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## 1. Introduction

In the last decades there has been a growing evidence on the fact that modern forms of the human way of living have contributed to an over-exploitation of both renewable resources such as land and non-renewable ones like earth minerals, fossil fuels and groundwater (Goodarzi et al. 2016, Jia et al. 2019, Pathak and Dodamani 2019, Zhou et al. 2019). These resources are essential to human development, these being major sources of energy and other goods. This is leading to a movement at an international level that advocates for a more sustainable way of living; namely, that it satisfies the needs of the present generations without compromising the quality of life of future ones (Brundtland et al. 1987, Marjaba et al. 2016, Roostaie et al. 2019). Sustainability stands for a way of improving people's welfare without degrading the environment or affecting the well-being of other people (Du Bose and Pearce 1997). It must be emphasised that, among all the industries, construction stands as one of the sectors that has the highest negative impacts on the environment (Ding 2008, Khasreen et al. 2009). As Levin 1997 points out, the construction of buildings is linked to eight of the major environmental stressor categories: use of raw materials, energy, water and land, pollution emission, water effluents, solid waste and other releases.

Sustainability in construction, as in many other fields, implies taking a lifecycle approach. Therefore, when considering the social, economic and environmental indicators, these need to be accounted for during the whole lifecycle of the structure, from its planning until its decommissioning. One barrier to sustainability in construction is the fact that sustainable infrastructure is usually misleadingly only linked to concepts such as green buildings or energy efficiency in buildings (Ding 2008, Haapio and Viitaniemi 2008, Moakher and Pimplikar 2012, Zuo and Shao 2014, Kim et al. 2018). Nevertheless, these aspects only accounting for factors encompassed in the environmental pillar of sustainability. When aiming at designing sustainable infrastructures, designers and engineers need, not only to incorporate information on factors that are related to environmental impacts but also on those related to economic and social aspects.

A key characteristic of buildings that can play a vital role in minimising a building's impact is the material used (Govindan et al. 2016). In the civil engineering evolution, the material used has had a huge influence on construction development. From natural materials such as stone and timber during ancient times, going through clay, stone and bricks and finally to steel and cement after the 18th century. More recently, in the 20th century, timber regained popularity thanks to the development of new technologies of production and proper preservation methods, as well as the application of high strength timber (Berge 2000, Deplazes 2005, Doran and Cather 2014, Vatan 2017). Current efforts in guaranteeing sustainable construction have posed a particular emphasis on the development of new technologies and new materials such as repurposed materials (Sieffert et al. 2014). Unfortunately, it must be emphasised that these innovative systems are infrequently used in practice because of the high costs linked to cutting-edge technologies or because of the inadequacy of these technologies respect to the existing sustainability assessment guidelines and tools.

Therefore, the need for assessing the extent to which the choice of material of specific structural elements contributes to the sustainability of a building is evident. There is actually a large body of literature dealing with multi-criteria methodologies aiming at establishing frameworks that consider the multidimensionality of real-world problems (Invidiata et al. 2018, Navarro et al. 2019, Stojcic et al. 2019). In this context, MIVES is a methodology that allows supporting multi-criteria decision-making processes. This has proven to be efficient and robust for this purpose in several fields, such as: underground (de la Fuente et al. 2017) and hydraulic (Pardo and Aguado 2014, de la Fuente et al. 2016) infrastructures; building components and systems (Pons and Aguado 2012, Pons and de la Fuente 2013, Pons et al. 2016, de la Fuente et al. 2019); industrial construction (San-José Lombera and Garrucho Aprea 2010); urban development (Pujadas et al. 2017); electricity generation infrastructure (Cartelle et al., 2015; de la Fuente et al., 2017) and, even, post-disaster housing management (Hosseini et al., 2015, 2016). Additionally, it is worth to mention that the Spanish Association of Structural Concrete (Aguado et al. 2012) and the *fib* (fédération international du béton) Commission 6 (prefabrication), with the launching of the *fib* bulletin 88 (fib 2018), have also included the model MIVES as a reference tool to deal with sustainability analyses of structural components for buildings and infrastructures (de la Fuente and Fernández-Ordóñez 2018).

In view of the abovementioned, the objective of this research paper is twofold: (1) to propose a MIVES-based model to assess the sustainability of structural components and, (2) to use this model to deal with the sustainability evaluation of the most representative alternatives (materials and structural typologies) for girders and trusts for the construction of sports halls' roofs in Spain. These facilities were found to be structurally representative and versatile of other uses as one-storey-framed buildings (e.g., industrial purposes, markets or shopping centres); likewise, the girders that are used for this application are also meant to fulfil several architectural, aesthetics and other social requirements which are rarely evaluated and, if so, this is done in a rather subjective manner. The MIVES model presented herein is designed to consider, objectively, the three pillars of sustainability.

The remainder of the paper is structured as follows: section 2 presents the study case that is analysed in this paper. Next, section 3 introduces the methodology that has been followed to build the sustainability assessment framework and describes the proposed model. Next, in section 4 the results of the study case are analysed and discussed. Then, in section 5 an extensive statistical sensitivity analysis is performed with the objective of guaranteeing the robustness of the results. Finally, in section 6 the main conclusions derived from the result are gathered.

## 2. Study case

### 2.1. Selection of alternatives for the study case and system boundaries

For the selection of the alternatives analysed, an initial study was conducted. As it has been mentioned, sports halls have been chosen due to the fact that one-storey frames constitute versatile building options for a wide range of purposes. Therefore, information on a total of 444 sports halls in the region of Catalonia was gathered. The buildings were classified according to the girder's material and structural typology used for supporting the roofs; the span length was also a classifying parameter. The Catalan Sports Council establishes that there are mainly three types of sports halls depending on the dimensions of the sports courts, whose width can be of 20, 23 or 28 m (Consell Català de l'Esport 2005). In the present analysis, a building with a span of 28 m has been chosen. The alternatives to be assessed were selected on the basis of the following criteria: (1) whether they were representative of all the existing structural typologies, not only at national level but also in a more general geopolitical context; (2) whether there was an interest of alternatives that are currently not being used because of misconceptions about their sustainability. In the present study, this is the case, for example, of concrete trusses.

The LCA stages that have been considered are the following: (1) extraction of the material and production; (2) production of the structural elements; (3) transportation to the construction site; (4) installation of the structural element; (5) basic maintenance during the service and operational life of the element, which has been considered to be of 50 years. Note that depending on the alternative considered, the order of steps (2) and (3) might change due to practical reasons, which were described in section 2.2.1.

A 28 m-span girder or truss was considered a functional unit. Reinforced or prestressed concrete, steel and timber were the structural materials considered for the construction of these elements. The structural design was dealt with the reference Eurocode associated with each structural material: reinforced/prestressed concrete EC-2 (EN 1992-1-1 2004), steel EC-2 (EN 1993-1-1 2005) and timber EC-Y (EN 1995-1-1 2004). Hence, the loads (permanent and live loads) to be considered and the partial safety factors applied to both loads and materials' strengths are consistent with a unique safety format. It must also be emphasized that the roof is non-accessible and, therefore, the design loads are only those associated to environmental aspects (snow, wind and thermal gradients) and other transient loads (repair, maintenance).

Finally, in terms of durability, it should be remarked that the service life exposure conditions are normal for all the structural materials considered and no special treatments or additional measures, except the minimum expected maintenance, is considered.

