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Research Article

Sustainability-Related Decision Making in Industrial Buildings: An AHP Analysis

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Few other sectors have such a great impact on sustainability as the construction industry, in which concerns over the environmental dimension have been growing for some time. The sustainability assessment methodology presented in this paper is an AHP (Analytic Hierarchy Process) based on Multicriteria Decision Making (MCDM) and includes the main sustainability factors for consideration in the construction of an industrial building (environmental, economic, and social), as well as other factors that greatly influence the conceptual design of the building (employee safety, corporate image). Its simplicity is well adapted to its main objective, to serve as a sustainability-related decision making tool in industrial building projects, during the design stage. Accompanied by an economic valuation of the actions to be undertaken, this tool means that the most cost-effective solution may be selected from among the various options.

1. Introduction

The environmental footprint of construction activity is immense. The building sector in the developed countries of the European Union consumes 40% of their total energy consumption [1]. The building industry consumes a somewhat similar percentage of all materials in the global economy. In the typical "life cycle" of a building (building, maintenance, and demolition), the building is "responsible" for 50% of total energy consumption and for 50% of total CO_2 atmospheric emissions [2]. The focal area of this study looks at the important area of nonresidential buildings and more specifically industrial buildings, which represent roughly 15% of all buildings.

The "ICLEI-Annual Sustainability Report 2011-2012" affirmed once again that sustainable development should be high on the agenda [3]. Up until its publication, the environmental requirement had been the focus of most studies, databases, design guides, and assessment tools on sustainable construction [4–7]. However, the number of research papers and assessment tools that also incorporate economic and/or social requirements [8–10] as well as the first standards which legislate social aspects [11, 12] has recently begun to emerge.

These tools may be described as follows:

(i) Life Cycle Analysis (LCA): tools that process complex data sets such as ECOQUANTUM and ENVEST [13].

(ii) Scientific standards: less complex but also accurate tools, such as DGNB, LEED, and BREEAM [14, 15].

(iii) Checklists: very simple tools based on best practice, such as IHOBE Guides [16].

Specific modules that are part of LEED, BREEAM, and DGNB, for example, exist for the evaluation of industrial buildings.

The methodology advanced in this paper sets a sustainability value for industrial buildings, by applying a limited number of easily quantifiable evaluation criteria, so as to assist decision making in relation to sustainability during the design stage of industrial building projects.

The Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluación Sostenible, MIVES), a Multicriteria Decision Making (MCDM) tool based on AHP (Analytic Hierarchy Process), is central to this assessment process. MIVES is applied in the Spanish structural concrete standards [17] and the Spanish structural

Table 1: Criteria in relation to the different requirements according to their stage of its life cycle.

Study scope	Life cycle			
	Conception	Materialization	Use	Reintegration
Safety	Cr_{SC1} Cr_{SC2} ⋮	Cr_{SM1} Cr_{SM2} ⋮	Cr_{SU1} Cr_{SU2} ⋮	Cr_{SR1} Cr_{SR2} ⋮
Society	Cr_{SoC1} Cr_{SoC2} ⋮	Cr_{SoM1} Cr_{SoM2} ⋮	Cr_{SoU1} Cr_{SoU2} ⋮	Cr_{SoR1} Cr_{SoR2} ⋮
Environment	Cr_{EC1} Cr_{EC2} ⋮	Cr_{EM1} Cr_{EM2} ⋮	Cr_{EU1} Cr_{EU2} ⋮	Cr_{ER1} Cr_{ER2} ⋮
Economy	Cr_{EcC1} Cr_{EcC2} ⋮	Cr_{EcM1} Cr_{EcM2} ⋮	Cr_{EcU1} Cr_{EcU2} ⋮	Cr_{EcR1} Cr_{EcR2} ⋮
Functionality	Cr_{FC1} Cr_{FC2} ⋮	Cr_{FM1} Cr_{FM2} ⋮	Cr_{FU1} Cr_{FU2} ⋮	Cr_{FR1} Cr_{FR2} ⋮
Corporate image	Cr_{CIC1} Cr_{CIC2} ⋮	Cr_{CIM1} Cr_{CIM2} ⋮	Cr_{CIU1} Cr_{CIU2} ⋮	Cr_{CIR1} Cr_{CIR2} ⋮

steel standards [18] as well as in many other areas [19]. As with the sustainable design of residential or office buildings [20, 21], in this study, the impact of the production process is not considered in the sustainable design of the industrial building.

2. Sustainability in Industrial Buildings

Our definition of a factory or an industrial building is as follows: "an area in which industrial production takes place as well as storage. The term factory as an alternative to industrial building covers generic aspects of industrial production. Nevertheless, both terms imply the existence of constructions, that is, areas of human design completed with the use of natural and artificial products, elements and construction systems within a controlled environment" [22].

In the past, the design of an industrial building was limited to its envelope, four walls, and a roof, under which productive activities took place. Today, their sustainable aspects refer mainly to the production processes that take place inside it. Attention centres on aspects such as pollution from the productive activity at all stages of the building life cycle (air, noise, water, etc.), as well as waste disposal and recycling, while very few resources are dedicated to research on the actual building [23, 24].

2.1. Sustainability Requirements and the Life Cycle of an Industrial Building. Factories may be perceived in terms of architectural elements interacting with sustainability requirements [15]. This innovative vision entails certain macro criteria or "sustainable requirements" in the design of an industrial building. So, the building should comply with sustainable global aspects, defined in terms of targets and needs. These should be identified at all stages of the building life cycle: that is, design, construction, usage, and reintegration.

