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Article

Implementing Sustainability Criteria for Selecting a Roof Assembly Typology in Medium Span Buildings

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Abstract: Technological advances have allowed the development of new roof assembly typologies with higher efficiency and less waste. However, in the construction sector the focus is generally on reducing cost and not in sustainable development factors. Short-sighted building planning based only on economic criteria should be avoided improving decision support systems. In addition, the selection of an appropriate roof assembly in a building's design stage is a complex problem due to the existence of different tangible and intangible factors and the multiple alternatives available. The roof typologies under study involve prefabricated concrete, steel and laminated wood structures. This research work applies a multi-criteria hybrid model combining the Analytical Hierarchy Process with the Delphi method and the VIKOR technique for implementing sustainability criteria in the selection of a roof assembly in medium span buildings. The proposed decision support system enables the use of the triple bottom line that considers economic, social and environmental criteria. Under the criteria analyzed, the compromise solution found is the self-supporting curved system.

Keywords: roof assembly; triple bottom line; multicriteria decision making

1. Introduction

Buildings account for forty percent of total energy consumption in Europe [1]. Therefore, the reduction of energy consumption in the buildings sector constitutes a key measure needed to improve the efficient energy use, greenhouse gas emissions, and will contribute towards fulfillment of the Kyoto Protocol [2]. For this reason, there is an increasing interest in studying sustainability [3–5] in the field of building design, mainly in residential and office buildings [6]. In this sector, the facade assembly chosen is the major design factor. However, when the function of the building requires greater spans than the ones used more commonly in this kind of building, the most important decision is the roof, not the facade. The roof typology chosen will determine the rest of the elements of the building: vertical structure, foundation, facades and building systems.

The choice of an assembly is the most important decision with long-term consequences and it must be made in terms of sustainability, not only taking into account the traditional bottom line reference to one metric (financial performance or cost), but also maintaining an interest in the triple bottom line that refers to the consideration of economic, social, and environmental concerns [7–10]. In addition, progressive industrialization, technological advances and innovation, both in materials and construction techniques, have allowed the development of new solutions to be used in each of the building's elements. Efforts to achieve sustainability must include innovation to all types of infrastructure [11]. However, construction is a sector that accepts innovations slowly. Therefore, a decision-making model for the assessment of technological solutions will facilitate the design and construction of sustainable buildings.

The selection of the appropriate building assembly is a complex decision-making problem because many alternatives and multiple selection criteria exist. For example, the cost of the materials depends on the energy used for its manufacturing. This energy determines the environmental impact. Thermal insulation influences the operating energy and a better insulation decreases the impact on the environment. This complexity often makes it difficult to decide on which alternative outweighs the others. A multi-criteria model and different techniques provide the means to solve the problem. Collier *et al.* [12] appointed the use of multi-criteria decision analysis with the triple bottom line for sustainable roofs. The novelty of this research work is the proposed hybrid decision-support system integrating the Analytical Hierarchy Process (AHP) with the Delphi method and the VIKOR technique (see Figure 1). The different criteria considered will be economic, social and environmental. Each of these, with their different weights, will be analyzed in relation to the possible alternatives. Decision support systems have been widely used in analyzing different building and environmental issues. The AHP is a theory of relative measurement on absolute scales, capable of dealing with intangible criteria and based on the paired comparison judgment of experts [13–17]. The Delphi technique is well suited for consensus-building by using a series of questionnaires to collect data from a panel of experts [18–21]. A systematic expert panel assessment process is carried out using Delphi Method and AHP as shown in Figure 1. Expert panelists were invited to participate according to their knowledge and experience in construction and environmental engineering. The experts are required to be chartered engineers and have applied experience in the building sector. The expert assessment process is supported by three surveys, the first is an open questionnaire while the second and third are based on pairwise comparisons with linguistics terms as illustrated in Tables 1 and 2. The resulting values from experts' answers in the form of linguistic terms are shown in Tables 3 and 7. The aggregation of the judgements made by the individuals is undertaken using the Aggregation of Individual Priorities method (AIP) as illustrated in Table 6. Finally, the VIKOR method finds a compromise solution to decision problems containing conflicting and non-commensurable criteria [22–28]. The alternatives are evaluated according to the criteria and the achieved compromise solution provides a maximum utility of the majority, and the minimum individual regret. This research work has focused on implementing sustainability criteria in decision making during the project of medium span roofs. This paper presents a decision support system capable of dealing with the triple bottom line that considers economic, social and environmental criteria, instead of the traditional bottom line referring only to economic criteria.

