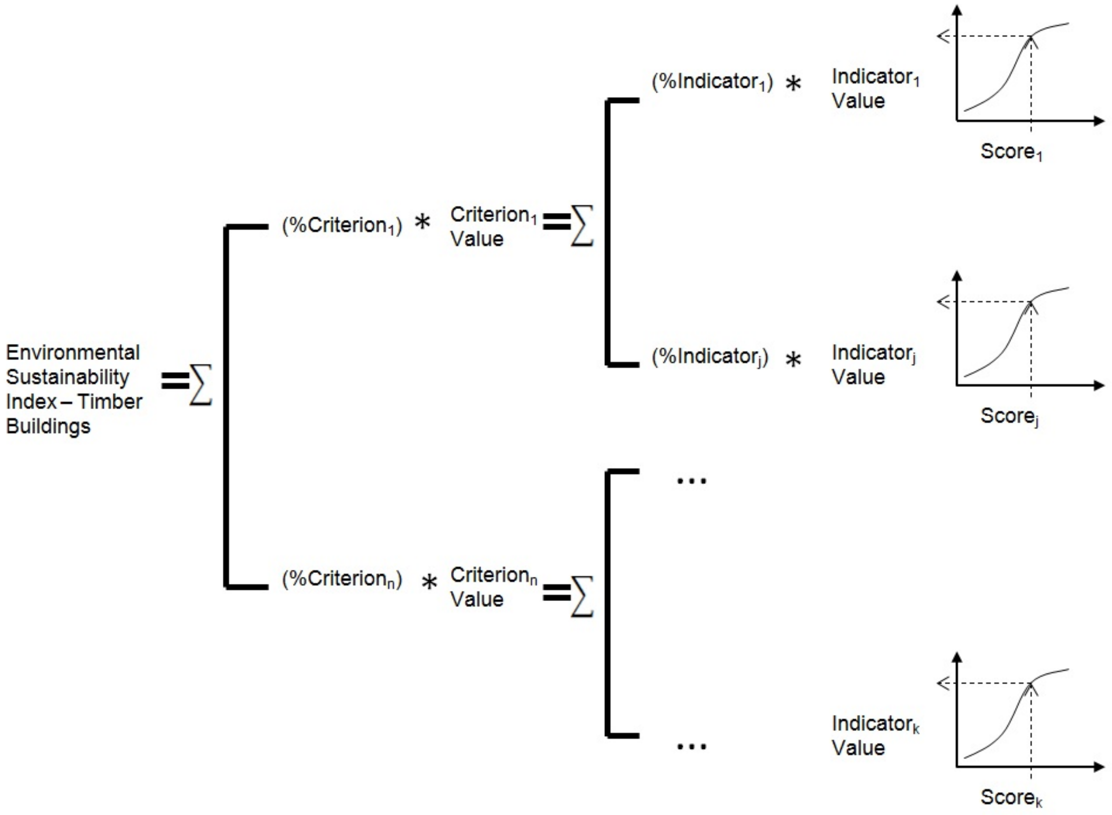

Figure 2. General Hierarchy Decision tree

In Figure 2, a series of weights are assigned to each criterion and indicator according to the guidelines of the AHP method, which ensures the objectivity of the process (Wong and Li, 2008).

4.2 Value function definition

Each of the indicators defined in the decision tree are valued through a value function. Value functions (Vi) assign values that vary between 0 and 1 and depend on five parameters, as previously mentioned (Zubizarreta et al., 2017, Cuadrado et al., 2016).

Therefore, the shape of the function can be defined as either linear, concave, convex or "S shaped".

4.3 Definition of the weighting system

Figure 3 shows the hierarchical evaluation tree, specifically designed to address the environmental sustainability assessment of timber structures (ESI-TS), consisting of two criteria and five indicators.

