MULTI-CRITERIA DECISION MAKING APPLIED TO ENGINEERING EDUCATION. ECONOMIC-ENVIRONMENTAL SUSTAINABILITY IN THE STRUCTURE OF SINGLE-FAMILY HOMES

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Abstract

This paper is based on the contents of the postgraduate course "Prediction and optimization models of concrete structures", taught in the Master of Concrete Engineering at the Polytechnic University of Valencia, in which civil engineering students are taught the various techniques of multi-criteria assessment, with a sustainable approach, applied to the optimal design of structures. This allows the student to compare complex aspects with generally contradictory objectives that characterize sustainability under criteria of economic, environmental and social efficiency, among others. Construction companies usually focus on cost optimization during the construction stage of structures that are currently not sufficient to meet the growing social demands of the 21st century world, needing to balance the criteria that support sustainability. The construction sector represents a relevant percentage of the total CO_2 emissions, being responsible for a great part of the environmental impacts, which is enough reason for the European Union policies to be more and more oriented to the reduction of these emissions. This document presents a case study on a research being carried out by the faculty and students who are part of the research team, comparing two different construction alternatives, namely "traditional" in-situ concrete versus "prefabricated" with blocks and plates of Ytong. The aim is to find the structural optimum of an urban single-family house from the economic and environmental point of view throughout its life cycle. The objective is to find the structural optimum of an urban single-family house from the economic and environmental point of view throughout its life cycle. An analysis of indicators including the production phase, construction, the use and maintenance stage and the end of life has been carried out. The environmental impacts throughout the life cycle of the alternatives have been evaluated on the basis of the Ecoinvent 3.3 environmental database, using the ReCiPe impact assessment methodology. Finally, to evaluate the different alternatives, we have applied the multiple attribute method TOPSIS, based on distance to establish the order of preference by similarity with the ideal solution. Our findings show that the most economical solution in each phase is not the most environmentally efficient. For sustainability-based decision making that does not lead to erroneous results a balance must be sought between all dimensions, including not only monetary aspects in the structure design process.

Keywords: Postgraduate education, multi-criteria decision-making, ReCiPe, Life cycle assessment, Sustainable criteria, single-family housing.

1 INTRODUCTION

1.1 Postgraduate civil engineering studies

The creation of the European Higher Education Area (EHEA), better known as the Bologna Process [1], has constituted a reform of the Higher Education systems in 29 EU countries. The integration into the Spanish educational system has meant a regulatory effort and adaptation by universities and higher education institutions, passing all previous diploma and degree titles to a single title, the Bachelor's degree, which qualifies for access to the labor market. It also appears as a new official title, the master's degree, which previously did not exist in public universities. This development in the knowledge society has given rise to a new philosophy in curricula, with profound changes affecting teaching methodologies [2], the structure of teaching, the guarantee of learning processes, student mobility, and the coordination of teaching staff.

In this new perspective, the student's role is modified and takes on a special meaning; first, because he himself should be the motor that generates his learning and, second, because not only will he learn within the higher institutions, but any situation and educational experience can bring him closer to knowledge throughout his life. The teacher must also adapt to a major reform [3] by transmitting not only a series of contents but also an approach that allows the student to open up to a broader professional future. To this end, coordinated teaching, with a greater practical focus and with a diversity of teachers to which the Spanish educational system has perhaps not always been accustomed, will be fundamental.

In the construction sector, most employers seek professionals with training in management skills [4, 5]. However, most university curricula related to technical degrees are concentrated in conventional construction programs, leaving little room for appropriate management courses. This is fortunately changing towards competency-based learning, which is presented as an end to be achieved by the student in his or her university phase. The Master's Degree in Concrete Engineering at the Universidad Politécnica de Valencia (UPV), awarded with the EUR-ACE international seal of excellence, may be a good example of how these studies widely meet the professional requirements that facilitate employability [6] in architecture and engineering.

In recent years, efforts have been made to incorporate sustainable design concepts into the curricula of civil engineering universities. In fact, in the master's program the academic content is largely the result of the research work of academics. In the Department of Construction Engineering of the UPV several researches have already been carried out related to the most updated techniques of multi-criteria decision [7, 8] as well as heuristic optimization applied to concrete structures [9-11]. In the context of sustainable design, the research team has also carried out other studies for the optimization of bridge design based on incorporated energy [12] or greenhouse gas emissions derived from construction [13]. Also, life cycle assessments have been applied to the sustainable design of concrete bridges [14, 15] and in practical examples of retaining walls [16] or railroads [17]. All these studies are framed within the subjects "Prediction and optimization models of concrete structures" and "Concrete and sustainability" belonging to the Master of Concrete Engineering of the UPV, acquiring transversal competences of the combination between the different subjects.

The main objective of this document is to present the content with some of the concepts taught in both subjects. Under this scenario, students have made an application of the MCDM to the sustainable design of the structural envelope for a single-family house under an economic and environmental perspective. In addition, this case study integrates environmental indicators as another learning object, whose impacts are obtained through the methodology of Life Cycle Analysis [18, 19], using the tools and resources described in the methodology of Section 2.

