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Environmental Assessment of Concrete Structures

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Abstract In recent decades, with the objective of reaching a more sustainable development, worldwide society has increased its concern about environmental protection. Nevertheless, there are still economic sectors, such as the construction industry, which produce significant environmental impacts. Life Cycle Assessment (LCA) is a tool that enables identifying environmental issues related to both finished products and services, and allows focusing efforts to resolve them. The main objective of this paper is to asses LCA applicability on concrete structures so that construction's environmental performance can be improved. For this purpose, an attempt is made to provide a decision-making tool for construction-sector stakeholders with reliable and accurate environmental data. The research methodologies used in this paper are based on a literature review and are applied to a case study. This review was performed to collect information on LCA methodologies currently in use and their practical application. The case study subsequently described in this paper involved identification of the most sustainable type of slab for a reinforced concrete structure in a residential building, using two different databases. It was observed that, depending on the database selected and inherent assumptions, results varied. Therefore it was concluded that in order to avoid producing incorrect results when applying LCA, it is highly recommended to develop a more constrained methodology and grant access to reliable construction-sector data.

Keywords Applicability, Concrete, Construction, Life Cycle Assessment (LCA), Structure, Sustainability

1. Introduction

In spite of the economic crisis that nowadays is being experienced world-wide, human population is expected to continue increasing. According to a report by United Nations Population Fund (UNFPA)[29], it is expected that world's population will increase from the current 7 billion to more than 8 billion in 2025. Consequently, resource and supplies are expected to show a similar behaviour, as that of pollutants emission. Therefore, it can be stated that nowadays Earth's scenario of growing population, high resources consumption and pollutants emission is driving the planet to a critical situation. Furthermore, according to a report from the World Wide Fund for Nature (WWF)[31] in 2007 humanity already overpassed Earth's bio-capacity by 1.5 times. This means that the capacity of our planet to replace natural resources consumed and to absorb all CO_2 emissions is currently exceeded. But it is most relevant to emphasize from this same source that by 2030 human requirements are expected to double Earth's bio-capacity. Therefore, it seems crucial to incorporate design criteria to minimize these impacts[32-33].

Since the early 1990's, sustainability already was considered in the construction environment as an issue of great importance. Nevertheless, when in 1992 "The Earth Summit" was celebrated, a new environmental trend took form with the motto: "*Sustainable Development*"[25]. This is based in a triple-factorized development considering: economy, society and environment. Therefore, in order to accomplish economic growth or development, there is no need to jeopardize human society or environmental integrity. In response to this trend, both governments and private institutions have worked on implementing more sustainable measures and policies, as the European Union's EPBD or CPD directives. The first measure, Energy Performance of Buildings Directive (2002/90/EC) is focused on reducing building's energy consumption by the optimization and efficiency when supplying its energetic requirements[4]. On the other hand, the Construction Products Directive (89/106/ECC) is a set of regulations established for construction and building products requiring various aspects before product's commercialization (in order to comply with sustainability concerns)[6]. But there are additional examples, such as Green Procurement (COM 2008-400)[8], product's green labelling (COM 2008-241)[7] or waste reutilization (Directive 2008/9/EC)[5].

Construction industry is considered to be one of the most important economic sectors worldwide but, at the same time, it is also one of the most pollutant emitting and resource demanding. It is held responsible for 25-40% of energy consumption in OECD countries[23] and according to other studies it is established that construction's environmental impact in developed countries can be as high as 40%[16].

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Concrete, with an estimated consumption of 6 billion tons per year (what is the same as 1 ton per person/per year)[20], is considered the most world-wide construction material used. Therefore, a better use of concrete is a relevant and challenging issue for construction industry, already pointed out in 1998 by the “Lofoten Declaration”[11].

In this scenario, numerous attempts to reduce environmental, social and economic impacts due to construction activities have already been made to this date. Nevertheless it is a fact that, when considering the complete life cycle of a construction project, effectiveness of measures decrease as the project progresses. Therefore, if improving sustainability is a must of the construction industry, it is necessary to provide decision-makers with effective tools to be applied at the initial phases of project’s life cycle (e.g., pre-design or design phases). This objective can be achieved by incorporating tools such as Life Cycle Assessment in the design, construction, operational and demolition phases of concrete structures.

