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SIMULATION SYSTEM FOR MANAGING UNCERTAINTY IN THE SUSTAINABLE DESIGN OF CONCRETE STRUCTURES

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This paper presents a simulation system for managing uncertainty in the sustainable design of concrete structures. This system was conceived and developed for professional use and grounded on a probabilistic method that combines requirement trees, value functions, the Analytic Hierarchy Process, and the Monte Carlo simulation technique. It embraces the approach to assessing sustainability taken by the Spanish Structural Concrete Code (EHE, in Spanish), but can be applied in other code frameworks. Obviously, there is uncertainty about the final sustainability index when this parameter is estimated before the structure has been finished. Managing the sustainability objective will be hindered. It is therefore helpful to assess how likely it is to achieve the sustainability objective throughout the project life cycle. The system presented here takes into account the uncertainty of the different sustainability parameters. It makes it possible to estimate the probability distribution for the potential final index. This in turn will facilitate managing uncertainty in the sustainable design of concrete structures, increasing the likelihood of achieving the sustainability objective.

Keywords: *concrete structures; sustainability assessment; uncertainty; simulation; MIVES*

SISTEMA DE SIMULACIÓN PARA LA GESTIÓN DE LA INCERTIDUMBRE EN EL DISEÑO SOSTENIBLE DE ESTRUCTURAS DE HORMIGÓN

Esta comunicación presenta un sistema de simulación para gestionar la incertidumbre en el diseño sostenible de estructuras de hormigón. El sistema ha sido concebido y desarrollado para uso profesional y se basa en un método probabilista que combina árboles de requerimientos, funciones de valor, el proceso analítico jerárquico y la simulación tipo Monte Carlo. Se ajusta al enfoque de evaluación de la sostenibilidad de instrucción española de hormigón estructural EHE-08, pero el método puede ser aplicado en otros marcos normativos. Resulta evidente que existe incertidumbre acerca del índice de sostenibilidad final, cuando dicho parámetro se estima antes de la culminación de la estructura. Esto dificulta la gestión del objetivo de sostenibilidad. Por lo tanto resulta de utilidad estimar cuán probable es alcanzar dicho objetivo, a todo lo largo del ciclo de vida del proyecto. El sistema que se presenta tiene en cuenta la posible incertidumbre de los diferentes parámetros de sostenibilidad, y permite estimar la función de distribución del potencial índice final de sostenibilidad. Esto facilitará la gestión de la incertidumbre en el diseño sostenible de estructuras de hormigón, aumentando la probabilidad de alcanzar el objetivo de sostenibilidad.

Palabras clave: *estructuras de hormigón; evaluación de la sostenibilidad; incertidumbre; simulación; MIVES*

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1. Introduction

The system presented here is inspired by a method based, in turn, on the MIVES technique (Integrated Value Model for Sustainability Assessment, in Spanish; Gómez et al. 2012; de la Cruz et al., 2014). MIVES is deterministic and underpinned by requirement trees (Fig. 1), value analysis (Alarcón et al. 2011), and the Analytic Hierarchy Process (Saaty 2006). It transforms different types of variables into one single unit, taking into account the relative importance of aspects related to sustainability.

