*Send Orders for Reprints to reprints@benthamscience.ae*

*The Open Construction and Building Technology Journal*, 2017, *11*, (Suppl-1, M5) 95-109



BENTHAM OPEN

CrossMark

The Open Construction and Building Technology Journal

Content list available at: www.benthamopen.com/TOBCTJ/

DOI: 10.2174/1874836801711010095


RESEARCH ARTICLE

# Sustainability Assessment in Singular Structures, Foundations and Structural Rehabilitation in Spanish Legislation

Pilar Mercader-Moyano[1,*], Jesús Roldán-Porras[2] and Antonio Ramirez-de-Arellano-Agudo[3]

[1] *Department of Building Construction I, University of Seville, Avda, Reina Mercedes, 2. 41012 Seville, Spain*
[2] *Department of Industrial Engineering and Civil Engineering, University of Cadiz. Avda, Ramón Puyol, S/N. 11202. Algeciras (Cádiz), Spain*
[3] *Department of Building Construction II, University of Seville, Avda, Reina Mercedes, 2. 41012 Seville, Spain*

Received: February 17, 2016 Revised: November 24, 2016 Accepted: November 28, 2016

**Abstract:** The objective of this work is twofold: to determine the scope of the tools currently available for the assessment of sustainability of structures in Spanish legislation; and to identify environmental aspects that have yet to be covered, especially in the case of foundations and of measures aimed at the structural rehabilitation of singular buildings. To this end, the method proposed in the Spanish Instruction of Structural Concrete is applied to the particular case of the supported foundations of the Cylindrical and Colonel buildings in the construction of the new Faculties of Law and of Work Sciences, of the University of Seville during the period between 2005 and 2008. This case was chosen for its special uniqueness and for its inclusion of environmental aspects that remain outside the scope of existing methods.

Most of these aspects are also of great relevance in structural rehabilitation activities carried out in urban environments and neighbourhoods, where a major surge is currently underway due to the economic crisis that has hit projects of newly constructed buildings. By virtue of the work carried out in recent years in the field of sustainability and the environment by several research groups at the University of Seville, a number of alternatives are proposed for the quantification of those aspects that remain to be considered. These techniques are based on tools that allow the agents to intervene in a flexible and effective way in the project implementation phase.

**Keywords:** Construction of structures and foundations, Constructive process, Environmental impact assessment, Load tests, Structural rehabilitation, Sustainability, Underground lines.

## INTRODUCTION

The structures and foundations destined for civil building works and executed in concrete, steel, or a combination of both, represent the vast majority of the actions undertaken since the beginning of the last century. Those structures contained in projects currently under development and projects that will be developed over the coming years are also mainly carried out in concrete and steel compared to other types of materials that have been used to a much lesser extent (wood, stone, ...) and other state-of-the-art synthetic materials currently under development (fibreglass-reinforced polyester, carbon, ...) [1]. On the other hand, the rehabilitation of buildings is booming as a result of the economic crisis suffered in recent years by the sector in relation to the construction of new buildings. The latest forecasts indicate that the value of production in the construction sector will grow by 3% in 2015 after seven consecutive years of decline, where the biggest growth will correspond to rehabilitation and maintenance (+ 3.9%), followed by non-residential construction (+ 3.2%), residential construction (+ 2.8%) and civil engineering (+ 1.8%) [2].

Regarding the tools that currently allow us to identify and assess the impact that a particular project or activity

* Address correspondence to this author at the Department of Building Construction I, University of Seville. Avda. Reina Mercedes, 2. 41012 Seville, Spain; Tel: +34 954 556 591; Fax: +34 954 557 018; E-mail: pmm@us.es

1874-8368/17 2017 Bentham Open

causes in the environment, there are many methods with widely differing approaches, where the global scale of application acquires a predominant position. It is true that, on a larger scale, the complexity in identifying the impact increases exponentially, mainly due to the various approaches that deal with sustainability: environmental, social (socio-political), and economic. The main tools for the assessment of impacts correspond to environmental sustainability indicators, where the approaches hold different preponderance depending on the indicators or methods considered, although it appears to be broadly accepted that sustainable development in any field is obtained at the confluence of the different approaches listed above [3].

The latest updates in the instructions relating to concrete and structural steel in Spain incorporate a methodology for the determination of the contribution to the sustainability of structures made thereunder. This methodology affects work performance as well as new actions included in projects of structural rehabilitation. Its application, however, suffers from certain limitations that are especially noticeable when it is applied to the field of foundations, given that constraints and environmental aspects appear that are not assessed, or objective quantification of the impacts cannot be made partially or completely [4].

## MATERIALS AND METHODOLOGY

Tools for the assessment of sustainability currently available for the planning and execution stage vary widely and to a great degree with very different objectives depending on the country concerned. Certain countries, mainly from the European Union, have developed or are developing their own schemes, either from other standards or the incorporation into national legislation of criteria of a more restrictive nature regarding the sustainability and preservation of the environment. The importance of the impact of a structure can be ascertained when considering the overall energy and impacts associated with its construction: this accounts for between 50% and 60% of the total impact [5].

Depending on the country of origin and following a classification hierarchy, there currently exist: commercial tools based on Life Cycle Analysis (LCA) for the specific case of building (Athena Estimator, Catalogue Construction CH, Metabase, OFEN, ...); tools for the evaluation of materials and constructive solutions (Athena Estimator, LCAid, Legep 1.2, Lisa, Metabase, TCQ2000, ...); tools for sustainability assessment in infrastructures and civil works [6] (PSM/FIDIC, CEEQUAL, AGIC, ASCE, ISI, ENVISION, INVEST, …); and finally tools for the certification of overall sustainability oriented towards the occupation stage (Breeam, Casbee, Enlace, GBTool, Green Globes, Leed, Verde, ...). Among all of these tools, and taking into consideration the downscaling required, we are interested in those tools based on the evaluation of materials and on constructive solutions that specifically address the implementation of structures, whose best example is Integrated Value Model for Sustainable Structures (MIVES) currently in force in the Spanish Structural Concrete Instruction (EHE-08) [7].

The Spanish Structural Concrete Instruction (EHE-08) introduced, throughout all its provisions, further steps towards the design and implementation of sustainable structures. In particular, Annex 13 establishes criteria to assess the so-called Contribution Index of Structure to Sustainability (ICES). The methodology used in this annex is for the MIVES (Integrated Value Model for Sustainable Structures) method, developed by a multidisciplinary group led by the University of the Basque Country, Labein-Tecnalia, and the Polytechnic University of Catalonia. Said group also exercised its coordination within the Working Group of the Permanent Commission on Concrete created for this purpose.

This index is obtained from various parameters related to the three basic levels of sustainability: environmental, social, and economic. In the first case, an Environmental Sensitivity Index (ISMA) is established, which includes various aspects related to the decrease in the consumption of natural resources and in the emission of pollutants, to energy conservation and recycling, among others. With regard to the social and economic levels, aspects such as those related to training and safety in the workplace, the application of research results, and extension of the life of the structure are included.