1.1. Life Cycle Assessment: Birth and Evolution

At some point in the late 1960’s, two researchers at the Midwest Research Institute began working on a technique for quantifying energy and resources, as well as environmental emissions, related to the manufacturing process and use of products[28]. Initially named “Resource and Environmental Profile Analysis” (REPA), it was first applied in 1969 by America’s Midwest Research Institute (MRI) together with Coca-Cola’s Corporation for analysing and selecting the environmental-friendliest vessel material (glass or plastic) in terms of whether disposable or recycled vessels produced less impact[10].

LCA development showed an accelerated growth during the energy oil-crises of the 1970’s. At the beginning LCA’s were used to study energy consumption of products packaging (glass bottles, plastic bottles, cardboard, etc.). Again, for a short period in the late 1980’s and early 1990’s, LCA achieved great significance for environmental marketing claims[24]. As this method became popular, and studies performed over same products gave great differing results, many initiatives to harmonize LCA methodologies were proposed. This tendency resulted in various methodological guidelines (known as the Dutch and Nordic Guidelines), which included different and often conflicting methodological recommendations. An effort to reach consensus on a broad international level was initiated in 1990 by the Society of Environmental Toxicology and Chemistry (SETAC). Later, in March 1993, the North American and European SETAC LCA advisory groups met in Sesimbra (Portugal) and produced the so-called “Code of Practice for Life Cycle Assessment”. In addition, many different initiatives to standardize LCA methodology were started (e.g., the Z-760-LCA guideline of the Canadian Standards Association), but the most recognized standardization process was begun in the late 90’s within the framework of the International Organization forStandardization[26].

During the 1990s, first Japan and later Australia and Korea increased their LCA practice activity performing a wide number of environmental studies. In contrast, LCA activity in the rest of Asia, Latin America and Africa was scarce. This trend has begun to change, as activity in LCA is increasing in Latin America, South Asia and Africa. The Brazilian government, for example, recently launched a national project to develop life cycle inventory data. LCA practitioners are also developing data and impact assessment methods, and applying them in both public and private sectors, in various Latin American countries, such as Mexico, Argentina, Chile, Colombia and Peru. The African LCA Network recently hosted an LCA training workshop in which the participants began to develop a life cycle inventory data specifically applicable to each country[21].

LCA practice on construction industry started in the last decade, but only for environmental assessment of building and construction materials selection. Therefore, LCA in the construction industry is less developed nowadays than in other industries, but appears to be developing quickly[27]. Furthermore, Life Cycle Assessment on buildings is nowadays a hot research theme in developed countries like, such as Japan, North America and the European Union[9].

1.2. Life Cycle Assessment Methodology

The International Organization for Standardization (ISO) issued four relevant international standards in 1997 for LCA practice. According to the standards of the fourth series of ISO 14040 standard Life Cycle Assessment can be defined as "*a method for summarizing and assessing the total investment of a product (or service) system in the whole life cycle, and the impact or potential influence on the environment*"[15]. Therefore, LCA can be considered as a methodology for estimating the environmental burdens of production processes of goods and services during their life cycle (e.g., from cradle to grave).

According to ISO 14.040, LCA is composed of four different phases, which are:

- Goal and Scope definition. In this phase a discussion of motivations, altogether with the scope and depth of the assessment, is performed in order to establish all preliminary concerns relating the LCA study.
- Inventory Analysis. In involves collecting data to quantify all materials, energy and emissions considered as inputs and outputs from the studied system during its life cycle.
- Impact Assessment. This stage is related mostly to converting data recovered from the inventory into effects and impacts over the environment due to production of the system assessed.
- Interpretation. The step presents the results obtained at the inventory and/or impact assessment steps, and includes conclusions and recommendations.

Firstly, the environmental assessment's goal and scope are established, subsequently followed by the inventory analysis. As pointed out by the ISO standard, the LCA can be finished at this step, providing a general perspective of the direct impacts generated by the assessed system; nevertheless, if the assessment is pursued further, then an impact assessment is performed. It is important to emphasize that, for both LCI and LCA studies; a sensitivity analysis of the assessment should be performed in order to identify mistakes or issues. Depending on the observations and results reached from this analysis, a revision of the previous steps can be required. Finally, all the impacts obtained from the LCI or LCA study, depending on the case, are summarised in the interpretation step, which provides a general view of the study results.