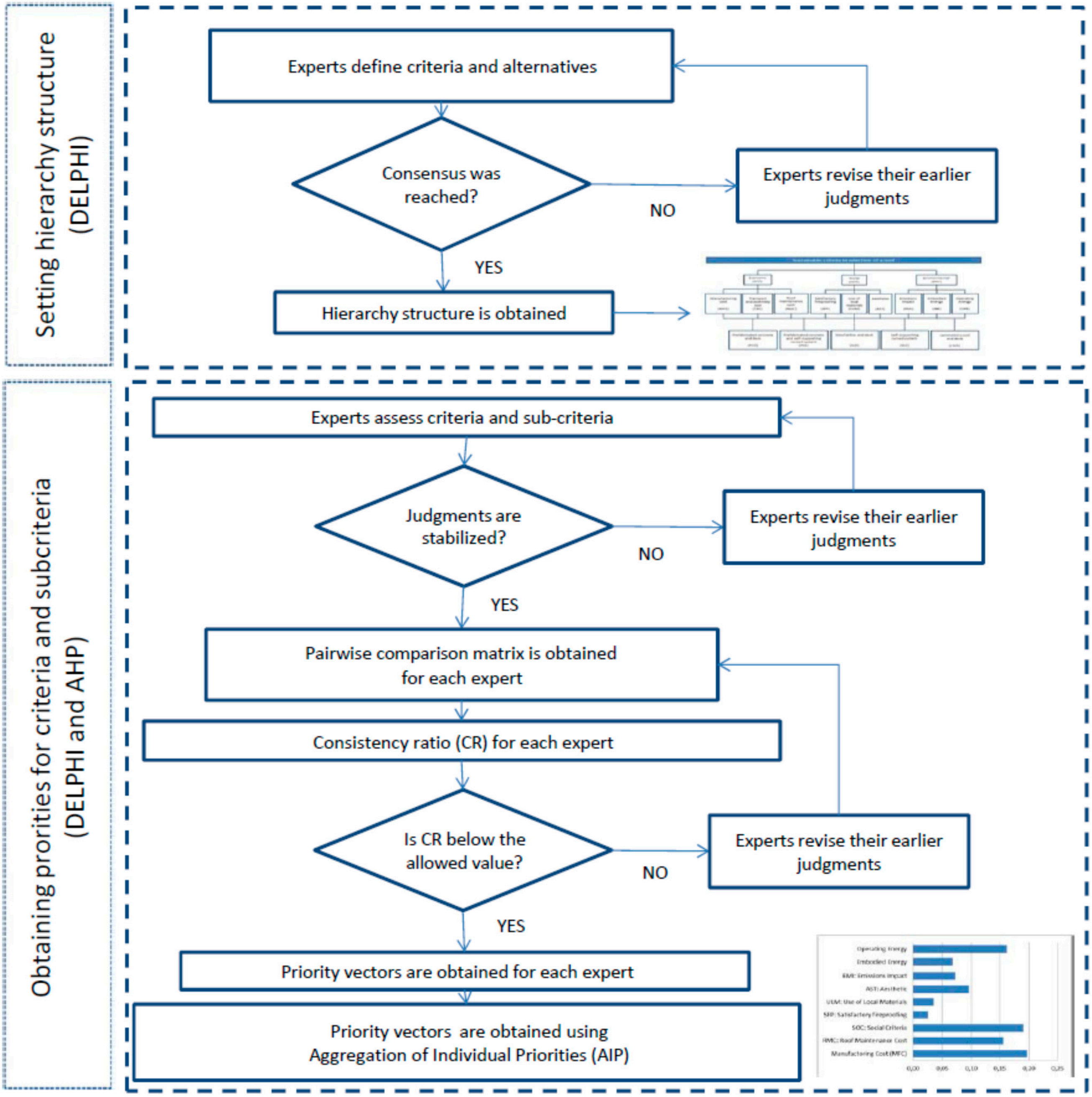

Figure 1. *Cont.*

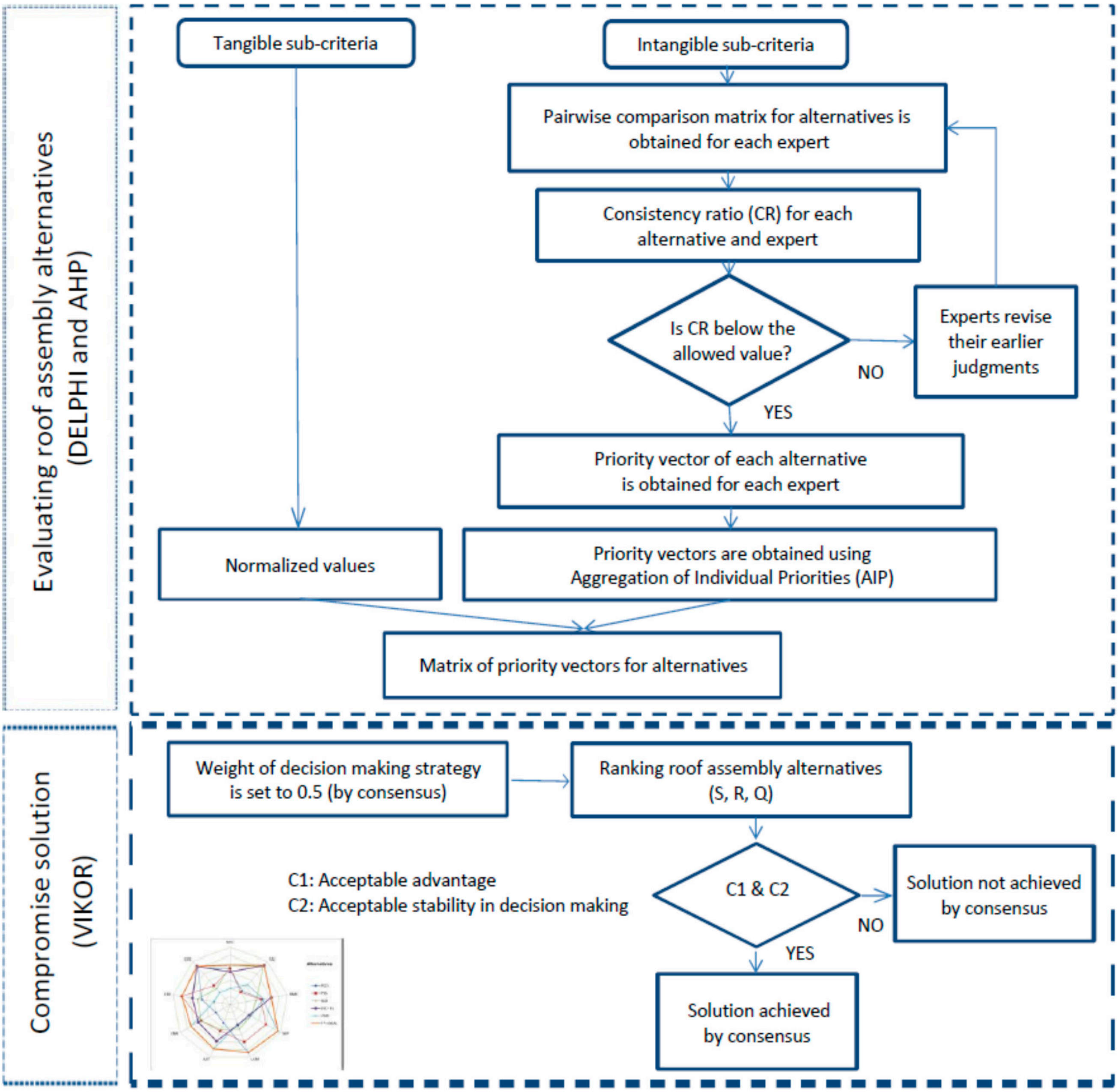

Figure 1. Workflow diagram.