Instruction EHE-08 allows property owners in particular and intervening agents in general, to estimate the sustainability of their structure. To facilitate this task, the Group of Engineering and Project Management (GRIDP) of the University of La Coruna has developed a computer tool (MIVES-EHE-08 V01) in the form of a calculation template, as a result of the application of the full text of Annex 13 of Instruction EHE-08 [8].

Similarly, Structural Steel Instruction (EAE-11) [9], in its Annex 11, provides criteria to assess the so-called Contribution Index of (Steel) Structure to Sustainability (ICES-EA) in the case of metal structures. This index is obtained in the same way as for ICES EHE-08, from various parameters also related to the three basic levels of sustainability. To this end, an Environmental Sensitivity Index (ISMA-EA) is also established that includes aspects related to the decrease in the consumption of natural resources and in the emission of pollutants, to energy conservation and recycling, among others, although, fewer environmental requirements are considered compared with those for concrete Instruction. With regard to the social and economic levels, the same aspects are included here as are included in Annex 13 of the EHE-08.

In general and on the required scale, resource optimization and waste minimization assume unique foundations and structural rehabilitation: two fundamental aspects in the degree of sustainability resulting from a given action both in the planning stage and subsequent implementation phase. Construction and structural rehabilitation of buildings imply certain environmental impacts that include: the use of materials derived from natural resources; and the use of large quantities of energy, mainly due to the employment of auxiliary means during the construction process, that leads to significant $CO_2$ emissions into the atmosphere. It should be borne in mind that the recycling and reuse of waste from demolition and of waste from the construction and structural rehabilitation of buildings constitute a solution that partially minimises the significant environmental impact stemming from this waste management. Various calculation methodologies are currently available for the quantification and classification of waste generated during construction [10]: these methodologies enable sustainable solutions to be complemented and, more importantly, anticipated in project planning, thereby resulting in better outcomes in the evaluation of the contribution of the structure or foundation towards sustainability.

The main objective of this article is to determine the representativeness of the method included in the Spanish Structural Concrete Instruction (EHE-08) as regards its contribution to sustainability in the implementation of structures when applied to the particular case of singular foundations and structural rehabilitation. To this end, other lower-level objectives have been developed, which can be sorted into two previous levels that are consistent both in the identification of the general and particular characteristics of the case study as well as in the implementation of the currently existing method, by using data collected thereof (see Fig. **1**).

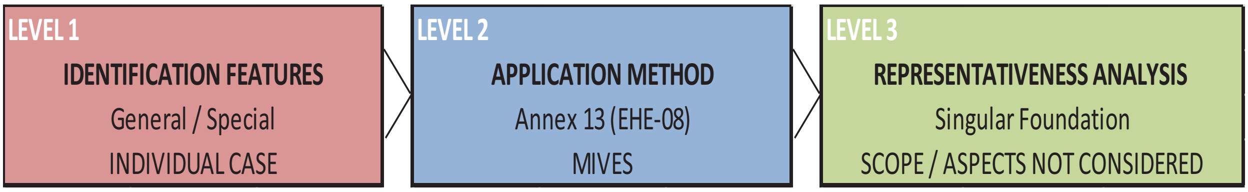


**Fig. (1).** Hierarchy of objectives.

The first level aims to determine the general and specific characteristics of the case study, that are necessary for the application of the method included in the instruction, in order to finally determine the representativeness and scope of the aspects considered when this method is applied to a singular foundation.

In order to achieve these objectives a methodology based on a plan of stages (see Fig. **2**) is proposed based on the hierarchized levels of objectives above, firstly to allow the identification of the unique conditions of the particular case selected and of the parameters required, and to enable the determination of the criteria included in the method developed by the Instruction. Finally, with the results obtained, this methodology analyses and evaluates the scope of the method in the particular case of singular foundations, by taking into account aspects that have not been covered and proposing possible evaluation alternatives.

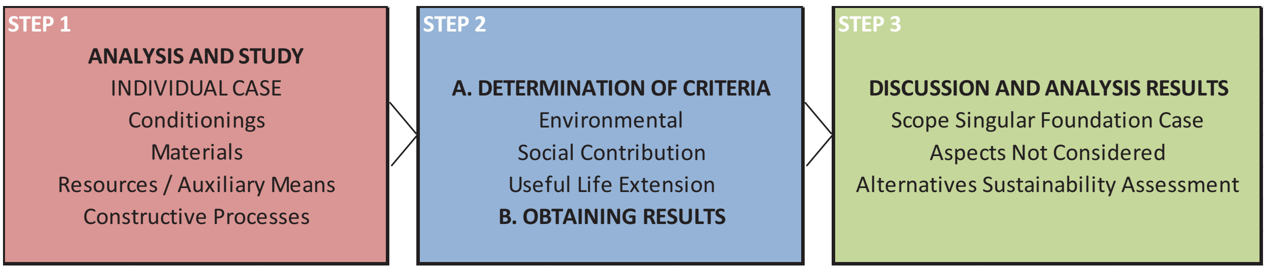


**Fig. (2).** Proposed methodology.

### Step 1: Analysis and Study of the Individual Case

It is necessary to explain the context, the type of construction, and the scope of the particular case of the foundation under analysis: Foundation of the Cylindrical and Coronel buildings Supported over the underground tunnel [11] in the construction of the new faculties of Law and Work Sciences of Seville University [12]. During the course of construction, an unscheduled interference occurred, due to diversion of the route of Line 1 of the underground, which was also under construction (see Fig. **3**). This interference caused an invasion of part of the plot, specifically in the north, which was for the construction of the most significant buildings at the university campus (the Cylindrical and Colonel Buildings). It also caused the loss of approximately 15% of the area of the basement previously set aside for parking. The most important consequence, however, involved the challenge of bridging the underground tunnel, for which it was necessary to design a supported foundation (avant-garde in Spain due to its major bridging dimensions) for both buildings on that path by means of the construction of a pre-stressed beam structure (prefabricated) with a slab interface of reinforced concrete.