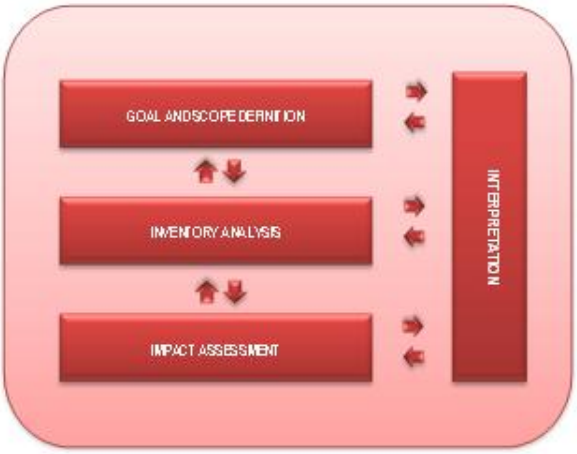

Figure 1. Life Cycle Assessment's procedure according to ISO 14040

Once the study is done, and according to ISO, a report will have to be produced. Nevertheless, there is a final step for the LCA methodology, known as critical review, which is not usually included in most studies. This step should always be conducted when quality or credibility of the LCA study wants to be reinforced[18]. Depending on the results of this critical review, which is normally done by a third party, with no boundaries to the LCA team, a revision and a series of improvements to the whole study may be required.

2. Methodology

Literature review was a fundamental part of this paper's research, in order to summarise the state of the art for this subject. Papers recovered from the review were submitted to a thorough analysis, with particular emphasis on literature relating LCA studies on concrete structures. These studies were analysed in two different ways, in order to establish:

- Current or trendy LCA methodological practice.
- Existing issues and limitations on LCA practice.

After all existing information was summarised from the literature review phase, a guide for LCA practice on the specific field of concrete structures was produced. Then, this same guide was tested with a case study located in Valencia (Spain). Data for the assessment was provided by two different databases, in order to demonstrate the applicability of the tool and to identify potential mistakes or weaknesses to be corrected.

2.1. Review of LCA Studies

As previously indicated, literature review was performed in two stages. First a general review of literature relating ordinary practice of LCA was done, which allowed identifying: existing methodologies, software, databases, etc. Then, a deeper analysis was performed on LCA studies that specifically considered concrete structures as the assessed system. This more comprehensive analysis was done in two different ways. First, a general review was conducted in order to identify either ordinary or popular LCA practice. The aspects considered in this review are the following: year of publication, scope of the study, functional unit, LCA methodology used, type of Inventory Analysis or Impact Assessment performed, databases or software used, and sensitivity or data quality analysis performed. The second step involved identifying limitations and issues of LCA practice for concrete structures; this was done considering facts specifically mentioned/pointed out in the studies themselves.

2.2. Case Study Introduction

Table 1. Construction unit's description

Code	Unit	Description	Alt. A	Alt. B
CRL010	m^2	Mass cast-in-place concrete for blinding surface	339.42	339.42
CCS010	m^2	Reinforced cast-in-place concrete for basement wall	85.20	85.20
CSZ010	m^3	Reinforced cast-in-place concrete for foundation pad	221.52	221.52
CSZ020	m^2	Modular steel-framed formwork for foundation pad	321.44	321.44
CAV010	m^3	Reinforced concrete cast-in-place for foundation beam	6.65	6.65
CAV020	m^2	Modular steel-framed formwork for foundation beam	33.26	33.26
CNE010	m^3	Reinforced concrete block cast-in-place for foundation	3.96	3.96
EHE010	m^2	Reinforced concrete cast-in-place stair slab	44.83	44.83
EHU020	m^2	Reinforced concrete cast-in-place for structure's one-way slab	3,049.39	-
EHS010	m^3	Reinforced concrete cast-in-place for structure's column	-	73.17
EHV010	m^3	Reinforced concrete cast-in-place for structure's beam	-	90.68
EHL010	m^2	Reinforced concrete cast-in-place for structure's slab	-	3,049.38
EHN010	m^3	Reinforced concrete cast-in-place for elevator's core	114.07	114.07

In the case study two alternatives were compared for a reinforced concrete structure of a residential building located in Valencia (Spain). The two alternatives were obtained from the automatic job module (Autopem), which is part of the CYPECAD software for reinforced concrete structures. These consisted of one basement, one ground floor and four floors with 500 m^2 each. In the subsequent computations, the two stairway slab structures and the elevator walls were also included as part of the building structure. The main difference between both alternatives were related to the slabs, as Alternative A considered a one-way spanning slab and Alternative B a mass reinforced concrete slab. Because of this difference on the slabs, construction units vary for both alternatives: Alternative A and B required 10 and 12 construction units, respectively.