### 2.2. Alternatives studied

After carrying out the analysis as described in section 2, seven alternatives resulted to be representative (see Table 1); the first letter of the coding refers to the material and the following letters correspond to the structural typology.

**Table 1**. Alternatives considered and chosen (in bold) in the study case

| Material | Structural type | Code | Percentage (%) |
|---|---|---|---|
| Steel | Flat truss | SFT | 35.78 |
| | Sloped truss | SST | 22.84 |
| | 3D truss | | 10.78 |
| | Beam | | 13.36 |
| Concrete | Truss | CT | 0.86 |
| | Beam | | 3.88 |
| | Lightened prestressed | CLP | 2.59 |
| | Prestressed | CP | 2.16 |
| Timber | Beam | TB | 6.90 |
| | Truss | TT | 0.86 |

As it can be seen in the table 1, there are three structural typologies that were disregarded for the analysis. On the one hand, from the beginning it has been said that plane frame structures are the structural typology considered in the analysis and, hence, 3D trusses were neglected as considered to be unfrequently used for this type of applications and spans. Some of the advantages that several authors attribute to spatial trusses are: stiffness and lightness, higher industrialised degree and aesthetic quality (Li 1997, Bradshaw et al. 2002). Therefore, this decision does not compromise the representability of the sample since these characteristics are also achieved to a certain extent by two-dimensional trusses. On the other hand, steel and concrete girders were disregarded because the span-length range of the sport hall's chosen is scarcely technically-economically compatible with these alternatives. In spite of the dismissal of these three structural typologies, the representativeness is still high and corresponds to 72% of the total. The dimensions and detailing of the alternatives that have finally been considered in the study case are shown in Figures 3 (steel structures), 4 (concrete structures) and 5 (timber structures).

As for the production of each alternative, the following situations have been considered. It has been assumed that the prestressed concrete beams and the timber beam are produced in a factory and transported to the construction site using special transportation. Regarding the steel trusses and timber truss, it has been considered that their components are produced in the factory and assembled so that no special transportation is required. Besides, in the case of the steel trusses, all the welding processes are considered to be performed in the factory and the parts left to the assembly *in situ* are joined using mechanical unions. Finally, the concrete truss has been considered to be completely manufactured in the construction site. With respect to the maintenance, the maintenance works for each of the structural elements have been decided as: a visual inspection every five years starting from the tenth year, as well as a superficial anticorrosion treatment every fifteen years for the steel trusses; a visual inspection every two years for the prestressed beams; a visual inspection every ten years starting in the second year for the concrete truss; an annual visual inspection for the timber truss and beam.