2. Setting Hierarchy Structure in Medium Span Roofs

From an environmental perspective, waste prevention should be the first priority of waste management [29], and prevention must be considered from the design stage. In buildings with medium-sized spans, traditional roofs are commonly used without a detailed study of the different existing solutions with less waste production. In order to find the optimal roof assembly, the problem is structured into a hierarchy of levels including as many relevant details as possible (see Figure 2). The Delphi technique was used to obtain this hierarchical structure. The first phase of the Delphi technique is to develop a set of criteria and alternatives by asking a panel of experts to complete an anonymous questionnaire.

In the proposed hierarchy, the highest level is the overall objective: Implementing sustainability criteria for selecting a roof assembly in medium span roofs. While the lowest level includes the different roof assemblies, which are:

- Prefabricated concrete and purlins (PCP). Main structure made of precast prestressed concrete beams, the secondary structure consists of precast concrete purlins roof serving as support for flat steel panels.
- Prefabricated concrete and self-supporting curved system (PSS). Main structure made of precast prestressed concrete beams serving as support for curved cold formed steel panels.
- Steel lattice and purlins (SLP). Main structure made of steel lattices, the secondary structure consists of steel purlins roof serving as support for flat steel panels.
- Self-supporting curved system (SSC). Self-supporting curved panels made out of steel ribs covering the largest span leaning on the facade beams.
- Laminated wood and purlins (LWP). Main structure made of wood lattices, the secondary structure consists of wood purlins roof, serving as support for flat steel panels.

In all options the same thermal properties have been considered. Panels are made up of two corrugated ribbed sheets which are separated by an auxiliary profile. An insulating material is placed between them.

The intermediate level of the hierarchy analyzes three criteria for evaluating the roof as shown in Figure 2. The first one is the economic criterion (ECO). This criterion is structured in three subcriteria: manufacturing cost (MFC), transport and assembly cost (TAC) and roof maintenance cost (RMC). A roof's economic operation should be considered throughout the construction stage and also in terms of its maintenance and conservation throughout its life cycle [30,31]. Manufacturing costs refer to the cost of acquiring raw materials, the manufacturing and material affordability. Transport and assembly costs refer to the cost of the transportation and positioning of the components, execution speed, supply storage and control that are necessary in the construction stage [32]. In roof maintenance costs the durability of the material must be taken into account [33]. This means its capability of maintaining its physical and mechanical properties over its life cycle: reaction with oxidizing agents; resistance in acidic or alkaline environments; and water resistance based on water absorption. It includes also the cost of inspections, necessary means for auscultation of the structure and essential procedures for the maintenance, repairs and reinforcement of both the structural and auxiliary elements [34,35].

The second criterion studied is the social criterion (SOC). The social criterion is arranged in three subcriteria: satisfactory fireproofing (SFP), requirements in materials and resources or use of local materials (ULM) and aesthetic or versatility when choosing the shapes (AST). User satisfaction and safety are key factors in the design stage. Fireproofing is an important quality for a structural material. It reduces the risk of a disaster, and lowers the need for additional protection to comply with the minimum required standards [36]. In addition, materials that are extracted, processed and manufactured regionally are considered preferable materials because they are easily accessible and help to develop regional economies [37]. In addition, last, aesthetic subcriterion assesses the visual quality achieved inside the building and the flexibility of the materials in the choice of shapes that improve this visual quality [38].

Finally, environmental criterion (ENV) is subdivided in three subcriteria: waste and emissions impact (EMI), embodied energy (EBE) and operating energy (OPE). Life cycle assessment optimizes design solutions favorable to the environment by taking into account the impact throughout construction, operation and final disposal of the roof [39]. In order to study the environmental impact of the roof, material and energy consumption and the consequent pollution and waste are considered through the three sub-criteria [40]. EMI refers not only to those from extraction and production of materials, but also to the impacts of construction. The anthropogenic greenhouse effect caused by the emissions is expressed in terms of their Global Warming Potential calculated as carbon dioxide equivalent. EBE is the energy utilized during the construction phase. It is the energy content of all the materials used in the building. Energy content of materials refers to the energy used to acquire raw materials, manufacture and transport them to a building site and energy incurred at the time of construction of the roof [41,42]. OPE subcriterion considers the necessary energy to heat and cool a building as a key factor in the operating energy, and therefore, in the building's life cycle energy demand [43]. The energy efficiency of a building depends not only on the thermal properties and heat capacity of the materials used, but also on its shape. The geometry has the strongest effect on the demand for energy of the buildings, because it influences the thermal inertia and energy losses [44]. Taking into account all these requirements and following the initial step of AHP [45], the analysis goal is decomposed into a hierarchy structure shown in Figure 2. Saaty and Ozdemir [46] have observed that an individual cannot simultaneously compare more than seven items (plus or minus two) without becoming confused. This study does not exceed these limitations in the number of pairwise comparisons.