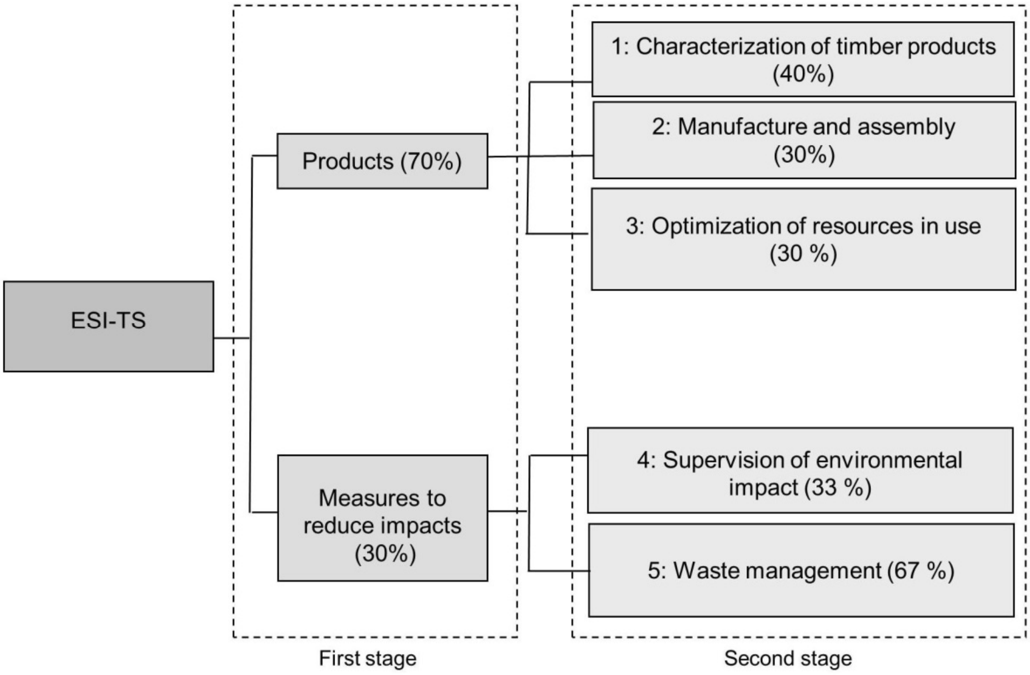

Figure 3. ESI-TS hierarchical evaluation tree

In the systematic approach to building this hierarchical decision tree, the first task is to estimate the sustainability priorities, by allocating weights (AHP) at the respective hierarchical levels (from indicator to criteria and global index ESI-TS).

The assignation of weights to each hierarchical level was performed using the Delphi method, in which a group of individuals (Expert Panel) addresses a complex problem (Linstone and Turoff, 2002). The correct selection of panel members, chosen for their skills, knowledge, and independence is one of the main keys for the successful completion of this process.

In this case, the Expert Panel was formed of professionals from the construction sector (raw materials, construction products, construction, engineering experts in health and safety, and researchers at technology centers and universities). There are different selection methods to identify the experts who will form the panel. Hallowell and Gambatese (Hallowell and Gambatese, 2010) defined certain criteria, according to which each expert should score at least 11 points in a set of achievement or experience categories to sit on the panel. According to the same authors, a diverse and highly qualified group of people, ranging between 8 and 16 individuals would form an ideal panel. The experts chosen to sit on the panel for this project were selected from a database of 72 professionals in the construction sector, belonging to 31 different organizations at national level (companies, technological centers, and universities). The selection process culminated in an Expert Panel of 11 members.

The environmental sustainability index was proposed on the basis of two criteria for a timber structures: the timber products and the measures taken to reduce environmental impacts. As in other cases (Spanish Ministry of Development, 2011, Spanish Ministry of Development, 2008), greater prominence was given to the timber materials (70%) in this study, rather than possible measures such as waste reduction to reduce impacts (30%).

4.4. Criteria and indicator definition

The proposed assessment model (tree) is used to quantify those actions that lead to an improvement in the environmental sustainability of the adopted solution. So, the actions to be strengthened from this point of view were as follows:

- Material-related aspects: The use of smaller quantities of raw material (timber), use of local wood resources and timber source traceability, associated with proper forest management.
- Process-related aspects: selection of production processes associated with lower CO_2 emissions and lower energy consumption, use of renewable energy sources and by-product reuse and recycling (waste management).
- Aspects related with timber structures: participation of companies that comply with current environmental and quality regulations (voluntarily certification), thereby improving the useful life of the building (durability).
- Aspects related to the construction stage: procedures for constructing timber structures according to environmental regulations (voluntarily certification) and the implementation of process innovations, in such a way as to increase the productivity and the efficiency of the construction phase.

The evaluation is divided into two parts: the product that is used and the environmental impact minimization measures, as specifically defined in the following Spanish Codes; the Structural Concrete Code (Spanish Ministry of Development, 2008) and the Structural Steel Code (Spanish Ministry of Development, 2011).

In the following part, only the methodology for the evaluation of the different proposed indicators within the "Products" criterion will be described, because this set of indicators is of greater weight, as well as limitations on the length of the paper. In the second level, the “Products” criterion was divided into three indicators, related to the characterization of timber products, their manufacture and the optimization of the resources that are used.