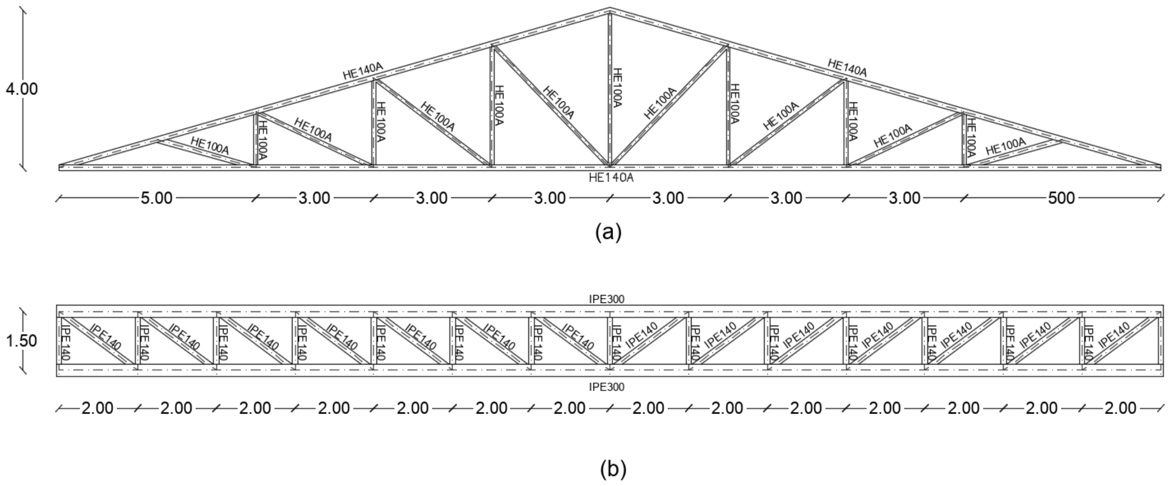

**Figure 1** Detailing of the design of the steel structures (the measurements are shown in metres)

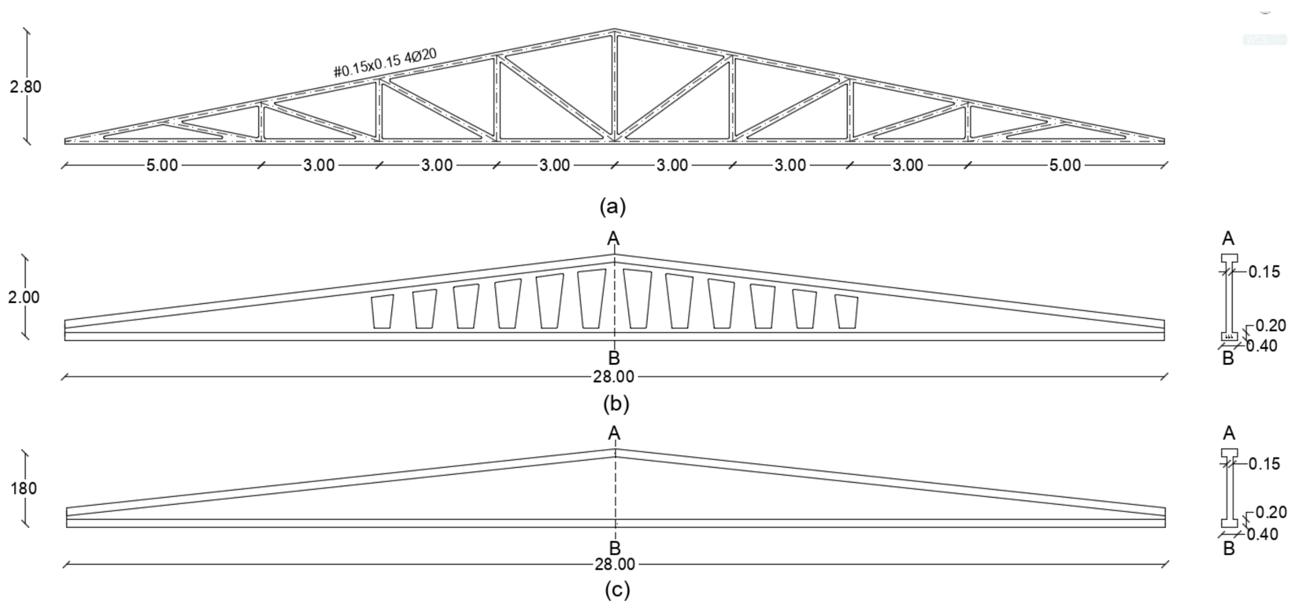

**Figure 2** Detailing of the design of the concrete structures (the measurements are shown in metres)

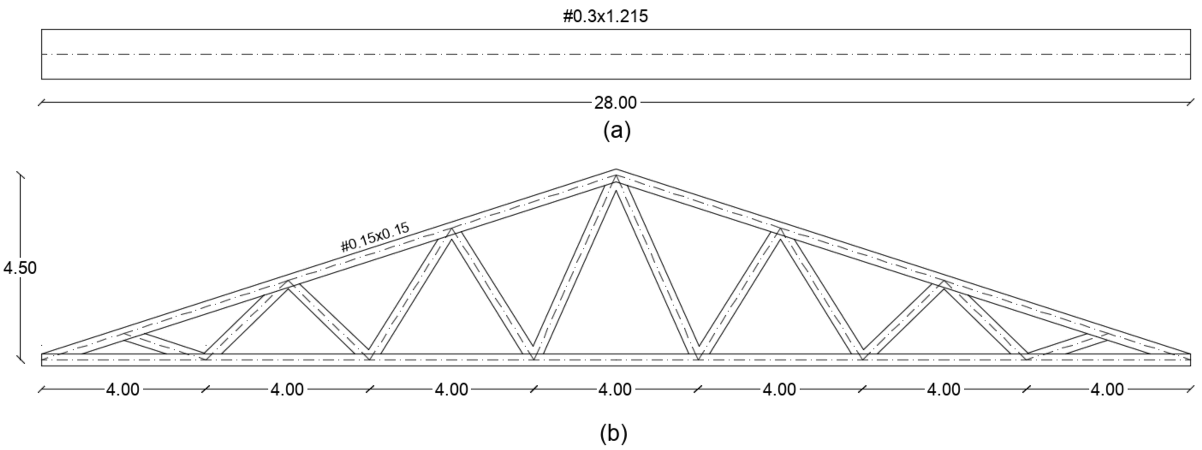

**Figure 3** Detailing of the design of the timber structures (the measurements are shown in metres)

## 3. Method

The following sections describe the most relevant methodological aspects of the sustainability assessment performed: the method MIVES (Integrated Value Model for the Evaluation of Sustainability), the proposed model and the selection of the alternatives for the study case, together with its system boundaries.

### 3.1. MIVES

MIVES (Integrated Value Method for Sustainable Evaluations) is a method aimed at supporting decisions based on the multi-attribute utility theory. The approach of the model and the definition of the weights of each of the aspects must be, in general, prior to the creation and evaluation of the alternatives. Doing so, a more complete objectivity is reached. Actually, the basic goal of any decision-making model is to objectify utmost the inherent subjectivity in those decisions in which not all the parameters are favourable to the same alternative.

Through this method, each one of the alternatives of a specific problem is evaluated in order to give an optimal resolution, which is based on the value of a final index. The value of this index is obtained through the aggregation of the evaluation of several different indicators, criteria and requirements that were previously chosen by the stakeholders. Generally, it is assumed that the preferences of the decision maker with respect to the indicators are known or can be estimated. Besides, MIVES structures the problem at different levels. Each level contains the parameters to be studied and depends on the studied case. The first levels include aspects that are more general and qualitative, whereas the last levels include the most specific aspects, which are referred to as indicators. In this project, a framework that is made up of three levels was used; this framework is comprised of requirements, criteria and indicators.

Among these three factors, indicators are the only aspects that are assessed during the process. The evaluation is carried out by applying a value function to the indicators; value functions allow transforming qualitative or quantitative variables with own scales and units into a non-dimensional value comprised between 0 and 1, corresponding to the minimum and maximum degrees of satisfaction respectively. More details on the characteristics and application of value functions can be found in the Appendix.

Having said this, the process to implement MIVES follows the steps shown in Figure 6. First, the theoretical framework on which the decision tree is based must be built, and the indicators corresponding to each of the last aspects in the last level defined (see section 3.2 for a detailed explanation on the decision tree). Afterwards, if there is an alternative for which there is missing data, the situation needs to be analysed in order to decide how to treat this lack. However, in the present study this step has been skipped since data was collected for all the indicators. Then, in order to be able to aggregate the indicators it is necessary that the variables are normalised; for this purpose, the above-mentioned value functions were calibrated and used. The weighting and aggregation come after obtaining all the indicators in a range between 0 and 1. Once the values for each alternative's index are gathered, it is necessary to examine the robustness of the results. For this, a sensitivity analysis is needed (this is detailed in section 5). Finally, the results can be contrasted so that the best alternatives in terms of sustainability can be identified.

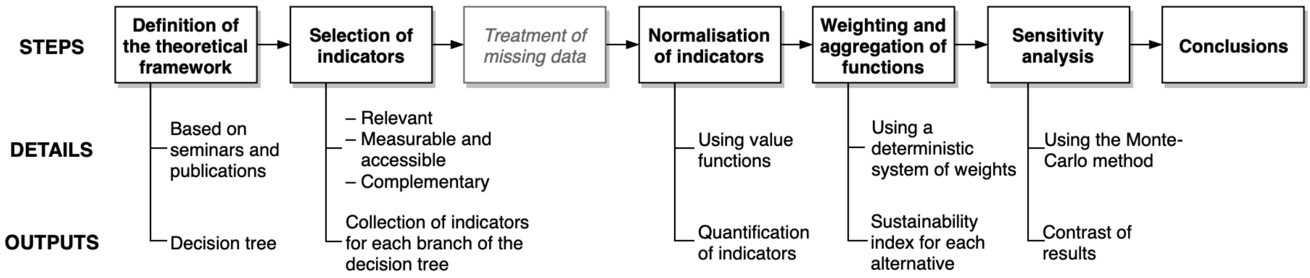

**Figure 4** Process followed to implement MIVES

In the following subsections, some specific methodological aspects that require further explanation are described.

### 3.2. Assessment model

Aiming at assessing the sustainability of the different alternatives, three requirements were established: economic, environmental and social, these being the three reference pillars onto which sustainability is supported according to (United Nations 2005). The definition of the criteria and indicators for each of the three requirements is of great importance for both the representativeness and reliability of the results. Therefore, the adequacy of the assessment model was ensured by carrying out seminars with experts throughout various sessions, as well as by searching academic and technical study case publications in the same field (e.g., Akadiri et al. 2013, Meysam Khoshnava et al. 2018, Mahmoudkelaye et al. 2019). There were experts from both academic and business sectors, and the expertise was in sustainability as well as in construction materials and structural design.

Figure 7 shows the making-decision tree with its three corresponding levels as well as with the weights assigned to each of the aspects. As for the weights, these were assigned based on guidelines given in publications made in the same field (*fib* Bulletin nº 88, 2018) and confirmed according to experts' criteria.

#### 3.2.1. Economic requirement

The economic requirement is represented by two criteria: *construction costs* (C1) and *maintenance costs* (C2). The first one, C1, is made up of an indicator that includes the *direct costs* (I1); namely, those costs attributable to the material, to the transportation and to the installation. These three items are added up in order to obtain the indicator's value. The evaluation of these costs has been carried out using two different methodologies. First of all, different costs databases and costs simulators were examined. For the material and installation costs, CYPE and ITEC databases were used (CYPE Ingenieros 2019, ITeC 2019). For the transportation costs, a costs simulator was used (OTEUS 2019). These databases were chosen because they provide prices adjusted to the context in Barcelona, Spain, which is the area and the country in which the study cases have been located. Secondly, three discussion boards (for steel, concrete and timber respectively) were held in order to verify that the results obtained from the databases were appropriate.