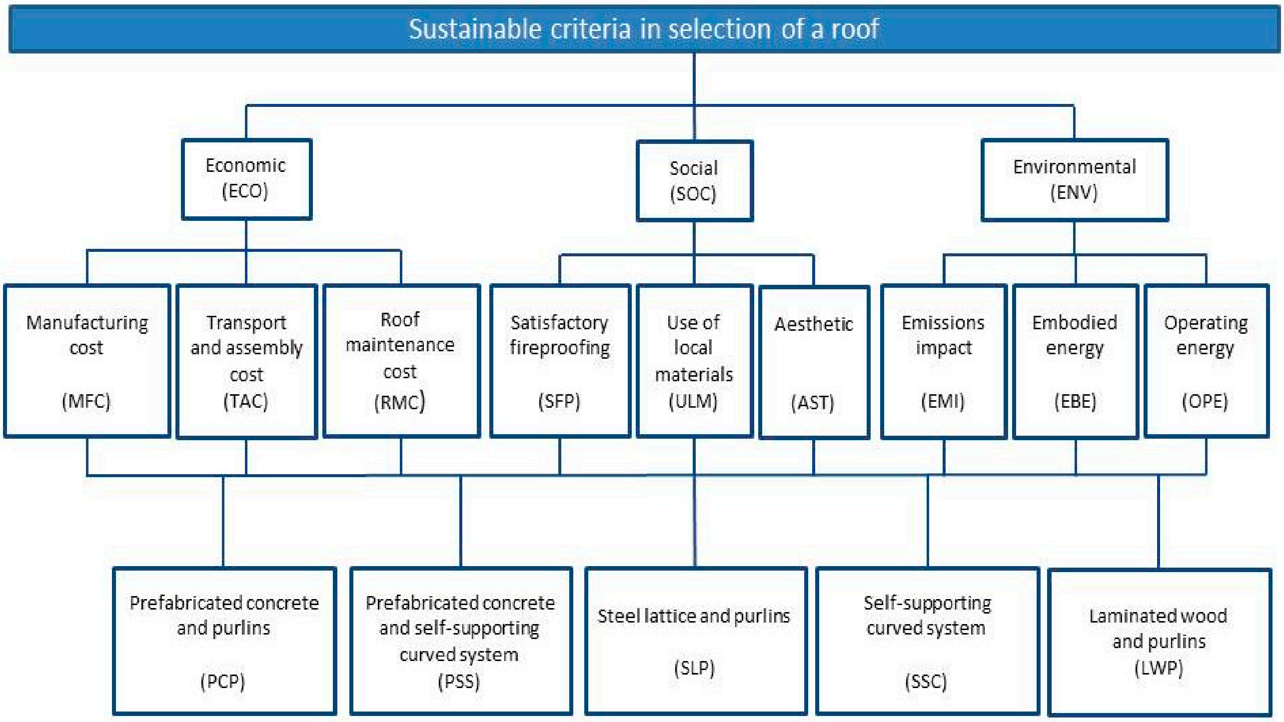

Figure 2. Hierarchy structure for selecting the roof assembly typology.

3. Obtaining Priorities for Criteria and Sub-Criteria

Continuing with the Delphi technique, experts assess different criteria in a second questionnaire. The Delphi process encourages interaction among the experts with anonymous feedback. The Delphi method helps to reduce the dispersion of the answers from the experts. AHP is used to break down a complex situation into its component parts. Table 1 shows particular questionnaires for evaluating criteria and sub-criteria with respect to the overall goal using a 9-point scale (see Table 2). Each expert performed a pairwise comparison to indicate his preference for each criterion. Pairwise comparison matrices for the criteria (A_{i0}) and sub-criteria (A_{i1} to A_{i3}) are formed for the *i*-th expert using the values obtained from Table 3.

The principal eigenvector of each matrix A_{ij} is the priority vector ω_{ij}. Vector ω_{i0} of A_{i0} determine the weight of each criterion with respect to the analysis goal, while A_{ij} (j = 1 to 3) determine the weight of each subcriterion with respect to its criterion. To find these priority vectors, each linear system $A\omega = \lambda\omega$ must be solved evaluating $\det [A - \lambda \cdot I] = 0$.

Table 1. Questionnaire implementing sustainable factors to assess main criteria and sub-criteria in the selection of roof typology.

Criteria	
QC1	How important are economic criteria (ECO) compared to social criteria (SOC)
QC2	How important are economic criteria (ECO) compared to environmental criteria (ENV)
QC3	How important are social criteria (SOC) compared to environmental criteria (ENV)
Sub-Criteria	
QS1	How important is manufacture cost (MFC) compared to transport and assembly cost (TAC)
QS2	How important is manufacture cost (MFC) compared to roof maintenance cost (RMC)
QS3	How important is transport and assembly cost (TAC) compared to roof maintenance cost (RMC)
QS4	How important is satisfactory fireproofing (SFP) compared to use of local materials (ULM)
QS5	How important is satisfactory fireproofing (SFP) compared to aesthetic (AST)
QS6	How important is use of local materials (ULM) compared to aesthetic (AST)
QS7	How important is emissions impact (EMI) compared to embodied energy (EBE)
QS8	How important is emissions impact (EMI) compared to operating energy (OPE)
QS9	How important is embodied energy (EBE) compared to operating energy (OPE)

Table 2. 9-point scale for pairwise comparisons in AHP with linguistic terms.

