

## SUSTAINABILITY EVALUATION OF THE CONCRETE STRUCTURES

ANTONIO AGUADO<sup>1</sup>, JAIME C. GÁLVEZ<sup>2</sup>, DAVID FERNÁNDEZ-ORDÓÑEZ<sup>3</sup>,  
ALBERT DE LA FUENTE<sup>1</sup>

<sup>1</sup> E.T.S Ingenieros de Caminos, Canales y Puertos. Technical University of Catalonia

<sup>2</sup> E.T.S Ingenieros de Caminos, Canales y Puertos. Technical University of Madrid

<sup>3</sup> E.T.S Ingenieros de Ingeniería Civil. Technical University of Madrid

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**Abstract.** Sustainability is a new and settled concept in advanced societies, even though the term is sometimes inappropriately used, which may represent a threat. For this reason it is suitable to supply methods of measuring sustainability. Given that the sustainability concept involves distinct requirements and criteria, it seems reasonable to use multi-criteria methods in the decision making process. This work shows a brief review of such methods applied to concrete structures. The MIVES method is applied in this work for assessing the sustainability of the concrete structures. Three examples are proposed to show the capacity of the method. One of them is based on the general application of the Spanish Structural Code for Concrete Structures (EHE-08), and the other two assess the sustainability of reinforced concrete columns by adopting distinct type of concrete and building procedures.

### 1 INTRODUCTION

Sustainability approach, if implicit in the history of human development, has had a remarkable boom in the last three decades after the definition of the term within the framework of the United Nations (Brundtland Report, 1987).

The scope of sustainability, with its three pillars (economy, environment and social), covers the activities of the humanity and in its various forms (goods, services, etc.). Obviously, it is included the construction sector. In this sector, concrete as a structural material is one of the most used (Sakai, (2009), Ahmad and Saker (2014)) and one of the cheapest.

However, from the environmental point of view, the concrete, mainly by the contribution of cement, it is one of largest producers of CO<sub>2</sub> emissions into the atmosphere. The global production is approximately 5-6% of the total CO<sub>2</sub>. Distinct actions have been developed for reducing this contribution of CO<sub>2</sub> (Metha, 2009): a) optimization of structural design, by incorporating an innovative engineering that reduce dimensions of elements, b) selection of more advanced ages as contractual age (56 or 91 days) to minimize the amount of cement, as it is already done in dams, c) advances in the binders that will reduce the content of clinker.

From the social point of view, the perception of the sustainability will be different, depending on the situation of the observer, both from a standpoint of social position, and depending on the general circumstances of the country. Thus, in a developing country, a new cement factory creates new jobs, but under the view of a developed country the same fact can be received as negative for the environment.

As a summary, from the point of view of sustainability, there are advantages and disadvantages in the use of concrete as the building material, both in construction in-situ and precast elements. Given that, the assessment of the sustainability of each alternative proposed by the construction sector seems a promising way for the decision making process.

In concrete structures, once fulfilled the functional requirements and safety, progress in the pillars of sustainability measures is uneven. From the economic point of view, historically there are numerous methods and the level of development is high. Latest environmental methods are incorporated, whether of general type: referring to several as more specific type (ACV, and others). The lowest level of progress, at the level of measures, occurs in the social pillar, although there are jobs in that direction.

This is usually done in a disaggregated way without integrating the set in an indicator for measuring sustainability. To address the issue jointly, the multi-criteria methods can be a reasonably approach to measure the indicators, variables or attributes.

The main objective of the present work is to highlight the importance of measuring the sustainability, as a tool for comparing alternatives. In addition, some examples are presented for showing the possibilities of the multi-criteria methods in the assessment of the sustainability.

## 2 CURRENT SITUATION AND TRENDS

Nobody disputes that the world changes quickly, exponential somewhat, and that the social, environmental and economic changes of the past 25 years, following the report of UN (1987), have led to a change of paradigm in decision-making at all levels and, of course, also in the sector of the construction, in relation to the project construction and the operation of our infrastructure. The concept of sustainability has become an aspect to consider that it can even influence the construction of the infrastructure.

The new paradigm in decision making process includes the incorporation of the point of view of the actors involved and affected by new construction or infrastructure. In this sense not only the promoter (public or private) and the technician decide, but also rather the opinion of society and its benefit come a growing weight.