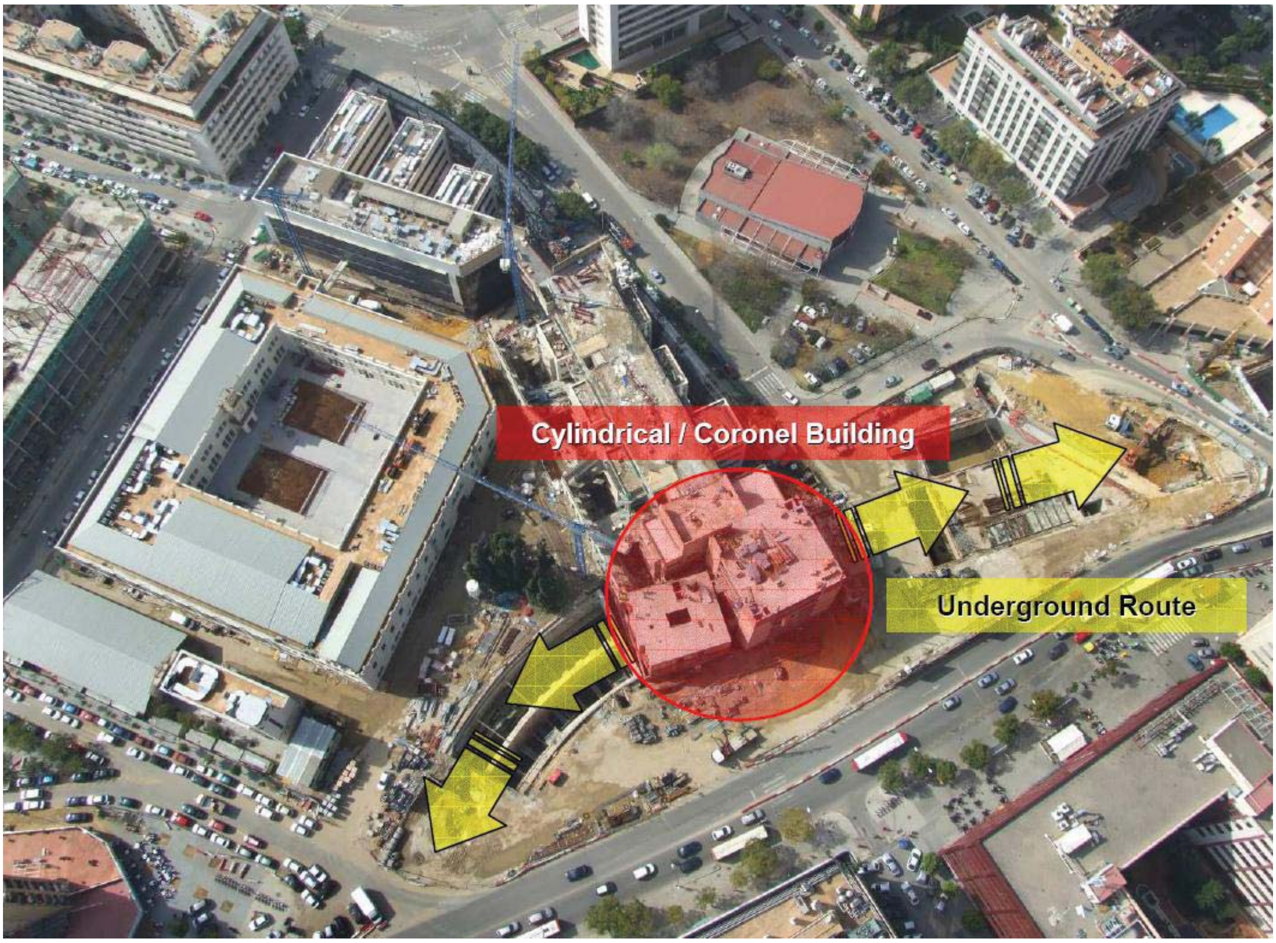


**Fig. (3).** Interference underground line 1 - cylindrical and colonel buildings.

The diversion of the underground route forced the technical office of the company builder of the new faculties to design a solution based on completely supporting the two affected buildings, by executing a double T-shaped beam structure, which would allow a maximum span of 26m to be bridged, and was supported on screens outside the underground tunnel (see Fig. **4**). The covered length reached 43.20m, and consisted of a stretch of 25.20m formed by 21 beams (I-200B120; h=2.0m), and a stretch of 18.0m formed by 15 beams (I-170B120; h = 1.70m), due to the difference in loads imposed by each of the buildings [13]. In both cases, the pre-stressed beams were projected in a double-T shape and were arranged in abutment in such a way that intermediate pre-slabs were rendered unnecessary and thereby the assembly was reinforced against the punching of the pillars of the buildings. Finally, on the double T-shaped pre-stressed beam structure, an upper slab of 60cm-thick reinforced concrete was available, which would act as the compressed head of the foundation assembly.

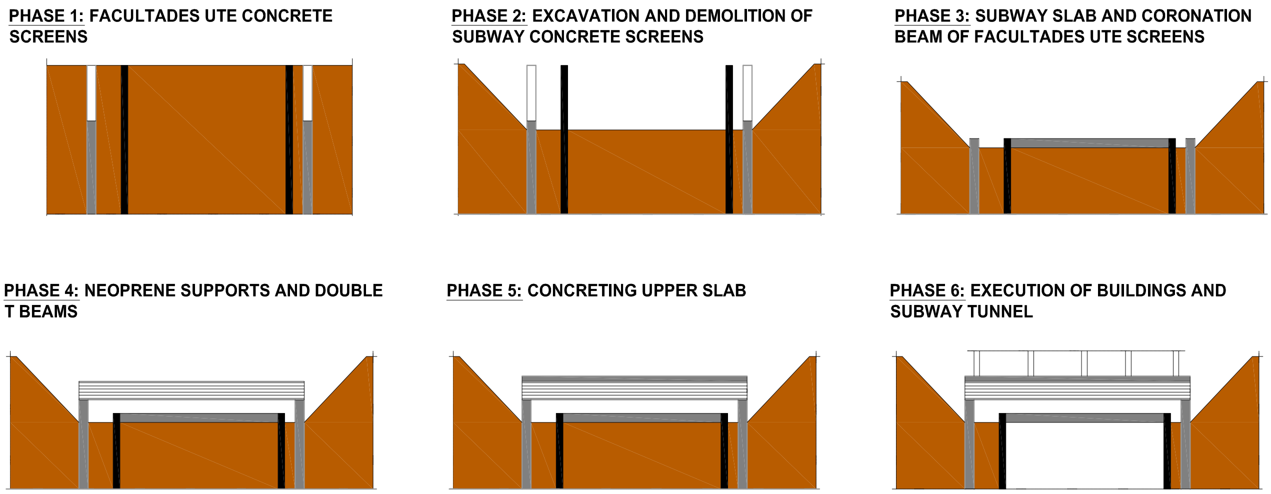


**Fig. (4).** Supported foundation solution.

The work began with the construction of the outer screen that served as a second support of the double T-shaped beam structure. Once UTE METRO SEVILLA, the construction company in charge of the work, had completed the slab of the underground tunnel, then work on the coronation beams of the support screens of the pre-stressed beams could be started. The screeds were implemented in non-shrink high-strength mortar as a levelling base for supporting devices, consisting of hooped neoprene. Regarding the lifting and placement of the beams, with their average length of 25.50 m, a 400-ton mobile crane was used, positioned on the slab of the underground tunnel, which lifted the beams, previously transported to the worksite by dolly-type trucks. These beams were then placed in their final position to perform the topographic checks for their alignment. By repeating these operations for all of the planned beams, and bracing them against overturning during the process, the foundation slab was formed (see Fig. **5**).

**Fig. (5).** Constructive process.

The subsequent tasks consisted of the reinforcement and concreting of the upper slab, taking the precaution of applying a Dywidag-type system of bars for the pillars of the buildings with threaded connection sleeves in order to avoid any problem during the dynamic load test.

One of the most important aspects of the foundation supported over the underground tunnel was that of the conception and subsequent development of the required load test to be carried out. Initially, given the special characteristics of the foundation, the "Recommendations on how to perform the load test for highway bridges" [14] was applied, which states that the load level reached during the load test should be representative of the service actions.