Indicator 1.1 **“Characterization of timber products”** accounts for the correct management of the materials, with the objective of economic viability, societal benefits, and compliance with responsible environmental management. The timber parts of a structure can be of different origin, so it is necessary to establish the percentages of each source, due to their different environmental impacts. The easiest way to ensure the origin of wood is through product certification, issued by

FSC (Forest Stewardship Council), PEFC (Programme for the Endorsement of Forest Certification), or another international body.

The use of uncertified wood has a low rating, which corresponds to 0 points, a value that increases rapidly when using certified wood. This growth rate is reduced in the case of having a percentage of certified wood between 50 and 100%, which is the range where the maximum value is reached.

Indicator 1.1: Characterization of timber products	$\mathbf{P_{prod}}$
Total volume of sawn timber	$\mathbf{V_s}$
Total volume of plywood timber	$\mathbf{V_p}$
Volume of sawn timber with product certifications	$\mathbf{V_{s/cert}}$
Volume of plywood with product certifications	$\mathbf{V_{p/cert}}$

Table 2. Valuation of Indicator 1.1: Characterization of timber products

where:

$$P1 = \frac{V_{s/cert} + V_{p/cert}}{V_s + V_p} * 100 \qquad [3]$$

P1 = “Characterization of timber products” indicator score Expression 3 yields the percentage of certified wood in relation to the total amount used in the structure of the building. from which the P1 value is obtained.

Once the P1 value has been defined, it is entered into the value function defined for this specific indicator (V_{i1}), which is shown in Figure 4, obtaining the final value of Indicator 1.1: a value between 0 and 1.

In the Spanish case, as mentioned, the curve gives a higher score as greater effort is made in this direction, because the consumption of certified wood is not very relevant.

In this case, the selected curve type was the concave ascending function (Figure 4), with the aim of encouraging the use of timber with an environmental certification.

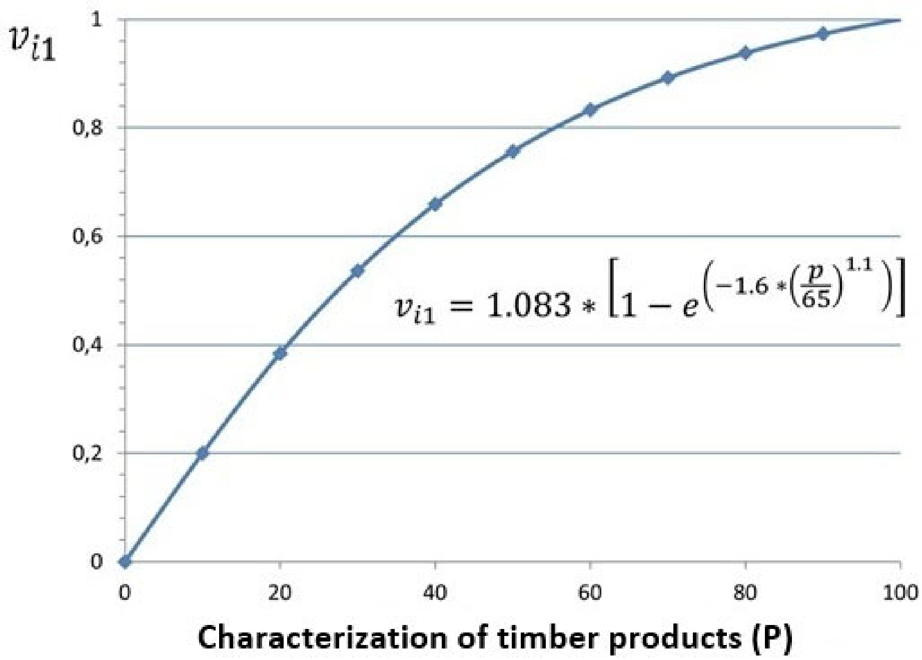

Figure 4. Value function of “Characterization of timber products” indicator

A similar scheme is proposed for the entire set of indicators, in all cases establishing the proposed objectives, the approach to the indicator valuation, and the proposed strategy, through different value functions.

Indicator 1.2 **“Manufacturing and assembly”** aims to assess the environmental sustainability of both the factory manufacturing processes and the on-site assembly process. Its valuation is through the environmental accreditations of the different companies that participate in the construction process. It is the easiest way of assessing the environmental commitment of these companies. Three types of companies were identified: the company in charge of manufacturing the wooden structures (Factory), the company in charge of their on-site assembly (occasionally the Factory), and the construction company (Contractor) responsible for all other activities necessary to complete the construction project. In this way, companies are encouraged to take measures to obtain environmental management certifications.