In conventional terms, three basic, interrelated pillars constitute sustainability: the environment, the economy, and the society [25]. As with all constructions, the factors that comprise these three basic pillars of sustainability have to be strengthened in industrial buildings. However, the characteristics of industrial constructions emphasize design and construction functionality (factors linked to plant performance), worker safety throughout all the phases of life cycle, and the public image of the firm in the building (factors linked to marketing and economics). Even though they might form part of three basic requirements in other sorts of buildings, these requirements are of great importance in this type of buildings and should be considered independently [26, 27].

A total of six scopes of study or requirements are therefore defined around these 3 basic pillars for the sustainability assessment of a factory. Further 3 requirements were separately defined, due to their relevance to industrial production, as shown in Table 1.

Each of the headings set out below relate to one of the various requirements.

Safety and Industrial Risk Prevention. Safety implies an accident prevention programme that protects the physical integrity of anyone in or near the building, particularly during construction and demolition processes and maintenance works. The main purpose of these programmes is the prevention of industrial accidents. Consideration should also be given to structural safety, should the building be exposed to explosions or fires, as well as security and the protection of products, equipment, and the know-how.

Society. An industrial building provides employment and brings positive economic advantages at a local level. In this area, working relationships, the quality of the environment, and mobility within the building should also be considered. Travel between the home and the workplace should also be highlighted here, including the offer of alternative modes of transport to the private vehicle and health alternatives such as travel on foot and by bike. Workers on a building site should also have access to services that fulfill basic human needs for hygiene and rest (changing rooms, wash rooms, rest areas, meeting rooms. . .).

Environment. Various alternative locations for industrial buildings should be compared. Moreover, the use of "ecological" materials with a lower environmental impact should be assessed to reduce the energy consumption of the plant with a view to the reduction of energy. The use of recycled materials may also be studied. The end of the building life cycle involves selective demolition and waste management that can also mitigate the overall environmental impact. Throughout its useful life, an industrial building can accumulate a series of waste products, disposal of which requires management and planning of storage space within the installations. Total energy consumption, which is significant throughout the life of the building, can be reduced by means of cogeneration techniques and the introduction of renewable energies.

Economy. Careful consideration must be given to the economic requirement of the building at the construction stage and to maintenance and preservation actions in the course of its useful life. In terms of sustainability, coordination of consumption patterns throughout the useful life of the building is of great importance. Where possible, contractual arrangements for construction work should refer to sustainability-related issues (material origin and quality) and any completion dates should be within an economically viable period so that the investment may be recovered within the shortest possible time.

Functionality. A functional design implies that certain activities may be easily performed without any problems that relate to the building. The space available in the building for the process must be assessed in case future economic growth may require further plant expansion, reducing any future need for new materials, lowering economic costs and any waste that may be generated. The interior working conditions and ambient setting can affect the performance of employees and, in consequence, plant productivity. Various parts of the building may contain aggressive agents that affect its useful life and generate further maintenance needs that can have serious economic consequences. Expert knowledge will help locate the necessary services for production, planning enough room for auxiliary and storage facilities, and loading and unloading bays, which are essential components in the smooth management of the plant.

Corporate Image. Building image and aesthetics is a further aspect to recall. An architectural asset can contribute to the built environment of the city and industrial area and specifically to the company image. The company that owns the building often promotes its own corporate image in the construction, with higher associated costs and impacts.

All of these sustainable requirements have clear roles in the different phases of the building life cycle, from the design and throughout its useful life to its demolition and the management of any waste products. A list of 31 study criteria was composed, connected to the 6 requirements described above for sustainability evaluation in industrial buildings.

3. Materials and Methods

The MIVES [28] assessment methodology, as explained, was combined with a simplified Life Cycle Assessment (LCA). MIVES is a Multicriteria Decision Making (MCDM) with added AHP-based value functions. Their incorporation makes it possible to add homogeneity to different indicators which have different measurement units (economy is measured in €; environmental impact is measured in CO_2 kg). A reliable assessment requires a relevant evaluation model with a suitable requirement tree, with a balanced number of indicators [29].

The hierarchical structure of the requirement tree defines the assessment object, scopes of study, criteria, and indicators. Following the definition of this requirement tree, the methodology is used to calculate the Industrial Building Sustainability Index (IBSI), as shown in (Figure 1).

The following requirements are also known as the scopes of study (SS): safety, society, environment, economy, functionality, and corporate image. These can be divided into more specific criteria (CR): external mobility, safety measures in the construction process, use of ecological materials, cost of supplies, durability, brand image of the firm, and so forth. In turn, each criterion can be subdivided into indicators (ID), estimated with quantifiable values.

The key aspect in the definition of the indicators is that, apart from allowing quantification and simplification of the study phenomena, they must reflect the changes that occur in the system. Moreover, the utility of the indicators varies greatly with the context, which suggests that they have to be very carefully selected. The available information on the processes, functions, and study factors is a further key point in the selection of the indicators. All these points have an effect on the indicators, on their development, and on the development of their defining variables.

3.1. Sustainability Assessment. The following steps have to be completed, to prepare the sustainability assessment.

Step 1. Prepare an evaluation tree consisting of scopes of study, criteria, and indicators. A requirement tree that has a balanced number of criteria is of great importance.