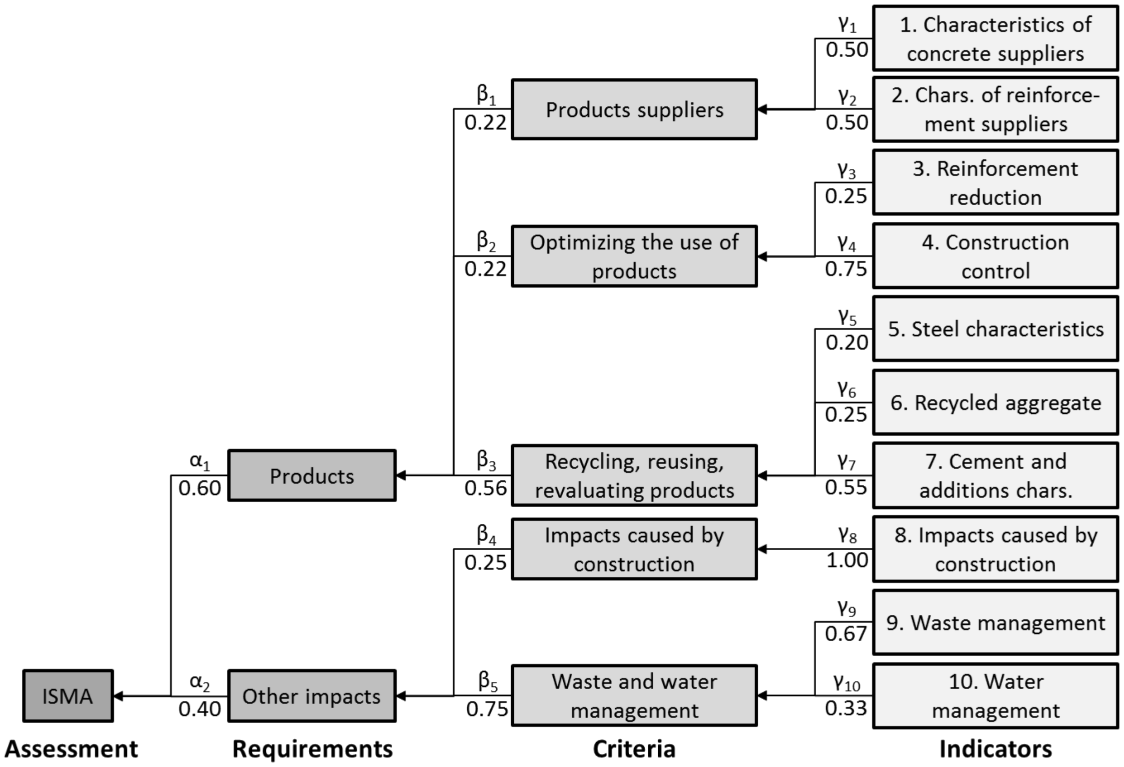


Figure 1. Requirement tree of the model.

One of its applications has been the sustainability assessment model for the Spanish Code on Structural Concrete (referred to from now on as EHE, in Spanish; Ministerio de la Presidencia 2008; Aguado et al. 2012), an internationally pioneering initiative. Two of the authors participated in the project in which it was created. EHE deals with assessing what has been called the Structure's Contribution to Sustainability Index (ICES, in Spanish). The underlying method of the system presented here is based on a modified, improved version of the EHE assessment model (hereinafter, EHEm). Finally, another one of its pillars is the Monte Carlo simulation technique (de la Cruz et al., 2014).

Once a structural sustainability objective has been established, the design will be carried out to achieve it. Obviously, there is uncertainty about the final ICES when this index is estimated before the structure has been finished. Sometimes, the value of specific variables depends on the characteristics of the companies contracted in the end. The same is true with the environmental certification of concrete suppliers.

Moreover, changes in the design or specs can generate significant oscillation in the ICES. These and other issues make it difficult to estimate this index. Managing the sustainability objective will also be less straightforward, as is the case with reaching the previously established goal. Hence, it is helpful to assess how likely it is to achieve the sustainability objective throughout the entire project life cycle. The system presented here takes into account the uncertainty of the different sustainability parameters, so that it is possible to estimate the probability distribution of the potential final ICES. This will make it easier to manage uncertainty in the sustainable design of concrete structures, increasing the likelihood of achieving the sustainability objective. The system can be freely downloaded in GRIDP (2013a).

2. The Method

2.1 Pre-Simulation Stage

This stage will be performed by users, and consists of identifying the model's probabilistic inputs and estimating the different deterministic and probabilistic ones (del Caño et al. 2012, de la Cruz et al., 2014). To understand this stage fully, the EHEm model must be summarized and, in turn, this means the MIVES technique must be explained.

2.1.1 The MIVES Technique

MIVES includes several stages. The first step entails identifying the problem to be solved, and the decisions to be made. Then, a hierarchical diagram of the decision model will be created. The breakdown structure of the assessment is established in the form of a requirement tree (Fig. 1). This graph may include qualitative and quantitative variables, with different units and scales. Specific mathematical functions serve to convert those variables into a set of parameters with the same units and scales.

The next stage is defining the relative weight of each aspect taken into account for the assessment. The various design alternatives will then be evaluated, using the previously created model. This will make it possible to reach the most suitable decisions and choose the most appropriate alternative.

MIVES is based on Multicriteria Decision Methods (MCDM). The indicator magnitudes and units are converted into a common, non-dimensional unit that can be called value. For a specific design alternative to be compared with others, the existence of a value function V: P→R can be considered, where $P = (P_1, P_2, \ldots, P_N)$ is the set of evaluation indicators included in the requirement tree. A non-dimensional value function V(P) will be constructed, integrating all the assessment indicators. The solution (Gómez et al. 2012; de la Cruz et al., 2014) is a non-dimensional function V, which is the weighted sum of N value functions V_i corresponding to the N indicators. For problems based on a requirement tree with three levels, the resulting V function takes the form of Equation (1).

$$V(P)=\sum_{i=1}^{i=N}\alpha_i\cdot\beta_i\cdot\gamma_i\cdot V_i(P_i) \quad (1)$$

V(P) measures the degree of sustainability for the alternative that is being assessed; α_i and β_i are the weights of the requirements and criteria to which each indicator i belongs; γ_i are the weights of the different indicators; $V_i(P_i)$ are the value functions used to measure the degree of sustainability for the alternative under study, with respect to a given indicator i; and, finally, N is the total number of indicators that are taken into account for the assessment (N=10 in Fig. 1). Weights α_i, β_i and γ_i are factors that represent the preference, respectively, of certain indicators (γ_i), criteria (β_i), and requirements (α_i) against others. MIVES (Alarcón et al. 2011;