This indicator also accounts for the distance from the factory to the site, as the minimization of the impact associated with transportation is another objective. Companies in the industry have quoted a maximum distance of 300 km. that acts as a restraint on competition with rival companies that are closer to the construction site.

Table 3 sets out the scores for Indicator 1.2, in which scores for the manufacturing firm, the installation firm, and the construction firm should be noted in relation to the complete building. In case 1, the maximum value that can be obtained from Pi is 100, where the distance is less than 300 km and the participating companies have environmental accreditations.

Manufacturing and Assembly: valuation scheme		**Distance ≤ 300 km**		**Distance ≥ 300 km**	
		Case 1 factory $P_{factory}$	**Case 2 on-site $P_{on-site}$**	**Case 1 factory $P_{factory}$**	**Case 2 on-site $P_{on-site}$**
Manufacture and assembly in the factory	(A) with environmental accreditation	80	0	75	0
	(B) with environmental commitment	60	0	55	0
	(C) others	30	0	25	0
On-site assembly	(A) with environmental accreditation	0	70	0	70
	(B) with environmental commitment	0	30	0	30
	(C)others	0	0	0	0
Construction firm	(A) with environmental accreditation	20	30	25	30
	(B) with environmental commitment	10	15	15	15
	(C) others	0	0	0	0

Table 3. Scoring of the “Manufacturing and assembly” indicator

In this case, as may be seen in Figure 5, the value function takes the “S” form, once again seeking to encourage companies participating in the constructive process to obtain environmental accreditations that many small companies from that sector lack.

$$P2 = \frac{1}{100} * \sum \left[P_{factory} \quad \text{or} \quad P_{site} \right] \qquad [4]$$

where:

P_2 = the score of the “Manufacture and Assembly” indicator for the project

$P_{factory}$ and P_{site} = Score placed in the corresponding column that reflects whether the structure is principally made in the factory or whether the timber has also to be assembled on site. These values are also a function of the distance between the timber works and the location of the site (Table 3).

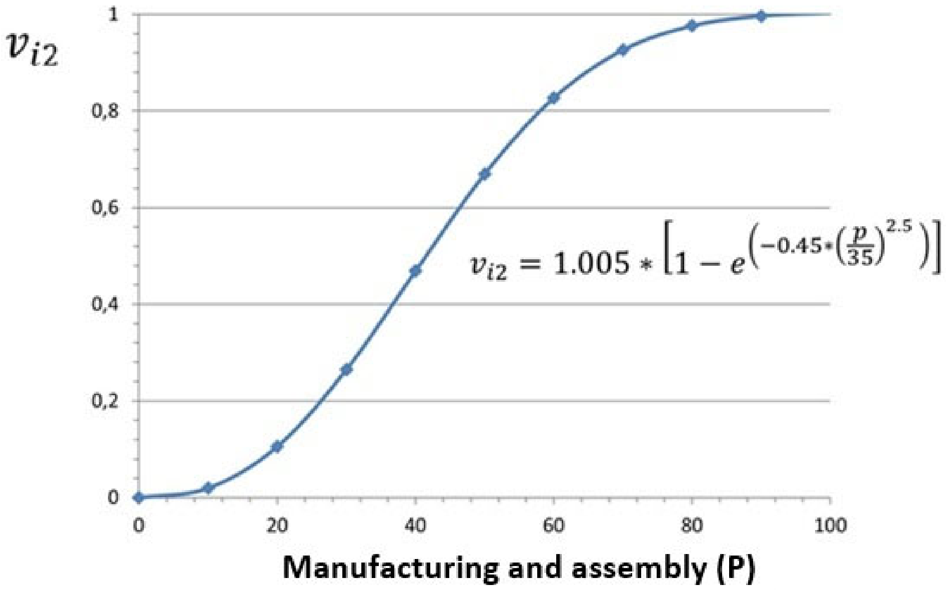

Figure 5. Value function of “Manufacture and assembly” indicator

Indicator 1.3 **“Optimization of resources in use”** represents the contribution associated with the reduction of the amount of timber for structural purposes, so that the use of appropriate high-performance materials is encouraged such as plywood rather than sawn wood.

Use of materials	P_{use}
Plywood	70
Sawn wood	30

Table 4. Scoring of “Optimization of resources in use” indicator

This same indicator also takes into account the source of the timber, so that local timber receives a higher score than the timber from forests that are at a greater distance. On the one hand, transport of timber over longer distances will have a higher environmental impact and, on the other hand, it will not be beneficial to the local economy and to local sectoral growth.