The second criterion, *maintenance* (C2), covers the costs related to the maintenance of the infrastructure. No reparations for accidental actions have been considered. On this point, the information that has been used is from the database elaborated by CYPE and from recommendations given in real projects. The two groups of data have been contrasted to check their coherence.

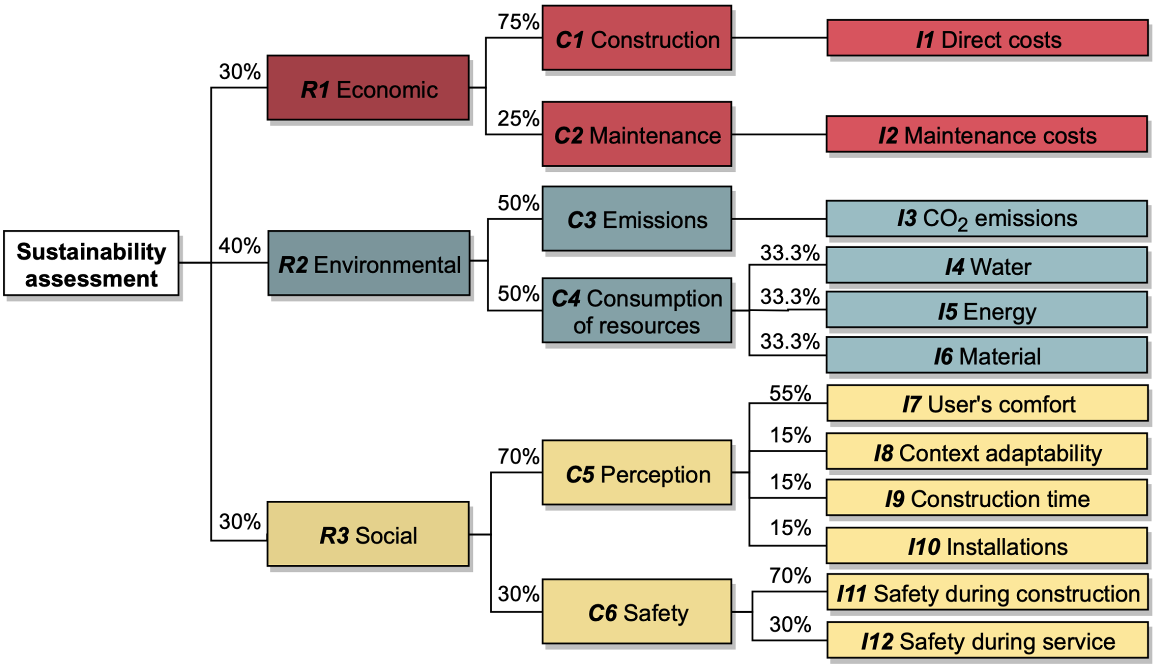

**Figure 5** Making-decision tree model for the study case

### 3.2.2. Environmental requirement

The environmental requirement is comprised of two criteria: *emissions* (C3) and *consumption of resources* (C4). The objective of criterion C3 is to favour those alternatives with a lower impact in terms of $CO_2$ emissions. Therefore, this criterion includes an indicator, *$CO_2$ emissions* (I3), which is a greenhouse gas and that, consequently, contributes to the greenhouse effect by absorbing and emitting thermal radiation. In the analysis of the lifecycle, the stages that were included were: (1) extraction of the materials, (2) manufacture of the element, (3) transportation to the sports hall.

The purpose of criterion C4 is, on the one hand, to minimise the consumption of resources and, on the other hand, to account for the possibility of reusability of different materials, both at the construction and at the decommissioning stages. For this, three indicators are proposed: *energy* (I4), *water* (I5) and *resources* (I6).

- The assessment of indicators I4 and I5 is direct and considers the same stages of the lifecycle as indicator I3.

- As for indicator I6, its main purpose is to consider the amount of each material that is used and also the inherent characteristics. Therefore, for its evaluation three different sub-indicators were defined: scarcity of the raw materials, recycling potential and potential for using recycled materials. These variables were adapted from Harris 1999 and Vefago and Avellaneda 2013 to the present project.
    - The scarcity of the raw materials considers whether the materials used for the production of the structural elements are easily found or are endangered by an insufficiency in the amount of the material at a global level (Wagner 2002).
    - Concerning the recycling of the materials, Gao et al. 2001 define a recycled building material as the "material which can be remade and reused as a building material after the building is disassembled". Maccarini Vefago and Avellaneda 2013 consider that the materials that reach the lifecycles at least once can be classified into four different groups: recycled materials, which are those materials that maintain the initial properties but these do not need to serve the same function in the next life cycle; infracycled materials, whose initial properties decrease and therefore do not need to serve the same function in the following life cycle; reused materials, which maintain the initial properties and do not need to serve the same function afterwards. Differently to recycled materials, reused materials do not pass through any chemical transformation or changes in their physical state and these have the same performance in the following cycles. Finally, the processes that infraused materials undergo have the same characteristics as reused materials, but their initial properties decrease and these cannot serve the same function as these did in the previous lifecycle. Therefore, the recycling potential seeks to evaluate the extent to which the materials can be used after the lifecycle ends. The indicator was calibrated by scoring from 1 to 5 depending whether the material can be used as landfill, it can be infraused, infracycled, recycled or reused, respectively.
    - As for the potential for using recycled materials, the sub-indicator assesses whether the alternative considered can make use of previously used materials, and the sub-indicator was scored between 1 and 3. The scoring of these sub-indicators was made according to Berge 2000, Thormark 2006, 2007, Vefago 2012, Vefago and Avellaneda 2013, Akanbi et al. 2018. In order to obtain I6, the total points given to each sub-indicator are directly aggregated, giving a number between 1 and 9.

### 3.2.3. Social requirement

The social criteria that were fixed in this model are two: *perception* (C5) and *safety* (C6). Firstly, criterion C5 aims at measuring how well the structural element adapts to its context and how it is perceived by its users and the local community. This first criterion encompasses four different indicators: *user's comfort* (I7), *context adaptability* (I8), *construction time* (I9) and *installations* (I10).

- *User's comfort* (I7) covers four areas: acoustic comfort, slenderness, warmth of the material and light. These areas were chosen following the research carried out by several authors about the impact on individuals' perception of materials and shapes:
    - Firstly, different materials have different acoustic properties; in a building that is occupied and where a high level of sound can be reached, which is the case of sports halls, the discomfort that occupants face needs to be considered. Factors that have been considered in the analysis of the acoustics of materials are its massiveness, density and rugosity (Rilo et al. 2002, Ijatuyi et al. 2007, Asdrubali et al. 2012). The acoustic comfort in this paper was measured giving a score between 1 (lowest comfort) and 3 (highest comfort).
    - Secondly, the slenderness seeks to assess the visual impact of the different alternatives (Burón et al. 1995, Menn 2012). The ratio of the height over the span length is calculated for each alternative and then points between 1 and 3 are given according to the value obtained.
    - Thirdly, the warmth of construction materials has been widely considered by architects, who argue that it's a property that highly influences user's experience in buildings (Bergmann Tiest 2010, Wastiels et al. 2012, 2013, Fleming 2014, Fujisaki et al. 2015, Wilkes et al. 2016). Again, the score between 1 and 3 is used to evaluate this sub-indicator.
    - In the fourth place, light in the interiors of buildings has been considered by many as an important aspect contributing to feelings of well-being (Jakubiec 2014). Even though there exist specific metrics for the measurement of visual comfort prediction, in this paper a more simplified method was used because it has been considered that more complex methodologies would not add more accuracy to the results given the weight of this sub-indicator with respect to the overall index. Therefore, a score between 1 and 5 has been assigned depending on whether light can or cannot go

through the structural element respectively. This sub-indicator is also considering what Menn 2012 calls the structural transparency. In the end, indicator I7 ranges between 1 and 14 as a result of adding up the four constituent sub-indicators.