To this end, it is advisable that the requests of the real train loading be approximately 60% of the theoretical values produced by the train loading as defined in the instruction, thereby adopting the characteristic values without any increase. In this case, and given the characteristics of the actions to be considered, especially the loads transmitted by the pillars of the building, which, in certain cases, exceeded 300 tons, made it almost impossible to reproduce the state of charge closest to that of the recommendation in the instruction. It was therefore decided to carry out a static load test with the help of a "load train" simulated with 40-ton trucks on four hypothetical loads by combining their number and position, thereby reproducing an overload of between 17-39% depending on the design loads considered. This load was complemented with a dynamic load test that would ultimately obtain the fundamental frequency of the foundation vibration and hence enable its rigidity to be estimated for its later comparison with that obtained in the calculation model [15].

Regarding the instrumentation, on one hand the strain gauge rings were placed under the mid-span of all the beams of the foundation in order to register the mid-span deflection produced during the static load test, under the various load hypotheses included in the aforementioned test (see Fig. **6**).

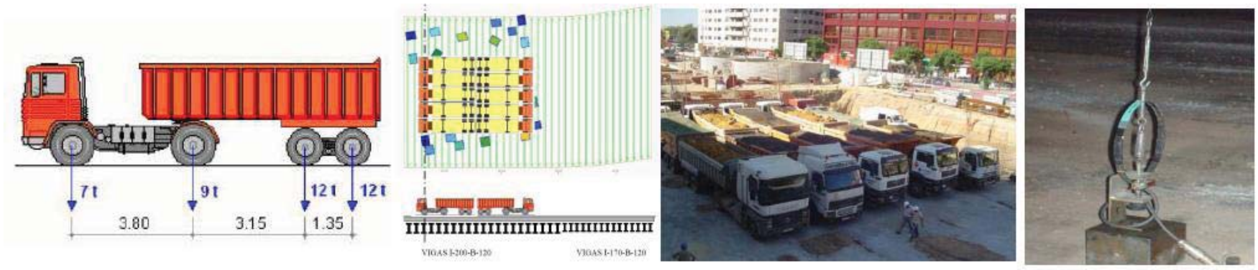


**Fig. (6).** Static load test.

On the other hand, two accelerometers were placed into two representative beams of each of the areas, in the Cylindrical Building (Beams 2.00 m) and the Coronel Buildings (1.70 m), in order to be able to register the vertical accelerations produced during the dynamic load test, consisting of the stimulation of the structure by means of moving a 40-ton truck on a RILEM plank placed on top of the foundation slab. With the registration of said vertical accelerations and by applying the appropriate mathematical treatment (in this case, the Fast Fourier Transform was used), we could attain the fundamental frequency of vibration of the foundation (see Fig. **7**).


**Fig. (7).** Dynamic load test.

Regarding the static, once the load test had been carried out, it was realized that the deflections obtained were acceptable: between 75% and 90% lower than the estimated deflections, and that the discharge recoveries were complete and instantaneous. However, as regards the dynamic load test, a fundamental frequency of vibration of 7.09 and 7.70 Hz was obtained, according to the two areas considered, mildly coincident with that estimated in the load test project as 6.54 Hz. According to these results, it was determined that the actual rigidity of the foundation was superior to the estimated rigidity [16], which means that the actual behaviour of the foundation was better, as it was more rigid, than that estimated in the load test developed. The final conclusion therefore was that the load test was developed in a completely satisfactory way, as the work of the foundation was essentially performed in an elastic regime.

**Step 2: Determination of Criteria and Obtaining Partial Results**

The ultimate objective of the implementation of the estimation of sustainability or environmental indicators included in the instruction is the comparison, in terms of sustainability, of various structural solutions for the same work or project, or the establishment of a quantitative parameter for the evaluation of the structure in relation to these environmental aspects. In general, a greater value for the purposes of establishing sustainability is established when, in the implementation or planning of a structure:

- The consumption and use of materials employed are optimized to the least quantity of materials (primarily concrete and steel according to the nature of the instruction).
- The useful life of the structure is extended, in such a way that a higher amortization of impacts is produced during execution.
- The use of raw materials from recycling processes (such as water, aggregates, and steel) is promoted and these are generally obtained through processes that incorporate raw materials that produce less $CO_2$ emissions into the atmosphere and require less energy, mainly through the use of primary fuels and waste recovery
- Environmental certification systems are implemented for all manufacturing processes of the products used, especially in the manufacture of concrete and the production of reinforcement (including the phase of transport to work); products in possession of officially recognized quality are employed that fulfil the basic requirements of structures; preventive criteria are implemented in addition to those requirements established; innovative approaches that increase productivity, competitiveness and efficiency during construction are applied and public access to such information is made available; and the potential impacts on the environment resulting from the construction process (noise, dust, vibrations ...) are minimized.

The contribution of the structure to sustainability is classified according to the levels listed below, where A is the highest end of the scale (maximum contribution to sustainability) and E is the minimum end of the scale (minimum contribution to sustainability):

Level A: $0.81 \leq \text{ICES} \leq 1.00$

Level B: $0.61 \leq \text{ICES} \leq 0.80$

Level C: $0.41 \leq \text{ICES} \leq 0.60$

Level D: $0.21 \leq \text{ICES} \leq 0.40$

Level E: $0.00 \leq \text{ICES} \leq 0.20$

From the general expression that allows ICES to be obtained, (ICES = a + b . ISMA), the following indices and coefficients can be derived:

- ISMA = Environmental Sensitivity Index
- a = Coefficient for Social Contribution
- b = Coefficient for the Extension of Useful Life

The "environmental sensitivity index" of a structure is defined as the result of applying the following expression:

$$\text{ISMA} = \sum_{i=1}^{i=11} \alpha_i . \beta_i . \gamma_i . V_i$$

where:

- $\alpha_i$, $\beta_i$ and $\gamma_i$: Weighting coefficients of each requirement, criterion or indicator.
- $V_i$: Value coefficients obtained for each criterion according to the following expression based on the representative parameter in each case:

$$V_i = K_i . \left[ 1 - e^{m_i \left( \frac{P_i}{n_i} \right)^{A_i}} \right]$$

where:

- $K_i$, $m_i$, $n_i$ and $A_i$: Parameters whose values depend on each indicator.
- $P_i$: Value taken by the representative function for each indicator.

A detailed description of the method in its entirety lies outside the scope of this article, and is well documented in the instruction itself. Facing its subsequent application to the particular case at hand, however, it is necessary to relate the environmental criteria taken into account to obtain ISMA, without going into the formulation proposal or representative functions. These criteria are:

- Environmental characteristics of concrete.
- Environmental characteristics of reinforcements.
- Optimization of reinforced elements.
- Environmental optimization of steel.
- Level of control of the building process.
- Use of recycled aggregates.
- Optimization of cement.
- Optimization of concrete.
- Specific measures for the control of impacts.
- Specific measures for waste management.
- Specific measures for water management.