When designing a structure, apart from the classical requirements, usually used: safety, durability, functionality, etc., it should be considered the requirements of sustainability: economic, environmental and social aspects. This process represents a disaggregated approach for measuring the sides of a polyhedron, which each face is every one of these requirements. However, it is possible to move forward and consider a joint assessment that represents the volume of the polyhedron (each of those requirements is a side).

Some improvements have been done in distinct directions, as evidenced Jato *et al.* (2014), showing by the increasing number of published papers in international journals focused on this topic. The direction of action may be different; on the one hand, the measure of the classical parameters, such as safety, durability, economic aspects, and even environmental and social parameters. On the other hand, the attempt for integrating measures of each plane into some set value, demonstrating, in any case, the need to measure to place the structure in its context and move forward.

The way to do these advances, in a multi-criteria approach, includes the incorporation of new requirements, since the methodology used in one of them. For example, from the

economic point of view is often to work on cost/benefit issues and intends to assess the economic value of the social and environmental aspects. This way faces great difficulties and disagreements among experts.

An additional way, in areas with less experience, is to start the evaluation with the use of checklists, regarding, for example, to social or environmental aspects. In such approach the models type BREAM, GBC, LEED and others may be a reference. It is also possible to perform more complex models, from the point of view of environmental such as Life Cycle Assessment (LCA) or other associated calculations, but in practice, they are difficult to apply to the standard type projects. There are steps of integration of similar methods at various levels, for example integrate Life Cycle Cost (LCC) and ACL in civil structures by means of Analytic Hierarchy Process (AHP), Kim *et al.* (2013).

There are distinct integration methods in the sector of the construction such as the MCDM multi-criteria methods: ANP, DEA/ELECTRE, TOPSIS, AHP, PROMÉTHÉE and other (Jato *et al.*, 2014), although each of them is only used in one geographical framework or habit of work determined. The approach is based on the treatment of problems with homogeneous alternatives, i.e. of the same type.

These advances are also shown by the regulations. An example is series of European standards that are developed by the CEN/TC 350 (see Figure 1), used in Europe for assessing the sustainability building construction. This Committee discusses the environmental efficiency of the buildings, the various aspects on the analysis of the life cycle of the buildings and the problems at the level of the products. The AEN CTN 198 "Sustainability in construction" Committee (Tenorio and Vega, 2011) follows the CEN/TC 350 regulations and proposals in Spain. In general, while the concept is clear, in practice there is a certain imbalance that shows a bias towards environmental issues, confusing a part to the whole, when the analysis must be global, integrated manner with other sustainability requirements.

With considered bias, not surprising that the concrete is now penalized by the high value of CO<sub>2</sub> emissions and its moderated recyclability. In addition to this bias, different studies do not defined properly the boundaries of the system by not including relevant aspects of transportation.

### 3 MIVES METHOD

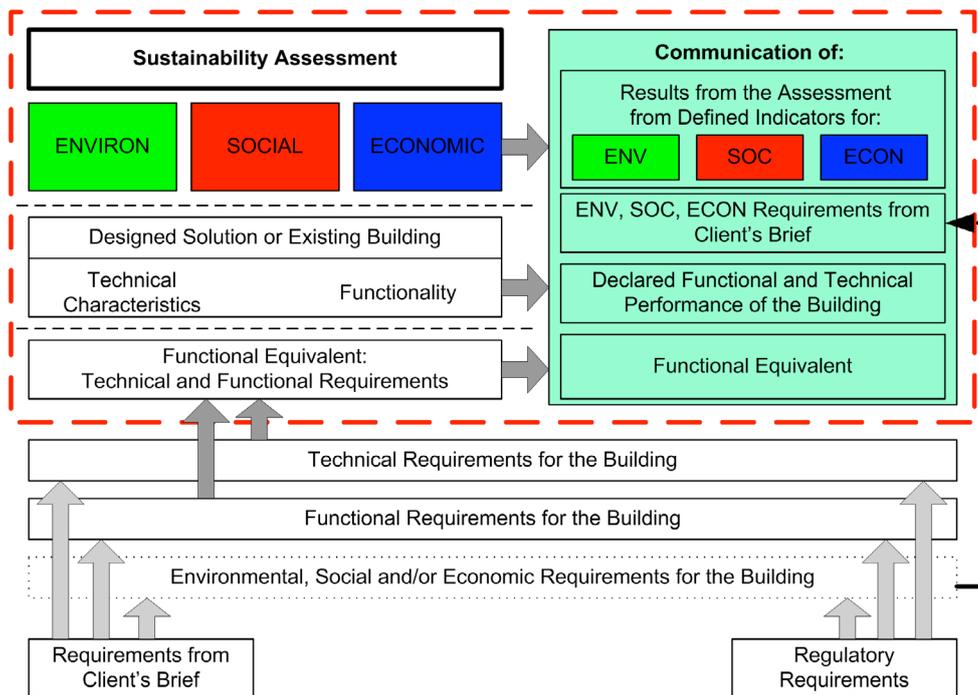
The above exposed shows the convenience to find multi-criteria methods (MCDM) that allow incorporate heterogeneous and, to the same time, flexible alternatives for measure the sustainability. These should be versatile for adapting to the different situations of projects (Basic projects or projects construction very elaborate) and to the different complexities of the structure (simple or very complex). The integrated model of value for sustainable assessments (MIVES) satisfactorily meets this challenge.