Gómez et al. 2012; de la Cruz et al., 2014) uses Equation (2) as the basis for defining individual value functions V_i.

$$V_i = \frac{1 - e^{m_i \cdot \left(\frac{P_i}{n_i}\right)^{A_i}}}{1 - e^{m_i \cdot \left(\frac{P_{i,\max}}{n_i}\right)^{A_i}}} \qquad (2)$$

In this equation, P_i is the score of the alternative under assessment, with respect to indicator i under consideration, which is normally between 0 and 100. $P_{i,max}$ is the maximum score that can reach P_i, normally 100. A_i, n_i, and m_i are shape factors used to generate concave, convex, "S" shape, or straight line value functions. The geometry of the functions V_i (concave, convex, and so on) makes it possible to consider non-linearity in the assessments, and also to establish greater or lesser exigency when complying with the requisites for satisfying a given indicator (see Alarcón et al. 2011). Finally, the divisor of Equation 2 ensures that the value function will remain within the range of [0; 1], and that the highest contribution to sustainability is associated with a value equal to the unit.

Experts in the field must establish numerical values for weights α_i, β_i, and γ_i within the requirement tree (Fig. 1). In the case of complex models or innovative fields, the Analytic Hierarchy Process (AHP) may be used, in order to organize the process with efficiency, reduce its complexity and subjectivity, and diminish potential divergences among the experts. Nevertheless, AHP entails using semantic labels. Doing so could create subjective bias, even though the probability of this is very low. To make it less likely, a subsequent process of analyzing, comparing, and, if appropriate, modifying the resultant weights is recommended.

The reader can find additional information on, and a very detailed explanation of, the MIVES method in Gómez et al. (2012) and de la Cruz et al., 2014.

2.1.2 The EHEm Model

The sustainability assessment model used here is based on EHE, but includes specific modifications to solve several practical problems, such as small errors, misprints, or omissions, detected by the authors. In any case, both models produce similar results, since the authors wanted to respect the spirit of the EHE, and these modifications lie outside the scope for this paper.

The typical environmental indicators used in life-cycle analysis (LCA) to evaluate the sustainability of a structure relate to climate change, acidification potential, eutrophication potential, smog formation, ozone depletion, and toxicity, among other parameters. Nevertheless, the reality of the situation in Spain and many other countries is that there are few professionals with enough knowledge and experience to perform LCA. To avoid implementation problems, a practical approach was embraced. It was based on the usual concepts and parameters that architects and engineers normally use when designing and constructing concrete structures, taking into account the life-cycle of the structure. Consequently, the method is easier for practitioners to understand, adopt, and apply.

The requirement tree of the environmental sub-model is included in Fig. 1. Its evaluation parameter is called the Environmental Sustainability Index (ISMA, in translation), and fits in with Equation (3), which is a specific case of Equation (1) for the problem dealt with here.

$$ISMA = \sum_{i=1}^{i=10} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i \qquad (3)$$

With respect to the value functions of each indicator, all follow Equation (2). Different types of value function have been used in order to reflect the experts' consensus.

On the other hand, each of the indicators in Fig. 1 may have several quantitative and qualitative aspects that are to be evaluated. Thus, there is a fourth level of breakdown, included in Table 1 because of its length. A specific scoring system for each indicator also exists to quantify the degree of compliance for all aspects under assessment. As a result, only one P_i value is calculated for each indicator, and then it is introduced into the corresponding value function. This scoring system uses specific functions. Various tables bring together the scores for the possible solutions to be adopted for each indicator.

Table 1. Variables for the model and their values in the case study. CS = CS #1 = case study corresponding to curve #1 of Fig. 3. p = (p1, p2, p3) = probability of (alternative1, alternative2, alternative3) with discrete distributions. (N1, N2, N3) = (min, modal, max) values for trigen distributions.