It should be borne on mind that the methodology employed, as mentioned earlier, is based on the MIVES (Integrated Model Value for Sustainability Assessments) methodology, and constitutes a model based on value analysis and on the multi-attribute utility theory (freely distributed software tool) of help in all kinds of decision-making (not only that related to sustainability), such as project procurement, work-contract systems, and procurement of all types of products [17]. The multi-attribute utility theory of value analysis provides a framework through a process of prioritization, evaluation, valuation, weighting, and aggregation. The general process to follow for the application of this methodology can be considered as composed of the following elements:

- Identification and structuring of relevant indicators (requirement tree) to facilitate analysis and valuation. The requirements are more general, and are divided into criteria of a more specific nature, eventually splitting into even more specific sub-criteria, until ending up with quantifiable indicators (through measurable physical units).
- Assessment of the indicators through their transformation into a common unit of value.
- Weighting of the different levels of the requirement tree according to their importance.
- Evaluation of the alternatives and identification of the optimal alternative.

The value function transforms the indicator with physical units into common units (value), for whose definition it is necessary to establish the trend, the points of maximum and minimum satisfaction, its shape, and its mathematical expression. In MIVES, a mathematical expression is used that enables different forms to be reproduced depending on the parameters adopted. With regards to the weighting, the assignation of weights is carried out by means of direct scoring for very clear values, using the proportion method for the comparison of a spectrum or by using the methodology based on the Analytic Hierarchy Process (AHP) proposed by Saaty in 1980, which is based on the idea that the inherent complexity of a problem of decision-making with multiple criteria can be resolved by the creation of a hierarchy of the problems, and by allowing comparison in pairs the attainment of weights through the subjective comparison of each element with respect to the others. As a result, a quantifiable value is obtained for each alternative analysed.

Based on the above, the methodology grounded on the MIVES methodology assigns a value function for each of the environmental criteria (representative functions), by means of the application of percentages and coefficients of tabulated value according to the intrinsic characteristics of each criterion. Once the history of the foundation that forms the object of study was ascertained, as well as its type and conditions during the construction process, we proceeded to assess the sustainability of the foundation according to the methodology described in the Structural Concrete Instruction. As discussed earlier, the implementation of Annex 13 (EHE-2008) grants the agents the ability to quantify the contribution of structures to sustainability through the so-called Index of Structure Contribution to Sustainability (ICES). Note that this annex is not mandatory, which, together with other factors, but primarily the logical difficulties involved early in the application of new methodologies, cause the appearance of doubts, problems, and discrepancies in relation to its application. At the root of this issue, the Group of Engineering and Project Management (GRIDP) of the University of La Coruna, published, in Reports of Construction (a scientific quarterly publication belonging to the Technical Institute of Construction and Cement), an article called “Early estimation of the level of sustainability of concrete structures, within the framework of the Spanish Instruction EHE.08” [18], which supplemented the computer tool developed by the group and which strives towards:

- Provision of information that enables periodic estimates of ICES in early moments of the project to be carried out in order to facilitate the implementation of realistic and conservative estimates, thereby increasing the chances of meeting the sustainability objectives pursued.
- Avoidance of the high probability of failure due to the intrinsic characteristics of a project, and the promotion of the continuous management objective of sustainability throughout the project life cycle by performing periodic ICES estimates.
- Resolution of uncertainties related to the emergence of problems and doubts. These problems are raised, on one hand, in the attempts to estimate the ICES in early phases of the project, at the time of writing, and even in later stages during the construction process, and on the other hand, they arise in connection with the application or interpretation of the Annex.

The proposed method, as laid out in the Instruction, has been implemented, and is supported by the calculation tool developed by the Group of Engineering and Project Management (GRIDP) of the University of La Coruna (MIVES-EHE-08 V01), for which it has been necessary to take the special characteristics of the case study into account, whose parameters can be summarised as follows:

- Volumes used for pre-stressed concrete beams and top slab.
- Distance of transport from concrete manufacturer plants to worksite.
- Total Amounts of active reinforcement (pre-stressed beams) and passive reinforcement (top slab).
- Reinforcement Optimization Systems employed during construction Distinctions and certifications from suppliers of active and passive reinforcement.
- Verification of control conditions corresponding to intense level.
- Distinctions and certificates of manufacturers and types of cements used.
- Distinctions and certificates of manufacturers and types of concrete employed.
- Measures taken to minimize environmental impacts.
- Measures taken in waste management in the construction stage.
- Measures aimed at streamlining and at the proper management of water.

Partial results of the scores of each considered environmental criterion, and of criteria for social contribution and for the extension of useful life, and the values of the indicators obtained are shown below (see Table **1**):

**Table 1. Determination of criteria (Case Study).**

| Determination of Environmental Criteria | Criterion Score | Indicator Value |
|---|---|---|
| 1. Environmental Criterion of Concrete Characterization | 87.04 | 0.95 |
| 2. Environmental Criterion of Reinforcement Characterization | 72.96 | 0.80 |
| 3. Environmental Criterion of Reinforcement Optimization | 73.07 | 1.00 |
| 4. Environmental Criterion of Steel Optimization | 30.00 | 0.31 |
| 5. Environmental Criterion of Execution Control | 40.83 | 0.88 |
| 6. Environmental Criterion of Recycling of aggregates | 0.00 | 0.00 |
| 7. Environmental Criterion of Cement Optimization | 30.00 | 0.31 |
| 8. Environmental Criterion of Concrete Optimization | 0.00 | 0.00 |
| 9. Environmental Criterion of Impact Control | 40.00 | 0.41 |
| 10. Environmental Criterion of Waste Management | 25.00 | 0.21 |
| 11. Environmental Criterion of Waste Management | 40.00 | 0.22 |
| ISMA | 0.37 | |
| Determination of Social Contribution Criterion | a = | 0.00 |
| Determination of Useful Life Extension Contribution Criterion | b = | 1.00 |

## RESULTS

The results obtained after the application of the various criteria and weights included in Annex 13 (EHE-08) using the MIVES-EHE-08 V01 software tool are listed below (see Fig. **8**); during the application, a number of difficulties associated with the interpretation of the criteria in the methodology have arisen and errors found. It should be borne in mind that, in this issue, from the same Research Group, the author of the software tool initially developed a modified version of Annex 13 and has subsequently developed a modified version of the software tool, MIVES- EHE-08mod-V02, in order to solve these problems. However, this modified version has yet to be applied since it fails to correspond to the current tool that is derived from the content included in the aforementioned Annex of the Instruction.