Notation	Meaning	Importance
EP	A criterion or alternative is **extremely preferred** to another	9
VP	A criterion or alternative is **very strongly preferred** to another	7
MP	A criterion or alternative is **moderately preferred** to another	5
SP	A criterion or alternative is **slightly preferred** to another	3
QP	A criterion or alternative is **equally preferred** to another	1
SN	A criterion or alternative is **slightly non-preferred** to another	1/3
MN	A criterion or alternative is **moderately non-preferred** to another	1/5
VN	A criterion or alternative is **very strongly non-preferred** to another	1/7
EN	A criterion or alternative is **extremely non-preferred** to another	1/9

One of AHP's advantages is the possibility of measuring the consistency of the pairwise comparison matrix. The consistency ratio (CR) is used as the main indicator for ranking consistency. Maximum consistency ratio should be 5% for a 3 by 3 matrix, 9% for a 4 by 4 matrix, and 10% for a larger matrix [47]. Any higher score indicates that the judgments need re-examination. CR is determined by the ratio between the consistency index (CI) and the random consistency index (RCI). The RCI value is fixed and depends on the number of evaluated criteria. In order to calculate the CI, the largest eigenvalue (λ_{max}) of the normalized pairwise comparison matrix should be determined. Then the consistency index (CI) is calculated as follows:

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

As an example, priority vector and consistency analysis for main criteria and sub-criteria for the first expert are shown in Table 4. Results of Consistency Ratio for the main criteria and sub-criteria for each expert are indicated in Table 5. The priority vectors for each sub-criterion with respect to the goal (ω_i) are obtained from priority vectors for criteria with respect to the goal and the subcriteria with respect to its criterion. This process is repeated for each expert and then information is aggregated and the priority vector for sub-criteria (ω) is obtained (see Table 6). The result is shown in Figure 3.

Table 3. Evaluation results of the main criteria and sub-criteria for each expert with respect to the overall goal.

Pairwise Criteria			**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**
ECO	*vs.*	**SOC**	MP	VP	SP	SP	MP	SP	MP	SP	SP	SP
ECO	*vs.*	**ENV**	SP	QP	QP	MP	SP	MP	SP	MP	QP	SN
SOC	*vs.*	**ENV**	SN	MN	SN	SP	SN	SP	SN	SP	SN	MN
Pairwise Sub-Criteria												
MFC	*vs.*	**TAC**	SP	SP	QP	MN	MP	QP	SP	QP	QP	SN
MFC	*vs.*	**RMC**	MP	MP	SN	SN	SP	MP	SN	MP	MP	MN
TAC	*vs.*	**RMC**	SP	SP	SN	SP	SN	MP	MN	MP	MN	SN
SFP	*vs.*	**ULM**	MN	SN	SN	QP	SN	SN	SP	SN	QP	SP
SFP	*vs.*	**AST**	EN	VN	MN	SN	EN	SN	SN	MN	MN	QP
ULM	*vs.*	**AST**	SN	SN	SN	SN	MN	QP	MN	SN	SN	MN
EMI	*vs.*	**EBE**	SN	MN	QP	MN	MP	QP	QP	QP	QP	MP
EMI	*vs.*	**OPE**	VN	EN	MN	MN	SP	MN	MN	SN	QP	SP
EBE	*vs.*	**OPE**	SN	SN	MN	QP	SN	SN	MN	SN	QP	SN

4. Evaluating Roof Assembly Typologies

The next step is to study the priority of typologies with respect to each subcriterion. Tangible subcriteria (MFC, TAC, EMI, EBE and OPE) only require direct measurement of an objective [48]. Values for priorities have been normalized for establishing a ranking [49]. If there are m typologies and n criteria, the j_{th} criterion can be expressed as $Y_j = (y_{1j}, y_{2j}, \ldots, y_{ij}, \ldots, y_{mj})$, where y_{ij} is the performance value of the j-th criterion in the i-th typology. The term Y_j can be translated into the comparability sequence $X_j = (x_{1j}, x_{2j}, \ldots, x_{ij}, \ldots, x_{mj})$ as follows. Performance values are scaled into (0,1) thereafter.

$$x_{ij} = \frac{Max(y_{ij}, i = 1,2,\ldots,m) - y_{ij}}{Max(y_{ij}, i = 1,2,\ldots,m) - Min(y_{ij}, i = 1,2,\ldots,m)} \tag{2}$$

for i = 1,2,…,m and j = 1,2,…,n.

Table 4. Priority vector and consistency analysis of the pairwise comparison matrix for main criteria and sub-criteria for the first expert.

	ECO	**SOC**	**ENV**	**Priority Vector**
ECO	1	5	3	0.6370
SOC	1/5	1	1/3	0.1047
ENV	1/3	3	1	0.2583
λ_{max} = 3.0385, CI = 0.0193, CR = 0.0370 < 0.05 OK				
	MFC	**TAC**	**RMC**	**Priority Vector**
MFC	1	3	5	0.6370
TAC	1/3	1	3	0.2583
RMC	1/5	1/3	1	0.1047
λ_{max} = 3.0385, CI = 0.0193, CR = 0.0370 < 0.05 OK				
	SFP	**ULM**	**AST**	**Priority Vector**
SFP	1	1/5	1/9	0.0629
ULM	5	1	1/3	0.2654
AST	9	3	1	0.6716
λ_{max} = 3.0291, CI = 0.0145, CR = 0.0279 < 0.05 OK				
	EMI	**EBE**	**OPE**	**Priority Vector**
EMI	1	1/3	1/7	0.0879
EBE	3	1	1/3	0.2426
OPE	7	3	1	0.6694
λ_{max} = 3.0070, CI = 0.0035, CR = 0.0068 < 0.05 OK				

Table 5. Consistency ratio (CR) for main criteria and sub-criteria.

Expert	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**
$\mathbf{A_0}$	0.037	0.012	0.000	0.037	0.037	0.037	0.037	0.037	0.000	0.033
$\mathbf{A_1}$	0.037	0.037	0.000	0.037	0.037	0.000	0.037	0.000	0.000	0.033
$\mathbf{A_2}$	0.028	0.007	0.037	0.000	0.028	0.000	0.037	0.037	0.025	0.025
$\mathbf{A_3}$	0.007	0.028	0.000	0.000	0.037	0.028	0.000	0.000	0.000	0.033

Table 6. Priority vector of sub-criteria.