Origin of the material	P_{origin}
Origin of the timber with regard to its consumption ≤ 300 km	55
Origin of the timber with regard to its consumption between 300 and 1000 km	35
Origin of the timber with regard to its consumption ≥ 1000 km	10

Table 5. Scoring of “Optimization of resources in use” indicator.

Expression 5, based on tables 4 and 5, gives a score to assign to the value function, which is a growing function in this case, as may be seen in Figure 6. A high value may therefore be obtained with a relatively low score. In this way, the use of local timber is strengthened, stimulating greater local activity in the sector and the use of plywood, stronger than sawn wood.

$$P3 = \frac{1}{200} * \sum \left[\%Vol_{use} * P_{use} + \%Vol_{origin} * P_{origin} \right] \qquad [5]$$

where:

P3 = Score of the indicator ‘Optimization of resources in use’ for the project.

%Vol use = Percentages by volume of sawn wood and plywood.

Puse = Score for the type of wood in use (Table 4).

%Vol origin = Percentages by volume of timber according to its origin.

Porigin = Score corresponding to the origin of the timber (table 5).

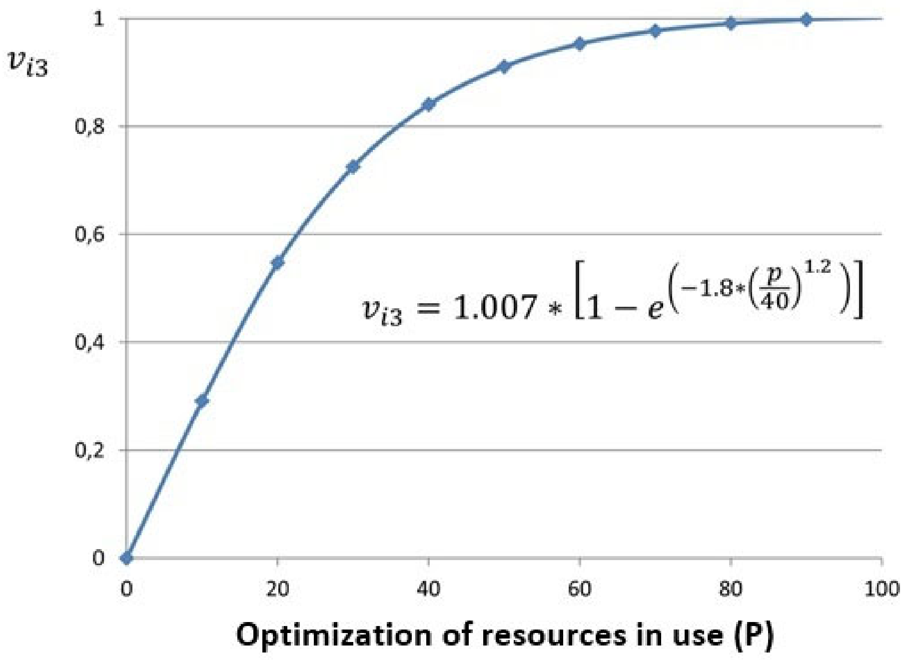

Figure 6. Value function of “Optimization of resources in use” indicator

5. CASE STUDY

This section presents the application of the model to a real residential building, so that both the results and any variations may be clearly seen. Specifically, this building is the largest and tallest residential building in south-western Europe that was built with timber as the main structural building material. The project consisted of 65 officially protected housing units in two buildings: 32 homes for sale and 33 for rental.

The building has 2 underground garage floors and a ground floor shopping mall made of reinforced concrete. The behavior and the durability of this material underground make it the most suitable for this part of the building and wood is incorporated from the ground floor as a structural material. The four upper floors and the roofs consist solely of timber (walls, floors, stairs ...), incorporating cross laminated timber (CLT) panels. In this type of construction, all elements, both the main walls and facades and interior partitions, collaborate in the transmission of loads and assume bracing functions for the stability of the whole building.

The following describes the different options that have been defined, to which the evaluation model has been applied; the first of the options is the real case already built, which is taken as reference and is called Option A. Based on the real case, two new options were defined (Options B and C), once several modifications had been introduced. The objective of proposing these two new options was to show the results of the modified options and their variations as clearly as possible.

Real Case - Option A

A local industrial manufacturer assembled the panels at a distance of (110 km). In total, 2,500 m3 of radiata pine cross-laminated timber (CLT) was sourced from surrounding forests (under 100 kilometers in distance) with PEFC certification at the express wish of the promoter, a regional-level Public Society. Industrialized construction in timber now involves short assembly times, minimizing the deviations caused by climate-related variables. In this project, the timber complied with "service class 1", according to the classification of the CTE (Spanish Ministry of Development, 2006): "covered structural element, protected from the weather and not exposed to humidity; the humidity content of timber is less than 20%". Following the installation phase, the panels were covered with gypsum interior wall panels (due to strict fire protection regulations) and a ventilated façade on the outside (to avoid further treatment of the timber and to increase its durability), so that the timber was not visible, although its benefits can be seen in issues such as humidity and air purification regulations.