1.2 Background of the MCDM in building structures

Almost half of the materials extracted each year in the world are used in the construction sector, and it is predicted that by 2,060 the equivalent of the city of Paris will be built weekly worldwide [20]. If this urbanization trend continues, it is estimated that global material consumption will grow by about 90 billion tons by 2,050 (in 2010 it was 40 billion tons), exceeding the levels that the planet can provide in a sustainable way. With this trend, by 2,050 CO_2 emissions from construction will be responsible for almost half of the emissions from the construction of new buildings, compared to 28% today. With this scenario, it is clear that we can not only count on renewable energy and energy efficiency, but we must also dramatically change the way we design and construct buildings and infrastructure.

The methods promoted by construction companies are usually focused on optimizing the economic aspects [21]. Meanwhile, public administrations or non-governmental organizations tend to reinforce environmental aspects. In other cases, a natural resource can have a vital impact on the productivity and wealth of a country, as in the case of the Beaches in Spain [22] where the environmental and economic perspective cannot be dissociated. In sectors such as transport, are the second source of emissions of greenhouse gases (GHG) worldwide, so we cannot ignore the environmental requirements against technical and economic [23]. Civil engineering studies have traditionally focused on the resistance and durability of structures, orienting the capacities of their students towards budgetary containment. In the case of architectural studies, the objectives have been marked by the search for spatial design and functionality, leaving economic control behind. The needs that have recently emerged in the society of the 21st century demand a change of paradigm where the interests in the education of the next technicians converge. Technology and sustainability will mark future intelligent cities with better infrastructure and advanced connections for the sustainable development of its three pillars: economic, environmental and social.

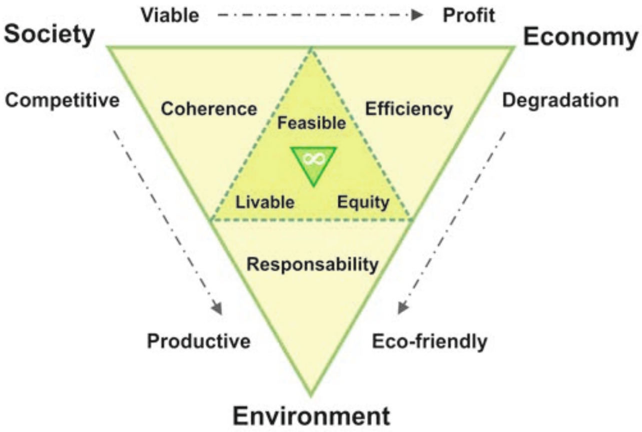


Figure 1. Dimensions of sustainable development

Therefore, design is of utmost importance when it comes to construction or infrastructure projects, since both aim at structuring cities and territories that will serve a significant group of the population for several generations. The sustainable design and management of structures are complex problems involving multiple criteria that often conflict with each other. Multi-Criteria Decision-Making Methods (MCDM) is a process that allows a solution to be selected from a set of options based on multiple criteria. Decision-making techniques provide a rational procedure for decisions based on certain information, experience, and judgment. These techniques can be classified according to the way the decision maker articulates his or her preferences. Multi-attribute decision-making methods (MADM) are used to solve discrete problems, being an "a priori" process, in which experts assign the weights of each criterion in the initial stage. Multi-objective decision methods (MODM) are used to solve continuous problems, being an "a posteriori" process in which no prior definition of preferences is required.

In the existing literature, different MADM methodologies have been used to assess sustainability. Among the best known [24] are SAW (Simple additive weighting) TOPSIS (Preference order technique for similarity to the ideal solution), VIKOR (Multi-criteria compromise and optimization solution), AHP (Analytical hierarchy process), PROMETHEE (Preference ranking organization method for enrichment assessments) or ELECTRE (Elimination and choice expressing reality). In this document the TOPSIS method is used, which, after the SAW, is the second most used technique to deal with MADM problems [25] and more robust than the VIKOR.

2 METHODOLOGY

2.1 Overall description of the courses

The course "Predictive and Optimization Models of Concrete Structures" enables students to understand the different predictive methods and optimization procedures of concrete structures providing them with the necessary tools for decision making in the field of project and construction of these typologies, considering the aspects of economic, social and environmental sustainability. This document focuses on the fourth thematic block of the course related to multi-criteria decision making. The students are explained how, before carrying out a multi-objective optimization, it is necessary to select the best structural typology based on criteria that are not always objective: economy, term, aesthetics, environment, social aspects or durability. The different MCDM techniques are introduced and their use is discussed, even for obtaining objective weights of criteria that can even be subjective, or for the selection of the best option within a Pareto border after a multi-objective optimization. From here, research projects such as BRIDLIFE (BIA2014-56574-R) have been derived, related to the decision making in the management of the life cycle of prestressed bridges of high social and environmental efficiency under restrictive budgets [8-11].