All reinforced concrete for structural purposes (according to Spanish regulation) was considered to be of type HA-25/B/20, while the concrete used for blinding was HL-15/B/20 type. Reinforcing steel was B-500-S type. The total quantities of concrete and steel for both alternatives are presented in Table 2:

Table 2. Concrete and steel measurements for each alternative

Alt.	HL-15/B/20	HA-25/B/20	B-500-S	Wood
A	35.64	1,042.03	79,275.49	3,394.68
B	35.64	1,593.15	126,539.35	3,712.04

Since during structure's construction phase taskforce requires of both man's labor and machinery, energy consumption and emissions related to these activities must be included in the system studied. The engine hours required by each construction unit, for both alternatives, are indicated in the table below.

Table 3. Taskforce time required by construction units

Code	Correlation	Alt. A	Alt. B
CRL010	0.057 h/m^2	19.35	19.35
CCS010	0.312 h/m^2	26.58	26.58
CSZ010	0.284 h/m^3	62.91	62.91
CSZ020	0.265 h/m^2	85.18	85.18
CAV010	0.057 h/m^3	0.38	0.38
CAV020	0.246 h/m^2	8.18	8.18
CNE010	0.189 h/m^3	0.75	0.75
EHE010	0.627 h/m^2	27.89	27.89
EHU020	0.494 h/m^2	1,506.40	-
EHS010	0.212 h/m^3	-	15.51
EHV010	0.193 h/m^3	-	17.5
EHL010	0.478 h/m^2	-	1,457.61
EHN010	0.349 h/m^3	39.81	39.81

3. Results

3.1. Methodological Analysis

Based on the review of published LCA studies, papers focusing on concrete structures range from 1998 to 2011. It is interesting to note that more than a half of these references (i.e., 59.26%) were published between 2005 and 2009, which indicated the current significance of the subject. When focusing on the methodology used for LCA practice, it was observed that the 67.34% of existing literature used process method and that the 51.85% completed the LCIA step. In 39.21% of all cases databases and software were used for the study's calculations. Finally, it was also observed that only a few of them (i.e., 7.12%) performed a sensitivity analysis or data quality assessment, situation that causes assessments to be uncertain and are lacked of transparency. Furthermore, when a sensitivity analysis was claimed to be performed, it was actually a comparison of different scenarios and not a sensitivity analysis per se.

An analysis of the deficiencies and limitations found while performing the case study, and in some of the analysed references, allowed establishing that LCA studies on concrete structures have the following weaknesses:

- Incomplete or inaccurate definition of the functional unit, which causes great difficulties for subsequent comparison among different studies.
- Limitations and assumptions of LCA study are not indicated. This significantly affects reviewing and reproducing the results obtained by others.
- Incomplete life cycle, as the operational phase of concrete structures is excluded from the study's scope.
- No description of the inventory phase performed; in some cases sources of data are not mentioned at all.
- Calculations of the impact assessment step are not included; therefore, many studies suffer from lack of transparency.
- No graphical representation of the interpretation phase of the study is provided.

Therefore, it can be concluded that LCA studies on concrete structures performed to the date show significant deficiencies. Among these, the most relevant are the following: lack of transparency, poor reliability and high uncertainty.

3.2. Case Study Assessment

The interpretation phase of the performed LCA study allowed identifying both construction units of each alternative and construction phases of the life cycle considered which had the worst environmental performance. It was also observed that, depending on the database selected, contradictory results for each alternative were obtained. E.g., according to ARQUÍMEDES-ACV, the best energy consumption and CO_2 emissions performance corresponded to that of alternative A (one way slab), but BEDEC selected alternative B (one-way slab) as the best one.

