

# SUSTAINABILITY APPLIED TO PREFABRICATION

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**Abstract:** Precast concrete elements are factory made products that permits to industrialize the construction industry and, therefore, to shift work from temporary construction sites to modern permanent facilities. Factory production entails rational and efficient manufacturing processes, skilled workers, systematization of repetitive tasks, and lower labor costs as a consequence of automated production. Automation is gradually being implemented in factories and is already in place in areas such as the preparation of reinforcing steel, mould assembly, concrete casting, and surface finishing on architectural concrete. And other stages in the processes that permits to increase the efficiency and productivity are sure to be followed. As there is a *fib* Bulletin under preparation in Commission 6 Prefabrication, by the Task Group 6.3 Sustainability, in which both authors are members, the conclusions of this document will be presented including a proposal for an evaluation model based on MIVES method that can be applied to assess the sustainability of precast concrete structures.

## 1 INTRODUCTION

As prefabrication makes optimal use of materials, its potential for savings is much greater than in cast-in-situ construction. Structural performance and durability are also enhanced through design, modern manufacturing equipment and carefully planned working procedures.

The environmental burden of prefabrication is mainly the burden caused by the raw materials of concrete (especially production of cement and steel). Usually, the environmental burden of precast concrete is less than that of other concrete construction because of the reduced use of materials in comparison with on-site construction [1-2].

In addition, thermal inertia of heavy materials is well known for both in warm and cold climates. Most people have experienced the comfort of coming into a comparatively cool stone building on a hot day in a warm climate. In precast structures, several systems have been developed using this characteristic.

Moreover, the use of new technologies like self-consolidating concrete (SCC) can significantly reduce the noise and vibration in the production process. The use of high-performance concrete (HPC) enables design and production of more reliable and more durable structures with optimized shape. The potential for savings in structural material consumption and consequently natural resources is evident [3].

However, the authors have not identified methods that allow assessing the global sustainability index associated to precast concrete systems with which the stakeholders can compare alternatives coupling objectively economic, social and environmental requirements and minimizing, at the same time, the degree of subjectivity in the decision process.

To this end, the MIVES method (from the Spanish, Integrated Value Model for Sustainability Assessment) is used in this research as a decision-making method to assess the sustainability of precast concrete structures/systems.

In this regard, the MIVES method is based on the use of value functions [4]. So far, MIVES has

already been used for industrial buildings [5-7], underground infrastructures [8], hydraulic structures [9], wind towers [10], sewerage systems [11], post-disaster site and housing selection [12-13] and construction projects [14-15]. It should be highlighted that in the current Spanish Structural Concrete Code [16] MIVES method is proposed for assessing the sustainability of concrete structures [17]. Finally, it must be added that the MIVES method has even been expanded to include the uncertainties involved in the process of analysis [18].

The main goal of this research contribution is to present the work in progress that is being carried out by the fib TG 6.3 Sustainability. Part of this task group is focused on proposing a model based on MIVES to assess the sustainability index of precast concrete elements/systems. The resulting *fib* bulletin will complement other bulletins on environmental aspects related to concrete structures [1; 19-20].

### 3 THE ESSENTIALS OF THE MIVES METHOD

#### 3.1. Application stages

The assessment of the sustainability index by using the MIVES method should be carried out following these steps:

- Define the problem to be solved and the decisions to be made.
- Produce a basic diagram of the decision model, establishing all those aspects that will be part of a requirements tree that may include qualitative and quantitative variables.
- Establish mathematical functions to convert the qualitative and quantitative variables into a set of variables with the same units and scales.
- Define the importance or relative weight of each of the aspects to be taken into account in the assessment.
- Define the various design alternatives that could be considered to solve the previously identified problem.
- Evaluate and assess those alternatives by using the previously created model.
- Make the right decisions and choose the most appropriate alternative.

In this particular case, the problem to be solved (stage A of MIVES) consists in assessing the sustainability index of a precast concrete structure or product to be posteriorly compared with other possible alternatives.