On the other hand, in the subject "Concrete and Sustainability", students are taught the application of sustainability indicators, such as the ecological footprint and the carbon footprint to concrete works, as well as in the methodology of the Life Cycle Analysis of the materials involved in the whole construction process. All of this is aimed at serving as another tool to calibrate the decision-making models in the search for eco-efficiency in concrete works. In this particular the lecturers show a wide experience based on the lines of research carried out in recent years [7, 13, 14]. Nowadays, environmental management is a fundamental aspect to be considered in any human activity, and of course in the field of construction, since this sector is one of the ones that has the most impact on the environment. It is necessary to go beyond energy efficiency, starting the path towards a circular economy, embedded energy, materials, waste and resource management, the water cycle, repair, recyclability and the correct management of the process from its beginning to the end of the useful life of the structure in question. In short, the idea is to incorporate the principles of sustainability and respect for the environment as basic objectives of any work projected with concrete.

2.2 Multi-Criteria analysis to support sustainable Decision-Making in the built environment

A multi-criteria decision problem is formed by a set of finite alternatives $A= \{A_i \mid i= 1,2,...,m\}$, m being the number of alternatives. These alternatives are evaluated according to established criteria, represented by $C= \{C_j \mid j = 1, 2,...,n\}$, where n is the number of criteria. The criteria can have different domains, be contradictory depending on whether the objective is to minimize (cost) or maximize (benefit). Some criteria may be more relevant than others, so that each one must be assigned a weight that weighs its importance, $W= \{w_j \mid j=1,2,...,n\}$. The weights should be standardized so that the sum is equal to one. The decision matrix (M^{mxn}) is composed with all this information.

Conceptually, an MDMC starts by taking the decision matrix and the weight vector as input data. Then, the method proceeds to the evaluation of the alternatives. Depending on the type of evaluation, the method returns as a final result a value to each alternative with which the preference ranking is ordered. This basic procedure is illustrated in Fig. 2.

Figure 2. Process of a multi-criteria decision method

2.2.1 Criteria tree and subjective weighting

In this MCDM assessment, seven different impact categories are considered as decision criteria belonging to the economic and environmental dimension. The 7 designated criteria lead to 11 sub-criteria and these finally to 25 indicators, which are the only concepts in the tree that are evaluated through qualitative or quantitative variables with different units and scales. In this work the criteria tree was defined through seminars of six experts, which according to some authors [26], is the number necessary to stabilize the AHP matrix with credible and reliable results. The participants were selected according to the background and experience of at least 5 years in the field of architecture, civil engineering or construction engineering. All of them are currently working in Spain on a freelance basis or in construction companies.

Weighting is a key step in the decision-making process, which in this case has been done by comparing the different criteria in pairs using the mathematical theory called Hierarchical Analytical Process -AHP- [27] according to a scale proposed by Saaty (1980). In order to do so, the decision-maker must indicate which of the two criteria compared is more important and how much more important it is by means of linguistic responses associated with numerical values. A matrix of comparisons is then formed, from which the weights of the criteria are obtained by means of estimation methods such as the main autovector.

Table 1 summarizes the decision criteria assumed here, as well as the local and global weights representing the relative importance of the criteria, sub-criteria, and indicators.

Table 1. Deployment of the criteria tree and weights (local and global)

Criteria (C)[1]		***Sub-criteria (G)***		***Indicators (I)***		***Global weights***
Construction cost **[28.42%]** [2]	**C1**	Materialization	G1 (50%)	Construction cost-bill of quantities (€/m^2)	I1 (100%)	**14.21%**
		Waste management	G2 (50%)	Transport of the land by truck (€/m^2)	I2 (25%)	**3.55%**
				Landfill fee to authorized manager (€/m^2)	I3 (25%)	**3.55%**
				Transport of inert waste by truck (€/m^2)	I4 (25%)	**3.55%**
				Fee for delivery of inert waste (€/m^2)	I5 (25%)	**3.55%**
Service life cost **[9.63%]** [2]	**C2**	Prevention	G3 (50%)	Corrosion protection (€/m^2)	I6 (20%)	**0.96%**
				Prevention of carbonation (€/m^2)	I7 (20%)	**0.96%**
				Water-repellent for concrete (€/m^2)	I8 (20%)	**0.96%**
				Facade waterproofing (€/m^2)	I9 (20%)	**0.96%**
				Protection against fire (€/m^2)	I10 (20%)	**0.96%**
		Use and maintenance	G4 (50%)	Maintenance (€/m^2 first 10 years)	I11 (100%)	**4.82%**
End-of-life cost **[4.85%]** [2]	**C3**	Demolitions	G5 (33.3%)	Full building demolition (€/m^2)	I12 (100%)	**1.62%**
		Pre-treatment of waste	G6 (33.3%)	Classification of CDW generated (€/m^2)	I13 (33.3%)	**0.54%**
				Shredding of non-stone waste (€/m^2)	I14 (33.3%)	**0.54%**
				Crushing of stone residues (€/m^2)	I15 (33.3%)	**0.54%**
		Inert waste management	G7 (33.3%)	Transport of inert waste by truck (€/m^2)	I16 (50%)	**0.81%**
				Fee for delivery of inert waste (€/m^2)	I17 (50%)	**0.81%**
Recycling (construction) **[8.52%]** [2]	**C4**	Management of construction waste	G8 (100%)	Use of recycled materials (%)	I18 (100%)	**8.52%**
Recycling (demolition) **[10.36%]** [2]	**C5**	Management of demolition waste	G9 (100%)	Reintegrability of materials (%)	I19 (100%)	**10.36%**
Impacts (Construction) **[13.29%]** [2]	**C6**	Endpoint scores (Construction)	G10 (100%)	Ecosystem quality (Construction) (Points)	I20 (33.3%)	**4.43%**
				Human health (Construction) (Points)	I21 (33.3%)	**4.43%**
				Resources (Construction) (Points)	I22 (33.3%)	**4.43%**
Impacts (OEL) **[24.93%]** [2]	**C7**	Endpoint scores (Construction)	G11 (100%)	Ecosystem quality (Construction) (Points)	I23 (33.3%)	**8.31%**
				Human health (Construction) (Points)	I24 (33.3%)	**8.31%**
				Resources (Construction) (Points)	I25 (33.3%)	**8.31%**