- The second indicator, *context adaptability* I8, aims at measuring the level at which a structural element can be customised in order to adapt to local characteristics, such as a region's emblem.
- Indicator I9, *construction time*, measures the degree at which a longer duration of a construction process can negatively affect how it is perceived, and vice versa.
- The fourth indicator, I10, is a measure of whether service elements such as pipes that need to be set up in the roof can easily be installed through the structural element. This has been considered for two reasons: first of all, because it can affect the aesthetics of the building's interior; secondly, because it can introduce difficulties in the construction process.

The criterion adopted for *safety* (C6) is comprised of two indicators: *safety during construction* (I11) and *safety during service* (I12). It must be noted that structural safety during construction and service is considered as covered by applying the design regulations. In this sense, all the alternatives have the same structural safety. However, the purpose of these indicators is to evaluate the risks involved during handling in the construction and service stages of the structural elements. Both indicators are scored in a scale between 1 and 3 corresponding to low, medium and high levels of safety. The scoring of these attributes was made on the basis of the ranking scale proposed by Casanovas et al. 2014. It must be noted that the same ratings as in the publication were not used, but only adopted as a guideline to score the different alternatives in the mentioned interval.

### 3.3. Quantification of the indicators

For the quantification of the established indicators, value functions (see Table 2) were established and calibrated. The shapes of the indicators' functions were also graphically represented and these can be found in the Appendix, Figure A.2.

**Table 2** Values of the parameters of each of the indicators' value functions

| Indicator | | Units | Function | $X_{min}$ | $X_{max}$ | C | K | P |
|---|---|---|---|---|---|---|---|---|
| *I1* | Direct costs | € | DS | 0 | 10000 | 7000 | 2.5 | 4 |
| *I2* | Maintenance/reparation costs | € | DS | 0 | 25 | 17 | 2.5 | 4 |
| *I3* | CO2 emissions | kg CO2 | DS | 0 | 13000 | 6500 | 0.1 | 2.5 |
| *I4* | Energy | MJ | DS | 0 | 130000 | 65000 | 0.1 | 2 |
| *I5* | Resources consumption | points | IL | 1 | 9 | 1 | ≪1 | 1 |
| *I6* | Water | $m^3$ | DS | 0 | 9 | 4.5 | 0.1 | 2.5 |
| *I7* | User's comfort | points | IL | 1 | 12 | 1 | ≪1 | 1 |
| *I8* | Context adaptability | points | IL | 1 | 3 | 1 | ≪1 | 1 |
| *I9* | Construction time | points | DL | 1 | 3 | 1 | ≪1 | 1 |
| *I10* | Installations | points | IL | 1 | 3 | 1 | ≪1 | 1 |
| *I11* | Safety during construction | points | IL | 1 | 3 | 1 | ≪1 | 1 |
| *I12* | Safety during service | points | IL | 1 | 3 | 1 | ≪1 | 1 |

## 4. Results

The values of the indicators for each of the alternatives can be obtained by using the quantification of each indicator (Table 3) and the respective value functions (Table 2 and Figure A.2). The values were obtained from databases and seminars with experts as described in the previous section.

Figure 8 gathers three graphs representing the overall index of the economic, environmental and social requirements, as well as the contribution of each of the criteria to the total requirement.

**Table 3** Values of the indicators corresponding to each alternative

| | | **Steel** | | **Concrete** | | | **Timber** | |
|---|---|---|---|---|---|---|---|---|
| | **Units** | **SFT** | **SST** | **CP** | **CLP** | **CT** | **TT** | **TB** |
| **I1** | € | 3246.62 | 2349.25 | 7861.03 | 6390.19 | 1449.22 | 3144.64 | 9345.24 |
| **I2** | € | 13.99 | 15.45 | 5.31 | 5.31 | 2.34 | 22.59 | 19.03 |
| **I3** | kg CO2 | 12472.71 | 8784.79 | 3267.88 | 2141.93 | 1478.08 | 79.24 | 367.82 |
| **I4** | MJ | 129404.35 | 91142.16 | 76849.17 | 73627.58 | 62803.10 | 2770.30 | 12859.56 |
| **I5** | points | 9 | 9 | 3.5 | 3.5 | 5 | 4.5 | 5 |
| **I6** | $m^3$ | 8.42 | 5.93 | 1.80 | 1.66 | 0.43 | 0.05 | 0.02 |
| **I7** | points | 10 | 9 | 10 | 10 | 10 | 11 | 10 |
| **I8** | points | 3 | 3 | 1 | 1 | 1 | 1 | 1 |
| **I9** | points | 3 | 3 | 2 | 2 | 2 | 3 | 1 |
| **I10** | points | 3 | 3 | 1 | 2 | 3 | 3 | 1 |
| **I11** | points | 2 | 2 | 3 | 3 | 1 | 1 | 1 |
| **I12** | points | 3 | 3 | 1 | 1 | 2 | 2 | 2 |

The results allow stating that the reinforced concrete, steel and timber trusses present the best results for the economic requirement in comparison to both girder solutions made with prestressed concrete or timber. This is mainly since the direct costs associated to the production of the prestressed concrete is particularly expensive compared to the other solutions. As for the timber beam, its production costs are so high because of the beam's high span. The installation, transportation and maintenance costs, though, are similar in all the alternatives.

Concerning the environmental requirement, the highest values are attained by the elements made with timber, whereas those lowest correspond to the steel trusses. Even though steel is environmentally appealing due to the fact that almost the totality of the material can be recycled, its production generates a high amount of $CO_2$ emissions and consequently both steel alternatives score very poorly in criterion 3. Additionally, the amount of water necessary for its production is relatively significant in comparison to timber and concrete.

Finally, with regard to the social requirement, both steel trusses present the highest indexes, notwithstanding it needs to be emphasised that in this case the dispersion of the requirement ($\sigma = 0.099$) is much less than in the economic and environmental cases ($\sigma = 0.349$ and $\sigma = 0.256$ respectively). Trusses are the elements that achieve highest values of criterion 5, this owing to the fact that these score higher in terms of light in the interior of the building.