The requirements tree (stage B of MIVES) consist in a hierarchical diagram (Fig.1) in which the various characteristics of the product or processes to be evaluated are organized, normally at three levels: indicators, sub-criteria, and criteria. At the final level, the specific requirements are defined and the previous levels (criteria and indicators) are included in order to desegregate the requirements; this permitting: (1) having a global view of the problem; (2) organizing the ideas and (3) facilitating the comprehension of the model to any stakeholder involved in the decision process.

Afterwards, mathematical elements from the general multi-criteria decision theory are used [21-23] to formalize a method to convert the different criteria magnitudes and units into a common, non-dimensional, unit that will be called value (stage C of MIVES). In this sense, it should be noticed that this method accounts for both qualitative and quantitative variables related with the indicators.

In any multi-criteria decision problem, the decision maker have to choose between a group of alternatives [22], this being discrete or continuous. In the field of the precast concrete technology, it is possible to enumerate all the existing alternatives to give response to a specific problem.

Thus, when the preferences ( $x$ ) are known with respect to a set of design alternatives ( $X$ ), a value function  $V:P \rightarrow R$  can be fixed such that  $P_x > P'_x$  so that  $V(P_x) > V(P'_x)$ ,  $P$  being equal to a set of criteria to be evaluated for alternative  $x$ . The problem consists of generating a non-dimensional value function  $V(P_x)$  that reflects the preferences of the decision maker for each alternative while integrating all the criteria  $P_x = (P_{1,x}; P_{2,x}; \dots; P_{N,x})$ .

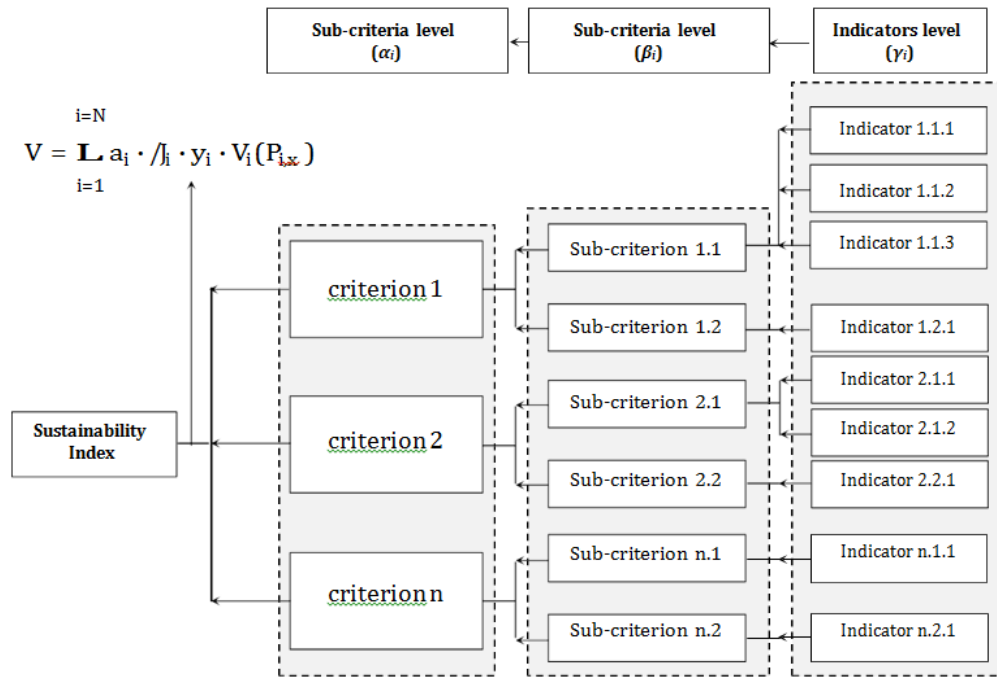


Figure 1: General requirements tree.