[1] *Fields of sustainability: Economy (C1, C2, C3); Environment (C4, C5, C6, C7)*

[2] *The criteria weights are in percent in brackets, calculated by the AHP hierarchical analysis process (Section 2.2.1)*

2.2.2 Impact assessment

The proposal for sustainable optimization in single-family housing structures is based on the evaluation of the life cycle impacts resulting from the different construction activities carried out during the building phases (materialization) and the demolition stage (end of life) of each structure. The evaluation of the impacts follows the four main steps suggested in the methodology proposed in the ISO 14040 standard for life cycle assessment (LCA), namely the definition of the objective and scope, the description of the inventory, the analysis of the impacts and the interpretation of the results. This document focuses on economic and environmental analysis. Generally, the most used criteria for the environmental impact assessment of a product or process are CO_2 and energy, although some authors [28] prefer to give a much more complete environmental profile. In our case, the evaluation of the environmental impacts of the life cycle follows the methodology of ReCiPe 2016 [29]. This method allows converting 18 mid-point indicators into 3 end-point indicators, namely, damage to human health, depletion of natural resources and damage to ecosystems. This method has been widely used in the existing literature [14-17]. With regard to economic impacts, there are no evaluation phases as such, since all impacts are expressed in the same unit of measurement and there is no standardization of the inventory data, defining the economic pillar as the sum of the cost of the different phases of the life cycle.

2.2.3 Multi-attribute decision-making procedure

Finally, the sustainability indicator for each alternative is obtained by applying the MCDM technique, taking into consideration the weightings of the seven criteria evaluated. Among the different MADM techniques [24], one of the distance-based methods has been chosen for this problem, whose basic principle is to calculate the distance between each alternative and a specific point. VIKOR takes into account the distance to the ideal solution and TOPSIS [25], which is used in this work, considers both the distance to the ideal solution and the non-ideal solution.

The basic principle in the TOPSIS method consists of looking for the solution that is closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS). The PIS of each criterion will be the maximum if you want to maximize the criterion and the minimum if you want to minimize the criterion, and the NIS will be the minimum if you want to maximize the criterion and the maximum if you want to minimize the criterion. Firstly, each score (r_{ij}) of the criteria of each alternative is normalized (r_{ij}') in the following way:

$$.r'_{ij} = r_{ij} \Big/ \sqrt{\sum_{j=1}^{m} r_{ij}^{2}} \tag{1}$$

Each of these values is multiplied by the corresponding relative weight (w_i) so that the normalized value (v_{ij}) is obtained multiplied by the relative weight. Then, the Euclidean distance (through the metric L_2) to the PIS (D_j*) and NIS (Dj-) of each alternative is obtained so that:

$$D_j^{*} = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^{*}\right)^{2}} \tag{2}$$

$$D_j^{-} = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^{-}\right)^{2}} \tag{3}$$

Finally, the relative distance to the ideal of each alternative j is calculated and classified, choosing the alternative that has the least distance to SIP and the furthest from NIS, i.e., the alternative with the highest score will be better.