Step 2. Calculate the weights to attach to each different stage in the evaluation; each criterion with its indicators, the requirement with its set of criteria, and the requirements that

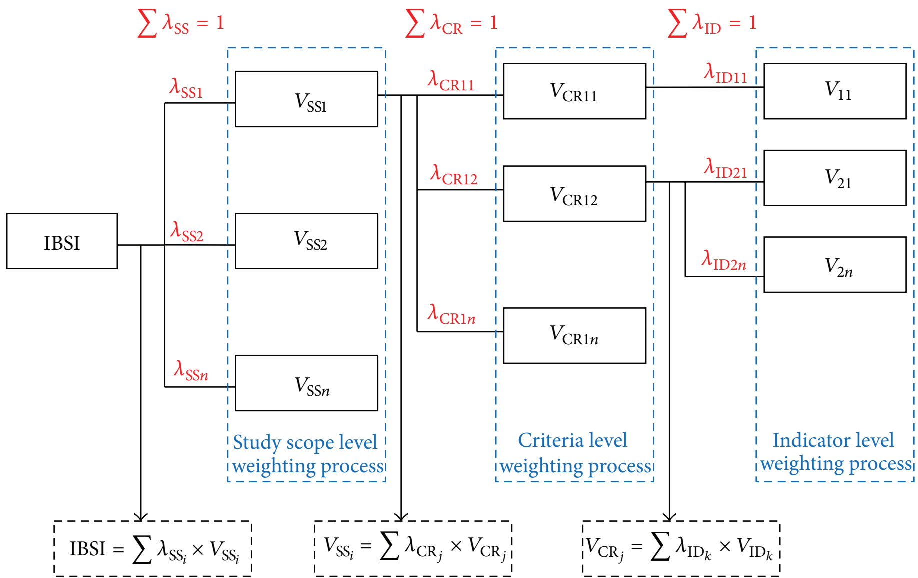

Figure 1: Hierarchical structure of the requirement tree.

comprise the "Industrial Building Sustainability Index" are all assigned to different levels of the evaluation tree.

Step 3. The value function of each indicator between a minimum value of "0" (the worst solution) and the maximum value of "1" (the best solution) offers a range of possible solutions, a set score or an output register.

Step 4. The requirements yield partial results, as well as the value of the "Industrial Building Sustainability Index," when the set of output registers are added, on the basis of the proposed system of weighting at each stage. All these values are in turn defined at some point between 0 and 1.

3.2. The Expert Panel and Selection of the Criteria. The most important criteria were selected using the Delphi method. This method addresses a complex problem through a group of individuals (Expert Panel) [30]. The group members followed this systematic process by choosing the evaluation criteria to assess the sustainability of industrial buildings. The first phase of this method began with open-ended questions, from which the items and issues were extracted for the continuation of the work. In a second phase, the questions were directed towards the evaluation, ranking, or comparison of the items. These successive questionnaires were intended to reduce the range of opinions and to clarify the consensus average opinion.

In the first phase, the Expert Panel obtained a total of 185 criteria, through an open-ended questionnaire. Following the initial collection of the criteria, the Expert Panel ranked these criteria, in the course of several successive meetings, and allocated a relative weight to each one, grouped under the requirements. These results were unified in the final phase, eliminating those with a relative weight of less than 5%. A total of 154 criteria were filtered out with this process, to arrive at 31 final evaluation criteria.

The Delphi method was selected for this study, because it offers the following advantages [30–32]:

(i) Group knowledge will always be superior to the knowledge of an individual participant who is better prepared than others, as the knowledge of each of the participants is complementary.

(ii) The opinions of each of its members may be contrasted.

(iii) The number of factors under study is higher, as each expert contributes a general idea of the topic from their specific knowledge domain to the discussion.

Using this method, it is necessary to avoid the dominant influence of any member of the group over the rest, in order to achieve an effective communication process. Many authors have pointed out that the Delphi method can minimize this aspect [33–35]. It is therefore necessary for each participant to remain unaware of the identity of the other participants.

An essential key to carry this process through successfully is the appropriate selection of panel members, selected for their skills, knowledge, and independence. The members of the Expert Panel comprised construction sector professionals (experts in raw materials, construction products, construction, engineering, and health and safety as well as researchers at technology centres and universities). Various panel member selection methods can be used. The criteria defined by Hallowell and Gambatese [36] require each expert to score at least 11 points in relation to categories of achievements or experience needed to sit on the panel. These authors considered an ideal panel in terms of a varied and a highly qualified group of between 8 and 16 individuals. The experts were chosen from a construction sector database of 72 professionals, employed by 31 different organizations at a national level (companies, technological

Table 2: Breakdown of the scopes of study.

Industrial Building Sustainability Index (IBSI)				
Scope of study	Weight	Criterion	Designation	Weight
SS1 Safety	16.67%	CR1.1	Structural safety against fire	19%
		CR1.2	Safety and health in the execution procedure	37%
		CR1.3	Safety measures in the construction process	19%
		CR1.4	Maintenance and conservation of the industrial plant	10%
		CR1.5	Safety against intruders	5%
		CR1.6	Safety and health during deconstruction	10%
SS2 Society	16.67%	CR2.1	External mobility	43%
		CR2.2	Respect for the urban environment	14%
		CR2.3	Auxiliary services for personnel	43%
SS3 Environment	16.67%	CR3.1	Integration in the natural environment	6%
		CR3.2	Environmental impact during construction	17%
		CR3.3	Use of ecological materials	10%
		CR3.4	Environmental impact during utilization	34%
		CR3.5	Waste management during utilization	10%
		CR3.6	Impact of materials from demolition	23%
SS4 economy	16.67%	CR4.1	Cost of executing the work	17%
		CR4.2	Construction timeframe	12%
		CR4.3	Cost of supplies	32%
		CR4.4	Cost of maintenance	32%
		CR4.5	Cost of building demolition	7%
SS5 Functionality	16.67%	CR5.1	Performance of the building in use	6%
		CR5.2	Constructability of ease of construction	11%
		CR5.3	Quality of internal environment	23%
		CR5.4	Durability	16%
		CR5.5	Flexibility	23%
		CR5.6	Ease of maintenance	11%
		CR5.7	Auxiliary production services	4%
		CR5.8	Deconstructibility	6%
SS6 corporate image	16.67%	CR6.1	Integration in the urban environment	20%
		CR6.2	Brand image of the firm	60%
		CR6.3	Aesthetic maintenance of the building	20%

centres, and universities). They have all taught on the Master's Degree in Construction Engineering at the University of the Basque Country (UPV/EHU). The details of the project were shared with professionals and the different stakeholder groups in workshops at the University of the Basque Country (UPV/EHU), where the content of the master's course are imparted. Following the selection process, the Expert Panel comprised 11 members.