MIVES is a multi-criteria method that began with a research project<sup>1</sup> in 2002, led by Prof. Antonio Aguado, in coordination with UPC, UPV and TECNALIA. Then, other universities (UaC, UIC and UPM) were incorporated to the project. As a result, since 2005, the year in which the first PhD thesis of this line was defended, a total of 16 additional PhD

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<sup>1</sup> *Quantification of the value of a constructive project evaluation of sustainability-oriented integrated model. Application to the industrial construction.* MAT2002-04310-C03-01. UPC, LABEIN, ETSII BILBAO. November 2002–October 2005. Lead by Prof. Antonio Aguado.

theses have been presented, in four Spanish universities. In addition, a significant number of papers and communications to congresses have been made.



**Figure 1:** Approach to the sustainability proposed by the CEN/TC 350 Committee.

The MIVES method responds to a classical structure of tree structured, usually in three levels (requirements, criteria and indicators), as shown in Figure 2. The sustainability requirements are economy, environmental and social aspects. The involved requirements and criteria, allow structuring the decision and easy the communication to third parties. The indicators allow measuring both variables and attributes.

In the evaluation is conversely as described in Figure 2. For the evaluation of each indicator a function of value previously established and agreed is used. It is a sigmoid of four parameters shape function; details may be consulted in Alarcón *et al.* (2011). The result of the measured indicator ( $V_{Ik}$ ) (using variables or attributes), enters the abscissa (see Figure 2) and, by using the value function the value of the indicator is obtained (values from 0 to 1).

The value of a generic criterion ( $V_{Cj}$ ) is supplied by Equation 1. The Equation 1 shows the addition from  $K = 1$  to  $n$  (where  $n$  is the number of indicators that there are in the criterion) of the product of the value of each indicator group ( $V_{Ik}$ ), by the weight associated with the same ( $w_{Ik}$ ).

$$V_{Cj} = \sum_{k=1}^n w_{Ik} * V_{Ik} \quad [\text{Eq.1}]$$

Same approach is used in the assessment of the requirements, obtaining the value of a requested generic ( $V_{Ri}$ ) in the Equation 2, which expresses the sum from  $j = 1$  to  $i$  (being  $i$  the number of criteria that are in the requirement) of the products of the value of each criterion of

the Group ( $J_{cv}$ ), by the weight associated with the same ( $w_{Cj}$ ).