$$C_j^{*} = D_j^{-} / D_j^{*} + D_j^{-} \tag{4}$$

3 CASE STUDY

3.1 Problem definition

In order to make concrete the abstract approach exposed before, a case study is presented, which is part of the assignment as a consultancy to study eco-efficient alternatives to the design of a conventional in situ concrete structure for a single-family dwelling among party walls. The plot is located in the town of Jaén (Spain), has a single access from street level (±0.00) and with a rectangular plot dimension of 6.20 m wide by 20.00 m deep. The house (B+1), consists of floor basement with use for garage (-1.30), first floor with living room, kitchen and toilet (+1.50), second floor with 3 bedrooms, bathroom and toilet (+4.40), second floor with terrace and pool (+7.40) and a small covered tower (+11.00). According to the geotechnical study, the land is very unfavorable, with a low bearing capacity, medium-high expansion and made up of marl with gypsum that presents strong chemical aggressiveness (Q_c) due to its sulfate content. In addition to the environmental aspects required, as it was a self-promotion of a habitual residence, a decisive condition was the budget limit. The study focused on the evaluation of the foundation, structure and the thermal envelope, which are the chapters of the construction budget with the greatest impact at all levels. In addition, we have considered it interesting to include the walls of facades and party walls in order to be able to compare later when the resistant support acts as an enclosure at the same time.

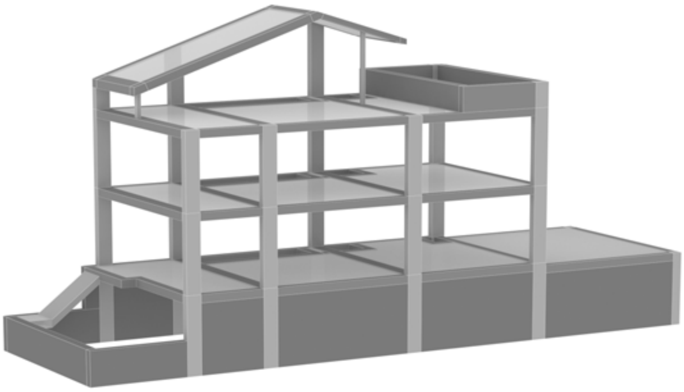


Figure 3. Model of the "traditional" structure for the single-family house

3.2 Features of the alternatives

To answer this problem, two designs have been proposed for comparison: a traditional solution (reference "A") and a prefabricated solution (alternative "B"). Table 2 describes these construction options for each of the components studied.

Table 2. Main features of the alternatives

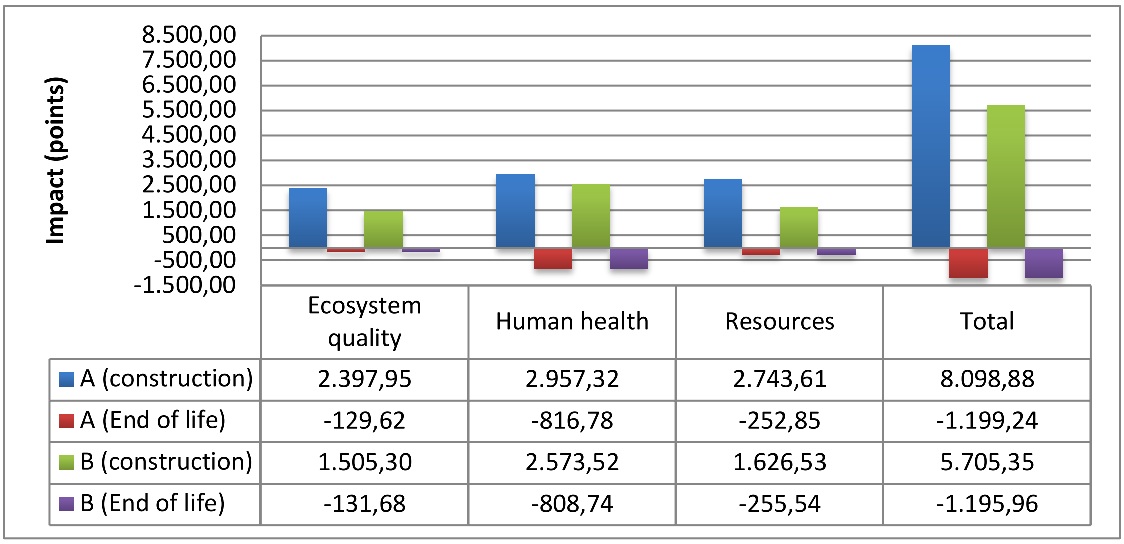
Alternative	*Components*	*Description*
A "Traditional"[1]	Foundation	Piles CPI-7 Ø35cm HA-35/F/12/IIa+Qc and steel quantity 7.38 Kg/m up to 8.80 m deep. Foundation beams HA-30/B/20/IIa+Qb and steel quantity 100 kg/m^3.
	Floor slabs	Reinforced concrete slab HA-25/B/20/IIa (24 cm type floor, 26 cm solarium), steel quantity 26 kg/m^2 and HA-30/B/20/IV in swimming pool area.
	Sloping floor slab	Reinforced concrete slab HA-25/B/20/IIa (22 cm); 10 cm PUR (0.035 m^{2}K/W).
	Supports	Concrete columns and metal profiles (only in props of the roof). Reinforced concrete basement perimeter wall (25 cm).
	Building enclosure	Brick outer wall (11.5 cm); air chamber insulated with 9 cm MW (0.031 m^{2}K/W). Interior brick partition wall (7 cm).
B " Prefabricated"[2]	Foundation	Same to alternative "A" (due to the problematic soil, not the service loads).
	Floor slabs	Reinforced plates (30 cm type floor, 17.5 cm solarium); Density 600 kg/m^3. Thermal conductivity 0.16 W/(mK), steel quantity 2 kg/m^2, in plate joints. Passable deck not ventilated, fixed flooring; 8 cm XPS (0.032 m^{2}K/W). Pool bottom with 30 cm plates (live load 1,100 Kg/m^2); "O" block anchored to the bottom and "U" block at the top and half height.
	Sloping floor slab	Reinforced plates (12 cm); 12 cm XPS (0.032 m^{2}K/W).
	Supports	There are no columns. Reinforced concrete basement wall is maintained.
	Building enclosure	Structural load-bearing walls with tongue and groove aerated concrete blocks with densities (400-350 Kg/m^3) and thicknesses of 20 and 30 cm.