The system employed in this project, in addition to its full compliance with all technical construction requirements, offered some advantages from an environmental perspective; the timber came from the surrounding forests and was also sawn nearby, which implies energy savings in all phases of a sustainable, circular economy. At the same time, the timber construction reduces water consumption, thereby making the work much cleaner. In fact, the work generated by cross laminated panels is almost completely dry. In addition, the reduction in weight of a timber structure also reduces the dimensions of the foundation and basement elements, unlike a conventional concrete structure.

The local company responsible for manufacturing and assembling the CLT panels holds the ISO 9001 and ISO 14001 certifications. In addition, the local company responsible for the civil works also holds the ISO 9001, ISO 14001, and OHSAS 18001 certifications.

Although the CLT panel manufacturer is responsible for all possible waste generated in the assembly process, using waste disposal services, no waste recovery agreement has been signed.

Figure 7. Option A: Real case study

Having applied the model to the proposed project, an Environmental Sustainability Index of 0.928 over 1 was obtained, as shown in Table 6. The distribution of the results in a spider graph can be seen in Figure 8.

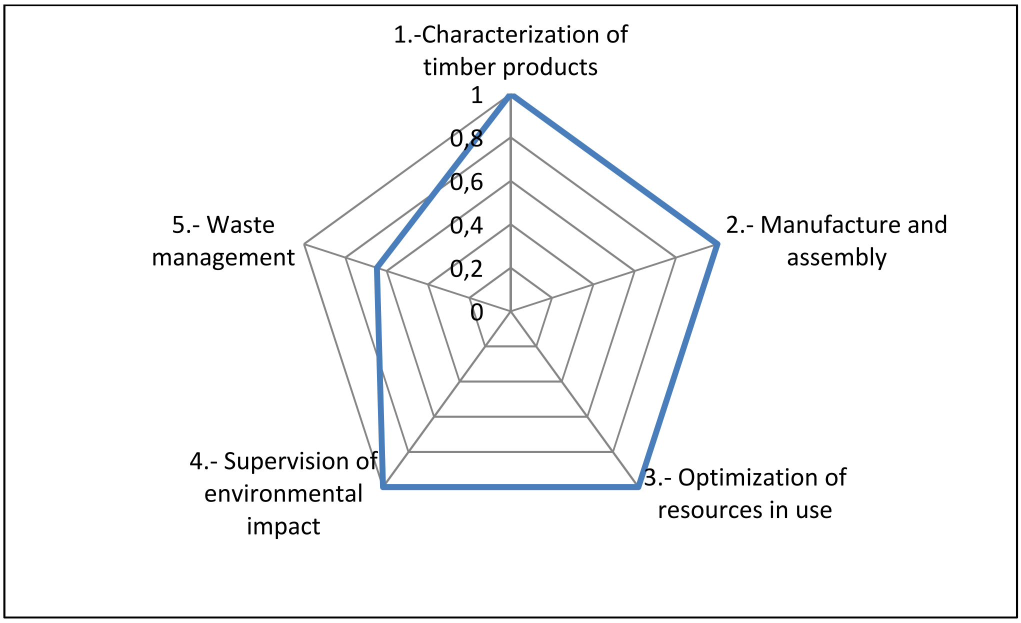

Figure 8. Case study results

This high value of the Environmental Sustainability Index was obtained at the insistence of the promoter, who wanted to build a highly sustainable building, not only in relation to the materials, but also in relation its energy efficiency, classified as "A".

Option B

The CLT panel manufacturing company could have purchased certified timber from another country, for example from Austria, in which case the material would have been transported over a distance of 1900 km. In the case of bringing timber from a distance of 1900km and leaving the other parameters constant, the sustainability value was 0.823, as can be seen in Table 6. The distribution of the results in a spider graph can be seen in Figure 9:

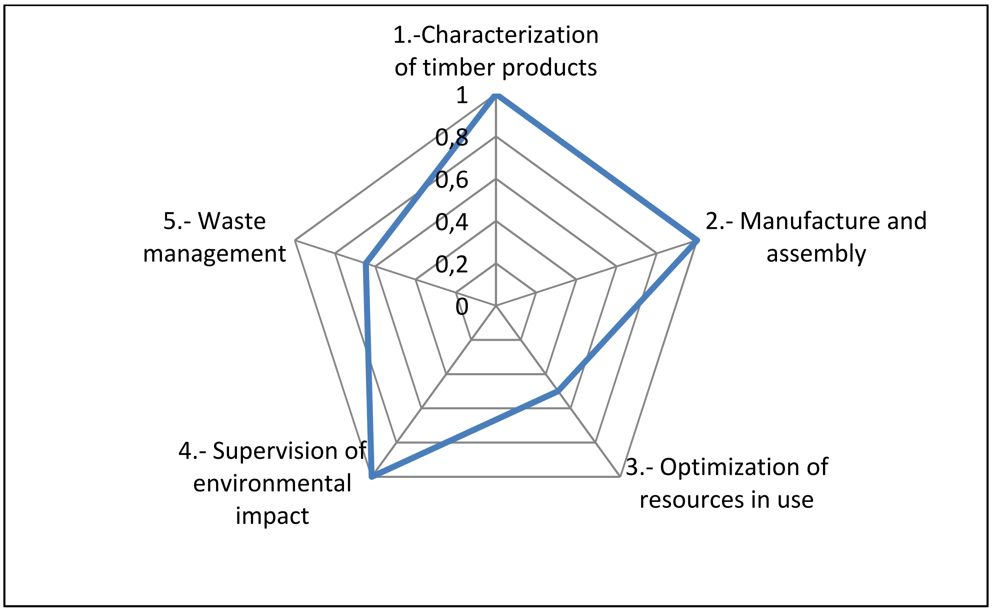

Figure 9. Option B results

As a consequence of the impact on timber transportation from Austria, the ESI-TS index was reduced by 12.7%.

Option C

The possibility of using non-certified timber was also considered, mainly due to the low level of certified timber consumption in the Spanish construction sector. In this case and using non-certified wood from the forests near the works and holding the remaining parameters constant, the value of the Environmental Sustainability Index was 0.648 (a 43.2% reduction), as described in Table 6. Its distribution in a spider graphic is depicted in Figure 10.

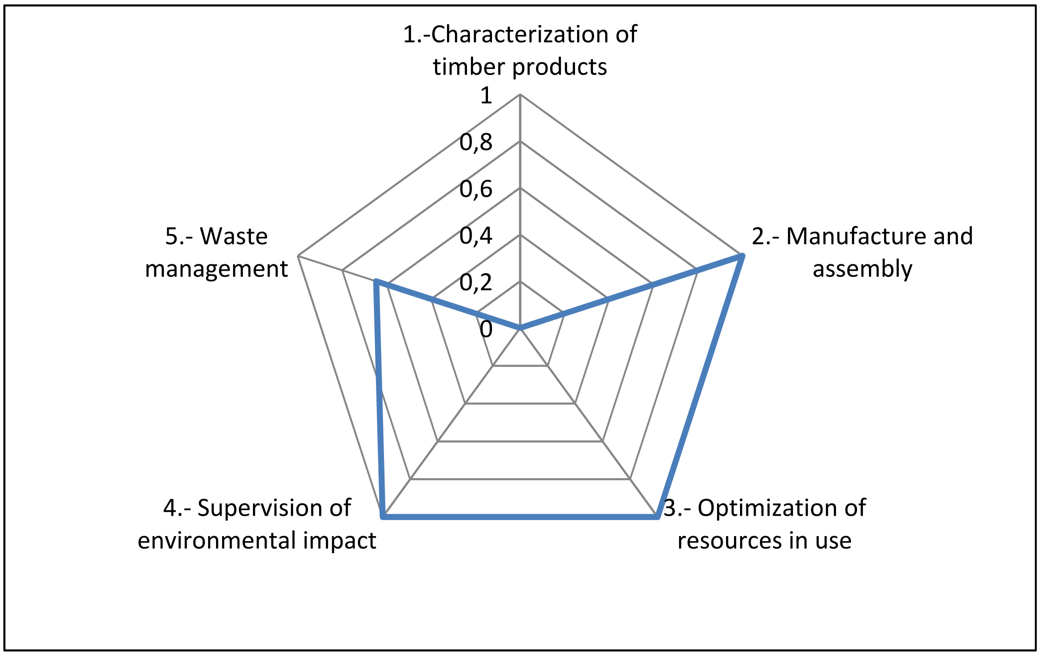

Figure 10. Option C results

Table 6 shows the final values of the indicators and the ESI-TS index in the real case (Option A) and in the two additional hypotheses that have been proposed (Option B and C), in which the values obtained by each indicator are shown in each of the options that have been defined.