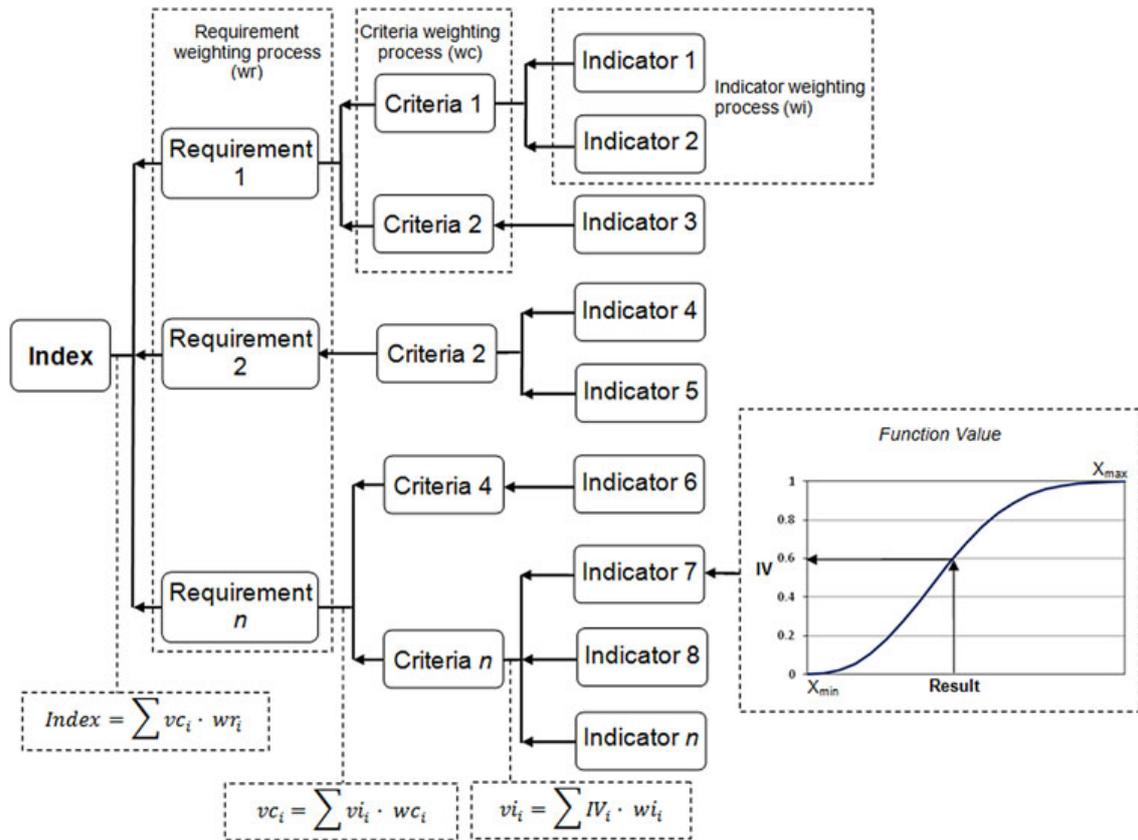


Figure 2: Structure of a generic decision tree.

$$V_{Ri} = \sum_{j=1}^l w_{Cj} * V_{Cj} \quad [\text{Eq.2}]$$

Finally, the rate of sustainability of a building (SI) is obtained by the sum of the dimensionless values of each of the requirements ( $V_{Ri}$ ) multiplied by the weight corresponding to each of them ( $w_{Ri}$ ) as shown in equation [3]. The subscript  $i$  represents the number of established requirements, which is 3 (economic, social and environmental) for sustainability studies.

$$SI = \sum_{i=1}^j w_{Ri} * V_{Ri} \quad [\text{Eq.3}]$$

The assessment of the indicators can be obtained deterministically or with probability approaches. The method allows a separation of components, for example, in the case of a building: structure, façade, foundations, facilities, etc., performing the assessment of the sustainability based on the contribution of each component of the building. For the assignation of weights, it can be used distinct methods. MIVES usually adopts directly assignation or AHP, in both cases, previously agreed, before studying alternatives.

The versatility shown by the MIVES method allows facing problems of decisions from different points of view, even with high plurality. The MIVES Method may evaluate highly technical aspects of construction, the social perception of a company, the selection of sites, the ranking of the staff of University departments, or prioritization of investments. The result of the sustainability index (SI) is a dimensionless value.

The above previously shown can directly apply when homogeneous alternatives are being evaluated. Nevertheless, in complex problems with heterogeneous alternatives, a phase called homogenization that fit the perception of the decision-maker between these heterogeneous alternatives is required (Pardo y Aguado, 2016).

#### **4 CONSIDERATIONS ON A PRACTICAL USE OF THE METHOD**

The method leads to good results if the decision tree is correctly built. It is of the highest importance that the decision taking party takes part in the definition of requirements and weights. Every theoretical development must be made without any alternative solutions to be independent when choosing indicators.

With respect to indicators it is advisable that only relevant ones should be considered. We propose that only indicators that have a relevance of more than 5% should be considered. Also only indicators that take into account differences for the alternatives that are under study should be considered.