[1] Reference: Conventional on-site reinforced concrete structure and brick enclosure walls.

[2] Ytong: Prefabricated blocks and slabs, autoclaving aerated concrete manufactured with densities 350-700 kg/m^3.

3.3 Results

The results shown below are those obtained by the students in this case study. In the analysis of environmental indicators, ReCiPe combines two approaches to show the results of environmental impact. A midpoint impact with 18 indicators that serve to compare results on a specific impact such as climate change, at both the ecosystem and human health levels, or resource depletion, such as aggregates for concrete in our case, which are the second most consumed raw material by humans after water. In order to obtain global results and impact categories that are easier to compare, the end point approach has been analyzed. Its three impact categories (human health, ecosystem and resources) can help designers choose the cleanest structural alternative depending on the impacts that could cause the most harm to the environment. Using a set of standards, the endpoint categories can be harmonized into a single unit rather than their own, resulting in an overall impact result that is useful when there is no preference for reducing a particular category of damage.



	Ecosystem quality	Human health	Resources	Total
🟦 A (construction)	2.397,95	2.957,32	2.743,61	8.098,88
🟥 A (End of life)	-129,62	-816,78	-252,85	-1.199,24
🟩 B (construction)	1.505,30	2.573,52	1.626,53	5.705,35
🟪 B (End of life)	-131,68	-808,74	-255,54	-1.195,96

Figure 4. Endpoints and total impact in construction and EOL stages

Based on the weights obtained for the criteria, the TOPSIS technique (Table 3) is applied to aggregate the 9 different impact categories into a single sustainability score by comparing each of the two design alternatives. Option B "prefabricated" gets the best score (0.63) against option A "traditional" in-situ concrete (0.370).

Table 3. Multi-criteria optimization solution with the TOPSIS method

Scope	**Criteria**		r_{ij}		r_{ij}' (Eq. (1))		w_i	$v_{ij} = r_{ij}' \cdot w_i$		v_i^*	v_i^-
			A	**B**	**A**	**B**		**A**	**B**		
Economic	**C1**	Min.	192.56	249.46	0.611	0.792	0.284	0.174	0.225	0.174	0.225
	C2	Min.	18.92	22.25	0.648	0.762	0.096	0.062	0.073	0.062	0.073
	C3	Min.	35.89	32.33	0.743	0.669	0.049	0.036	0.032	0.032	0.036
Environmental	**C4**	Max.	0.53	17.85	0.030	1.000	0.085	0.003	0.085	0.085	0.003
	C5	Max.	72.22	82.66	0.658	0.753	0.104	0.068	0.078	0.078	0.068
	C6	Min.	8,098	5,705	0.818	0.576	0.133	0.109	0.077	0.077	0.109
	C7	Min.	1,199	1,195	0.708	0.706	0.249	0.177	0.176	0.176	0.177
	(Eq.(2))	$Dj*$	0.089	0.052							
	(Eq.(3))	$Dj-$	0.052	0.089							
FINAL	(Eq.(4))	$Cj*$	0.370	**0.630**	[1] Best the highest score (farthest from						

Alternative B is based on the use of Ytong as the only material for the construction of the structural shell. As a modern construction method (MMC) has been studied only from the efficiency in the cost of insulation (savings in the consumption of heating and cooling), having much more potential as a comprehensive structural system for load-bearing walls, enclosures, partitions, floors and roofs. For its manufacture, autoclave-cured cellular concrete is used, which can be obtained with different densities between 350-700kg/m^3, being a much lighter material than conventional concrete, but providing great strength and mechanical capacity to the building. It is an ecological material 100% mineral (formed by sand, lime, cement and water) and fireproof, being totally recyclable. Its nature contributes to the climatic comfort of the house since it is a natural regulator of temperature and humidity.