As pointed out before, concrete structure slabs are the construction units responsible for the most relevant part of impacts (energy consumption and CO_2 emissions) to the environment. If results from the ARQUÍMEDES-ACV database are considered, it is observed that slabs generate 61-66% of the total impact, whereas the results obtained from BEDEC database vary between 65 and 80% (table 4).

Table 4. Construction unit behavior for each database

Alt.	Energy consumption		CO_2 emissions	
	ARQUIMEDES	BEDEC	ARQUIMEDES	BEDEC
A	EHU020 (66%)	EHU020 (80%)	EHU020 (66%)	EHU020 (80%)
B	EHL010 (61%)	EHL010 (65%)	EHL010 (61%)	EHL010 (65%)

When a comparison of energy consumptions and CO_2 emissions was performed on the different construction phases for the reinforced concrete structure life cycle, it was observed that, independently of the alternative considered or database used, the production/manufacturing of materials and supplied products are the items that generate the highest environmental impact.

Finally, in order to analyze more accurately differences observed within each data source considered in the study, life cycle results were compared. Based on this analysis, the BEDEC database resulted in higher percentages for Alternative A and lower percentages for Alternative B. These results were completely different than those produced when considering ARQUÍMEDES-ACV database. Therefore, the selection of alternative A or B cannot be made based on the results gained, as the environmental impact results from both databases are utterly contradictory.

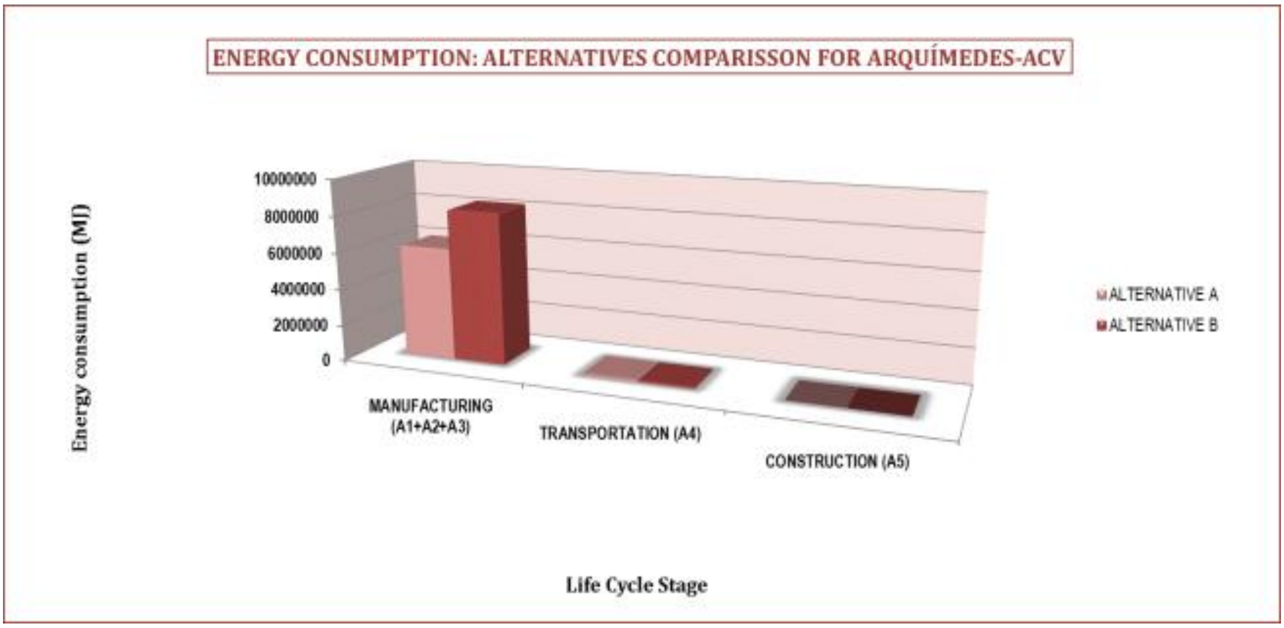

Figure 2. Distribution of energy consumption by each life cycle phase (ARQUÍMEDES-ACV database)

