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# Uncertainty analysis in the sustainable design of concrete structures: A probabilistic method

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## HIGHLIGHTS

- ▶ There is uncertainty about the final characteristics of a structure.
- ▶ This makes it difficult to estimate the final sustainability index of the structure.
- ▶ The method serves to manage uncertainty, facilitating on-time decision making.
- ▶ It informs about the likelihood of finally reaching the sustainability objective.
- ▶ It serves for comparing the consequences of making different decisions.

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ABSTRACT

This paper presents a sustainability assessment model based on requirement trees, value analysis, the Analytic Hierarchy Process, and the Monte Carlo simulation technique. It embraces the approach for assessing sustainability taken by the Spanish Structural Concrete Code. Nevertheless, the deterministic model of the Spanish Code can cause significant problems in terms of adequately managing a project's structural sustainability objective. Thus, a method not only has to assess the potential sustainability index at the end of the project. It also has to evaluate the degree of uncertainty that may make it difficult to achieve the sustainability objective established by the client or promoter.



## 1. Introduction

The MIVES method (Integrated Value Model for Sustainability Assessment, in Spanish) [1,2] is based on requirement trees (Fig. 1), value analysis [3], and, optionally, the Analytic Hierarchy Process [4,5]. Its methodology transforms any kind of quantitative or qualitative variables into the same type of non-dimensional variable. Moreover, it takes into account the relative importance of the various environmental, social, and economic aspects included in a sustainability assessment. MIVES makes it possible to compare project alternatives and choose those that contribute more than others to sustainable development.

This method has been applied to the sustainability model of the Spanish Code on Structural Concrete (*Instrucción Española del Hormigón Estructural* EHE-08, hereinafter EHE) [6,7]. Two of the authors were part of the project in which it was created. EHE covers mass, reinforced, and prestressed concrete. It also deals with the design, construction, maintenance, and recycling of these types of structures. The EHE sustainability assessment model is known as the Structure's Contribution to Sustainability Index (in translation, ICES, used throughout this text). Although this kind of assessment is still not compulsory in Spain, this was the first time a structural code included a sustainability model. Thanks to it, a similar one was included in the new Spanish Code on Structural Steel (*Instrucción Española del Acero Estructural* EAE-11) [8,9]. These initiatives are very important, given that construction has an immense impact on the environment, economy, and society, in terms of employment.