Table 2 presents the selected scopes of study and criteria in the calculation of the IBSI, together with their relative weights.

Certain tangible and therefore directly measurable criteria were selected. Other more subjective and intangible criteria as in the case of "quality of internal environment" had also to be considered. In these cases, quantifiable indicators were used to assess the criteria. Measurement of the "quality of internal environment" was quantified through an evaluation of the following 5 indicators: "light level," "interior ventilation," "temperature in the work area," "noise present in the building," and "electromagnetic pollution." The relevant weights were attached to the indicators that constituted each criterion for its quantification.

3.3. Assignment of the Relative Weights. Initially, sustainability priorities or weights have to be attached to the respective hierarchical levels of the assessment model (λ_i, λ_{CR}, and λ_{SS}).

In recent years, various studies have examined the preferential assignment of some criteria in relation to others, based on attributes wherever complete information is missing [37–42]. The "Analytic Hierarchy Process (AHP)" Decision Method [43, 44] was used for calculating the sustainability weights.

Following this method, the relative priority of each alternative is placed on a quantifiable scale. It thereby emphasizes the intuitive criteria of the decision-makers and the reliability of their comparisons when rating different options. The methodology incorporates the principle that knowledge and experience guide the judgments of decision-makers.

It also organizes both tangible and intangible factors in a systematic manner, to arrive at a simple structured solution. As explained, this methodology constitutes a numerical assessment of alternatives based on the systematic assessment of a set of decision alternatives [45].

3.4. The Industrial Building Sustainability Index (IBSI). The addition of each dimensionless value (V_{SS}) of the 6 requirements or scopes of study yields the Industrial Building Sustainability Index (IBSI). These values have previously been corrected according to their own final weight (λ_{SS}), as shown in

$$\text{IBSI} = \sum_{i=1}^{j} \lambda_{SS_i} \times V_{SS_i}, \tag{1}$$

where IBSI is Industrial Building Sustainability Index. λ_{SS_i} is weight of the study scope i. V_{SS_i} represents value of the study scope i. j is total number of study scopes.

The addition of the specific dimensionless values (V_{CR}) of the 3-to-8 criteria of each requirement yielded the dimensionless values (V_{SS}) of each of the 6 requirements. These values were previously corrected according to their own final weight (λ_{CR}), as shown in

$$V_{SS_k} = \sum_{i=1}^{j} \lambda_{CR_{i,k}} \times V_{CR_{i,k}}, \tag{2}$$

where V_{SS_k} is study scope k value. $\lambda_{CR_{i,k}}$ represents criterion weight i of study scope k. $V_{CR_{i,k}}$ is criterion value i of study scope k. j represents number of criteria hanging from study scope k.

Each of the dimensionless values (V_{CR}) of the 31 criteria was obtained by adding up the dimensionless value functions ($V_{i,k}$) of the 1-to-4 indicators of each criterion. These values were previously corrected according to their own final weight ($\lambda_{i,k}$), as shown in

$$V_{CR_k} = \sum_{i=1}^{j} \lambda_{i,k} \times v_{i,k}\left(x_{alt}\right), \tag{3}$$

where V_{CR_k} is criterion k value. $\lambda_{i,k}$ represents indicator weight i of criterion k. $v_{i,k}(x_{alt})$ is indicator value i of criterion k. j represents number of indicators hanging from criterion k.

The value functions ($v_{i,k}$) range from 0 to 1, which are the minimum and the maximum level of satisfaction with each indicator. Each value function is defined by 5 parameters. The function shape and, consequently, the variation in each indicator value may be defined with these parameters in relation to the dimensionless scale. Function (4) assigns a numerical value to the different coefficients and parameters to model the physical behaviour of the indicator:

$$v_i = A + \frac{1}{B} X \left[1 - e^{-k_i X (|x_{alt} - x_{min}|/C_i)^{P_i}}\right], \tag{4}$$

where x_{min} is minimum reference point on the indicator scale under consideration. Response to the indicator generates a value equal to 0. x_{max} represents maximum reference point on the indicator scale under consideration. Response to the indicator generates a value equal to 1. x_{alt} is response to the assessed alternative regarding the indicator under consideration, which will lie between the values x_{min} and x_{max}. Response to the indicator generates a value equal to $v_i(x_{alt})$, which is sought. P_i is a form factor defining whether the curve is concave, convex, lineal, or "S" shaped, where concave curves are obtained for $P_i < 1$ values, convex or "S" shaped curves if $P_i > 1$, and lineal if $P_i \approx 1$. k_i defines the ordinate value of point C_i. A represents value of response "x_{min}," $A = 0$, or $A = 1$ (generally $A = 0$). B is a factor enabling maintenance of the value function in the range (0.00; 1.00) and the best response always has a value equal to 1. This factor is defined by

$$B = \frac{1}{1 - e^{-k_i X (|x_{max} - x_{min}|/C_i)^{P_i}}}. \tag{5}$$

By entering different values in the 5 variables of the expression, we can get different modes of adaptation to the nature of the study variable (indicator). Thus, the obtained values can vary from a linear response (ascending or descending), to concave shaped responses, convex shaped responses, or even "S" shaped responses, as seen in Figure 2.

3.5. Example of a Criteria Evaluation Process. In the following section, only the example of the evaluation of the indicator associated to "safety measures in the construction process (CR 1.3)" criterion will be described, due to limitations on the length of the paper.

The input values that are taken into account to assess this specific indicator are shown in Table 3.