The solution is a function  $V$  consisting of the sum of  $N$  value functions  $V_i$  corresponding to the  $N$  criteria which comply with  $V_i: P \rightarrow R$  so  $P_{i,x} > P'_{i,x} \leftrightarrow V_i(P_{i,x}) > V_i(P'_{i,x})$ . For the case of problems structured in the form of a requirements tree, the resulting *Sustainability Index* (SI) can be assessed by using the Eq. 1.

$$SI = V(P_x) = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i(P_{i,x}) \quad (1)$$

In Eq. 1,  $V(P_x)$  measures the degree of sustainability (value) of the alternative  $x$  evaluated with respect to various criteria  $P_x = (P_{1,x}; P_{2,x}; \dots; P_{N,x})$  considered.  $\alpha_i$  and  $\beta_i$  are the weights of the criteria and sub-criteria to which each criteria  $i$  belongs;  $\gamma_i$  being the weights of the different indicators.  $V_i(P_{i,x})$  are the value functions used to measure the degree of sustainability of the alternative  $x$  with respect to a given criterion  $i$ . Finally,  $N$  is the total number of criteria considered in the assessment. Weights  $\alpha_i$ ,  $\beta_i$ , and  $\gamma_i$  represent the preference, respectively, of certain indicator ( $\gamma_i$ ), sub-criterion ( $\beta_i$ ) and criterion ( $\alpha_i$ ).

The main objectives of the  $V_i$  functions are:

- To homogenize the criteria units. In this regard, it is also highly recommended to delimit the values that these functions can generate. In this way, all the criteria have one single scale of assessment, normally between 0 and 1. These values represent the minimum and maximum degree of sustainability, respectively.
- To make it possible to weigh the  $V_i$  functions by weights  $\alpha_i$ ,  $\beta_i$ , and  $\gamma_i$ . It also makes it easier to obtain these weights ( $\alpha_i$ ,  $\beta_i$ , and  $\gamma_i$ ) since it will only be necessary to establish the relative priority of certain criteria, sub-criteria, or indicator with respect to other ones, regardless of whether some may present different scales of quantification.

Once the value functions have been defined, it is necessary to calculate weights  $\alpha_i$ ,  $\beta_i$ , and  $\gamma_i$  for each branch of the requirements tree (stage D of MIVES). To this end, numerical values established by experts in the field are used. First, the weights of each criterion ( $\alpha_i$ ) are calculated. Then, within each criterion, weights  $\beta_i$  for the several sub-criteria are calculated, and finally, the same process is done for each sub-criterion to obtain the indicator weights  $\gamma_i$ .

The initial trees are often excessively complex, or discrepancies occur among the experts, or, simply, it is desirable to carry out an organized process to avoid difficulties in establishing the weights. In these situations, the analytic hierarchy process (AHP) [24-25] may be used. Afterward, to compensate for possible subjective bias because of the use of semantic labels in AHP, a subsequent process of analysing, comparing and, in case of being necessary, modifying the resulting weights is recommended.

The various alternatives  $x$  are defined in the following stage (stage E). After that, these alternatives are evaluated (stage F), and the sustainability index associated with each of them is calculated by using Eq. 1.

### 3.2. Definition of the value functions

Defining the value function requires measuring preference or the degree of satisfaction produced by a certain alternative. Each measurement variable may be given in different units; therefore, it is necessary to standardize these into units of value or satisfaction, which is basically what the value function does. The method proposed a scale for which 0.0 reflects minimum satisfaction ( $P_{min}$ ) and 1.0 reflects maximum satisfaction ( $P_{max}$ ).

To determine the satisfaction value for an indicator, the MIVES model outlines a procedure consisting in the definition of:

- The tendency (increase or decrease) of the value function.
- The points corresponding to  $P_{min}$  and  $P_{max}$ .
- The shape of the value functions (linear, concave, convex, S-shaped).
- The mathematical expression of the value function.