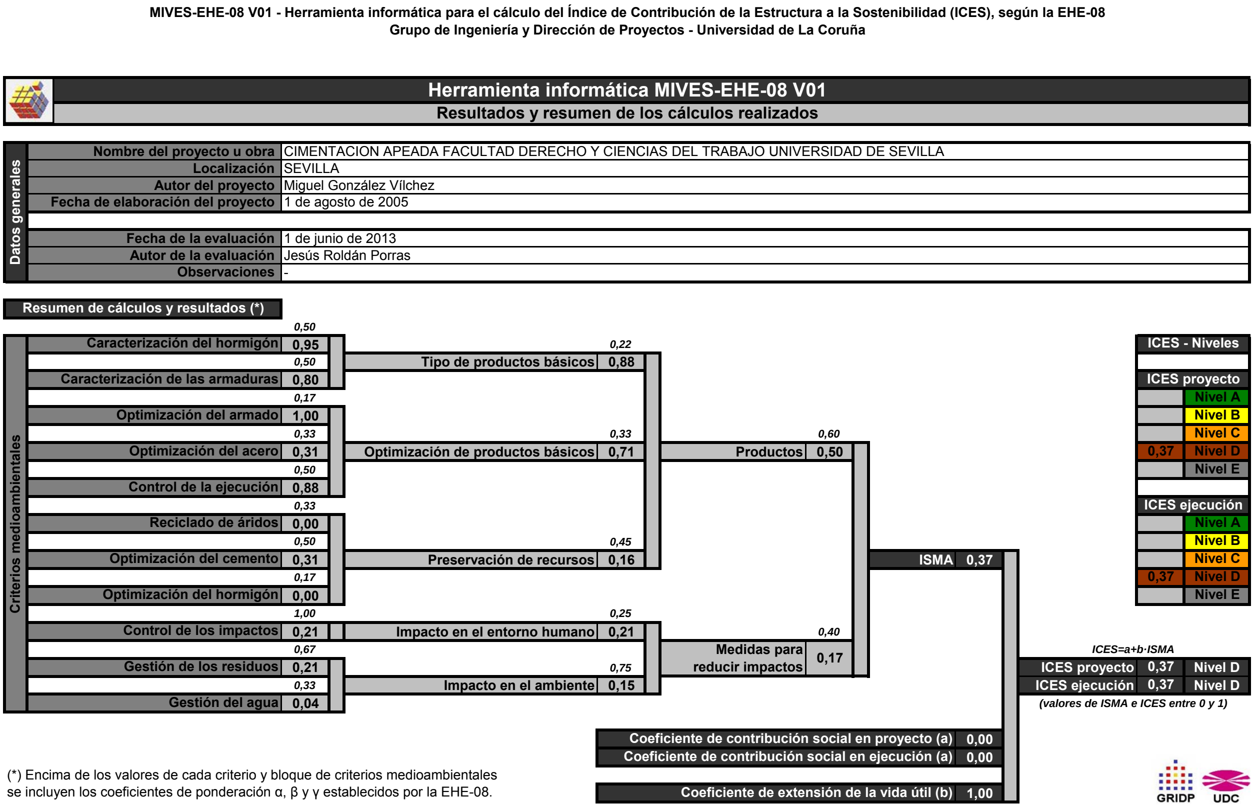


**Fig. (8).** Application of MIVES-EHE-08 V1. Results.

On finally obtaining the results, it can be observed that, according to the Contribution Index of Structure to Sustainability contained in Annex 13 (EHE-08), the supported foundation under study has obtained an $ICES_{execution}$ = 0.37 corresponding to Level D according to the classification contained therein. This corresponds to the second "less sustainable" level although it remains close level C, which is established as the intermediate reference level. It is, however, important to clarify that during the drafting and subsequent implementation of the project (between 2005 and 2008), the software tool contained in the current Instruction was not yet available, and hence there was no section that would determine the degree of contribution of the structure or foundation to sustainability. Simply having slightly improved the degree of social contribution (application of innovative methods, worker training, public information ...) would have helped achieve a sustainable level greater than by all the rest of the conditions.

It should be underlined that the application of the software tool allows a double entry of values, first to evaluate the contribution at the planning stage and secondly to assess work in progress. One advantage of the tool is that it provides a simple way to evaluate the way in which sensitivity triggered by various decisions on work in progress, unlike those within the planning stages of the project, may influence the calculation of the benchmarks both favourably and unfavourably. Also this tool allows us to establish, measures to lead towards improvements in the contribution of the structure during the execution by instantly assessing the impact of these measures, which may constitute a corporate competitive edge when tendering public contracts where control measures and environmental management play increasingly greater roles in bidding terms.

## DISCUSSION

Once the methodology available in the current regulations is applied, several considerations can be established that arise from the application of the methodology to the particular case of foundations, especially to the foundation of this analysis with its intrinsic singularities during its design and subsequent construction. In accordance with Step 3 contained in the methodology as outlined at the beginning of this article, the following can be highlighted:

## Constructive Process

It may seem obvious, but at no time has the constructive process been considered. It can be understood how, in most structures and foundations (within the scope of the Instruction), the constructive process presents major similarities, but this is not always the case. Differences in construction procedures can be highly significant: the structure or foundation may correspond to a civil construction (bridge, hydraulic work, maritime work, ...) or to edification, which in turn can greatly differ depending on whether it is a singular construction, conventional edification, or structural rehabilitation, whose differences are evident and specific in terms of the scope and degree of intervention.

These differences can lead to significant variances in the employment of labour (workers), and the use of auxiliary means (tower cranes, mobile cranes, machinery specialized in deep foundations, specific machinery for structural rehabilitation of underpinning foundations ...), from which, in turn, differences in consumption of energy (mainly electricity), fuel, water and, in some cases, runtime are derived. It is clear that a structure or foundation that requires fewer resources is more sustainable, as is clearly derived from the application of the methodology proposed by the Instruction which focuses on materials and application of the main materials, such as concrete and steel. However, all development focuses primarily on quantitative criteria in the case of volumes used (including transport distance) and qualitative criteria related to the environmental characterization of the manufacturing centres (including that of the construction company itself), intermediate processing installations, degree of recycling and reuse, optimization of reinforced concrete and of cement, monitoring of execution, control of impacts (related exclusively to dust production and tyre cleaning), waste management and water management (mainly by employing control and water-saving devices during the curing of concrete and at points of provisional consumption on the worksite). On an equal basis in the characterizations of supply companies, centres of production, and of construction companies with the same waste management plan and use of the same techniques of water management, it is evident that different constructive solutions might provide identical, or very similar, results on applying the methodology described. However, with the same indicator value, we could be faced with completely contrasting solutions from the point of view of the construction process, due to the energy consumption and the percentage of $CO_2$ emissions resulting from the use of completely different auxiliary machinery.

Taking the particular case under study as a basis, and with the logical proviso for the difference in volume (albeit insignificant), one solution based on trough beams would have significantly decreased the number of beams required for the formation of the board of the supported foundation, however two cranes would have been necessary for placement, and a greater number of workers would have been needed for local formwork and punching shear reinforcement inside the troughs in the areas of influence of the pillars of the buildings since this solution fails to the ensure adequate transmission of forces from the top slab to the wings of the troughs. Hence, very similar a priori solutions (even with similar values obtained in the index) present considerable differences in the number of workers and auxiliary means, therefore it would be necessary to quantify the energy and fuel consumption in order to determine which of these two contributes more towards sustainability.