As an evaluation example, Case Study 1 (oil mill housing) has been selected, which is described in more detail in the next section (Section 4). Based on this case and once all points have been checked, the score obtained in the indicator associated with criterion CR 1.3 was 40 points. By entering this score in the value function associated with this indicator (Figure 3), which is a lineal function in this case, a dimensionless value of 0.4 is obtained. The next step in the evaluation consists in multiplying this value by the corresponding relative weight of criterion 1.3, which has been defined in Table 2, in this case 19%. Thus, the final value of Criterion 1.3 for the Case Study 1 is 0.077, as can be seen in Table 4.

4. Results and Discussion

Three case studies of industrial buildings were performed with the methodology: a building housing an oil mill, another housing slag pits at a steel plant, and a construction materials storage depot and showroom. The three examples have very different characteristics, so as to test the responsiveness of the proposed methodology and its behaviour. These characteristics reflect different locations, from rural to highly urbanized zones with large-scale public communications infrastructure. Steel and precast concrete were the main construction materials found in the buildings. The various

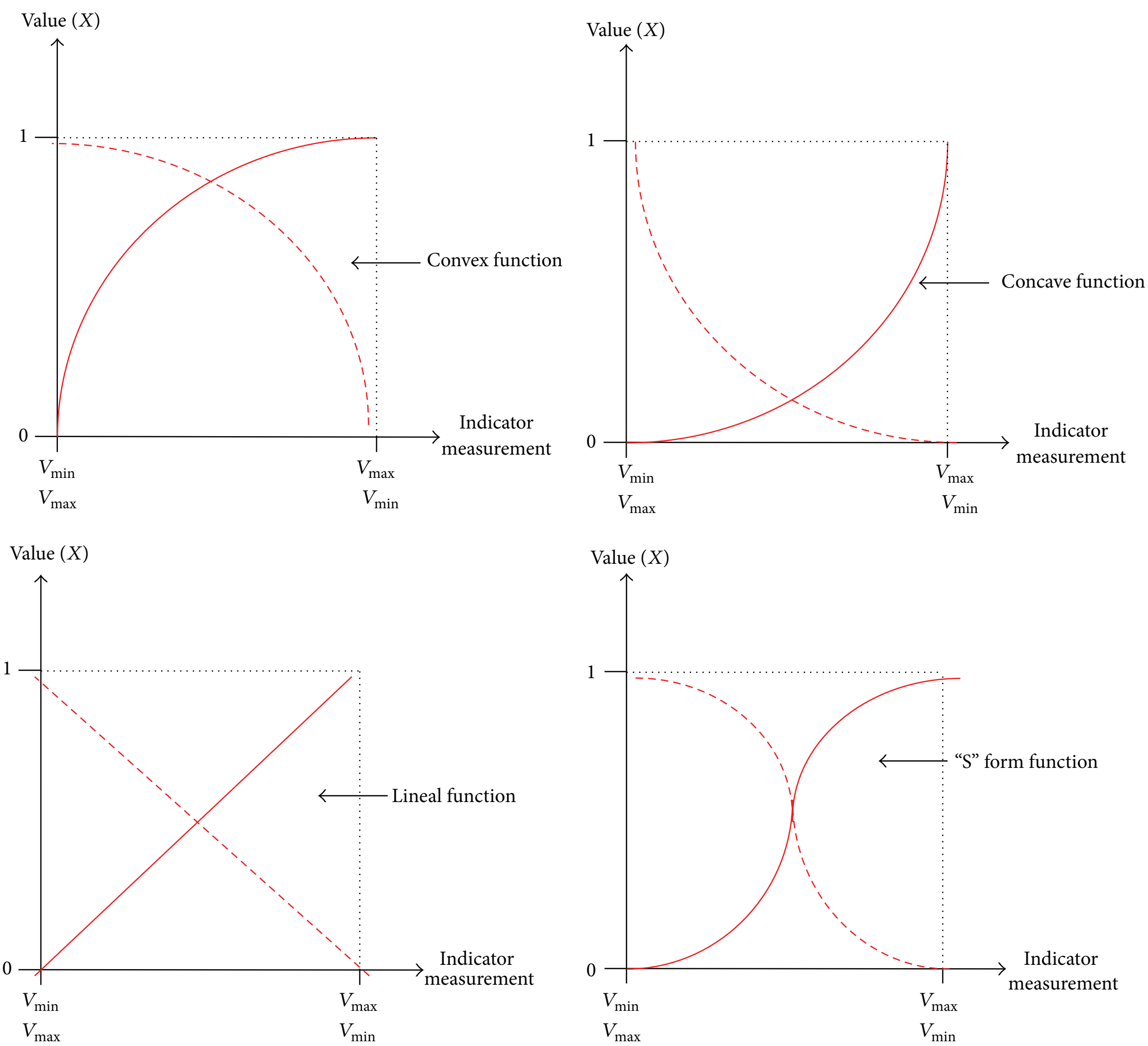

FIGURE 2: Modes of adaptation to the nature of the indicator.

TABLE 3: Input values of the indicator associated with criterion CR1.3.

Number	Input value	Satisfied	Not satisfied	Case Study 1
1	Strict compliance with the safety rules in force	0	Evaluation is not allowed	0
2	Existence of a health and safety coordinator, which has to belong to the construction company and must not be outsourced	30 points	0 points	0
3	In the technical specifications, the existence of the requirement that all personal and collective protection systems must have the CE marking	30 points	0 points	0
4	Promotion of the use of collective protection measures, rather than individual protective equipment, which are only used when it is essential	40 points	0 points	40 points
	Total			**40 points**

Table 4: Breakdown of "safety" study scope at its different hierarchical levels.