Indicator	Variables of the model and their values for the case study
Characteristics of concrete suppliers	1. **Origin of concrete (prefabrication company, external ready-mixed company, on-site facility).** ***Case study (CS)***. *100% (volume) by an external ready-mixed company.*
	2. **Environmental condition of the companies supplying concrete (certification, commitment, other cases).** ***CS.*** *External ready-mixed company: p = probability of (certification, commitment, other cases) = (Medium, Medium, Low).*
	3. **Environmental condition of the contractor (certification, commitment, other cases).** ***CS.*** *p = (Medium, Medium, Low).*
	4. **Distances from the concrete manufacturers plants to the site.** ***CS.*** *External ready-mixed company: (minimum, modal value, maximum) = (4, 15, 30) km.*
Characteristics of reinforcement suppliers	5. **Origin of the reinforcement (prefabricated elements, external facility, on site facility).** ***CS.*** *100% (weight) reinforcement supplied by an external facility.*
	6. **Environmental condition of the rebar supplier (certification, commitment, other cases).** ***CS.*** *External facility: p = (Medium, Medium, Nil).*
	7. **Environmental condition of the contractor (certification, commitment, other cases).** ***CS.*** *p = (Medium, Medium, Low).*
	8. **Distances from the rebar manufacturers plants to the site.** ***CS.*** *External facility: (50, 100, 150) km.*
Reinforcement reduction	9. **Percentage of pre-stressed reinforcement.** ***CS.*** *0%.*
	10. **Percentage of reinforcement with quality mark.** ***CS.*** *0%.*
	11. **Percentage of rebar joined with mechanical means (not welded).** ***CS.*** *(33%, 73%; 73%).*
Construction control	12. **Percentage of steel with diminished safety coefficient, in accordance with EHE.** ***CS.*** *0%*
	13. **Percentage of concrete with diminished safety coefficient, in accordance with EHE.** ***CS.*** *0%.*
Steel characteristics	14. **Percentage of steel of each type.** ***CS.*** *100% B-500S.*
	15. **Environmental certification of the steel production (EMAS, ISO, nothing).** ***CS.*** *Nothing.*
	16. **Steel with quality mark (yes, no).** ***CS.*** *Yes.*
	17. **Quality mark certifying that at least 80% of its production uses recycled scrap (yes, no).** ***CS.*** *No.*

	18. **Quality mark certifying steel production subject to the demands of the Kyoto Protocol (yes, no). *CS.*** *Yes.* 19. **Quality mark certifying that the steel manufacturer makes use of more than 50% of steel slag (yes, no). *CS.*** *No.* 20. **Raw materials and steel subjected to radiological emission testing (yes, no). *CS.*** *p (yes) = Medium.*
Recycled aggregate	21. **Percentage of concrete of each type. *CS.*** *4.5% of HM-20. 86% of HA-25. 9.5% of HA-40.* 22. **Percentage of recycled aggregate. *CS.*** *0% in all cases.*
Cement and addition characteristics	23. **Percentage of concrete produced with each type of cement. *CS.*** *100% of concrete produced with the same type of cement.* 24. **Environmental certification of cement production (EMAS, ISO, nothing). *CS.*** *p = (Medium, Medium, Low).* 25. **Cement with quality mark (yes, no). *CS.*** *p (yes) = High.* 26. **Production subject to the demands of the Kyoto Protocol (yes, no). *CS.*** *p (yes) = High.* 27. **Quality mark certifying production of cements using fuels and raw materials that produce fewer emissions of CO_2 (yes, no). *CS.*** *p (yes) = Medium.* 28. **Types of additions (additions to the cement; additions to concrete, in cases of concrete with quality mark, produced by a company with environmental certification; other cases). *CS.*** *Additions to the cement.* 29. **Percentage of additions to the cement (< 20%, ≥ 20%). *CS.*** *p = (Medium, Medium).* 30. **Percentage of additions of fly ash to concrete. *CS.*** *0% in all cases.* 31. **Percentage of additions of silica fume to concrete. *CS.*** *0% in all cases.*
Impacts caused by construction processes	32. **Site accesses paved (yes, no). *CS.*** *Yes.* 33. **Use of pneumatic cleaning systems (yes, no). *CS.*** *No.* 34. **Use of dust retention devices (yes, no). *CS.*** *No.* 35. **Use of sprinklers on-site to avoid generating dust (yes, no). *CS.*** *Yes.* 36. **Use of chemical stabilizers to reduce dust production (yes, no). *CS.*** *No.* 37. **Use of tarpaulins or canvasses during transportation, for covering material that can generate dust (yes, no). *CS.*** *p (yes) = Low.*
Waste management	38. **Management of excavation products (recycling, reusing or revaluating; dumping). *CS.*** *50% reusing; 50% dumping.* 39. **Management of construction and demolition waste (recycling, reusing or revaluating; dumping). *CS.*** *30% recycling; 70% dumping.* 40. **Percentage of concrete with quality mark. *CS.*** *0%.* 41. **Percentage of cylindrical specimens without sulfur capping, for testing concrete. *CS.*** *0%.* 42. **Percentage of cubic specimens for testing concrete. *CS.*** *0%.*
Water management	43. **Environmental condition of the contractor (certification, commitment, other cases). *CS.*** *p = (Medium, Medium, Low).* 44. **Use of efficient curing techniques with regard to water consumption (yes, no). *CS.*** *Yes.* 45. **Use of water saving devices (yes, no). *CS.*** *p (yes) = Medium.* 46. **Use of containers for collecting and using rain water (yes, no). *CS.*** *p (yes) = Medium.*
Social contribution	47. **Applying innovative design or construction methods deriving from R&D and innovation projects (yes, no). *CS.*** *No.* 48. **Training the on-site staff beyond legal requirements (yes, no). *CS.*** *No.* 49. **Adopting voluntary health and safety measures that go beyond legal requirements (yes, no). *CS.*** *p (yes) = Medium.* 50. **Establishing measures to inform the public of the features and timescales, as well as the economic and social implications of the project (yes, no). *CS.*** *p (yes) = High.* 51. **Having the project declared of public interest by the Administration (yes, no). *CS.*** *No.*
Extended lifetime contribution	52. **Minimum lifetime established by EHE for this kind of structure. *CS.*** *15 years.* 53. **Estimated lifetime of the structure. *CS.*** *50 years.*