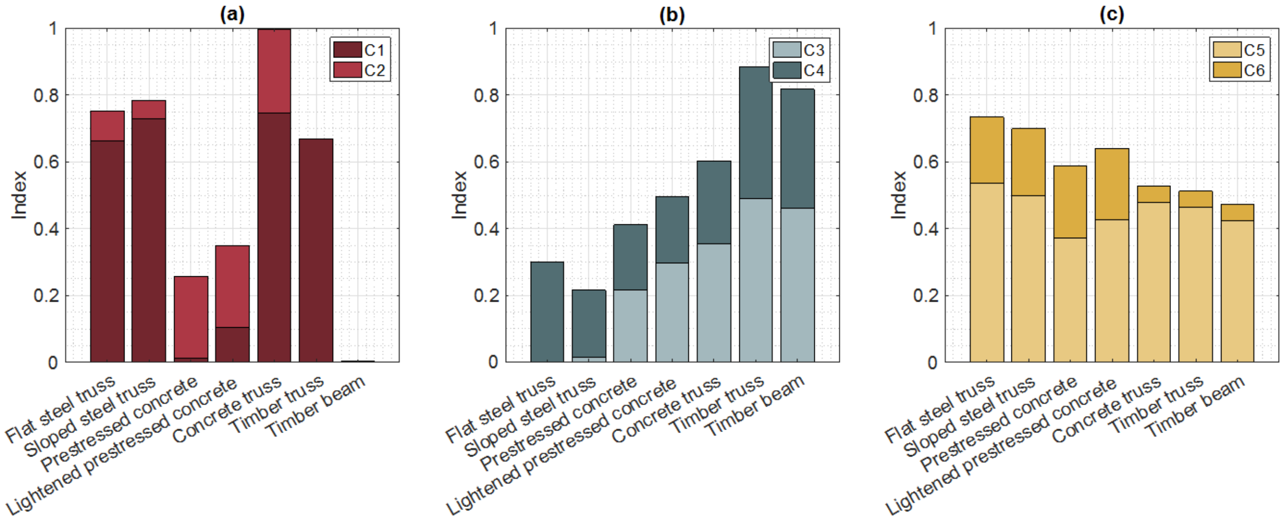

**Figure 6** Results of the analysis for the economic (a), environmental (b) and social (c) requirements of each alternative

Concerning the global sustainability index (SI), the values of each of the alternatives' indexes are shown in Figure 9. In the light of the results, it can be seen that the maximum index is obtained by the timber truss (SI = 0.71), albeit its index is closely followed by the concrete truss (SI = 0.70); next to these alternatives the flat steel truss (SI = 0.57) and the sloped steel truss (SI = 0.53) achieve the fourth and fifth highest indexes, even though again both values are quite similar; the three last alternatives are the lightened prestressed concrete, the timber beam and the prestressed concrete, with SIs of 0.50, 0.47 and 0.42, respectively. Nevertheless, the robustness of the results needs to be examined in view of the fact that there might be uncertainties in some of the results. Mainly, the concrete and the timber trusses achieve very similar SIs values; the same occurring with both steel trusses and with the prestressed concrete and the timber beams. The sensitivity analysis is described in the following section.

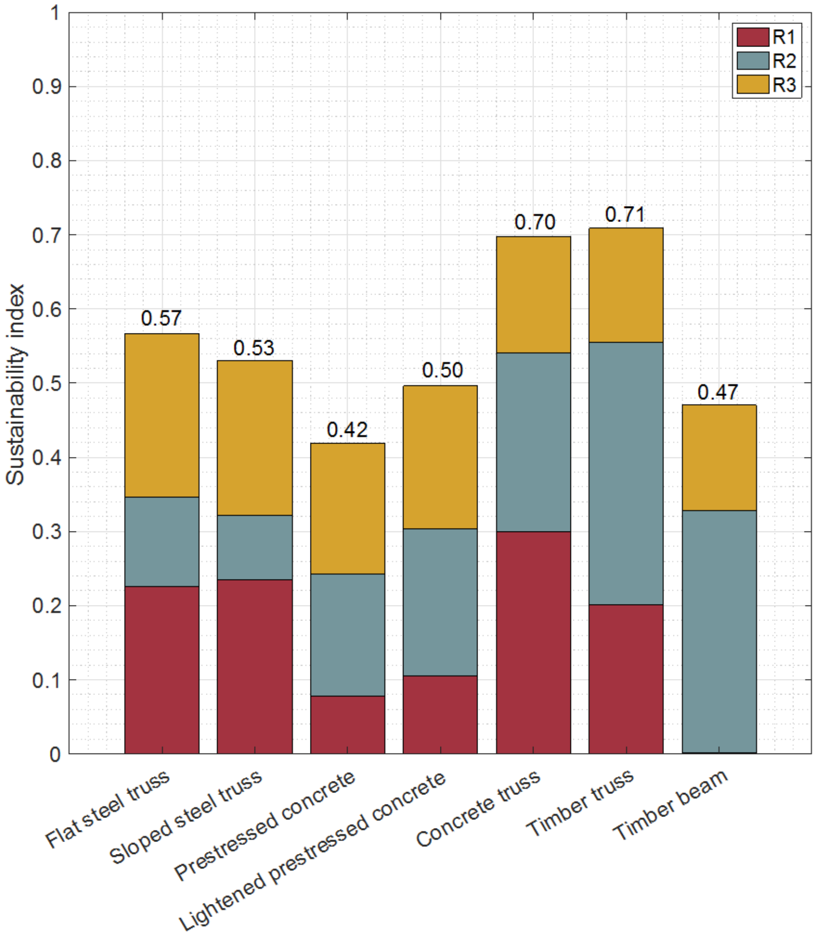

**Figure 7** Global sustainability index obtained for each alternative

## 5. Sensitivity analysis

In order to check the robustness of the results, a sensitivity analysis was carried out. Some authors assessing sustainability through indexes perform the sensitivity analysis by contemplating only a few cases which differ by the weights given to each requirement (see, for example, de la Fuente et al. 2016, García-Segura et al. 2018). However, del Caño et al. 2012 recommend using more complex statistical techniques when the results of the alternatives are tighter, which is what characterises the present study. On account of this fact, the Monte Carlo method was resorted to approach the problem probabilistically. Monte Carlo is based on the stochastic simulation done by repeating multiple times an experiment, so that a numerical approximation is found as a solution to the initial problem. In these simulations, it is necessary to produce a large enough quantity of random numbers as inputs, which can afterwards be used in order to estimate their respective outputs for the model. As del Caño et al. 2012 describe, to apply the method, it is necessary to define the distribution functions of those values treated probabilistically. Once these are defined, then the next phases cover the simulations: generating pseudo-random values and evaluate the model with the obtained values. Finally, it is possible to obtain a frequency histogram of SIs, as well as its cumulative distribution function. This last curve allows to better understand and interpret the results of the statistical analysis.

For the present study two probabilistic scenarios have been considered. The first one admits uncertainties in the data, whereas the second one has the uncertainties in the weighting system. In both scenarios the constitutive parameters of the value functions were maintained as originally defined (see Table 2). The uncertainties in the data were calculated using the different values of each of the indicators that have been obtained from consulting miscellaneous databases. As for the uncertainties in the weights, total deviations of 25% from the mean were considered.

Figures 10 and 11 gather the results of the sensitivity analysis. In the graphs, both the probability distribution function and its corresponding cumulative distribution function of the SIs obtained for each alternative are plotted.

The first scenario, where uncertainties are introduced in the indicators, is shown in Figure 10. It can be observed that the ranking obtained in the deterministic approach is maintained.