The general expression of the value function  $V_i$  used in MIVES to assess the satisfaction of the stakeholders for each indicator responds to the Eq. 2.

$$V_i = K_i \cdot \left[ 1 - e^{-m_i \cdot (|P_{i,x} - P_{i,min}|/n_i)^{A_i}} \right] \quad (2)$$

In Eq. 3, variable  $K_i$  is a factor that ensures that the value function will remain within the range of 0.0-1.0 and that the best response is associated with a value equal to 1.0:

$$K_i = \frac{1}{1 - e^{-m_i \cdot (|P_{i,max} - P_{i,min}|/n_i)^{A_i}}} \quad (3)$$

In both Eq. 2 and Eq. 3:

- $P_{i,max}$  and  $P_{i,min}$  are the maximum and minimum values of the indicator assessed.
- $P_{i,x}$  is the score of alternative  $x$  that is under assessment, with respect to indicator  $i$  under consideration, which is between  $P_{i,min}$  and  $P_{i,max}$ . This score generates a value that is equal to  $V_i(P_{i,x})$ , which has to be calculated.
- $A_i$  is the shape factor that defines whether the curve is concave ( $A_i < 1$ ), a straight line ( $A_i \approx 1$ ) or whether it is convex or S-shaped ( $A_i > 1$ ).
- $n_i$  is the value used, if  $A_i > 1$ , to build convex or S-shaped curves.
- $m_i$  defines the value of the ordinate for point  $n_i$ , in the former case where  $A_i > 1$ .

The geometry of the functions  $V_i$  allows establishing greater or lesser exigency when complying with the requisites needed to satisfy a given criterion. For example, the convex functions experience a great increase in value for scores that are close to the minimum value, and the increase in value diminishes as the score approaches the maximum. This type of function is used when one wishes to encourage compliance with minimum requirements. That may be the case, for instance, with sufficiently exacting standards in which mere compliance is highly satisfactory. Another instance

may be when the aim is to reward the use of new technologies, and their implementation is seen as very positive (even when it is a partial or a minor one), with a view to encouraging better practices. This is particularly the case, for instance, of using recycled aggregate.

It can be seen that the shape of the function depends on the values that the parameters  $A_i$ ,  $n_i$  and  $m_i$ . The interpretation of these parameters facilitates the understanding and the use of Eq. 2. Table 1 gives characteristic values of these parameters for the definition of value functions. These parameters may vary according to the preferences of the decision maker.

Table 1: Typical values of  $n_i$ ,  $m_i$  and  $A_i$ .

Increasing function			
Function	$n_i$	$m_i$	$A_i$
Linear	$n_i \approx P_{i,min}$	$\approx 0.0$	$\approx 1.0$
Convex	$P_{i,min} + \frac{P_{i,max} - P_{i,min}}{2} < n_i < P_{i,min}$	$< 0.5$	$> 1.0$
Concave	$P_{i,min} < n_i < P_{i,min} + \frac{P_{i,max} - P_{i,min}}{2}$	$> 0.5$	$< 1.0$
S-shaped	$P_{i,min} + \frac{P_{i,max} - P_{i,min}}{5} < n_i < P_{i,min} + \left(\frac{P_{i,max} - P_{i,min}}{2}\right)\frac{4}{5}$	0.2 - 0.8	$> 1.0$
Increasing function			
Function	$n_i$	$m_i$	$A_i$
Linear	$n_i \approx P_{i,min}$	$\approx A_o$	$\approx 1.0$
Convex	$P_{i,max} + \frac{P_{i,min} - P_{i,max}}{2} < n_i < P_{i,max}$	$< 0.5$	$> 1.0$
Concave	$P_{i,max} < n_i < P_{i,max} + \frac{P_{i,min} - P_{i,max}}{2}$	$> 0.5$	$< 1.0$
S-shaped	$P_{i,max} + \frac{P_{i,min} - P_{i,max}}{5} < n_i < P_{i,max} + \left(\frac{P_{i,min} - P_{i,max}}{2}\right)\frac{4}{5}$	0.2 - 0.8	$> 1.0$

When the shape of the value function for an indicator is unclear, this may be defined by a working group. In these cases, several value functions (discrete or continuous) may be defined according to the members of the group. Therefore, a family of functions is obtained as can be seen in Fig. 2.