The method does not need to consider many indicators but just the principal indicators that are relevant for the comparison. With this procedure we can save time in the calculation and higher accuracy because otherwise principal indicators may be shadowed by a large quantity of less important indicators.

Value functions of each indicator must be defined before the alternatives are discussed. Better results are obtained if are defined by consensus of experts with the help of seminars.

Of course, when we compare alternative solutions, limits of the system have to be homogeneous and consequently have to introduce associated transportations to resources movements like aggregates, cement and other products. It is also a key factor to consider decision taking party for each aspect like for example the selection of a typology for a construction decision may be different if we only consider promoting agency, contractor, end user or just a citizen. The decision is not a generic one but has to take into account the point of view of the final decision party and also economic, social and environmental aspects when the decision is taken.

Decision tree has to incorporate all aspects to be considered. If we try to measure resilience of a solution or the survival against unknown changes (like climate change) this concept has to be included explicitly in the tree.

On the other hand, it is important to state at the early stages which are boundary conditions that the alternatives that will be studied have to comply with. If some of the boundary conditions are not fulfilled, then the alternative cannot be tested. Also if all boundary conditions are fulfilled then what it has to be evaluated are the increments over the base value. For example, it protection time against fire as a starting point is 120 minutes and one of the alternatives guarantees 150 minutes, does these supplementary 30 minutes have to be considered? In this same direction are other aspects related with service life of a structure that

has to be established previously and if all alternatives comply then, should increments have a value?

A decision tree can be defined to evaluate which alternative solution is better to make better a process or production from the sustainability point of view. For example, the ones already said in point 1 by Metha (2009) or Sakai (2009). Also other aspects related with them in a decision tree or in a general point of view. We see then that when we include a decision branch for the use of resources in environment part of the tree we are also considering design aspects that reduce the use of resources (aggregates, etc.). Other example can be when considering different types of binding components, that can reduce the amount of clinker (Josa *et al.* 2005 and Josa *et al.* 2007) it is also taken into account in emissions branch (i.e. CO<sub>2</sub>) within the environmental branch

## 5 EXAMPLES

To make evident the use of the method we describe some examples of its application that cover several aspects in decision taking:

- Sustainability Contribution Index for Structures (ICES) used in Spanish Normative EHE08
- Sustainability evaluation of precast products made of different materials like concrete or steel
- Selection of building process taking into account sustainability

### Sustainability Contribution Index for Structures (ICES)

Current Spanish Normative on structural concrete (EHE-08) (M.F., 2008) includes Annex 13 (not mandatory) with the title Índice de contribución de la estructura a la sostenibilidad (Contribution index of the structure to sustainability). It has been in international normalization for structures that at this level a sustainability index is included. ICES evaluation is done after structural design is developed and after the comply to structural and functional requirements. In that 1<sup>st</sup> version it was done under the environmental aspect only. It also included other aspects from the social point of view and indirectly from the economic point of view.

With this development as are explained by Aguado *et al.*, (2012) one could obtain the ISMA or Environmental Sustainability index for the later incorporation of social aspects, as for equation 4.

$$ICES = a + b \times ISMA \quad [Eq.4]$$

Where: a is a social contribution coefficient, that considers several factors in this aspect and b is a coefficient for the extension of service life of the structure.

The decision tree for this example is described in Figure 3. We can see that the different branches considered in the ISMA decision tree includes measurements as previously described (Metha, (2009), Sakai (2009)). In the same figure the different weights considered for each branch can be seen and also that the decision tree is not large to make every aspect

decisive. The tree is designed so that homogeneous solutions, that are built with different processes, can be evaluated (in situ or with precast elements). In both solutions also different transport distances can be considered for materials to take into account emissions and costs.

After the publication of the structural concrete normative the same idea has been implemented in the structural steel normative (EAE-10) and in the composite structures normative. Also in the revision of the not published structural code also is considered the same model with a slightly more precise different approach.