	MFC	**TAC**	**RMC**	**SFP**	**ULM**	**AST**	**EMI**	**EBE**	**OPE**
ω_1	0.4058	0.1645	0.0667	0.0066	0.0278	0.0703	0.0227	0.0627	0.1729
ω_2	0.3102	0.1258	0.0510	0.0068	0.0189	0.0521	0.0274	0.1155	0.2923
ω_3	0.0857	0.0857	0.2571	0.015	0.0369	0.091	0.0612	0.0612	0.3061
ω_4	0.0667	0.4058	0.1645	0.0517	0.0517	0.155	0.0095	0.0476	0.0476
ω_5	0.4058	0.0667	0.1645	0.0074	0.0187	0.0787	0.1645	0.0271	0.0667
ω_6	0.2895	0.2895	0.0579	0.0369	0.1107	0.1107	0.0164	0.0194	0.0690
ω_7	0.1645	0.0667	0.4058	0.0271	0.0110	0.0667	0.0369	0.0369	0.1845
ω_8	0.2895	0.2895	0.0579	0.0271	0.0667	0.1645	0.0209	0.0209	0.0628
ω_9	0.0612	0.0612	0.3061	0.0223	0.0265	0.0941	0.1429	0.1429	0.1429
ω_{10}	0.0271	0.0667	0.1645	0.0425	0.0119	0.0503	0.4058	0.0667	0.1645
ω	0.1969	0.1559	0.1896	0.0248	0.0348	0.0961	0.0723	0.0674	0.1621

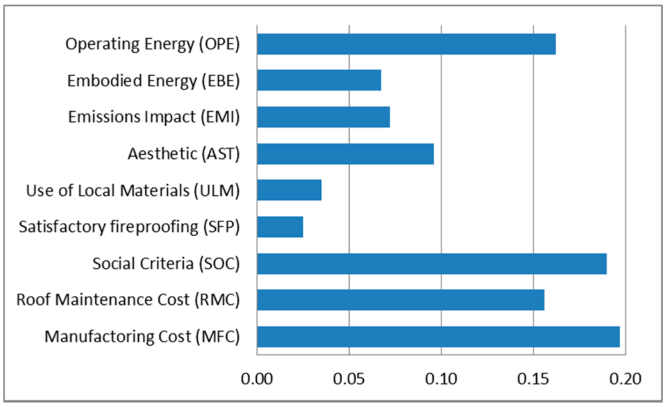

Figure 3. Priority vector for sub-criteria.

Non-tangible subcriteria (RMC, SFP, ULM and AST) will be evaluated through a third questionnaire which is sent to the panel of experts using Delphi technique. To illustrate the proposed method, Table 7 shows the results obtained with respect to non-tangible sub-criteria. Then, a pairwise comparison matrix for the alternatives is obtained using judgments provided by each expert. As in previous steps, the eigenvector method had been applied to obtain the priority vector, and consistency analysis was performed for each case and expert. The results of the pairwise comparison of the alternatives with respect to the intangible sub-criteria for the first expert are shown in Table 8. A matrix of priority vectors for alternatives is formed linking tangible and intangible sub-criteria as shown in Table 9.

Table 7. Roof evaluation results for each expert with respect to non-tangible sub-criteria.

Expert	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**10th**
RMC										
PCD *vs.* PSS	QP	QP	QP	SP	SP	MN	MP	SP	SN	MP
PCP *vs.* SLP	MP	MP	SN	SN	MP	QP	SP	VP	QP	SP
PCP *vs.* SSC	SN	MN	MN	MP	MP	SN	MP	SN	SN	MP
PCP *vs.* LWP	SP	SN	SN	MN	MP	SP	SP	MP	SP	QP
PSS *vs.* SLP	MP	MP	SN	MN	QP	MP	SN	MP	SP	SN
PSS *vs.* SSC	SN	MN	MN	SP	QP	SP	QP	MN	QP	SP
PSS *vs.* LWP	SP	SN	SN	MN	SP	MP	SN	MP	MP	SN
SLP *vs.* SSC	VN	EN	SN	MP	QP	MN	MP	VN	SN	SP
SLP *vs.* LWP	SN	VN	QP	QP	QP	MP	SP	SN	SP	SN
SSC *vs.* LWP	VP	SP	SP	MN	QP	MP	MN	VP	MP	MN
SFP										
PCP *vs.* PSS	QP	QP	SP	MP	QP	SP	QP	SP	QP	VP
PCP *vs.* SLP	SP	MP	VP	EP	EP	EP	MP	MP	VP	EP
PCP *vs.* SSC	SP	MP	EP	EP	VP	VP	MP	VP	VP	EP
PCP *vs.* LWP	MP	VP	VP	SP	MP	MP	VP	MP	EP	VP
PSS *vs.* SLP	SP	MP	SP	VP	EP	MP	MP	SP	VP	MP
PSS *vs.* SSC	SP	MP	VP	VP	VP	SP	MP	MP	VP	MP
PSS *vs.* LWP	MP	VP	MP	QP	MP	SP	MP	SP	VP	QP
SLP *vs.* SSC	QP	QP	MP	SP	SN	SN	SP	SP	SP	SP
SLP *vs.* LWP	SP	SP	SP	MN	MN	QP	SP	QP	MP	SN
SSC *vs.* LWP	SP	SP	SN	VN	MN	QP	SP	MN	SP	MN
ULM										
PCP *vs.* PSS	QP	SP	SP	SP	SP	QP	QP	QP	QP	MP
PCP *vs.* SLP	VP	MP	VP	MP	SP	SP	SP	MP	MP	SP
PCP *vs.* SSC	VP	VP	EP	VP	MP	SP	SP	MP	MP	VP
PCP *vs.* LWP	EP	EP	VP	MP	MP	MP	MP	EP	VP	VP
PSS *vs.* SLP	VP	SP	MP	SP	QP	SP	SP	MP	MP	QP
PSS *vs.* SSC	VP	MP	EP	SP	MP	SP	SP	MP	MP	SP
PSS *vs.* LWP	EP	VP	SP	SP	SP	MP	MP	EP	VP	SP
SLP *vs.* SSC	QP	SP	SP	SP	MP	QP	QP	QP	SP	MP
SLP *vs.* LWP	SP	MP	SN	QP	SP	SP	MP	MP	MP	SP
SSC *vs.* LWP	SP	SP	MN	MN	MN	SP	SP	SP	SP	SN
AST										
PCP *vs.* PSS	MN	MN	VN	MN	QP	MN	SN	MN	SP	VN
PCP *vs.* SLP	SN	SN	MN	EN	MN	SN	QP	SN	SN	QP
PCP *vs.* SSC	VN	VN	EN	VN	MN	MN	MN	VN	QP	EN
PCP *vs.* LWP	EN	EN	MN	MN	VN	MN	VN	EN	MN	MN
PSS *vs.* SLP	SP	SP	MP	MN	MN	MP	SP	SP	MN	MP
PSS *vs.* SSC	SN	SN	SN	SN	MN	QP	MN	MN	SP	SN
PSS *vs.* LWP	MN	MN	SP	QP	VN	SP	VN	MN	VN	QP
SLP *vs.* SSC	MN	MN	EN	SP	QP	MN	MN	VN	MP	VN
SLP *vs.* LWP	VN	VN	SN	MP	MN	MN	VN	VN	MN	MN
SSC *vs.* LWP	SN	SN	MP	MP	MN	QP	MN	SN	EN	SP

