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APPLICABILITY OF LIFE CYCLE ASSESSMENT TECHNIQUE TO CONCRETE STRUCTURES

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This work is dedicated to my beloved niece,
always and forever light, joy and happiness of my live.

I am really thankful to my family and friends,
who have supported and helped me to make this work become real.

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B.1. ABSTRACT.

In recent decades society has increased its concern about environmental protection, in order to achieve the goal of sustainable development. However, there are several economic sectors like construction industry, which still are cause for a wide number of environmental impacts and, therefore, require improvement in their processes. The purpose of this final work for the Master in Planning and Management in Civil Engineering is to establish the current state of the art regarding Life Cycle Assessment (LCA), particularized to its applicability to concrete structures. In order to accomplish this, first a bibliographical research has been carried out to find the published literature on the subject to recent date. Next, a quantitatively and qualitatively analysis of the publications recovered from the research has been done. Then, with the aim of analysing the general framework of its current state, it has been undertaken a SWOT analysis. Finally, a methodological guide for the specific application of LCA to concrete structures has been introduced and, subsequently, it has been applied to a case study considering two different databases. The elaboration of the work has not been free of limitations, since there have been restriction on access to scientific articles as well as software tools and databases when performing the practical use of the guide. The case study of the work, which consisted on the comparison of two reinforced concrete structures, has shown LCA's usefulness for identifying items of the construction processes (as it can be the life cycle stages or construction units) that require of improvement, as for comparing and selecting more sustainable alternatives. However, the work done also has revealed that LCA practice on concrete structures suffers from two main problems which affect the reliability of the results obtained, which are: lack of construction-related data and assumptions introduced by the practitioners. Therefore, considering the applicability of LCA on concrete structures, it has been appreciated that is generalization and implementation to real world case passes through the improvement of the two issues outlined above.

KEYWORDS: Sustainability, Life Cycle Assessment (LCA); applicability; construction; structure; concrete.

B.2. RESUMEN.

En las últimas décadas la sociedad mundial ha incrementado su preocupación por la protección del medio ambiente, con el objetivo de alcanzar un desarrollo más sostenible. Sin embargo, existen sectores como el de la construcción, que todavía son causa de un elevado número de impactos medioambientales y, por lo tanto, requieren de una mejora en sus procesos. El objetivo del presente Trabajo Final del Máster en Planificación y Gestión en Ingeniería Civil es establecer como se encuentra el estado actual del conocimiento en relación a la herramienta de Análisis del Ciclo de Vida (ACV), particularizado a su aplicabilidad a estructuras de hormigón. Para ello, en primer lugar se ha efectuado una búsqueda bibliográfica de la documentación publicada sobre el tema hasta la fecha. A continuación, se ha analizado cuantitativa y cualitativamente las publicaciones recuperadas para, posteriormente, exponer el estado de la cuestión. Seguidamente, y con el objetivo de analizar el marco general de su estado actual, se ha llevado a cabo la elaboración de un análisis DAFO. Finalmente, se ha propuesto una guía metodológica para la aplicación específica del ACV a estructuras de hormigón y se ha aplicado a un caso práctico empleando dos bases de datos diferentes. La elaboración del trabajo no ha estado exenta de limitaciones, dadas las restricciones de acceso a artículos científicos así como a las herramientas informáticas y a bases de datos para la utilización práctica de la guía. De la aplicación de la herramienta a un caso de estudio, en el que se comparaban dos estructuras de hormigón, se ha desprendido su utilidad para identificar ítems del proceso constructivo (como puedan ser las fases del ciclo de vida o las unidades de obra) susceptibles de mejora, así como para comparar y seleccionar alternativas más sostenibles. No obstante, el trabajo efectuado también ha permitido observar que la aplicación del ACV a estructuras de hormigón en el sector de la construcción sufre de dos problemas esenciales que afectan a la fiabilidad de sus resultados, que son: falta de datos específicos del sector y las hipótesis introducidas por el usuario. Por lo tanto, y tras haber analizado la aplicabilidad del ACV a estructuras de hormigón, se ha apreciado que su generalización y puesta en práctica a casos reales pasa por la mejora de los dos aspectos apuntados anteriormente.

PALABRAS CLAVE: Sostenibilidad; Análisis del Ciclo de Vida (ACV); aplicabilidad; construcción; estructura; hormigón.

B.3. RESUM.