## Runtime

Another aspect to be reviewed that takes advantage of the singularity of the foundation in question, and should make us reflect, is the concept of time. It may also seem obvious that the execution period of the structure alone is not indicative of its sustainability. However, and according to the previous reasoning in relation to the constructive processes, the factor of time holds a special relevance. Two solutions for comparison in terms of the auxiliary means and manual labour to be employed should incorporate the time of execution as an indispensable element in the quantification of energy consumption and $CO_2$ emissions into the atmosphere. For instance, according to the same example, the solution outlined above based on trough beams requires a larger number of cranes but requires less time for their placement (since considerably fewer beams are necessary) in comparison with the solution presented using pre-stressed double-T beams, which requires only a single mobile crane to mount a larger number of beams, and hence depends on the crane-usage time with a certain tonnage (and therefore with different fuel consumption and percentage of $CO_2$ emissions). The results can clearly differ from the point of view of sustainability. The same reasoning could be used in terms of the number of workers needed for formwork tasks and assembly of reinforcement, and usually in the execution phase, these factors can easily be determined a priori in accordance with the contractual requirements as given in the works programme. It seems also clear that the times of structural rehabilitation work can be very different in terms of the degree of intervention and the characteristics of the execution itself (such as type of foundation or structure to rehabilitate, necessary materials, and availability of space and access).

### Provisional Traffic Diversions

In relation to the duration of execution, another specific consideration to be taken into account, and is related to the temporary occupation of the land area, would be provisional traffic diversions. Paradoxically, this situation may stand for or against sustainability in the evaluation of a given execution. Note that for the execution of the supported foundation used herein as a reference, it was necessary to make a provisional traffic diversion in *Ramon y Cajal* avenue, Seville, which also served for the subsequent execution of the Cylindrical Building and Colonel House structures. A temporary diversion of traffic directly influences the fuel consumption and $CO_2$ emissions into the atmosphere of the vehicles affected. If we consider a given original route, then the provisional diversion of traffic needed for a given execution (foundation, structure, complete work ...) can be longer or shorter than the original route, depending on the environment and the conditions of the implementation. Any of a variety of conditions may force traffic to be provisionally diverted(temporary occupation for stockpiles, for special manoeuvres, for security reasons, etc.) depending on the action in question, but it seems that its importance is emphasized on construction worksites within urban centres, where again the time reacquires special significance, since the need (by the conditions of the work themselves) to maintain a provisional diversion for a longer period would, from the point of view of the contribution to sustainability (consumption fuel and $CO_2$ emissions), constitute a disadvantage in the event that such a diversion takes longer than the original route. It remains true that it would be essential to consider various subtleties among which the most influential being the percentage with respect to the Average Daily Intensity (ADI) of the original route that would use the provisional diversion. This factor would have to be calculated a priori and would need traffic counts of at least 24 hours (weekdays and holidays) before and after the commissioning of the provisional diversion in order to render it representative of the model to be used. The Average Daily Intensity (ADI), in units of vehicles/day, reflects the average number of vehicles passing through gauging stations grouped according to the type of vehicle: in light vehicles including motorcycles, passenger cars and commercial vehicles with loads lower than 1,000 kg; and heavy vehicles that include trucks with and without trailers, and buses. In the specific case of structural rehabilitation, it is very likely that this is the case in urban environments for which the need for provisional diversions for considerable periods of time can prove decisive in the choice of solution to be adopted.

### Emissions: Dust, Noise, and Vibration

In this case, in relation to the urban environment, three of the aspects that cause greater impact to citizens and the adjoining buildings are the generation of dust, noise, and vibration. The methodology included in the Instruction focuses exclusively on the emission of particles and dust generation, without taking into account the effect of noise and vibration, the latter especially noticeable in the case of the construction of foundations in urban environments. The complexity of objectifying the noise and vibration occurring in a particular building or in the foundation of a structure should be borne in mind. However, noise emission levels of the auxiliary machinery used could be considered (whose data is available in the majority of cases in the technical data files provided by their manufacturers) and also the use of quantification models based, in terms of the different levels of sound emission, on the largest energy consumption, which, in the hottest seasons of the year, may mean an increase in the use of air conditioning systems due to the prospective attitude of the owners of the surrounding houses to keep the windows closed for longer in order to mitigate the effect of the noise.

### Load Test

Finally, the case study shows the singularity of performing a load test on the foundation of a building, despite its implementation being mandatory in the construction of road bridges in Spain. In the case of foundations, the assessment of auxiliary means (loaded trucks and materials that constitute the load specified in the specifications of the load test) and the staff to carry out the test, can and should constitute an additional factor for assessment as regards the consumption of fuel and energy that will affect the contribution to the sustainability of a given option. It is therefore of interest to assess the possibilities offered by current technology for the execution of load tests, since fewer auxiliary means may be required and sustainable alternatives can be considered in order to reproduce the load fraction with reusable materials, thereby minimizing transport times and distances.

### Alternatives for the Evaluation of Aspects Not Covered in Singular Structures and in Cases of Structural Rehabilitation

For the evaluation of aspects not covered by the methodology analysed, there are several alternatives. First, the development or expansion of the methodology contained in the Instruction following the fundamentals of the multi-attribute theory and the value function. This method, however, would suppose partly reduced access to the intervening agents since this tool is not a formal part of Instruction. Furthermore, a subjective component that always exists when choosing the value function and assigning weights is again unavoidably incorporated. It should be borne in mind that, at this level of scale, the breakdown of the constructive processes enables us to identify the human resources, auxiliary means, and execution times required for each of the alternatives evaluated, and hence it seems more appropriate to perform the evaluation by means of quantitative indicators that allow energy, fuel and $CO_2$ emissions into the atmosphere to be considered.

In recent years, several studies have been developed at the University of Seville, related to the quantification of the resources consumed and of $CO_2$ emissions [19], and to the assessment of the ecological footprint in the sector of construction in Andalusia [20]. In such work, tools are presented that could be applied for the objective quantification of those aspects that the methodology described fails to take into account.. It would, however be necessary to integrate the construction process and its derived peculiarities (including temporary detour traffic, load testing, noise and vibration) into a disaggregated model, so that it could easily employed as a tool complementary to the application of the methodology proposed in the Instruction and would serve as a key element in decision-making, primarily in cases where, for different solutions, similar levels of the sustainability contribution index are obtained.

## CONCLUSION

The existence of a tool, in the Spanish legislation, that enables intervening agents to assess sustainability at the design stage and in the implementation phase simply and effectively represents a major qualitative leap forward, both nationally and in comparison with regulations of other countries. However, the complexity of standardizing the conditions that affect the execution of each structure, whether they be heterogeneous or variable in nature, so that the contribution to sustainability of any structure can be evaluated within the same frame of reference imposes the greatest obstacle and can exert major influence on the representativeness of the results.

The fundamentals of the methodology used and of current tools based on value analysis and multi-attribute utility theory generally tend towards aggregation to facilitate the framework for comparison between different solutions, thereby allowing selection criteria to be established that are relatively easy to apply at the design and execution stages of structures. In keeping with all tools based on this methodology, it has its own limitations, many of which could be resolved through the incorporation of new criteria and new value functions that permit the evaluation of those aspects not therein considered, but that with the passage of time and with experience in their application will certainly be incorporated to a greater or lesser extent in future revisions of the Instruction. However, for each particular case, the generation of a specific model that incorporates all the differential aspects to be considered may prove to be largely ineffective from the point of view of its usefulness for all agents involved. Clearly, a bespoke model in accordance with the intrinsic characteristics of a particular project may be the best assessment tool for this case, but it would hardly establish a useful comparative framework for the remaining cases.