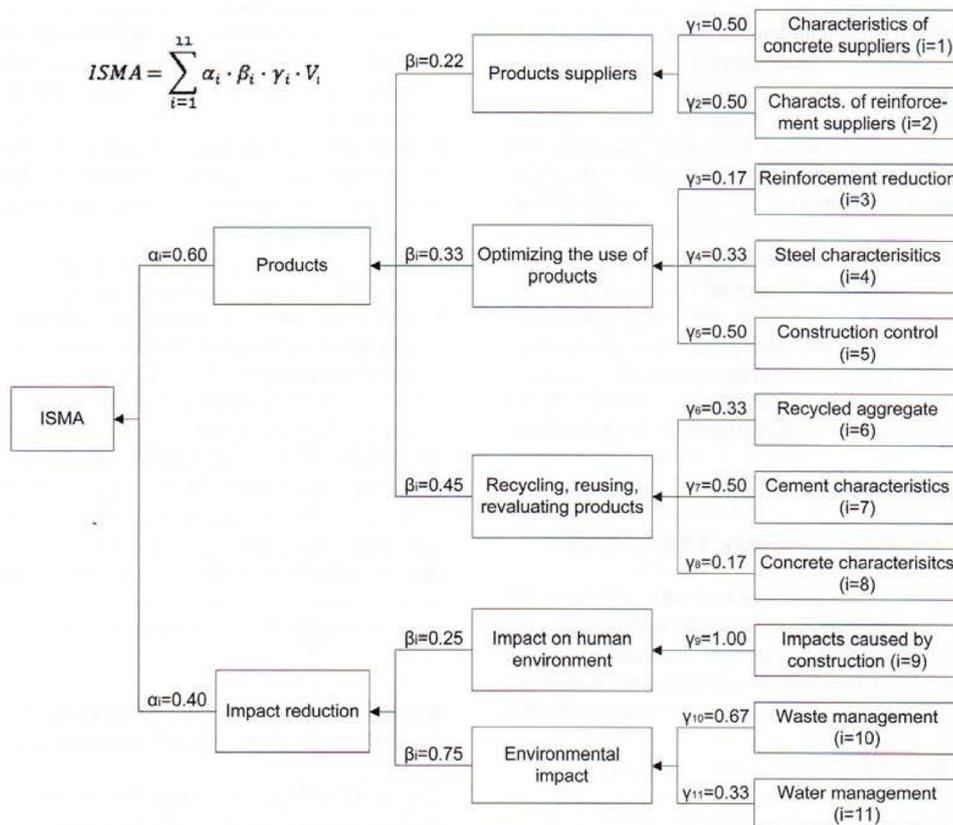


Figure 3: Decision Tree for EHE-08 (Sources: M.F. (2008) y Aguado et al. (2011))

### Sustainability evaluation of precast products made of different materials

Other problem that can be studied with this method is the sustainability assessment of precast elements it is different solutions with constructive differences or different materials (concrete, steel, plastics, etc.). For these solutions an example of the evaluation of the sustainability of sewerage pipes with different alternative solutions (Viñolas (2011), de la Fuente *et al.*, (2016)). There are also other examples for the evaluation of sustainability of wind turbines (de la Fuente *et al.*, 2016).

In Table 1 are presented different solutions of pipes with the following names: HM: Unreinforced concrete R class, HA: Reinforced concrete, class IV, PP: Structural Polypropilene, class SN8, PVC: Compact Vynil Polycloride, class SN, PVC: Compact Vynil Polycloride, Class 10.

In Table 2 it can be reviewed the decision tree with the considered assigned weights. In the table it has been considered the three columns of sustainability, incorporated for this example. In this case the additional functionality has been incorporated in the decision tree.

Alternativa	Diámetro ext.	Diámetro int.	Espesor	Peso (kg/m)
HM 400 mm	520 mm	400 mm	60 mm	240,00
HA 800 mm	1000 mm	800 mm	100 mm	705,00
HA 1200 mm	1480 mm	1200 mm	140 mm	1395,00
HA 2000 mm	2430 mm	2000 mm	215 mm	3650,00
PP 450 mm	450 mm	400 mm	50 mm	8,32
PVC 800 mm	800 mm	748 mm	26 mm	87,87
PE 1200 mm	1200 mm	1030 mm	85 mm	67,50
PRFV 2000 mm	2047 mm	1958 mm	44,5 mm	383,66

Table 1: Geometrical data of the alternatives.