Study scope	Criterion (CR)	Oil mill housing $V_{CR1,k}$	Slag pit housing $V_{CR1,k}$	Storage depot $V_{CR1,k}$
Safety (SS1)	Structural safety against fire (CR1.1)	0.000	0.000	0.087
	Safety and health in the execution procedure (CR1.2)	0.037	0.257	0.184
	Safety measures in the construction process (CR1.3)	0.077	0.193	0.135
	Maintenance and conservation of the industrial plant (CR1.4)	0.036	0.051	0.068
	Safety against intruders (CR1.5)	0.051	0.051	0.051
	Safety and health during deconstruction (CR1.6)	0.098	0.098	0.065

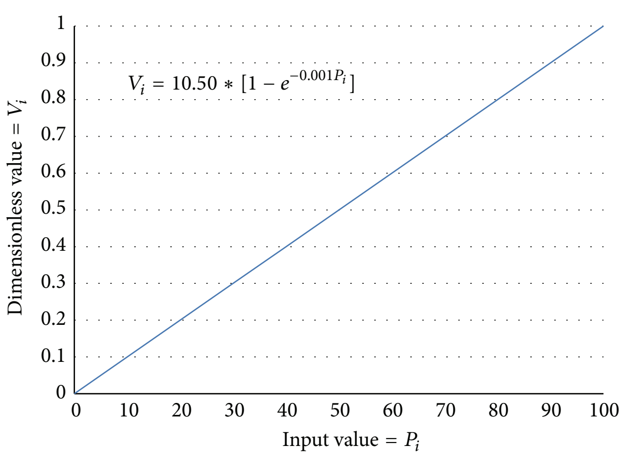

Figure 3: Value function of the indicator associated with criterion CR1.3.

agents who intervened in the construction held different quality and environmental certifications. The processes that take place inside them differ and, in consequence, so do their environmental requirements. The proposed sustainability assessment methodology is applied to the different practical case studies in the following sections.

4.1. Case Study 1: Oil Mill Housing. The manufacturing process of pressing olive oil takes place regularly at the same time of year in this building. Throughout the rest of the year the building remains open to sell and to distribute the product. The oil mill is near a rural agglomeration of 4,000 inhabitants, without any public transport links. The building occupies an area of 1,092 m^2, on a shallow foundation, poured with 105.94 m^3 of concrete. Its metallic frameworks are finished off with laminated profiles (38,542.47 Kg) and it has a 70 m^2 mezzanine floor. The warehouse is enclosed with panels made of two sheets joined by a 100 mm thick polyurethane foam core, with a total area of 802.40 m^2. This same system of panels covers the gable roof at an inclination of 15%, occupying a total area of 1,122 m^2. The facade covering the hallway that leads to the different work areas has large windows to take in natural light and for ventilation, with a total glass area of 74.11 m^2. The building has standard installations, with a mixed boiler partially fuelled by the waste from the oil extraction process. A small engineering firm, with no quality or environmental certification, completed the design. The same may be said of the construction firm and the promoter and owner of the plant. The industrial activity of the firm according to Spanish legislation is an activity that is classified as unpleasant, unhealthy, or dangerous, which also generates toxic waste.

4.2. Case Study 2: Slag Pit Housing. This industrial building houses one part of the steel coil production process. Its industrial site is nearby two large urban areas, with reliable public transport links via interurban train and bus networks. The built area of the building is 3,175 m^2. It has a continuous shallow foundation, poured with 610 m^3 of concrete. It supports a concrete wall with 6 mm sacrificial shuttering in the form of steel sheets that also serve as a means of fire protection. The main structure is covered with oversized laminated profiles to counter the risk of explosions (245,788 Kg). The walls and roof consist of simple sheet metal, painted with the corporate image of the firm, over a total surface area of 2,905 m^2. The sewer system collects industrial waters and moves them to the sewage network for further treatment. The project was designed by a large engineering consultancy firm that, along with the construction firm, has ISO 9001 and ISO 14001 accreditation. The corporate promoter and owner of the installation have gained the following four accreditations: ISO 9001, ISO 14.001, EMAS, and OHSAS 18001.

The firm carries out an unpleasant, unhealthy, or dangerous activity under Spanish legislation that involves a risk of explosions. Moreover, slag vapours can involve short-term damage to the metal sheeting on the walls and roof and the metallic structure. All parts of the roof are accessible for inspection purposes, to ensure good repair that will reduce the dangers associated with explosions.

4.3. Case Study 3: Storage Depot for Construction Materials. This building stores construction material for retail and wholesale business. It is located in an urban area with widespread business and industrial activity. Public transport links the industrial zone to the rest of the city with frequent services. The building is not precisely an industrial one, as its serves as a storage depot for the retail sale of construction material to the general public and the building trade, so it is usually clean and well arranged. Its built area occupies 1,584 m^2 and the foundation was poured (112.5 m^3 concrete) with 30 separate footings, joined by a perimeter

Table 5: Breakdown of "social" study scope at its different hierarchical levels.

Study scope (SS)	Criterion (CR)	Oil mill housing $V_{CR2,k}$	Slag pit housing $V_{CR2,k}$	Storage depot $V_{CR2,k}$
Society (SS2)	External mobility (CR2.1)	0.080	0.428	0.428
	Respect for the urban environment (CR2.2)	0.057	0.057	0.028
	Auxiliary services for personnel (CR2.3)	0.172	0.086	0.258

Table 6: Breakdown of "environment" study scope at its different hierarchical levels.

Study scope (SS)	Criterion (CR)	Oil mill housing $V_{CR3,k}$	Slag pit housing $V_{CR3,k}$	Storage depot $V_{CR3,k}$
Environment (SS3)	Integration in the natural environment (CR3.1)	0.017	0.033	0.025
	Environmental impact during construction (CR3.2)	0.087	0.066	0.167
	Use of ecological materials (CR3.3)	0.000	0.000	0.000
	Environmental impact during utilization (CR3.4)	0.127	0.042	0.212
	Waste management during utilization (CR3.5)	0.000	0.099	0.099
	Impact of materials from demolition (CR3.6)	0.000	0.000	0.235

Table 7: Breakdown of "economic" study scope at its different hierarchical levels.