On the other hand, from the field of structures in general and of foundations and structural rehabilitation in particular, the factor of scale plays a predominant role. The most significant limitations arising from the methodology of the Instruction are derived from the lack of consideration of the stages of the construction process already carried out, where human resources, auxiliary means required for execution, and the time factor are decisive in the amount of energy and fuel consumed and therefore in the level of $CO_2$ emissions released into the atmosphere. Equally, certain situations exist that either due to their own singularity, as in the case of the test loads, or to the complexity in the quantification of the impacts, as with noise and vibrations, they are not taken into account in the methodology included in the regulations.

It appears logical that the tools currently available should be used for the assessment of the contribution of structures to sustainability since they suppose the basis for a homogeneous comparison between the various agents involved. However, as has been shown in this article, these must be complemented by other tools based on the breakdown of the construction process and determination of quantitative indicators (such as energy consumption, fuel consumption, $CO_2$ emissions, and ecological footprint), in order to make a comparison between various solutions (including those with similar contribution indices) with a greater degree of representativeness of their results.

It is important to bear in mind that models based on value functions inherently lead to an implicit subjectivity in the methodology itself by allocating the type of value function and assigned weights, and hence, depending on the hierarchization carried out and the allocation made, the results can differ greatly. Therefore, before resorting to the addition of developments and improvements of the method contained in the Instruction that would fail to be generally applicable to the remaining agents due to being excluded from those officially collected in the Instruction, this paper proposes the complementarily use of disaggregated models and quantitative indicators, which largely limit the subjective component in the selection of alternatives, for the assessment of the contribution of sustainability in the particular case of structures, foundations and structural rehabilitation in urban environments.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

## ACKNOWLEDGEMENTS

Declared none.

## REFERENCES

[1] X.R. Ramon, "*Estudio de la aplicabilidad de materiales compuestos en la construcción de edificios industriales*", 2015. Available at: http://hdl.handle.net/10803/6162

[2] "Informe sectorial de la economía española. Sector construcción", *CESCE (Compañía Española de Seguros de Crédito a la Exportación), Velázquez 74, Madrid,* 2015, pp. 12-13. Available at: http://www.saladeprensacesce.com/informe-sectorial-2015/sectores/sector1/

[3] F.F. Latorre, "Capítulo 4", In: A. Consejería de Medio, Ed., *Indicadores De Sostenibilidad y Medioambiente: Métodos y Escala.,* Junta de Andalucía, Egondi Artes Gráficas S.A., 2011, pp. 65-71.

[4] M.J. Marcilla del Valle, "Aproximación cuantitativa a la evaluación de la sostenibilidad de las estructuras", *Trabajo Fin de Master: Universidad Politécnica de Madrid,* 2012. Available at: http://oa.upm.es/12666/2/Tesis_master_Miguel_Garces_de_Marcilla_del_Valle.pdf

[5] F. Molina-Moreno, and V. Yepes, "Análisis comparativo de la valoración propuesta por herramientas de evaluación de sostenibilidad en edificación", In: *6th European Conference on Energy Efficiency and Sustainability in Architecture and Planning,* Donostia-San Sebastián, 2015, pp. 143-148.

[6] S. Sattary, A. Kumar, and D. Hood, "Existing infrastructure tools", *Queensland university of technology, Brisbane (Australia),* 2011. Available at: https://www.researchgate.net/publication/262488166_EXISTING_INFRASTRUCTURE_TOOLS

[7] Ministerio de la Presidencia, *Real Decreto 1247/2008, de 18 de julio, por el que se aprueba la instrucción de hormigón estructural (EHE-08).,* BOE: Madrid, 2008.

[8] Project Engineering and Management Group, "Software MIVES-EHE-08-V01, for sustainability assessment in the design of concrete structures, according to the EHE-08 Spanish Code", *Universidad da Coruña..* (in Spanish) Available at: http://www.ii.udc.es/GRIDP/castellano/software.html

[9] Ministerio de la Presidencia, *Real Decreto 751/2011, De 27 De Mayo, Por El Que Se Aprueba La Instrucción De Acero Estructural (EAE).,* BOE: Madrid, 2011.

[10] P. Mercader-Moyano, A. Ramirez de Arellano, and M. Olivares, "Calculation methodology to quantify and classify construction waste", *The Open Construction and Building Technology Journal,* vol. 5, Suppl. 2-M3, pp. 131-140, 2011.

[11] M.G. Vílchez, *Proyecto Modificado Para La Construcción De La Facultad De Derecho y La Facultad De Ciencias Del Trabajo de la Universidad de Sevilla en parcelas SIPS del PERI-SU-2 Pirotecnia-Cross de Sevilla. Interferencia Con La Ejecución De La Línea 1 Del METRO SEVILLA, Project,,* University of Seville, Seville, 2007.

[12] M.G. Vílchez, *Proyecto De Ejecución Para La Construcción De La Facultad De Derecho y La Facultad De Ciencias Del Trabajo De La Universidad De Sevilla En Parcelas SIPS Del PERI-SU-2 Pirotecnia-Cross De Sevilla, Project,,* University of Seville, Seville, 2005.

[13] C.B. García, *"Memoria De Cálculo Cimentación Apeada Sobre Túnel Del METRO SEVILLA", Calculations Report. PRECON, Seville,* PRECON: Seville, 2007.

[14] *Recomendaciones Para La Realización De Pruebas De Carga De Recepción En Puentes De Carretera, Dirección General De Carreteras (Ministerio de Fomento),,* Centro De Publicaciones, Madrid, 1999.

[15] S.D. Sánchez-Toscano, "Proyecto de Prueba de Carga de la Cimentación de dos edificios sobre el Túnel del METRO SEVILLA", *Load test Project, INTEMAC, Madrid, I/OC-07023/CE-A,* 2007.

[16] J.F. Ordoñez, "*Informe de resultados de las pruebas de carga estáticas y dinámicas realizadas sobre la cimentación de dos edificios a construir sobre el Túnel del METRO SEVILLA*", *Results report,* INTEMAC, Madrid, E/LC-07013/AU, 2007.

[17] A. Josa, "Introducción a MIVES y el análisis multicriterio", In: *Jornada sobre la Importancia de un método para la toma de decisiones: modelo MIVES para una ingeniería sostenible.,* Bilbao, 2012.

[18] D. Gómez-López, A. del Caño, and M.P. de la Cruz, "Early estimation of the sustainability level of concrete structures, in the framework of the EHE-08 spanish code", *Informes de la Construcción,* vol. 65, no. 529, pp. 65-76, 2013.

[19] P. Mercader-Moyano, *Cuantificación de los recursos consumidos y emisiones de $CO_2$ producidas en las construcciones de Andalucía y sus implicaciones en el protocolo de Kioto.* In: PhD Thesis, Department of Building Construction I. University of Seville: Seville, 2010.

[20] J.S. Guzmán, *Evaluación de la huella ecológica del sector edificación (uso residencial) en la comunidad andaluza.* PhD Thesis. Department of Building Construction II. University of Seville: Seville, 2010.