Regarding the sustainability evaluation, the alternative "A" has had a better response in the economic dimension because it is a traditional system very tested by practice, with conventional construction solutions that use equipment and materials accessible to any builder. Alternative "B", presents a cost overrun in the construction and maintenance stage of 29.5% and 17.60% respectively. However, despite the fact that only criteria C1 and C2 represent 38% of the decision, as the answers of design

"B" in the set of criteria have been more balanced, it has proved to be the structural optimum between both alternatives without the need to have the highest score in the most relevant criteria. Its mineral composition has also contributed to stand out in the environmental criterion C4.

In the hierarchical structure defined in Table 1, indicators were included that contemplated the perspective of long-term impacts, because this study considers the recycling of materials used in construction and the subsequent reintegration of concrete and steel once the life of the structure is over. The final phase of the life cycle of the structures, either its demolition or its recycling, has been studied by very few authors. In our case, between the two alternatives there is not a substantial differentiation in the impacts of the EOL phase, being very similar the answers of the criteria (C3, C5 and C7).

In the light of the results, it follows that conclusions regarding the optimal structural design of a building from the point of view of sustainability will not be successful if only its individual performance in the various dimensions of sustainability is considered. Current design codes do not always take into account the objectives and priorities of a changing society. Concerns about building a more sustainable future require that aspects such as environmental be considered in addition to economic impacts. This has led the industry to develop materials and produce low-carbon building systems, as well as to search for new designs that reduce environmental impact, maintenance planning to prolong the life of structures, and life cycle assessment to consider impacts as a whole.

4 CONCLUSIONS

In this document the influence of environmental and economic aspects on the life cycle of concrete structures, in situ or precast, has been presented. This training belongs to the postgraduate courses "Methods and advanced technologies in construction" and "Concrete and sustainability" integrated in the curriculum of the Master of Concrete Engineering of the UPV. In these courses it is taught to apply MCDM techniques in the selection of the best structural typology for the resolution of complex engineering problems. At a teaching level, students have acquired the ability to use Open LCA software with the Ecoinvent database, and have learned the importance of selecting the most appropriate structural design from a set of possible solutions following a rigorous MADM process to achieve the most sustainable one. When it comes to optimizing environmental performance within budgetary constraints, the structure must be analyzed from all its attributes simultaneously, and not as an aggregation of optimal strategies for each individual design. Building structures are a crucial element for a sustainable future, as they are responsible for a great deal of environmental damage and economic costs, but they are also essential for the social welfare and economic development of cities. It is necessary that the next engineers and architects develop critical thinking through transversal skills during their graduate studies in order to face with future guarantees the complex relationship between the opposite dimensions on which the pillars of sustainability are based.

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REFERENCES

[1] European Ministers of Education, "The Bologna Declaration," Retrieved June, 1999.

[2] L. Kane, "Educators, learners and active learning methodologies", *International Journal of Lifelong Education*, vol. 23, no. 3, pp. 275-286, 2004.

[3] D. Kember, K.P. Kwan, and J. Ledesma, "Conceptions of good teaching and how they influence the way adults and school leavers are taught", *International Journal of Lifelong Education*, vol. 20, no. 5, p. 393-404, 2001.

[4] V. Yepes, E. Pellicer and J.A. Ortega, "Designing a benchmark indicator for managerial competences in construction at the graduate level", *Journal of Professional Issues in Engineering Education and Practice*, vol. 138, no. 1, p. 48-54, 2012. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000075

[5] E. Pellicer, V. Yepes, C.L. Correa and L.F. Alarcón, "Model for Systematic Innovation in Construction Companies", *Journal of Construction Engineering and Management*, vol. 140, no. 4, B4014001-1/8, 2014. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000468

[6] C. Torres-Machí, A. Carrión, V. Yepes and E. Pellicer, "Employability of graduate students in construction management", *Journal of Professional Issues in Engineering Education and Practice*, vol. 139, no. 2, p. 163-170, 2013. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000139

[7] A.J. Sánchez-Garrido and V. Yepes, "Multi-criteria assessment of alternative sustainable structures for a self-promoted, single-family home", *Journal of Cleaner Production*, vol. 258, 120556, 2020. https://doi.org/10.1016/j.jclepro.2020.120556

[8] V. Penadés-Plà, V. Yepes and T. García-Segura, "Robust decision-making design for sustainable pedestrian concrete bridges", *Engineering Structures*, vol. 209, 109968, 2020. https://doi.org/10.1016/j.engstruct.2019.109968

[9] T. García-Segura, V. Yepes and D.M. Frangopol, "Multi-Objective Design of Post-Tensioned Concrete Road Bridges Using Artificial Neural Networks", *Structural and Multidisciplinary Optimization*, vol. 56, no. 1, p. 139-150, 2017. https://doi.org/10.1007/s00158-017-1653-0

[10] V. Yepes, M. Dasí-Gil, D. Martínez-Muñoz, V.J. López-Desfilís and J.V. Martí, "Heuristic techniques for the design of steel-concrete composite pedestrian bridges". *Applied Sciences*, vol. 9, no. 16, 3253, 2019. https://doi.org/10.3390/app9163253