Study scope (SS)	Criterion (CR)	Oil mill housing $V_{CR4,k}$	Slag pit housing $V_{CR4,k}$	Storage depot $V_{CR4,k}$
Economy (SS4)	Cost of executing the work (CR4.1)	0.117	0.089	0.121
	Construction timeframe (CR4.2)	0.076	0.098	0.092
	Cost of supplies (CR4.3)	0.054	0.051	0.065
	Cost of maintenance (CR4.4)	0.116	0.198	0.234
	Cost of building demolition (CR4.5)	0.075	0.075	0.000

Table 8: Breakdown of "functionality" study scope at its different hierarchical levels.

Study scope (SS)	Criterion (CR)	Oil mill housing $V_{CR5,k}$	Slag pit housing $V_{CR5,k}$	Storage depot $V_{CR5,k}$
Functionality (SS5)	Performance of the building in use (CR5.1)	0.064	0.064	0.064
	Constructability of ease of construction (CR5.2)	0.098	0.078	0.101
	Quality of internal environment (CR5.3)	0.085	0.103	0.194
	Durability (CR5.4)	0.049	0.098	0.131
	Flexibility (CR5.5)	0.153	0.076	0.153
	Ease of maintenance (CR5.5)	0.000	0.080	0.053
	Auxiliary production services (CR5.6)	0.038	0.017	0.033
	Deconstructibility (CR5.7)	0.059	0.050	0.045

beam brace that supports the facade panels. The structure of the building was designed with prefabricated concrete. Its structural elements contain 148.5 m^3 of concrete volume. Its mezzanine floor consists of precast hollow core slabs. The facade enclosures are concrete panels with an interior insulation core, covering an area of 1,442 m^2. The gable roof, with an inclination of 5%, is covered with steel panels and a 50 mm thick mineral-blanket core, with an area of 1,317 m^2. Uniformly distributed skylights occupy an area of 233 m^2 on the roof, which is in addition to the overhead lighting inside the building. There are various security systems to prevent intruders from illegal entry. Both the engineering consultancy and the promoter have gained the ISO 9001 and ISO 14001 quality and environmental certifications.

Tables 4, 5, 6, 7, 8, and 9 present the hierarchical breakdown of each requirement or study scope in the three case studies.

Table 10 shows the final values of the different requirements and the final value of the Industrial Building Sustainability Index (IBSI) in the three case studies.

These results can be represented in a bar diagram, for better observation of the strong and the weak points in each

TABLE 9: Breakdown of "corporate image" study scope at its different hierarchical levels.

Study scope (SS)	Criterion (CR)	Oil mill housing $V_{CR6,k}$	Slag pit housing $V_{CR6,k}$	Storage depot $V_{CR6,k}$
Corporate image (SS6)	Integration in the urban environment (CR6.1)	0.066	0.033	0.000
	Brand image of the firm (CR6.2)	0.000	0.451	0.451
	Esthetic maintenance of the building (CR6.3)	0.147	0.100	0.196

TABLE 10: Values of the different requirements and IBSI values.

Study scope (SS)	Oil mill housing $V_{SS,k}$	Slag pit housing $V_{SS,k}$	Storage depot $V_{SS,k}$
Safety (SS1)	0.298	0.650	0.590
Society (SS2)	0.308	0.571	0.714
Environment (SS3)	0.231	0.240	0.737
Economy (SS4)	0.439	0.510	0.513
Functionality (SS5)	0.545	0.566	0.773
Corporate image (SS6)	0.213	0.584	0.647
IBSI	**0.339**	**0.520**	**0.662**

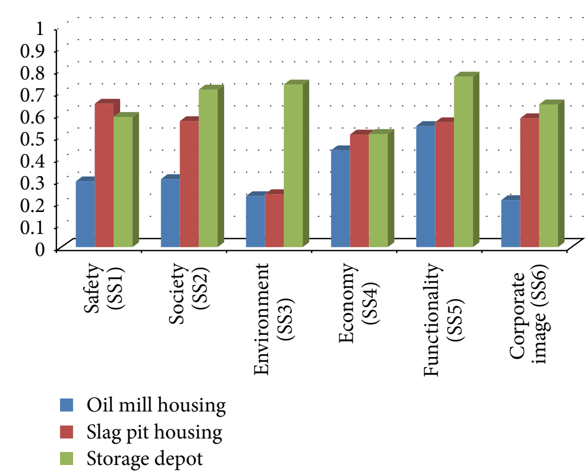

FIGURE 4: Results of the 3 case studies.

case study, so as to facilitate decision making regarding the selection of the best improvement measures to take, as shown in Figure 4.

5. Practical Relevance and Potential Applications

The proposed methodology is capable of improving the sustainability level of a construction project during the design stage. Its application incorporates features of interest: it gives aggregated global and partial indexes as a result and quantifies each indicator, criteria, requirements, and results and it has been configured and specially adapted for this area of study. Thus, the proposed modifications at the design stage may be studied to see how they would affect the different requirements. Therefore, at this stage, the proposed solution may be improved in terms of its sustainability, because the changes at the design stage have less economic impact than the changes at the construction phase and in subsequent phases.

5.1. Improvement of the IBSI Rate in Case Study 1: Oil Mill. This section describes how the methodology can help decision making in relation to the sustainability value of a construction project. Consequently, we may see how the decisions taken at the design phase modify the final sustainability values of the construction project. Case Study 1 has been selected for this purpose because it has the lowest IBSI rate. In Table 11, a series of improvements are described to visualize how changes affect each criterion and, consequently, the level of sustainability of the plant. The improvement actions were introduced through requirements and those with the lowest economic impact were selected.

