Construction and Building Materials 49 (2013) 882–893

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Integrated sustainability assessment method applied to structural concrete columns

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HIGHLIGHTS

- The most sustainable reinforced concrete columns are built using high performance concretes.
- Columns built using self-compacting concretes are more sustainable than those vibrated.
- Reinforced concrete circular columns have a higher sustainability index than square ones.

ARTICLE INFO

Article history:
Received 18 June 2013
Received in revised form 31 July 2013
Accepted 3 September 2013
Available online 29 September 2013

Keywords:
AHP
Columns
Economic
Environmental
Index
MCDM
MIVES
Social

ABSTRACT

This research paper presents a general model for integral sustainability analysis of columns. This assessment tool has been obtained by using MIVES, a Multi-Criteria Decision Making (MCDM) model which considers the sustainability main plans (economic, environmental and social) and incorporates a value function concept in order to homogenize the indicators and consider the degree of satisfaction. This tool is general and could be applied to assess other structural components within the building sector after introducing minor changes. Nevertheless, for this research project, it has been designed to assess reinforced concrete columns in buildings in situ. Therefore, the influence of determining variables such as concrete compressive strength, cross-section geometry and building process have been studied based on this defined model.

1. Introduction

It is known that the construction sector causes a significant part of environmental impact in the most developed countries. For instance, in 2011, studies revealed [1] that, in the European Union, the construction and use of buildings was responsible of 42% of its energy consumption, 35% of its CO_2 emissions and more than 50% of extracted materials. This data highlights the necessity for a change in the building sector in order to improve its sustainability and accomplish the objective of conciliating economic, environmental and social demands as was established at the 2005 World Summit [2].

In this vein, the research group MIVES has been working in this direction since the early 2000s and has developed the Integrated Value Model for Sustainable Assessment (MIVES). This is a general assessment method which considers the aforementioned three basic sustainability plans. Therefore, MIVES is a Multi-Criteria Decision Making (MCDM) tool which has already been presented to the scientific community and applied to make assessments and decisions in different fields, for example to assess university professors [3], to make technic-economic decisions related to the construction of a new metro line in Barcelona [4], to assess the environmental impact of industrial buildings [5], the sustainability of concrete structures within the Spanish structural concrete code [6], the sustainability of concrete pipes [7], the sustainability of building technologies used to construct school edifices [8] and, developing the probabilistic method MIVES–EHEm–Mcarlo, to give the likelihood of reaching the sustainable objective during the project phase, especially for large and complex edifices [9].

On the other hand, within this context, the building sector has gained sensibility towards sustainability and awareness during recent years, by proposing and developing assessment and

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http://dx.doi.org/10.1016/j.conbuildmat.2013.09.009

certification tools such as BREEAM [10], CASBEE [11], DGNB [12], LEED [13], through which sustainability is intended to be quantified using objective parameters.

These certification systems take into account the main sustainability requirements but they are too general and not representative enough to evaluate specific load bearing building structure elements such as beams, columns, slabs and foundations.

In this sense, columns are the structural components which receive loads from the upper floors and transmit them downward to the foundations. In residential buildings with reinforced concrete structures, columns comprise from 10% to 25% of the total concrete and steel consumption. So columns are not only fundamental for structural functionality and safety but also to improve structural sustainability, provide they are designed and executed with the adequate geometry, materials and construction process.

Structural concrete and its components have been highly improved and nowadays it is possible to achieve fast hardening and high strength concretes at only slightly increased costs compared to low and medium strength concretes. These improvements can result in:

1. Columns having a smaller cross-section and the same or even higher load bearing capacity compared to traditional concretes. This permits a more optimum profit in available building space, which is crucial in high density cities with limited surface area open for construction. Moreover, thinner cross-section columns consume less material, which counterbalances their increase in cost compared to traditional concretes.
2. Increased work performance and consequent lower construction time, which reduces social nuisances such as noise, traffic cuts and special transports.

Until present times, these types of concretes were only applied to unique structures such as long-span bridges [14] or skyscrapers [15], among others, due to economic reasons. At present however, due to the aforementioned advantages, these high performance concretes are a real alternative to traditional concretes when it can be rationally verified that their use leads to more sustainable solutions.

To that purpose, MIVES is a highly recommended methodology to integrally assess the sustainability of building columns, a specific structural component which lacks mention of expressly designed assessment tools in scientific literature.

The objective of this research project is to develop a MIVES – based requirements tree which incorporates discriminatory and not interdependent indicators, with which researchers can assess different building columns alternatives. Moreover, due to its technical and economic interest, columns having different cross-section shapes, concrete compressive strengths and construction processes are analyzed.

2. Methodology

As has been previously stated, MIVES is a methodology which permits sustainability evaluation and decision-making in multi-criteria processes. It differs from other MCDM available in technical literature [16–18], because it incorporates value function and satisfaction concepts [7].