The scope of this text makes it impossible to give a detailed description of all the environmental indicators. Although only the basic points are provided in Table 1, the reader can find the complete EHE model in Ministerio de la Presidencia (2008; in Spanish) and Ministerio de

Fomento (2011; in English), as well as the modified model used by the authors in GRIDP (2013b). As for Table 1, when applicable, the design or construction alternatives that bring a higher or lower score are shown in parentheses. As for transportation, a lower distance means a higher score. Finally, in aspects expressed by percentages, the score increases with these percentages.

After using the various specific formulae for assessing the different indicators and applying Equation (3) to obtain the ISMA, other sustainability aspects are taken into account to obtain an overall value for the ICES, using Equation (4).

$$ICES = a + b \cdot ISMA \quad (4)$$

with the following restrictions:

$$ICES \leq 1$$

$$ICES \leq 2 \cdot ISMA$$

In Equation (4), *a* is the coefficient associated with the social contribution, which evaluates the five issues reflected in Table 1 (variables 47 to 51). On the other hand, economic aspects are taken into account in a simplified manner, using coefficient *b*, which increases with structural durability. The reader should remember that other economic aspects, such as material savings, have already been considered in the environmental indicators. Coefficient *b* is calculated by using Equation (5), dividing the estimated lifetime (t_g) by the minimum compulsory lifetime required by EHE ($t_{g,min}$).

$$b = \frac{t_g}{t_{g,\min}} \leq 1.25 \quad (5)$$

A level scale has been established that is similar to the one used to compare appliance energy consumption. It gives each structure a sustainability level of A, B, C, D, or E, depending on the numerical ICES obtained.

2.2 Simulation Stage

After the relevant information has been entered, the computer system will now perform a Monte Carlo simulation using the EHEm model. In this way, it is possible to know the uncertainty and thus the risk of not meeting the sustainability objective. Decisions that increase the likelihood of success can be made. Monte Carlo has moderate convergence speeds, although the speed is hardly affected by the number of inputs for the problem. It is therefore a useful and rapid method for problems in which many variables intervene. Such is the case of the problem featured in this text, which includes about 50 input variables.

2.3 Post-Simulation Stage

Once the simulation has been done, the resulting sample of possible final ICES will be now analysed. The opportune statistic parameters (maximum, minimum, average, mode, typical deviation) will be calculated, as well as the corresponding graphs of the resulting distribution function. Then the user will interpret the statistical analysis and reach the necessary decisions about structural design.

Pre-simulation, simulation and post-simulation stages are performed on a periodical basis throughout the life cycle of the project and whenever there are major modifications. Thus new data are fed into the process. Over time, there are changes in the nature and degree of uncertainty. With these steps, one can have at hand complete and useful information to manage the sustainability objective throughout a project's entire life cycle.

There is a final stage that is crucial. In it, the authentic final data are recompiled to produce a historical data base. This will make it possible, in the future, to perfect the model and estimate its variables more effectively.