Table 8. Priority vector and consistency analysis of the pairwise comparison matrix for the roof typologies, with respect to intangible sub-criteria for the first expert.

RMC	**PCP**	**PSS**	**SLP**	**SSC**	**LWP**	**Priority Vector**
PCP	1	1	5	1/3	3	0.1951
PSS	1	1	5	1/3	3	0.1951
SLP	1/5	1/5	1	1/7	1/3	0.0422
SSC	3	3	7	1	7	0.4887
LWP	1/3	1/3	3	1/7	1	0.0790
λ_{max} = 5.1308, CI = 0.0327, CR = 0.0295 < 0.10 OK						
SFP	**PCP**	**PSS**	**SLP**	**SSC**	**LWP**	**Priority Vector**
PCP	1	1	3	3	5	0.3435
PSS	1	1	3	3	5	0.3435
SLP	1/3	1/3	1	1	3	0.1290
SSC	1/3	1/3	1	1	3	0.1290
LWP	1/5	1/5	1/3	1/3	1	0.0551
λ_{max} = 5.0556, CI = 0.0139, CR = 0.0125 < 0.10 OK						
ULM	**PCP**	**PSS**	**SLP**	**SSC**	**LWP**	**Priority Vector**
PCP	1	1	7	7	9	0.4129
PSS	1	1	7	7	9	0.4129
SLP	1/7	1/7	1	1	3	0.0703
SSC	1/7	1/7	1	1	3	0.0703
LWP	1/9	1/9	1/3	1/3	1	0.0337
λ_{max} = 5.1164, CI = 0.0291, CR = 0.0262 < 0.10 OK						
AST	**PCP**	**PSS**	**SLP**	**SSC**	**LWP**	**Priority Vector**
PCP	1	1/5	1/3	1/7	1/9	0.0333
PSS	5	1	3	1/3	1/5	0.1290
SLP	3	1/3	1	1/5	1/7	0.0634
SSC	7	3	5	1	1/3	0.2615
LWP	9	5	7	3	1	0.5128
λ_{max} = 5.2375, CI = 0.0594, CR = 0.0535 < 0.10 OK						

Table 9. Priority matrix for implementing sustainability criteria in the selection of a roof assembly.

	MFC	TAC	RMC	SFP	ULM	AST	EMI	EBE	OPE
PCP	0.2463	0.0211	0.1938	0.4657	0.4388	0.0441	0.0000	0.1449	0.4099
PSS	0.2518	0.0000	0.1769	0.2969	0.2973	0.1522	0.2035	0.3947	0.1065
SLP	0.2927	0.4170	0.1198	0.0849	0.1251	0.1310	0.2059	0.1989	0.0587
SSC	0.2092	0.4378	0.3028	0.0638	0.0714	0.2856	0.2449	0.2615	0.4248
LWP	0.0000	0.1240	0.2067	0.0888	0.0676	0.3870	0.3457	0.0000	0.0000

5. Achieving Compromise Solution with VIKOR Method

The VIKOR method improves the proposed decision support tool by enabling to assess the stability and consensus of the roof assembly selected. In order to reach consensus among experts, VIKOR technique provides a compromise solution that is the closest to the ideal. VIKOR analyses the stability of the compromise solution and performs sensitivity analyses before accepting a solution as the optimal one [50]. The VIKOR method provides a maximum group utility for the majority and a minimum of individual regret for the opponent. The ranking of roof assembly typologies is obtained from comparison of alternatives according to each subcriterion [51,52].

For the j-th typology, the rating of the i-th criterion is denoted by f_{ij}. Development of the VIKOR method is started with the following form of L_p-metric:

$$L_{pj} = \left\{\sum_{i=1}^{9}\left[\omega_i\left(f_i^* - f_{ij}\right)/\left(f_i^* - f_i^-\right)\right]^p\right\}^{1/p} \quad 1 \leq \mathrm{p} \leq \infty; \mathrm{j} = 1,2,\ldots,5 \tag{3}$$

Within the VIKOR method L_{1j} (S_j) and $L_{\infty j}$ (R_j) are used to obtain ranking measures. The solution obtained by means of min S_j implies a maximum group utility (majority rule), and the solution obtained by means of min R_j corresponds to a minimum of individual regret for the opponent.