[11] T. García-Segura, V. Penadés-Plà and V. Yepes, "Sustainable bridge design by metamodel-assisted multi-objective optimization and decision-making under uncertainty", *Journal of Cleaner Production*, vol. 202, p. 904-915, 2018. https://doi.org/10.1016/j.jclepro.2018.08.177

[12] J.V. Martí, T. García-Segura and V. Yepes, "Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy", *Journal of Cleaner Production*, vol. 120, p. 231-240, 2016. https://doi.org/10.1016/j.jclepro.2016.02.024

[13] V. Yepes, J.V. Martí, and T. García-Segura, "Cost and CO_2 emission optimization of precast-prestressed concrete U-beam road bridges by a hybrid glowworm swarm algorithm", *Automation in Construction*, vol. 49, p. 123-134, 2015. https://doi.org/10.1016/j.autcon.2014.10.013

[14] I.J. Navarro, V. Yepes, J.V. Martí and F. González-Vidosa, "Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks", *Journal of Cleaner Production*, vol. 196, p. 698-713, 2018. https://doi.org/10.1016/j.jclepro.2018.06.110

[15] V. Penadés-Plà, J.V. Martí, T. García-Segura and V. Yepes, "Life-cycle assessment: A comparison between two optimal post-tensioned concrete box-girder road bridges", *Sustainability*, vol. 9 no. 10, p. 1864, 2017. https://doi.org/10.3390/su9101864

[16] J.J. Pons, V. Penadés-Plà; V. Yepes and J.V. Martí, "Life cycle assessment of earth-retaining walls: An environmental comparison", *Journal of Cleaner Production*, vol.192, p. 411-420, 2018. https://doi.org/10.1016/j.jclepro.2018.04.268

[17] J.J. Pons, I. Villalba-Sanchis, R. Insa and V. Yepes, "Life cycle assessment of a railway tracks substructures: comparison of ballast and ballastless rail tracks". *Environmental Impact Assessment Review*, vol. 85, 106444, 2020. https://doi.org/10.1016/j.eiar.2020.106444

[18] UNE-EN ISO 14040:2006, *Gestión ambiental. Análisis del ciclo de vida. Principios y marco de referencia*, AENOR, Madrid/ Spain, 2006.

[19] J.W. Owens, "LCA Impact Assessment Categories. Technical Feasibility and Accuracy", *The International Journal of Life Cycle Assessment*, vol. 1, no. 3, p. 151–158, 1996.

[20] UAM Observatory - Via Célere, "Estimation of the carbon footprint of the residential development", 2020. https://www.viacelere.com/sites/default/files/2020-03/Informe%20Huella%20Carbono.pdf

[21] I. Payá-Zaforteza, V. Yepes, F. González-Vidosa and A. Hospitaler, "On the Weibull cost estimation of building frames designed by simulated annealing", *Meccanica*, vol. 45, no. 5, p. 693-704, 2010. https://doi.org/10.1007/s11012-010-9285-0

[22] V. Yepes, J.R. Medina, "Land Use Tourism Models in Spanish Coastal Areas. A Case Study of the Valencia Region", *Journal of Coastal Research*, SI 49, p. 83-88, 2005.

[23] C. Torres-Machí, E. Pellicer, V. Yepes and A. Chamorro, "Towards a sustainable optimization of pavement maintenance programs under budgetary restrictions", *Journal of Cleaner Production*, vol. 148, p. 90-102, 2017. https://doi.org/10.1016/j.jclepro.2017.01.100

[24] I.J. Navarro, V. Yepes and J.V. Martí, "A review of multi-criteria assessment techniques applied to sustainable infrastructures design", *Advances in Civil Engineering*, vol. 2019, Article ID 6134803, 2019. https://doi.org/10.1155/2019/6134803

[25] E.K. Zavadskas, A. Mardani, Z. Turskis, A. Jusoh and K. Nor, "Development of TOPSIS method to solve complicated decisionmaking problems: An overview on developments from 2000 to 2015". *International Journal of Information Technology & Decision Making*, vol. 15, no. 3, p. 645–682, 2016. https://doi.org/10.1142/S0219622016300019

[26] T.U. Daim, A. Udbye, A. Balasubramanian, "Use of analytic hierarchy process (AHP) for selection of 3PL providers", *Journal of Manufacturing Technology Management* , vol. 24, no. 1, p. 28-51, 2012. https://doi.org/10.1108/17410381311287472

[27] T.L. Saaty, *The Analytic Hierarchy Process*. McGraw-Hill, New York, 1980.

[28] H. Gervasio and L. Simões da Silva, "A probabilistic decision-making approach for the sustainable assessment of infrastructures", *Expert Systems with Applications*, vol. 39, no. 8, p. 7121–7131, 2012. https://doi.org/10.1016/j.eswa.2012.01.032

[29] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F.Verones, M. Vieira, M. Zijp, A. Hollander and R. van Zelm, "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level", *The International Journal of Life Cycle Assessment,* vol. 22, p. 138-147, 2017. https://doi.org/10.1007/s11367-016-1246-y