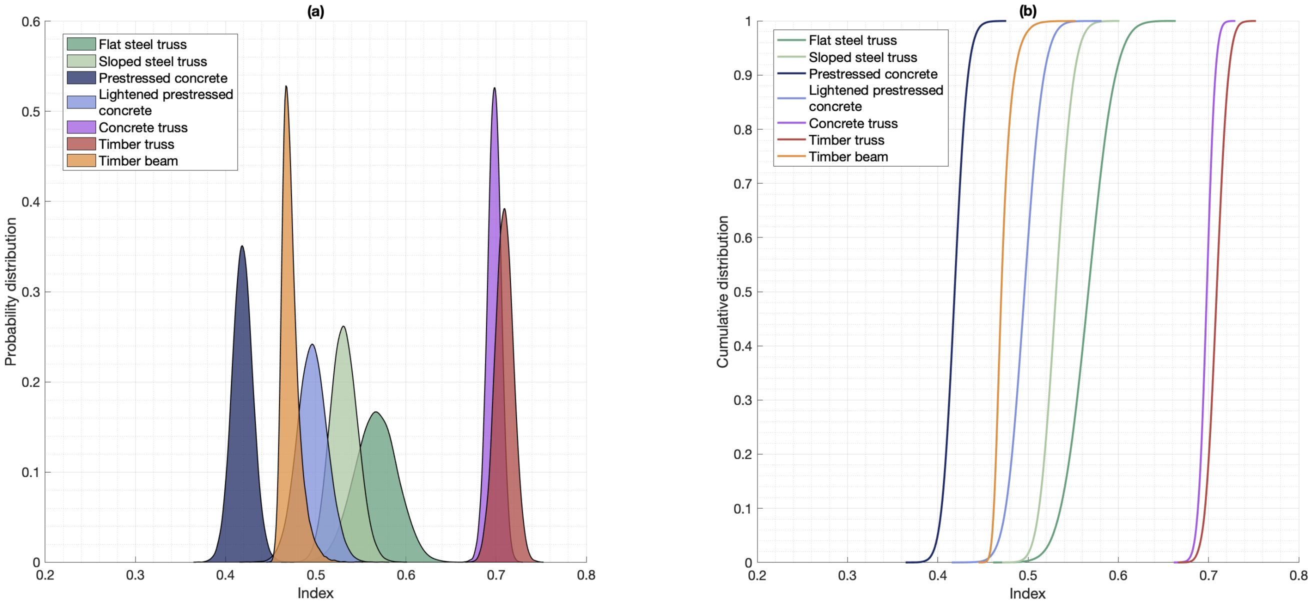

**Figure 8** Probability distribution functions (a) and cumulative distribution (b) for the sustainability indexes with uncertainties in the indicators

Regarding the second scenario, where uncertainties were introduced through weighting system, the results are shown in Figure 11. It can be seen in Figure 11 that, again, the ranking in terms of SIs is maintained for all the alternatives, the order being the following: timber truss, concrete truss, flat steel truss, sloped steel truss, lightened prestressed concrete beam, timber beam, prestressed concrete beam.

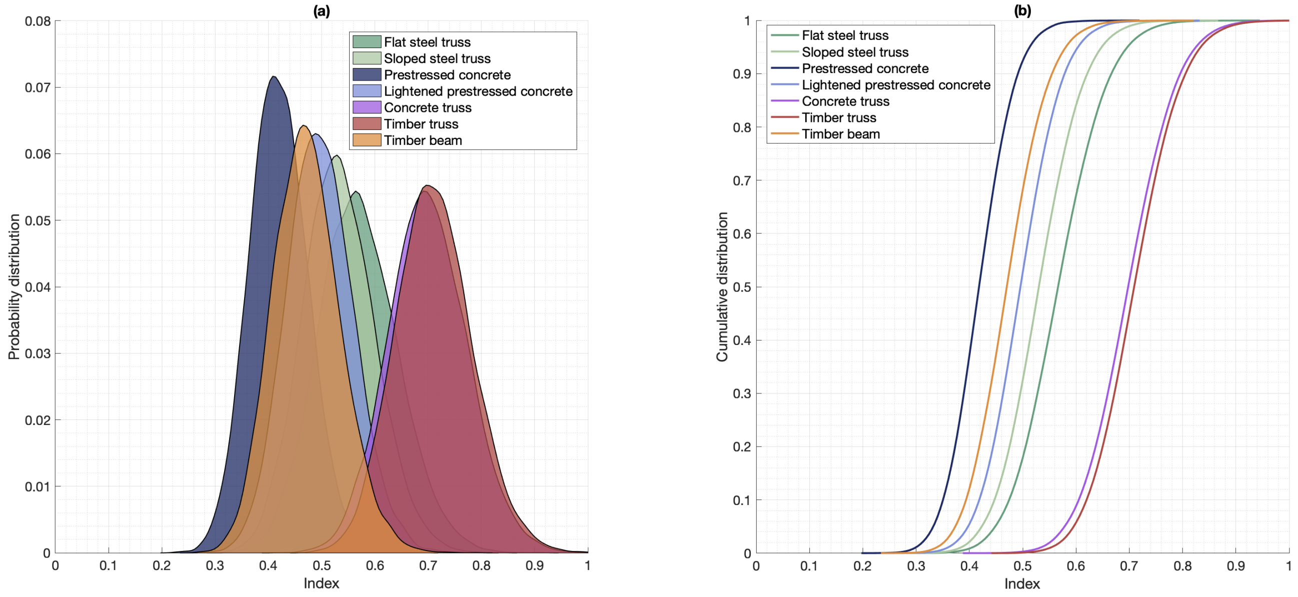

**Figure 9** Probability distribution functions (a) and cumulative distribution (b) for the sustainability indexes with uncertainties in the weighting system

## 6. Conclusions

In this paper a multi-criteria model for sustainability assessment based on the method MIVES has been proposed. The model can be used to assess the sustainability of structural elements of different materials. Particularly, the developed model has been used to assess the sustainability of structural truss and girders made with different materials for non-accessible roofs of sports halls. The study case consisted of seven alternatives, namely: a flat steel truss, a sloped steel truss, a prestressed concrete girder, a lightened prestressed concrete girder, a concrete truss, a timber truss and a timber girder. The specific conclusions that derived from the analysis are summarised below:

- The MIVES-based method used has proved to be an adequate sustainability assessment tool; value functions allow to take the step of normalisation to a further level by allowing to evaluate the indicators in a way that they are sensitive to certain parts of the distribution. The sustainability of structural elements made of different materials has been assessed by considering three requirements, six criteria and twelve indicators.
- As for the requirements, economically the best solution is the concrete truss. The alternatives achieving highest indexes are the timber beam and truss. Finally, socially all the alternatives yield very similar results, the steel alternatives being slightly better.
- The differences in terms of the sustainability index of the timber and reinforced concrete trusses and of the timber and prestressed concrete girders are not significant.
- By performing a sensitivity analysis, it can be concluded that the results are robust: changes in the value of the indicators or in the weights assigned yield the same rankings between solutions.