Criteria	**Indicator**	**Indicator score**		
		Option A	**Option B**	**Option C**
Products (70 %)	**P1 (40%)**	1.000	1.000	0.000
	P2 (30%)	1.000	1.000	1.000
	P3 (30%)	1.000	0.499	1.000
	Result:	1.000	0.849	0.6
Measures to reduce impacts (30 %)	**P4 (33%)**	1.000	1.000	1.000
	P5 (67%)	0.647	0.647	0.647
	Result:	0.763	0.763	0.763
	Value of ESI-TS	**0.928**	**0.823**	**0.648**

Table 6. Assessment results

6. SENSITIVITY ANALYSIS

The Environmental Sustainability Index (ESI-TS) values directly depend on the criteria and indicator weights and therefore, small changes in these weights can cause important changes in the final value of the assessment (Chang et al., 2007, Delgado and Sendra, 2004). These weights rely on the opinion of the expert panel members. The validity, stability and robustness of the results are very important; therefore, a sensitive analysis including the variation of the weight criteria seems to be the most appropriate.

A One-At-a-Time (OAT) sensitivity analysis was selected as the most popular AHP-based methodology (Chen et al., 2008); it is a simple methodology, computationally effortless which draws understandable-easy results (Chen et al., 2013). If the results are very sensitive to slight changes in the weight of the criteria, then a careful review of these weights is recommendable.

In this work, the criteria weights were modified in a separate and independent way, through the introduction of ± 15%, ± 30% and ± 40% changes respectively, defining 4 new scenarios for each change in this process. The rest of the criteria weights were altered on a proportional basis, so that the sum of all the weights always reached 100%. The percentage variations of the Environmental Sustainability Index for Timber Structures (ESI-TS) were calculated with that process and are presented in Table 7. Despite significant variations from the criteria weights were observed, similar results among the four scenarios were observed. These findings suggest that the evaluation model correctly describe the ESI-TS (Chen et al., 2009). In the present study, the Environmental Sustainability Index (ESI-TS) underwent a maximum variation of 7.14%, which can be qualified as small, considering that it was generated as a consequence of a significant variation in the criteria weights (40%).

±15% Variation	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
	2.68%	-1.15%	-2.68%	1.15%
±30% Variation	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**

	5.36%	-2.30%	-5.36%	2.30%
±40% Variation	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
	7.14%	-3.06%	-7.14%	3.06%

Table 7. Percentage of ESI-TS rate variations

7. CONCLUSIONS

Timber has unique characteristics as a versatile construction material. Nowadays, it is seen from the environmental point of view as a real alternative to steel and concrete in mid-rise structures, which explains the increasing use of timber as the main construction material in many new buildings.

The model that has been presented in this paper is one of few to address the evaluation of timber structures and specifically their environmental sustainability. It is based on the MIVES methodology and, like the Spanish Structural Concrete Code (Spanish Ministry of Development, 2008) and Steel Code (Spanish Ministry of Development, 2011), its objective is to establish a quick index in a way that is not excessively time consuming so that decisions can be made in the project phase. In this sense, the model is not designed to compete with other models that offer a comprehensive sustainability evaluation method of the whole building and ancillary facilities. Instead, the model presented in this paper focuses in a more detailed way on improving the sustainability level of the timber that constitutes its structure, for which purpose it defines specific structure-related parameters.

Therefore, this model may be used to improve the environmental sustainability of timber structures at a design stage and to reduce the impacts that may be generated, in those aspects where the score is lower. It is flexible for application in other parts of the world, although it would have to be adapted to the particular context of each country.

Regarding the application of the model to the case study, it can be concluded that changes in the material, such as those related to its origin and environmental certification, generate meaningful changes (respectively, 12.7% and 43.2%) in the overall results of the assessment.

8. LIMITATIONS AND FURTHER RESEARCH

The objective has been to design a global model, applicable in different countries to timber-based buildings, although it has been applied and tested in the Spanish construction sector. Its application to buildings located in other countries would require the formation of a national-level Expert Panel to analyze the specific characteristics of the timber-based construction sector, processing this information when adapting and adjusting the weights of each indicator and criteria to its own reality. It is a necessary stage, as the weighted criteria are extremely dependent on the characteristics of the construction sector at a national level.

Additionally, case studies applied to larger samples of timber-based buildings with different dimensions and characteristics would be of interest for the analysis of the results and for testing the proposed model in a wider sample. Two future lines of research could therefore be outlined: the export of the model and its working method to other countries and the application of the model to a wider sample of timber structures.

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