With this set of actions taken in the case study of the oil mill, the IBSI rose from an initial value of 0.339 to a final value of 0.581.

Figure 5 presents the results of the IBSI, before and after the improvement proposals.

6. Conclusions

The advanced vision of the sustainable construction concept that has been described in this paper focuses on the following requirements in the context of industrial building: safety and industrial health, functionality, and corporate image. These requirements may be added to generic ones—environmental, economic, and social requirements—which are standard in all construction work. The noncommercial MIVES methodology that we have proposed has been used to calculate a global sustainability index and partial indicators of an industrial building. It has meant that we can now ascertain the strengths and weaknesses of a project, at the design stage, identifying those indicators and criteria in need of

Table 11: Improvement proposals.

		Previous value	Improved value
	SS1: safety		
CR 1.1	The introduction of fire detection systems and alarms The existence of a health & safety coordinator	**0.000**	**0.019**
CR 1.2	The construction company must be responsible for its own preventive activity, so that this activity is not outsourced The inclusion of the requirement that all personal and collective protection systems must have the "EC" label in the tender specifications	**0.037**	**0.220**
CR 1.3	The health & safety coordinator must belong to the construction company and must not be outsourced	**0.077**	**0.135**
CR 1.4	Placing anchoring systems and lifelines, in order to facilitate maintenance and cleaning under safe conditions, throughout the life of the building	**0.036**	**0.070**
	SSS2: Society		
CR 2.1	Changes to the planned location of the plant to an industrial estate closer to the town centre, with access to public transport lines, improving worker access to the plant	**0.080**	**0.153**
CR 2.2	The introduction of a budget heading on water spraying systems to reduce the generation of dust in the environment	**0.057**	**0.085**
CR 2.3	An increased level of hygiene above the legal minimum, because the plant has an area dedicated to the sale of olive oil products to the public	**0.172**	**0.258**
	SS3: environment		
CR 3.1	The installation of solar photovoltaic panels on the roof, with the aim of reducing external energy consumption and therefore CO_2 emissions The promotion and the encouragement of public transport among workers, leading to reductions in CO_2 emissions	**0.017**	**0.033**
	SS4: economy		
CR 4.2	The imposition of clauses threatening economic sanctions, in case of delays, in order to ensure compliance with deadlines	**0.076**	**0.094**
CR 4.3	Rain water collection tanks for subsequent reuse of rainwater in other applications, thereby reducing resource consumption The use of energy produced in the solar photovoltaic system, for own consumption or for sale to the electric network	**0.054**	**0.106**
	SS5: functionality		
CR 5.3	The implementation of a system to regulate the use of lighting, to reduce energy consumption The installation of a forced ventilation system for the circulation of air The installation of acoustically insulated panels in equipment that generates noise	**0.085**	**0.137**
CR 5.4	The requirement that quality accreditation must be held by the engineering company that bids for the design of the project	**0.049**	**0.065**
CR 5.6	The implementation of security systems, in order to facilitate access to the roof and in consequence, to enable operators to perform maintenance work safely	**0.000**	**0.080**
	SS6: corporate image		
CR 6.1	Reduction of the visual impact of the parking of the factory, considering the trees growing on the plot where it is located	**0.100**	**0.133**
CR 6.2	The requirement that the company should hold quality and environmental management accreditations	**0.000**	**0.451**
	Total value of IBSI	**0.339**	**0.581**

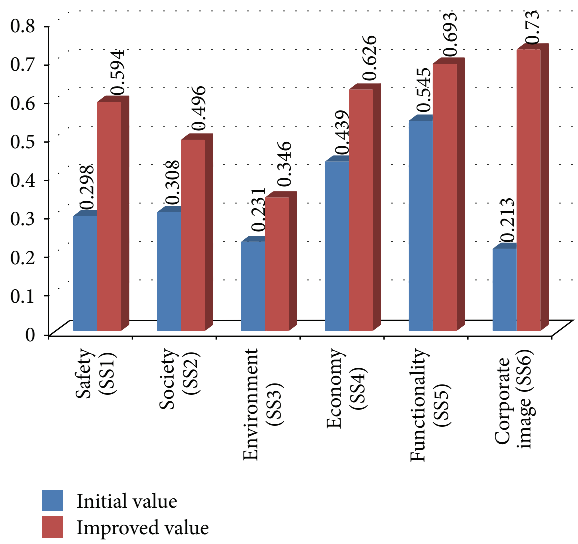

FIGURE 5: Initial results and improved results.

improvement, and facilitating sustainability-related decision making.

In the 3 case studies that were contrasted, the storage and sale of construction materials, which is not strictly a productive process, obtained the highest scores for the environmental, economic, societal, functional, and corporate image requirements. The presence of this firm in the tertiary or service sector influenced this assessment, where there is greater contact with the general public. New and improved images are sought to improve sales, along with better communications systems and proximity to significant residential areas, as it is a nonpolluting process.

Functional and economic requirements were given greater priority in the two specifically industrial processes. As firm size grows, concerns for other requirements also grow such as security and the social factor, above all when the firm has a brand image, which also leads to increased environmental awareness. From this comparison, it may also be seen that the scores of the smallest firm are lower than the scores of the larger firms, principally due to their having fewer available economic resources. A number of improvement proposals have been proposed for the case study of the oil mill, which has the lowest sustainability index. In this way, the IBSI has increased from an initial value of 0.339 to a final value of 0.581.

The development of this methodology was made possible thanks to the work of the Expert Panel, comprising qualified professionals in the construction sector, who defined the evaluation tree, identifying criteria, indicators, and the specific weights for each one, following Delphi methodology guidelines, which has proved itself suitable in these types of problems.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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