As a consideration of the abovementioned conclusions, it is worth to note that timber is usually seen as one of the most sustainable construction materials, albeit this can be misleading. The results of the analysis show that, even though timber is environmentally friendly, it can be an economic stressor depending on the structural element for which it is used. Particularly, the analysed glue laminated timber truss performs well in terms of sustainability; on the contrary, the timber girder is ranked as one of the worst options due to the high costs of its production. Regarding concrete, even though it has a negative perception among society, it can actually be a sustainable alternative as the results for concrete truss show. Currently, concrete trusses are not being used as a structural alternative in roofs, while steel trusses are widely used; this is in spite of the fact that actually the former perform well in terms of sustainability in contrast to the later.

In view of the previous conclusions, it is necessary that future studies focus on the comparison of sustainability indexes of different construction materials, as well as on the analysis of the reasons why the most sustainable options are those being the least used. These future studies would contribute to moving forward towards more sustainable framed structures.

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## Appendix

The value functions that have been used for the transformation of the indicators to a scale between 0 and 1 are defined using five different parameters. These parameters allow adapting the sensitivity of the function to certain parts of the distribution of the indicator. The functions can adopt various forms, being the typical ones the concave and convex shapes, the linear and the S-shaped one (see Figure A.1).

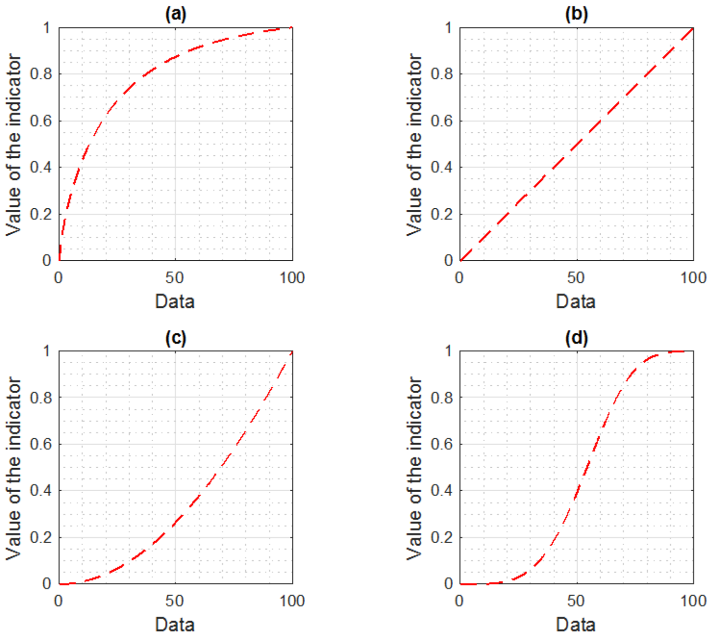

**Figure A.1** Diagrams of typical value functions used in MIVES

The parameters that allow to define the function are the following ones: $X_{min}$, $X_{max}$, $C_i$, $K_i$, $P_i$ (see Equation A.1). In this equation, $X_{min}$ is the minimum value in the interval of the indicators that are assessed; $X$ is the x-value for the specific indicator that is being assessed; $C_i$ approximates the inflexion point's abscissa value; $K_i$ is a value that tends towards $V_{ind}$ at the inflexion point; $P_i$ is a shape factor that defines the curve's form ($P_i<1$ for concave curves, for $P_i>1$ convex curves, $P_i=1$ for linear shapes and $P_i>1$ for S shapes); finally, $B$ is obtained using Equation A.2 and it allows to normalise $V_{ind}$ within a range between 0 and 1.

$$V_{ind} = B\left[1 - \exp\left(-K_i\left(\frac{|X - X_{min}|}{C_i}\right)^{P_i}\right)\right] \qquad \text{Eq. A.1}$$

$$B = \left[1 - \exp\left(-K_i\left(\frac{|X_{max} - X_i|}{C_i}\right)^{F_i}\right)\right]^{-1} \qquad \text{Eq. A.2}$$

Figure A.2 shows the functions that have been defined for each of the indicators used in the sustainability assessment framework of the present paper.

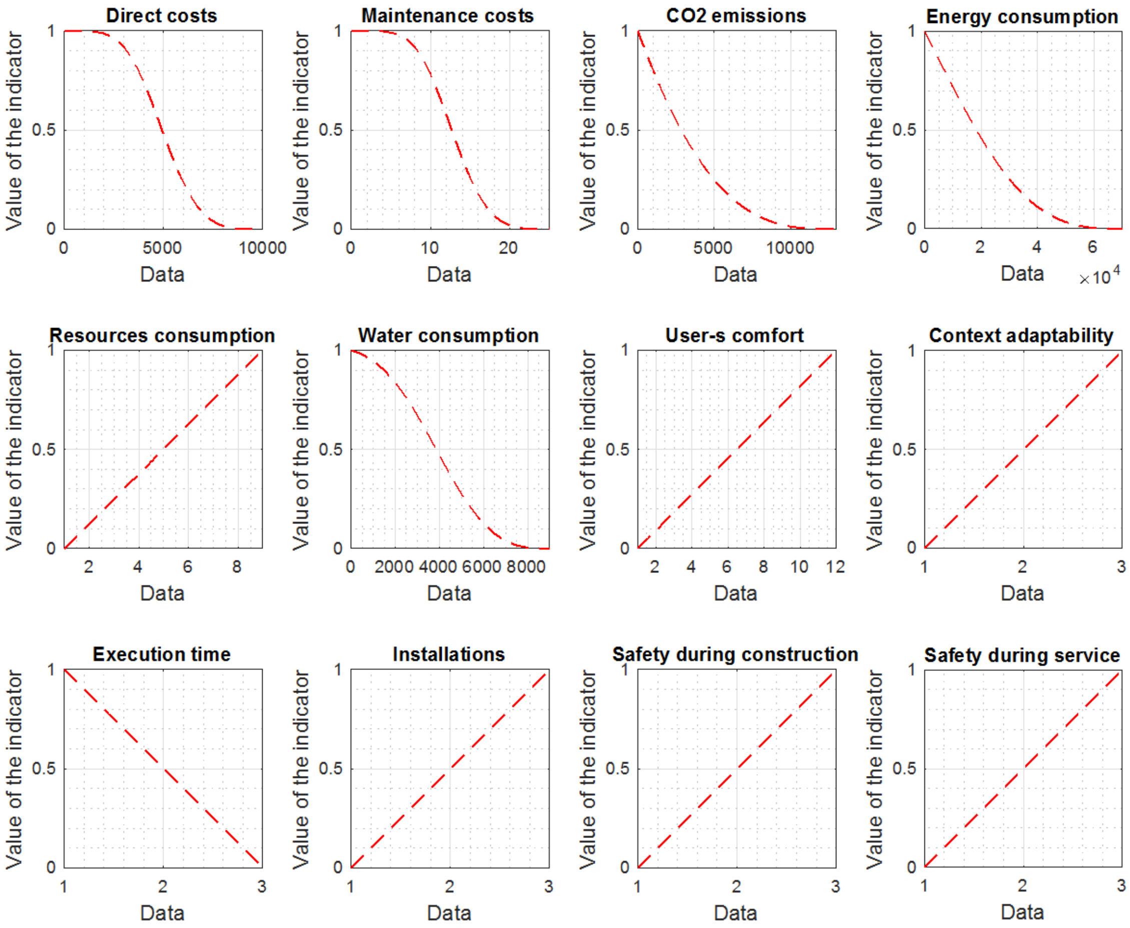

**Figure A.2** Diagrams of the value functions used in the study case for each indicator

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