Requirements	Criteria	Indicators
Functional (11,11%)	Pipe Dysfunctions (33,3%)	Pipe surface degradation (100%)
	joints Dysfunctions (33,33%)	Risks in the connections between tubes; (100%)
	Added Capacity (33,33%)	Added mechanical capacity; (100%)
Economic (33,33%)	Costs (80%)	Cost production + transport + erection: (100%)
	Time (20%)	Construction time (100%)
Environmental (33,33%)	Production and transportation; (20%)	Emissions de CO <sub>2</sub> ; (100%)
	Used resources (60%)	Raw material consumption in construction; (33,33%)
		Percentage of recycled water; (33,33%)
		Energy required; (33,33%)
Environmental corrective measures (20%)	Environmental sensibility of the production plant; (100%)	
Social (22,22%)	Third party affections (75%)	Repair and affection time; (33,33%)
		Pollution of water; (33,33%)
		Reliability to possible breakage from external agents; (33,33%)

Table 2.- Decision tree for sewerage pipes made of different materials.

Results arising from this study are presented in Figure 4, in which results from 3 different scenarios are presented (A: favourable conditions, B: Intermediate conditions, C: Unfavourable conditions). They are associated to some of the environmental indicators (% of recycled water, sensibility to environment in production plant). We can observe that, for small diameters (400mm) the solution with structured polypropylene, class SN 8 (PP) is the solution that obtains the best result while for larger diameters reinforced concrete solutions obtain the best results and are clearly the best for large diameters (2000mm).

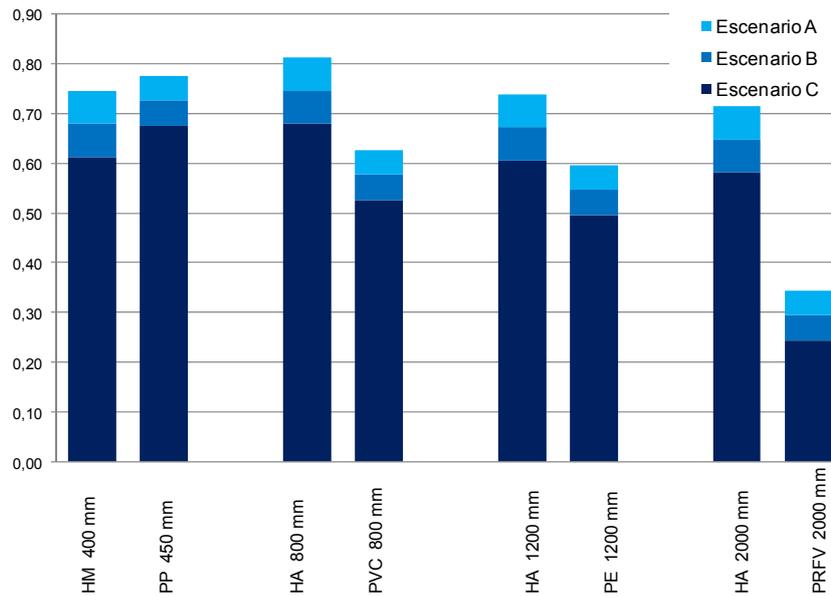


Figure 4.-Sustainability Index results for sewerage pipes.

#### Selection of building process taking into account sustainability

Other example is for the evaluation of sustainability in different process of construction solutions. To show this solution an example is now described. The example is based on the comparison of different solutions of building columns with the following parameters: characteristic strength of concrete (hormigón (HA-25, HA-50 y HA-75), compacting of concrete (Self compacting, vibrated), geometry of the cross section (rectangular, circular). More information can be found in (Duran (2011) y Pons y de la Fuente (2014)).

For the sake of comparison the forces resisted are the same in all cases and also steel is B500SD (characteristic yield stress  $f_{yk}$  of 500 N/mm<sup>2</sup> and Young Modulus  $E_s$  of 200.000 N/mm<sup>2</sup>). In Table 3 it is shown different combinations from the study and the dimensions of the columns.

To make the different alternative solutions comparable regarding concrete specific and not generic corresponding to the different components used in each type of concrete depending on the compaction system and strength as it is shown in Table 4. In this table it can be checked how aggregates differ and also the fines content. Other data with relation to formwork, costs and other variables can be found in Duran (2011) y Pons y de la Fuente (2014).

The defined decision tree in this evaluation and the weights adopted are presented in Table 5. Both decision tree and weights were decided in a seminar with an expert committee. They considered which indicators were fundamental to decide the alternatives.