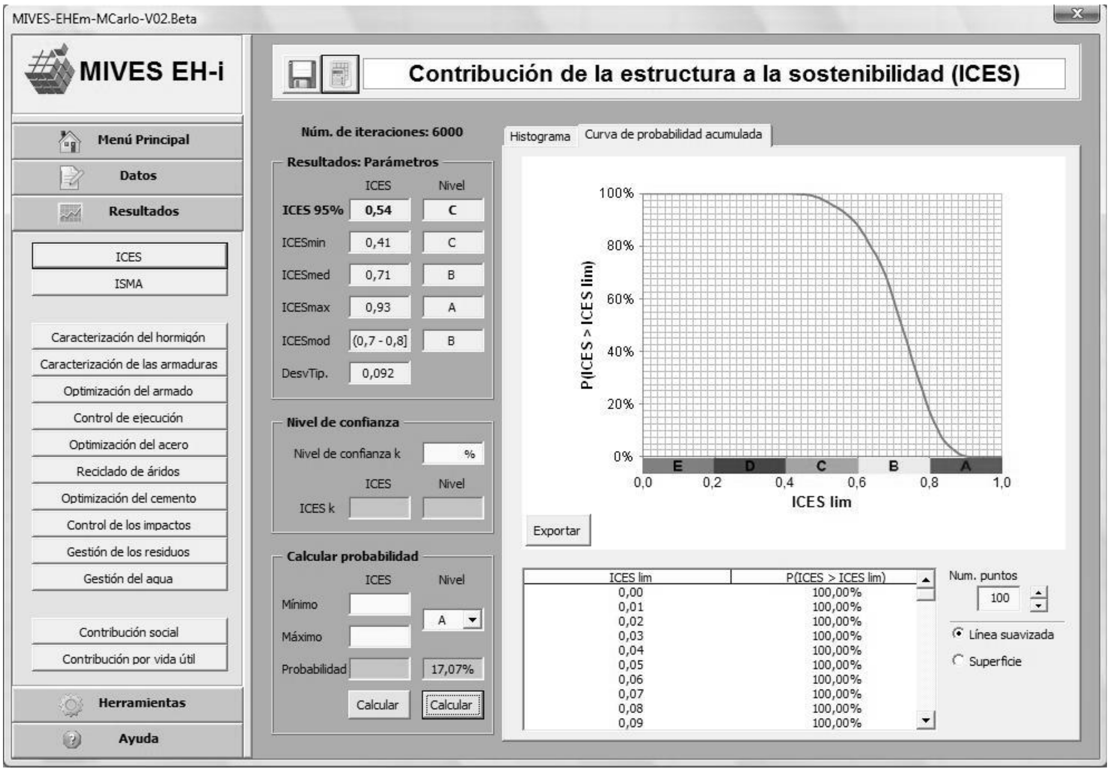
3. The System

3.1 Introduction

The system presented here includes a user-friendly design and carries out the calculations mentioned earlier. It has been developed in the Microsoft Visual Basic for Applications language (from here on VBA) and works within Microsoft Office Excel. In this way, data previously stored in spreadsheet files can be easily introduced.

3.2 Input Interface

The system is structured into three modules: data entry, simulation, and outcomes. The user interface has a zone for general menus, situated on the left (Fig. 2). On the right, different screens for each menu option can be seen. The ***Datos*** (Data) option is for introducing and editing the structural data (see Table 1). There are 12 data entry forms, one for each environmental indicator, one for social aspects, and another for those related to structural durability.



Núm. de iteraciones: 6000

Resultados: Parámetros

	ICES	Nivel
ICES 95%	0,54	C
ICESmin	0,41	C
ICESmed	0,71	B
ICESmax	0,93	A
ICESmod	(0,7 - 0,8]	B
DesvTip.	0,092	

Nivel de confianza

Nivel de confianza k: %

	ICES	Nivel
ICES k		

Calcular probabilidad

	ICES	Nivel
Mínimo		A
Máximo		
Probabilidad		17,07%

ICES lim	P(ICES > ICES lim)
0,00	100,00%
0,01	100,00%
0,02	100,00%
0,03	100,00%
0,04	100,00%
0,05	100,00%
0,06	100,00%
0,07	100,00%
0,08	100,00%
0,09	100,00%

Num. puntos: 100

● Línea suavizada
○ Superficie

Figure 2. Interface showing the results of the statistical analysis for simulated ICES values.

To introduce the data for a variable, the first task is to indicate if it brings uncertainty with it. Three options can be taken: ***Determinista***, ***Probabilista***, and ***Desconocido*** (Deterministic, Probabilistic, and Unknown). Unknown lets users handle the system when they have little idea of the possible extreme (maximum and minimum) and most probable (modal) values. The system stores a series of data to be used in these cases, establishing prudent hypotheses that are not necessarily the most pessimistic ones. The Unknown option is not available for the variables that are always going to be known by the designer, as they deal with crucial data or aspects that, defined by legislation, have to be included in every design.

On the other hand, for the Deterministic variables, it is necessary to introduce the corresponding numerical value or semantic label, according to the type of variable being dealt with. Labels are used for specific conditions that may or not be fulfilled.

As for Probabilistic variables, architects and engineers currently lack the necessary knowledge and experience to establish the use of specific distribution functions. There are no historical data bases for the parameters evaluated here. Consequently, the user cannot choose the type of distribution function to be used. For continuous numerical variables- such as transport distances- triangular distributions come into play. The user should only enter the modal and extreme (max., min.) values. These distributions (Williams 1992) are easy to handle, because they only entail estimating the extreme and most frequent values. They are also simple to understand.

Furthermore, these distributions can be configured as asymmetric ones. This is a necessary concern here because, in the field related to this study, the distances between mode and the two extremes of the distribution usually differ. On the other hand, assuming that the user may make small errors when estimating extreme values, trigen distributions are used (open or general triangular ones; Hillson and Simon 2007). This leaves a 5% probability, which exceeds those extreme values.