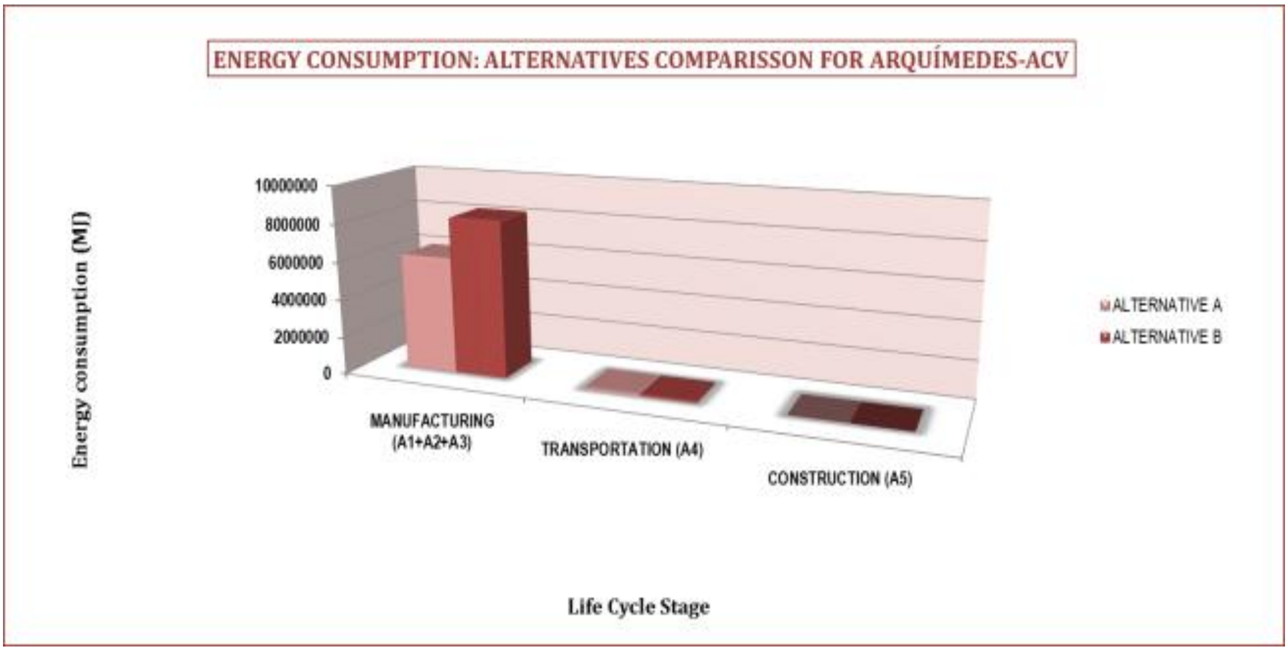

Figure 3. Distribution of energy consumption by each life cycle phase (BEDEC database)

Table 5. Construction unit behavior for each database

Alt.	Energy consumption (MJ)		CO_2 emissions (Kg)	
	ARQUIMEDES	BEDEC	ARQUIMEDES	BEDEC
A	6,256,976.75	8,666,249.73	EHU020 (66%)	EHU020 (80%)
B	8,470,639.26	EHL010 (65%)	EHL010 (61%)	EHL010 (65%)