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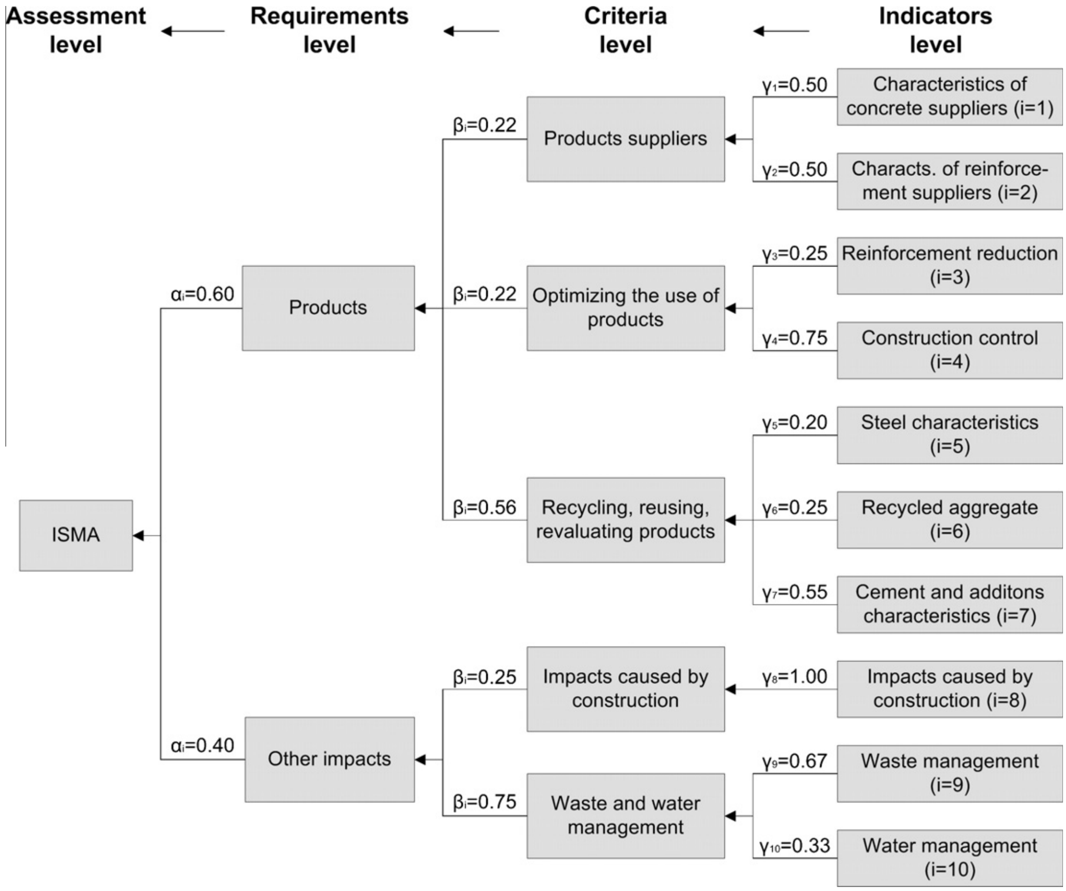


**Fig. 1.** Requirement tree of the model.

Once a client establishes a sustainability objective for the structure, the architect or engineer will carry out the design to achieve this and other objectives, such as cost, time, or quality. After the contract has been done, the on-site works will produce a final product that should have the required ICES, but not necessarily in the way the designer initially established. It is therefore necessary for the client, designer, and construction manager to assess the ICES at different moments of the project life cycle. The purpose of this is to estimate the potential final index value and make the opportune decisions, if needed.

However, there is uncertainty about the real, final ICES when the index is estimated before the structure has been finished. There are two main reasons for this. First, the value of specific variables depends on which contracting companies are finally chosen. A case in point is the environmental certification of contractors. Second, during building works, the client or construction manager could decide to change some parts of the design or specs, such as the percentage of recycled aggregate used to prepare the concrete.

These sources of uncertainty may cause significant differences between the ICES estimated at various moments of the project and the final, real one. The main risk resulting from these uncertainties is that a certain investment is made to improve structural sustainability, without achieving the desired ICES. Moreover, in the case of a client applying for subsidies, or hoping to obtain a specific sustainability certification, these aims would not be achieved, despite the investment made. The key stakeholders need to know how likely it is for the sustainability objective to be reached in the end, to respond to that risk. The method presented here allows the user- the architect or engineer- to take into account the uncertainty of different sustainability parameters.

## 2. The MIVES–EHEm–MCarlo method

### 2.1. Components of the method

#### 2.1.1. The MIVES method

MIVES includes several stages. After defining the problem to be solved, and the decisions to be made, a basic diagram of the decision model is created. In this, all aspects of the assessment are established in the form of a requirement tree. This tree includes qualitative and quantitative variables (Fig. 1), with different units and scales. At this point 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 of the aspects taken into account for the assessment. The various design alternatives are then evaluated, using the previously created model. It is thus possible to make the most suitable decisions and choose the most appropriate alternative. In fact, MIVES can be used for helping decision makers in fields outside of sustainable development.

As for the mathematical foundations of the method, MIVES is based on Multicriteria Decision Methods (MCDMs). In general terms, 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 to others, the existence of a value function $V$: $P \rightarrow R$ 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 $V(P)$ is constructed, integrating all the assessment indicators. The solution is a 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