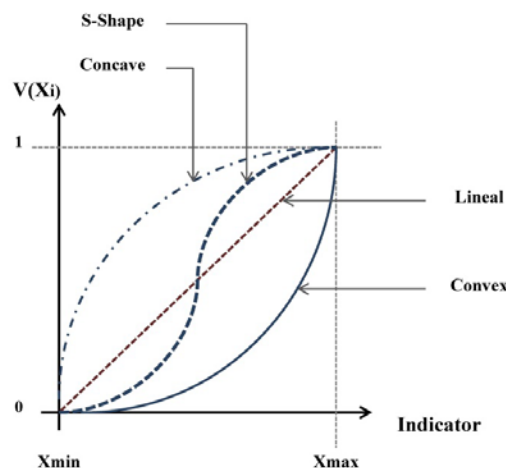


Figure 2: Value function generated by a working group composed of different decision makers.

The simplest way to solve these differences consist in taking the mean of the different values (after excluding extreme cases). The parameters  $A_i$ ,  $A_i$ ,  $n_i$  and  $m_i$  can then be estimated through a minimum squares approach. It is also possible to work with a range of values in such a way that two values correspond to each y-value (the mean and the standard deviation). This would require a statistical approach in the subsequent decision process.

#### 4 REQUIREMENTS TREE PROPOSED BY THE FIB TASK GROUP 6.3 FOR THE SUSTAINABILITY ASSESSMENT

The requirements tree proposed by the members of the *fib* TG 6.3 Sustainability of Precast Structures is presented in Table 2. This tree has been established after several meetings of the sub-committee and this is meant to assess the sustainability index of structural concrete systems or its elements.

**Table 1:** Requirements tree proposed by the *fib* TG 6.3 for the sustainability assessment of structural concrete elements.

Requirement	Criteria	Indicator	Units	Value function
R <sub>1</sub> Economic ( $\lambda_{R1} = 40\%$ )	C <sub>1</sub> Total Costs ( $\lambda_{C1} = 50\%$ )	I <sub>1</sub> Total costs ( $\lambda_{I1} = 100\%$ )	€	DS
	C <sub>2</sub> Quality ( $\lambda_{C2} = 10\%$ )	I <sub>2</sub> Non quality costs ( $\lambda_{I2} = 100\%$ )	Attrib.	DL
	C <sub>3</sub> Dismantling ( $\lambda_{C3} = 10\%$ )	I <sub>3</sub> Dismantling costs ( $\lambda_{I3} = 100\%$ )	€	DS
	C <sub>4</sub> Service Life ( $\lambda_{C4} = 30\%$ )	I <sub>4</sub> Maintenance ( $\lambda_{I4} = 50\%$ ) I <sub>5</sub> Resilience ( $\lambda_{I5} = 50\%$ )	€ €	IS IS
R <sub>2</sub> Environmental ( $\lambda_{R2} = 45\%$ )	C <sub>5</sub> Materials consumption ( $\lambda_{C5} = 55\%$ )	I <sub>6</sub> Cement ( $\lambda_{I6} = 20\%$ )	Tn	DS
		I <sub>7</sub> Aggregates ( $\lambda_{I7} = 20\%$ )		
		I <sub>8</sub> Steel ( $\lambda_{I8} = 30\%$ )		
		I <sub>9</sub> Water ( $\lambda_{I9} = 10\%$ )		
		I <sub>10</sub> Plastics and others ( $\lambda_{I10} = 10\%$ )		
		I <sub>11</sub> Reused Material ( $\lambda_{I11} = 10\%$ )	Tn	IS
	C <sub>6</sub> Emissions ( $\lambda_{C6} = 55\%$ )	I <sub>12</sub> CO <sub>2</sub> emissions ( $\lambda_{I12} = 60\%$ )	TnCO <sub>2</sub> -eq	DS
		I <sub>13</sub> Total waste ( $\lambda_{I13} = 40\%$ )	Tn	
	C <sub>7</sub> Energy consumption ( $\lambda_{C7} = 10\%$ )	I <sub>14</sub> Embodied Energy ( $\lambda_{I14} = 33\%$ )	MWh	
		I <sub>15</sub> Construction Energy ( $\lambda_{I15} = 33\%$ )	MWh	
		I <sub>16</sub> Service Energy ( $\lambda_{I16} = 33\%$ )	MWh	
R <sub>3</sub> Social ( $\lambda_{R3} = 15\%$ )	C <sub>8</sub> Interaction with third parties ( $\lambda_{C8} = 50\%$ )	I <sub>17</sub> Comfort. Thermal, air, noise ( $\lambda_{I17} = 50\%$ )	Attrib.	
		I <sub>18</sub> Noise pollution. Construction ( $\lambda_{I18} = 10\%$ )	Db	
		I <sub>19</sub> Particles pollution. Construction ( $\lambda_{I19} = 30\%$ )	Tn	
		I <sub>20</sub> Traffic disturbances. Construction ( $\lambda_{I20} = 10\%$ )	Attrib.	
	C <sub>9</sub> Risks ( $\lambda_{C9} = 50\%$ )	I <sub>21</sub> Health and Safety. Production ( $\lambda_{I21} = 33\%$ )	Attrib.	
		I <sub>22</sub> Health and Safety. Construction ( $\lambda_{I22} = 33\%$ )	Attrib.	
		I <sub>23</sub> User's Safety ( $\lambda_{I23} = 33\%$ )	Attrib.	