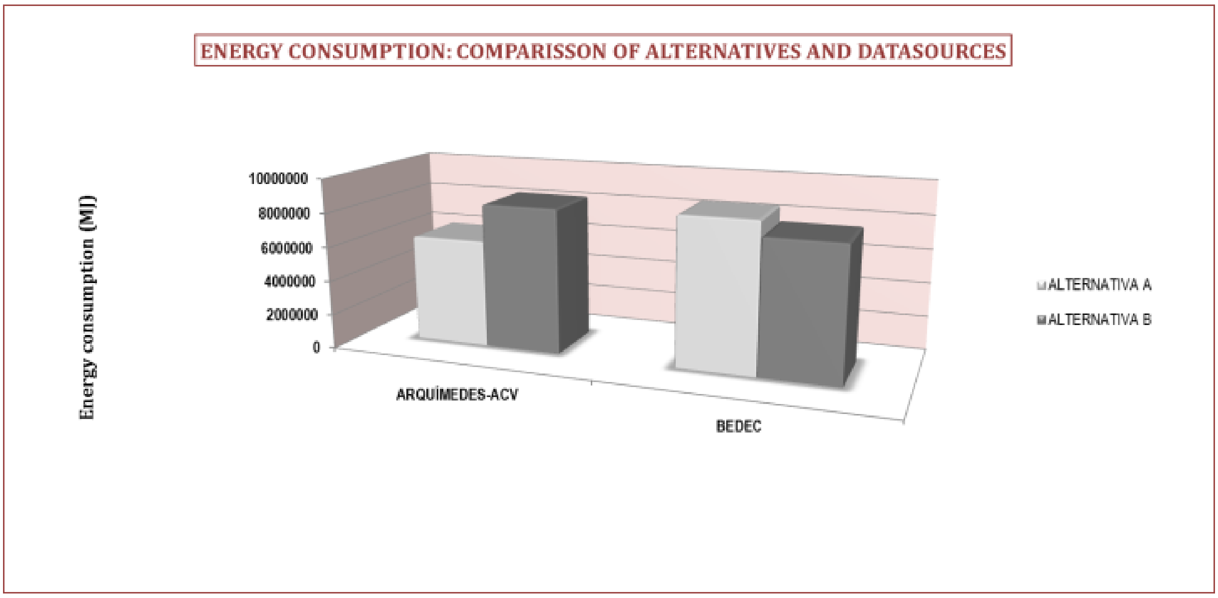

Figure 4. Energy consumption comparison for each alternative and data source considered

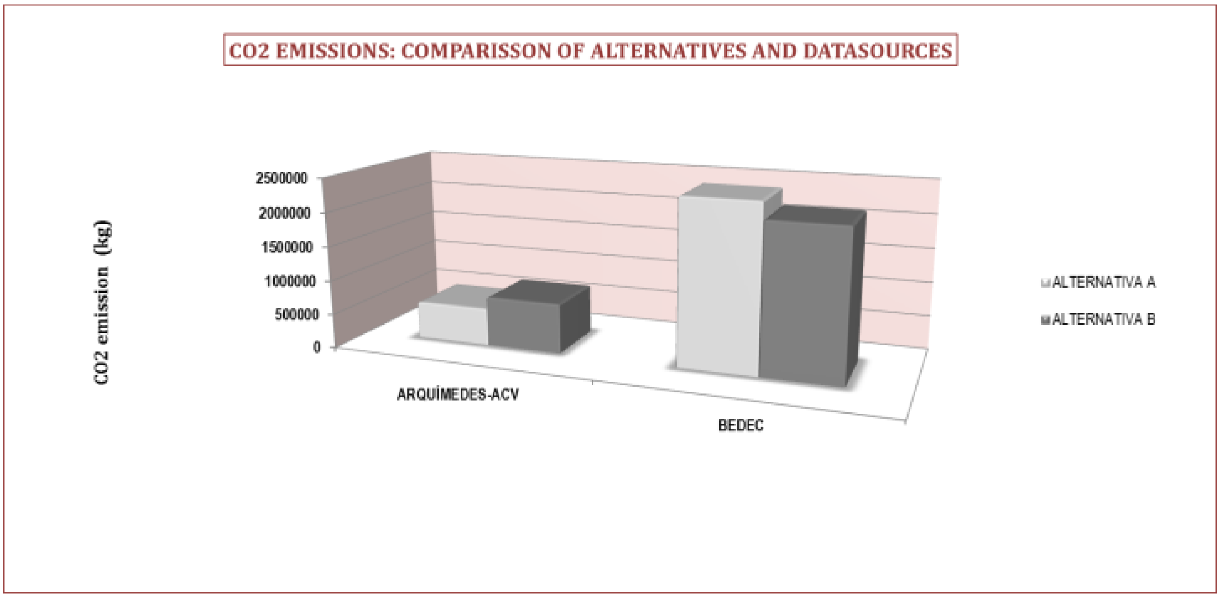

Figure 5. CO_2 emissions comparison for each alternative and data source considered

4. Conclusions

Sustainability concerns have reached the construction industry, and its environmental impacts are being gradually considered more seriously when designing, selecting materials or making operational decisions, among others. Therefore, it can be said that construction is getting greener and greener with time. Nevertheless, decision-makers have lacked reliable tools and managerial resources to evaluate construction impacts on the environment. With the introduction of LCA to this scheme, it is assumed this situation can be changed, as it is a tool capable of identifying items with the greatest environmental improvement (as it was observed in the results obtained from the case study).