Type $f_{ck}$	Compacting system	Section	Dimensions (cm)	$A_c$ (mm <sup>2</sup> )	$A_s$ (mm <sup>2</sup> )	Ref.
C25	Vibration	Rectangular	40x40	158743	1257	C25/V/S
		Circular	50	195331	1018	C25/V/C
	Self Compacting	Rectangular	40x40	158743	1257	C25/SC/S
		Circular	50	195331	1018	C25/SC/C
C50	Vibration	Rectangular	30x30	88743	1257	C50/V/S
		Circular	35	96211	792	C50/V/C
	Self Compacting	Rectangular	30x30	88743	1257	C50/SC/S
		Circular	35	96211	792	C50/SC/C
C75	Vibration	Rectangular	25x25	61243	1257	C75/V/S
		Circular	30	70685	679	C75/V/C
	Self Compacting	Rectangular	25x25	61243	1257	C75/SC/S
		Circular	30	70685	679	C75/SC/C

Table 3.- Alternatives considered in the example.

MATERIALS		HA-25		HA-50		HA-75	
		B	AC	B	AC	B	AC
Cement	CEM I (kg)	262	300	450	450	500	500
Additions	Filler (kg)	-	100	-	-	-	-
	Nano silica (kg)	-	-	-	-	10	10
Aggregates (kg)		1851	1725	1803	1803	1705	1705
Water (kg)		145	175	180	195	190	215
a/c		0.55	0.58	0.4	0.43	0.38	0.43
Pozzoloth (ligno)	% spc	0.7	0.9	0.3	0.8	0.3	0.8
	(kg)	1.8	2.7	1.4	3.6	1.5	4.0
Glenium (PCE)	% spc	0.3	1.5	0.7	1.3	0.7	1.3
	(kg)	0.8	4.5	3.2	5.9	3.5	6.5

Table 4.- Components for each type of concrete

Requirements	Criteria	Indicators
R1. Economic (50%)	C1. Construction costs (67%)	I1. Building costs (85%)
		I2. Non acceptance costs (15%)
	C2. Efficiency (33%)	I3. Maintenance (60%)
		I4. Habitability (40%)
R2. Environmental (33%)	C3. Emissions (67%)	I5. CO <sub>2</sub> Emissions (100%)
	C4. Resources consumption (33%)	I6. Concrete consumption (90%)
		I7. Steel consumption (10%)
R3. Social (17%)	C5. Negative effects on the producer industry (80%)	I8. Workers' inconveniences (20%)
		I9. Workers' safety (80%)
	C6. Effects to third party (20%)	I10. Environment nuisances (100%)

Table 5.- Decision Tree and considered weights

The results of the Sustainability Index (SI) of each one of the alternatives are presented in Table 6. It can be observed that are all with a minimum value of 0,558 (corresponding to C25, C25, vibrated and square cross-section) and a maximum value of 0,852 (corresponding to C75, self-compacting and circular) because in a way to the reduced use of raw materials and to the increment of usable space in the building. This corresponds to the higher strengths used in high-rise buildings.

Ref.	SI	Ref.	SI	Ref.	SI
C25/V/S	0.608	C50/V/S	0.662	C75/V/S	0.707
C25/V/C	0,558	C50/V/C	0.716	C75/V/C	0.794
C25/SC/S	0.623	C50/SC/S	0.717	C75/SC/S	0.771
C25/SC/C	0,564	C50/SC/C	0.768	C75/SC/C	0.852

Table 6. Result of Sustainability Index (SI)

On the other hand it can be checked that in general the alternatives that use self compacting concrete result in higher SI values that the ones that use vibrated concrete. This corresponds in a way to aspects that have to do with non-quality costs, for voids in the base of the columns due to its compaction difficulties.

Lastly square columns result in higher values when concrete strengths are low (C25). When concrete strength is higher (C50 and C75), circular alternatives allow better results for sustainability due mainly to construction costs.

## 6 CONCLUSIONS

We can extract the following conclusions from the examples explained above:

- Sustainability as a concept is a well-established idea in our society and it is slowly being considered in the construction sector where it is difficult to produce changes. Evaluation methods are a necessary tool that will allow producing advances in the process.
- MIVES method is a very flexible tool to evaluate sustainability in structures from different points of view and different levels. It allows studying and evaluating in situ or precast solutions if they are efficient to solve a certain problem.
- Each decision requires a specific decision tree because if only a general is adopted it will not evaluate detailed aspects. This is shown in the examples described, each one on a different aspect.

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