The most important criteria for an integral sustainability assessment have been chosen: economic, environmental and social; while indicators have been decided during seminars, in which a sufficiently plural and representative group of technicians have participated. This group weighed requirements, criteria and indicators by using either Analytical Hierarchically Process (AHP) [19] or direct assignment. This research requirements tree for reinforced concrete columns is presented in this chapter.

Moreover, the use of value functions in the analysis allows researchers to transform the results obtained by each indicator, which might have different measurement units, to a non-dimensional magnitude value. This magnitude is intended to indirectly measure the satisfaction grade. Each indicator adimensional value can then be aggregated according to the established weighing, obtaining partial and global sustainability indexes for each alternative. Comparing these indexes it is possible to achieve an objective decision, as has been done for 12 alternative reinforced concrete columns analyzed in the fourth part of this article.

In order to develop a specific tree and its associated weights (see Fig. 1) to assess the sustainability of reinforced concrete columns, a seminar was organized. The stakeholders at this workshop represented different agents involved in the building sector. Weights were defined according to the direct assignation method applied during a multidisciplinary seminar attended by architects and engineers. The technicians came from the building contractors "FCC Construction, S.A." and "Ferrovial Agroman, S.A.", the architectural firm "BIS Architects, S.A.", the concrete producers "PROMSA", the chemical company "BASF", and the pre-stressing reinforcement company "VSL".

During this seminar, this sustainability assessment tool was specifically configured to analyze reinforced concrete columns. However, although the requirement tree is general for this specific application field, additional considerations were brought to bear in the study: standard residential building columns which do not have any additional complexity and an economic recession context in which the public administration is the investor. In this sense, these considerations directly affect the values of the weights, mainly those related to economic aspects. However, these could be modified so as to account for other scenarios and hypotheses. To that end, in the final part of this article there is a sensitivity analysis which assigns different weights to this investigation's economic requirement in order to take into account other aspects such as promoter investment.

The requirements tree has different levels. The requirements, which are the base of the hierarchic method, comprise the first level of this decision-making tree. The economic, environmental and social requirements have been chosen. In the second hierarchical level, the criteria are stated; these organize concepts and provide useful structure for the analysis of each alternative. Finally, indicators comprise the decision-making tree's base of measurement. Unlike requirements and criteria, indicators are measurable variables which are aggregated to quantify each reinforced concrete column alternative.

In this sort of analysis, to exclusively consider the main variables of the decision process in order to avoid an excessive number of indicators is of relevant importance, which would decrease the resulting assessment tool's precision and its discriminatory capacity. Table 1 presents both the criteria and the indicators considered. It should be mentioned that the final number of elements in each tree branch shall be the minimum number necessary since others have been disregarded due to either their lack of representativeness or since they present a certain overlapping with other indicators already considered. Both disregarded and considered indicators are described in detail in the following paragraphs.

The economic requirement compares the economic impact of each column alternative. I1 evaluates construction costs of the columns in €/m^3, for example the reinforced concrete column includes the cost of formwork, concrete, steel, labor, auxiliary means and indirect costs [20]. I2 assesses the economic repercussion of nonconformities derived from quality problems, which were analyzed in the seminar and measured by assigning points.

To assign these points, the following aspects were taken into account: incorrectly positioned reinforcement, incorrectly compacted concrete, liquid concrete loss between joints; these aspects are influenced by: execution control level (which is assumed intense), concrete workability and cross section shape. I3 takes into account the maintenance cost over a ten year period in €/m^3, considering the compressive strength of concrete, construction process and formwork typology. I4 analyses habitability by comparing each column cross-section area and considering a theoretical common distribution of columns for all alternatives. Construction timeframes have not been considered as an isolated indicator but have been taken into account indirectly in I1, I8, I9 and I10.

The environmental requirement assesses the environmental effects of each alternative construction process. From the whole life cycle phases [21] only the initial extraction, transport and production phases have been taken into account, since these phases are the most discriminatory factors for the alternatives and variables studied. I5 considers CO_2 emissions per concrete volume (kgCO_2/m^3). CO_2 emissions were obtained by calculating concrete environmental product declarations (EPD) [22]. The consumption of embodied energy [23] was included in the calculation of this EPD [24], along with transport and mixing process emissions, water consumption and solid waste. Table 2 presents the data for this EPD analysis. At the seminar, the technician from the concrete and additive producer company assistant assumed that silica fume and nano-silica generated the same emissions as cement. They also considered that filler generates the same emissions as aggregate. Table 3 presents the results for this EPD analysis. Water consumption was not considered as a sole indicator because the maximum water consumption difference between column solutions was less than 3% of the total concrete process water consumption [25].

A material flow analysis (MFA) [26] from a territorial point of view [27] would not have assisted to decide the best column solution since all the alternatives studied are located in the same territory, which is defined in part 3. A MFA taking into account the differences between each column alternative building process [28] would have pointed out the best column in a similar way the EPD did, but with less precision because the material differences between the alternatives were