Although the methodology to practice LCA studies was standardized by the ISO standard 14040, it requires further improvement in order to prevent present limitations and uncertainties on its results[17]. Furthermore, limitations of LCA's standardized methodology are not the only issue this tool is facing nowadays, but also subjectivity introduced by real practice[16,18,26]. Unfortunately, when conducting a LCA study, there are a wide number of tools and databases which in turn introduce more variation to each study. These elements cause LCA studies to produce significantly different results when assessing a system, depending on the practitioner's criteria, inherent assumptions and choices made, even when the system assessed is exactly the same. This issues could be resolved by clearly establishing each assumption on the assessment's goal and scope definition step[17].

Moreover, as the impact inventory step is directly based on data, its transparency and reliability are essential. Therefore, previous evaluation of input data used in LCA studies is a must[1]. Some authors have even introduced the concept of statistical methods to minimize inaccuracy and improve reliability on data used for LCA studies[24]. But, contrary to this recommendation, only a few LCA studies published to the date have taken into account statistical analysis of data incorporated.

As far as the specific practice of LCA on concrete structures, its main purpose has been to compare and identify the environmental friendliest frame materials. Concrete structures have been assessed and compared to wooden frames[10], steel frames[12] and bamboo frames[30]. LCA studies have mainly been focused on building structures, and very few studies have been applied on other types of constructions, although examples on concrete bridges[3,14] or concrete sidewalks[22] can also be found in the scientific literature reviewed.

Regarding the methodology used by the authors to assess concrete structures, it was observed that process analysis (ISO 14040) was predominant. Notwithstanding, in the literature review it was found one EIO-LCA[14], and three Hybrid LCA[1,10,12]. In relation to the scope of these studies, it was seen that the predominant life cycle considered were cradle-to-gate and cradle-to-grave. As far as the LCA calculations, a few studies included materials reutilization or recycling at the structures' end-of-life. This can be explained by the scarcity of data and limited information on construction's end-of-life.

Based on the results obtained from the case study described in this paper, and following the indications established in the LCA guide to concrete structures, steel offered a greater impact when compared to concrete, as it was also indicated by the study performed by Guggemos and Horvath[12]. Moreover, in relation to the embodied energy and emissions produced, it was also concluded that the frame materials manufacturing caused greater impacts than the construction process (also indicated at the study by Guggemos and Horvath[12]). Finally, when comparing the different construction units assessed at the case study, it was observed that the largest environmental impacts corresponded to the concrete slab, as it was already concluded in the study performed by Lopez-Mesa et al[19]. These results lead to concluding that, independently of the LCA methodology used, assumptions taken or databases used consulted for assessing a concrete structure, there are some common results that can be accepted as standards.

As it was already indicated, when performing a LCA study on a concrete structure there is a lack of data for operational/maintenance and end-of-life activities. Moreover, there are significant constraints in access to software and database available in the market, as they required license purchase for their use. In our case study, these constraints limited our scope but, when performing LCA on a real scenario, available project data and assumptions from the designer allow overcoming these limitations.

Finally, as pointed out by ISO 14040, the objective of LCA studies is the assessment of environmental performance of products and services. Nevertheless, actions in the direction of integrating economic and social issues to LCA assessments are in course. For example, integration of LCA with LCCA (Life Cycle Cost Analysis) has already been achieved in different papers[12], but the most difficult challenge comes when trying to integrate social concerns. If LCA developments achieve to utterly integrate environmental, economic and social issues; then LCA practitioners will be counting with a tool for decision-making that meets the triple-bottom objectives of Sustainable Development.

So according to everything previously exposed, it is stated that Life Cycle Assessment counts with wide applicability and great number of opportunities for the construction environment. Nevertheless, it requires of great efforts for eliminating issues relating to results variability and unreliability. Moreover, if the integration of sustainable development concerns is achieved, LCA practitioners will count on a trustful and reliable tool that will provide scientific basis and objectiveness to decisions taken all along a construction life cycle.

Back to the applicability of LCA on concrete structures, despite its great potential, nowadays it is not a common tool neither in the international construction environment nor much less in the Spanish context. Therefore, it is required to improve and develop specific databases considering the whole life cycle. Moreover, if this objective is reached, practice of LCA on other types of construction projects will be feasible too.

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