It should not be cause for concern that these distributions have a geometry that fails to adjust perfectly to the possible real distribution. As long as estimates for key parameters are reliable, it is better to perform simulations than to depend on deterministic models. These are less able to capture the underlying complexity of the reality. A final point is that, for obvious reasons, Bernoulli and general discrete functions are used for the discrete probabilistic variables with two or three possible alternatives. In this way, the probabilities for each one of those alternatives can be estimated.

For discrete variables with two possible options (Yes / No), one must establish how probable it is for the evaluated structure to comply with the corresponding requisite. There are also discrete variables that may have three posible situations: for example, the ones related to a supplier having ISO 14001 certification, EMAS certification, or no certification whatsoever. Here it is necessary to estimate the probability for each one of those situations.

As mentioned earlier, there are no historical data bases covering this field. Therefore, it is unsurprising that users have difficulties in estimating these probabilities in numerical terms. To solve this problem, the system uses semantic labels: Null, Low, Medium, and High Probability. These labels are then converted into appropriate numerical figures and an incoherent combination of labels is thus avoided.

3.3 Simulation

3.3.1 General Issues

With the data entered, ***Herramientas*** (Tools) helps with performing the simulation. To generate pseudo-random numbers adjusted to other probability distributions, the inversion technique (inverse transformation; Ríos et al. 1997) has been used.

3.3.2 Data Matrices

It was necessary to develop a VBA matrix system (VBA matrices; Walkenbach 2004), to handle the great quantity of values, variables, and results used in and generated with the simulation.

The computation time is dramatically reduced when compared with work that relies on data stored on a spreadsheet.

Firstly, the data entered are saved on spreadsheets. Then, these data are stored in VBA matrices called input matrices. They are then to be used in the calculation. Just as there are 12 entry forms and 12 spreadsheets to save these data, the system counts on 12 input matrices, one for each indicator in the EHEm model.

On the other hand, the values used for calculating the ICES in each iteration are stored in another set of matrices, called intermediate data matrices. For deterministic variables, the values saved in these matrices will always be the same. In contrast, the values for the probabilistic variables will be generated (simulated) in each iteration. Once again, there are twelve intermediate data matrices, one for each indicator.

Moreover, when pseudo-random values are being generated, the system needs to know for which input variables it is necessary to generate those values. It must also know where within the intermediate data matrices they should be stored. This information is stowed in a third set of matrices. These are called address matrices and contain the rows and columns (addresses) for the intermediate data matrix elements corresponding to the probabilistic variables. It is possible to use only one address matrix for each indicator. However, twenty-four address matrices come into play: 12 for probabilistic variables and another dozen of them for those that have been declared as unknown, given that the system treats them internally as probabilistic.

Lastly, so that one can analyze not only the possible ICES, but also the potential score that could achieve the 12 ICES indicators, the system stores the points obtained in each iteration for each indicator, as well as the ISMA value. This is performed through the use of 14 VBA matrices, called output matrices.

3.4 Statistical Analysis and Results Interface

Once the simulation has finished, ***Resultados*** (Results; Fig. 2) carries out a thorough statistical analysis of the simulation results. Users can see the outcomes of that analysis and select the variables whose distribution function they want to study. These variables may be an environmental indicator, the social criterion, the one related to durability, the ISMA, or the global one, the ICES.

The key parameters for the distribution function can also be found here (Fig. 2; ***Resultados: Parámetros***; Results: Parameters). The first of these is called characteristic value. Analogous to the characteristic strength of concrete, this value indicates the ICES that the structure will reach, with a 95% confidence level. Besides the characteristic value, the minimum, average, maximum and modal values, as well as the typical deviation, are calculated (Fig. 2).

The frequency histogram (***Histograma*** tab) and the curve of cumulated probability (***Curva de probabilidad acumulada*** tab) can also be analyzed (Fig. 2), the latter for estimating, at a glance, the probability of reaching the established sustainability objective.

The ***Nivel de confianza*** (Confidence level) box makes it possible to calculate, in accordance with the results of the simulation, the ICES and ICES level for a confidence level k previously established.

Finally, the ***Calcular probabilidad*** box (Calculate probability) lets one calculate the probability of the structure's ICES falling within a specific values interval. The interval can be set numerically, or through suitable ICES levels (A, B, C, D, E).

4. Case Study

Serving as a case study is the project for an industrial building to be located in north-western Spain. It is to have a surface area of approximately 800 m^2. The structural materials are wood for the roof structure (beams and purlins), steel for the roof bracing, and concrete for the rest of the structure (columns, façade bracing, and foundations). In total, the structure has 295 m^3 of concrete and 16 t of steel reinforcement. Other general features of the concrete structure are summarized in Table 1. This table also provides the detail necessary for performing the corresponding calculations.