DS: decreasing S-shape; IS: Increasing S-shape; DL: decreasing linear.

As it can be noticed, the requirements tree consists of 23 indicators (I) groups in 9 criteria (C). The number and type of indicators result from the different meetings carried out by the members of the committee; these indicators have been considered as those representatives to deal with the sustainability assessment of construction systems or structural elements (in particular precast and in-situ constructed structural concrete elements) covering from the extraction of the materials to the dismantling operations.

The economic requirement (R<sub>1</sub>) is represented by four criteria related to costs: total (C<sub>1</sub>), quality (C<sub>2</sub>), dismantling (C<sub>3</sub>) and service life (C<sub>4</sub>) costs. Five indicators have been included; among these, the resilience, as beneficial property, is taken into account. The environmental requirement (R<sub>2</sub>) gathers three criteria: material consumption (C<sub>5</sub>), emissions (C<sub>6</sub>) and energy consumption (C<sub>7</sub>) and eleven indicators. Finally, the social requirement (R<sub>3</sub>) consist of two criteria: interaction with third parties (C<sub>8</sub>) and risks (C<sub>9</sub>).

The experts' panel have fixed and defined these indicators aiming at guaranteeing the independence of these and avoiding potential overlapping. In this regard, more indicators could have been included; nevertheless, the addition of extra indicators (with weight below 5%) can: (1) difficult the application of the method (more indicators to be assessed); (2) potential overlapping

between the indicators and (3) lead to lose the general view of the problem. Thus, indicators with less than 5% of weight have been disregarded.

Finally, the distribution of weights proposed for this initial requirements' tree has been fixed by using the direct assignment method; that is: the experts agreed the weights of each indicator based on the own experience. Needless to say that this distribution can be adjusted to other stakeholders' preferences in order to take into account other economic scenarios or environmental and social sensitivities. In this regard, the next step to be carried out by the *fib* TG 6.3 is to send this requirements tree to the members of other *fib* commissions so that other distributions can be assumed. This process would help to guarantee the representativeness of the sustainability assessment method proposed.

The bulletin includes two real application examples with the aim of illustrating the whole sustainability assessment process using MIVES. Besides, other examples published in the research literature are cited in the references section of the bulletin.

#### 4 CONCLUSIONS

In this research contribution, a method for assessing the sustainability index of construction system/elements based on the MIVES method has been presented. This consists in part of the work in progress carried out by the members of the *fib* TG 6.3 Sustainability of Precast Structures. The method allows:

- Assessing the sustainability of construction systems and, in particular, precast and in-situ structural concrete elements.
- Minimizing the subjectivity in the decision-making while considering the three main requirements of the sustainability: economic, environmental and social.

There is still work to be performed in order to calibrate the method and define all the components; however, to the authors' knowledge, this would be the first sustainability assessment method available for precast concrete structures.

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