The compromise ranking algorithm of the VIKOR method has the following steps:

- The best f_i^* and the worst values f_i^- of the nine subcriteria are computed using the equations $f_i^* = \max_j\{f_{ij}\}$; $f_i^- = \min_j\{f_{ij}\}$. S_j , R_j and Q_j values are calculated using the following equations:

$$S_j = \sum_{i=1}^{9} \omega_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \tag{4}$$

$$R_j = max_i\left(\omega_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-}\right) \tag{5}$$

$$Q_j = \upsilon \frac{S_j - S^*}{S^- - S^*} + (1-\upsilon)\frac{R_j - R^*}{R^- - R^*} \tag{6}$$

where

$S^* = min_j S_j$
$S^- = max_j S_j$
$R^* = min_j R_j$
$R^- = max_j R_j$

and υ is the weight for the strategy of the majority of criteria or maximum group utility and ($1 - \upsilon$) is the weight of the individual regret. To achieve consensus using VIKOR, the weight of decision making strategy υ will be set to 0.5, that is by consensus [53]. The results for the five studied typologies are shown in Table 10.

- The roof assembly typologies are now ranked using the *S*, *R* and *Q* values in ascending order. Three ranking lists are obtained (see Table 11).
- The SSC typology, which is the best ranked by means of the Q value (minimum), is proposed as a compromise solution if the following two conditions are satisfied:

  Condition 1: *Acceptable advantage*: The difference between the first and second positioned typologies in the ranking list by *Q* is greater than *DQ*, being $DQ = 1/(J - 1)$, where *J* is the number of studied typologies. In this case, $Q(PCP) - Q(SSC) = 0.64 > 0.25$.

Condition 2: *Acceptable stability in decision making*: The first typology in the ranking resulting from *Q* values is also the best ranked by means of *S* and *R*. In our case, this second condition is fulfilled as shown in Table 11.

Table 10. S_j, R_j and Q_j values for the five analyzed roof typologies.

	PCP	PSS	SLP	SSC	LWP
S_j	0.5093	0.5545	0.5241	0.1877	0.6958
R_j	0.1483	0.1559	0.1896	0.0561	0.1969
Q_j	0.6439	0.7150	0.8051	0.0000	1.0000

Table 11. Ranking obtained from VIKOR method for the five roof typologies.

Position	1	2	3	4	5
S_j	SSC	PCP	SLP	PSS	LWP
R_j	SSC	PCP	PSS	SLP	LWP
Q_j	SSC	PCP	PSS	SLP	LWP

6. Discussion and Conclusions

The choice of roof assembly typology is one of the most important decisions with long-term consequences in medium span buildings. This selection must be made in terms of sustainability taking into account the triple bottom line that includes economic, social and environmental criteria. Industrialization, technological advances and innovation have allowed the development of alternatives with higher efficiency and less waste, but often such roof typologies are not applied because the construction industry does not have the ability to try before build and this is a sector that accepts innovations slowly. Therefore, the roof assembly selection is a complex problem due to the different factors that could be analyzed. In this research work, a hybrid decision support system based on Delphi, AHP and VIKOR methods has been applied to implement sustainability criteria.

In our case, a self-supporting curved system is the compromise solution to the selection problem. A self-supporting curved system is the alternative best ranked by the *Q* value and presents an acceptable advantage with respect to the one ranked second in the list by *Q* and an acceptable stability in decision making, because it also is the best ranked by *S* (majority rule) and *R* (minimum individual regret). As can be observed in Figure 4, the self-supporting curved system matches the ideal alternative when transport and assembly costs, roof maintenance costs and operating energy are considered. The manufacturing cost criterion has the greatest global weight but with the VIKOR method its importance is reduced because it has four alternatives with values near to the ideal one and the cost of the fifth alternative is much larger. Therefore, the factors considered previously are the most relevant ones and the main advantages of self-supporting curved system are its lightness and compactness. The next roof typology closest to the ideal solution is prefabricated concrete and purlins roof. Its value mainly results from clear prominence with respect to the other alternatives when fire resistance and the use of local materials are considered. Its greatest disadvantage is the transportation and assembly cost because of its high weight.

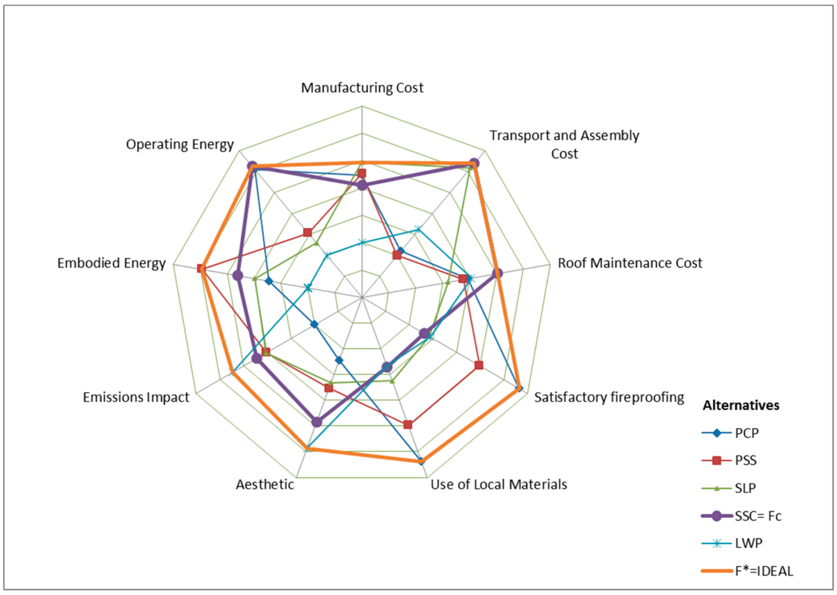

Figure 4. Comparison of roof tipologies with ideal F^* and compromise F^c solutions (PCP: Prefabricated concrete and purlin, PSS: Prefabricated concrete and self-supporting curved system. SLP: Steel lattice and purlin, SSC: Self-supporting curved system, LWP: Laminated wood and purlin).

Author Contributions

All the authors contributed equally to this research work.

Conflicts of Interest

The authors declare no conflict of interest.

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