Once the simulation is performed, the minimum, average, and maximum ICES values are 0.21, 0.52, and 0.74 respectively. Put in terms of ICES levels, this means D, C, and B. The distribution mode coincides with the interval (0.5; 0.6), making it a level C. Moreover, the typical deviation is 0.093, and with a 95% confidence level, the ICES for this structure exceeds 0.34 (level D). Curve #1 of Fig. 3 summarizes this situation. It is therefore obvious that, in order to have the slightest possibility of reaching a high sustainability level (A or B), a good number of modifications have to be made.

For instance, the potential ICES could be increased improving the values for variables 22 (from 0% to 20%: see Table 1), 38 (now 100% is to be reused), and 39 (now 60% for recycling and 40% for dumping). In this way, the cumulative probability curve moves to the right (Curve #2 of Fig. 3). The new (minimum, average, and maximum) ICES values are (0.41; 0.71; 0.93), which correspond to levels C, B, and A. The mode is now in the interval (0.7; 0.8), which would mean a level B. With a 95% confidence level, the ICES exceeds 0.54 (level C). There is thus some possibility of achieving a level A objective, but it is very low (17%). On the other hand, the typical deviation is about the same (0.092), since the modifications mentioned only affect deterministic inputs. Obviously, it is possible to increase the potential ICES, diminishing the uncertainty of some probabilistic inputs. For instance, one can assure that:

- The ready-mixed concrete company and the contractor participating in the project have an environmental certification (inputs 2, 3, 7, and 43 of Table 1).
- The cement production has an environmental certification, either EMAS or ISO (input 24 of Table 1). Now P(EMAS, ISO, nothing) = (Medium, Medium, Nil).
- The cement has a quality mark and its production is subjected to the demands of the Kyoto Protocol (input 25 and 26 of Table 1).
- Tarpaulins or canvasses are used during transportation, to cover material that can generate dust (input 37 of Table 1).

In the next step, the cumulative probability curve will move again to the right (Curve #3 of Fig. 3). Now the (minimum, average, and maximum) ICES values are (0.71; 0.85; 0.96) which, despite everything, correspond again to (B; A; A) levels. The mode changes at the interval (0.8; 0.9) and, with a 95% confidence level, the ICES exceeds 0.78 (level B). However, the probability of an A level is now 88%. In the end, uncertainty has been reduced and the typical deviation is 0.044.

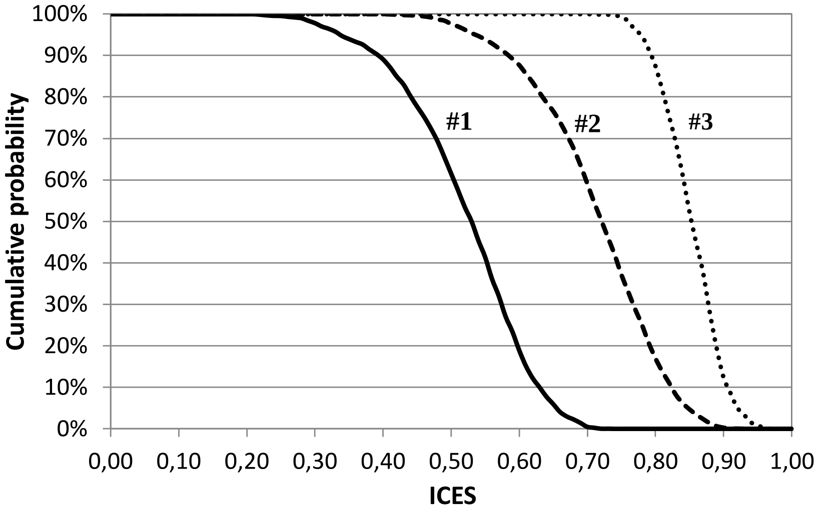


Figure 3. Curves of cumulative probability for the case study.

5. Conclusions

Just as they define project time, cost, and quality targets, it is increasingly more common for the promoter, proprietor, user, and even the constructor to set sustainability objectives. Nevertheless, uncertainty constitutes a problem for estimating sustainability, especially in the early project phases. The potential effectiveness of the sustainability management function is diminished and it is therefore much less likely that the corresponding objective is achieved. This makes it difficult to apply deterministic assessment systems.

The system presented here is a solution to this problem. It sheds light on the likelihood of reaching the sustainability objective throughout the entire project life cycle. It also comes into its own when the consequences of making different decisions are being compared. This will facilitate on-time decision making, in order to achieve the sustainability objective. The method is applicable to any type of structure, although it can be more effective in large and complex projects.

Conceptually, the method can be more or less easily understood by architects and engineers. Nevertheless, it entails using computational techniques. To apply this method it is necessary to design and build computer systems that an architect or structural engineer would not normally be able to develop. This paper has presented a free, user-friendly system for applying the method, which has been conceived and developed to make sustainability management easier for professionals from the construction sector.

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