En les últimes dècades la societat mundial ha incrementat la seva preocupació per la protecció del medi ambient, amb l'objectiu d'assolir un desenvolupament més sostenible. No obstant això, hi ha sectors com el de la construcció, que encara són causa d'un elevat nombre d'impactes mediambientals i, per tant, requereixen d'una millora en els seus processos. L'objectiu d'aquest Treball Final del Màster en Planificació i Gestió en Enginyeria Civil és establir com es troba l'estat actual del coneixement en relació a l'eina d'Anàlisi del Cicle de Vida (ACV), particularitzat a la seva aplicabilitat a estructures de formigó. Per això, en primer lloc s'ha efectuat una recerca bibliogràfica de la documentació publicada sobre el tema fins ara. A continuació, s'ha analitzat quantitativament i qualitativament les publicacions recuperades per, posteriorment, exposar l'estat de la qüestió. Seguidament, i amb l'objectiu d'analitzar el marc general del seu estat actual, s'ha dut a terme l'elaboració d'una anàlisi DAFO. Finalment, s'ha proposat una guia metodològica per a l'aplicació específica de l'ACV a estructures de formigó i s'ha aplicat a un cas pràctic emprant dues bases de dades diferents. L'elaboració del treball no ha estat exempta de limitacions, donades les restriccions d'accés a articles científics així com a les eines informàtiques i a bases de dades per a la utilització pràctica de la guia. De l'aplicació de l'eina a un cas d'estudi, en què es comparaven dues estructures de formigó, s'ha desprès la seva utilitat per identificar ítems del procés constructiu (com ara les fases del cicle de vida o les unitats d'obra) susceptibles de millora, així com per a comparar i seleccionar alternatives més sostenibles. No obstant això, el treball efectuat també ha permès observar que l'aplicació de l'ACV a estructures de formigó en el sector de la construcció pateix de dos problemes essencials que afecta a la fiabilitat dels seus resultats, que són: manca de dades específiques del sector i les hipòtesis introduïdes per l'usuari. Per tant, i després d'haver analitzat l'aplicabilitat de l'ACV a estructures de formigó, s'ha apreciat que la seva generalització i posada en pràctica a casos reals passa per la millora dels dos aspectes apuntats anteriorment.

PARAULES CLAU: Sostenibilitat; Anàlisi del Cicle de Vida (ACV); aplicabilitat; construcció; estructura; formigó.

C.1. EXECUTIVE SUMMARY.

Global population is continuously growing, as its demand for both resources and goods/services. This situation leads to a progressive depletion of the planet's natural resources, as well as an increase in the generation and emission of pollutants, whose main sign of their impact is found on global warming. Meanwhile, according to results of several studies, the construction sector is responsible in developed countries about 40% of energy resources consumed and wastes generated annually. Thus it is evident the relevance and contribution of construction industry to the nowadays global environmental framework.

In order to achieve the goal of sustainable development, it is essential to undertake measures aimed at reducing the environmental impacts of the construction industry. This objective can be achieved by incorporating new methodologies and tools with greater environmental component, such as Life Cycle Assessment (LCA). LCA is a tool for environmental assessment that allows calculating impacts generated during the life cycle of a product or service. It has been integrated to the date into other productive sectors its related impacts. With its incorporation into the field of construction, the industry would account a tool to identify and evaluate those processes that offer more environmental impact, or what is the same, a tool to improve the efficiency of environmental measures applied.

In this final work for the Masters in Planning and Management in Civil Engineering attention has been focused on analysing the applicability of LCA to concrete structures, as a tool to identify the impacts caused by its construction. It has also been sought to propose a guide to realize its implementation, taking into account the characteristics and limitations of the tool, for the assessment of the impacts caused throughout the life cycle of a concrete structure (from obtaining raw materials, through construction and put into operation until its final demolition).

To do this, as a first step a literature search of articles and documents published to date regarding the applicability of LCA to concrete structures was performed. This phase was carried out using a defined search strategy that allowed recovering the articles and scientific publications related to the topic, coming from different databases (such as IEEE Xplore, Science Direct or Scopus), and subsequently analysed in a quantitative way. From the analysis results obtained, we observed that the issue turns out to be relative present, since most of the publications date back 15 years (since 1996). On the other hand it was also observed that the greatest number of publications came from the United States (around 28.60% of the total). However, by adding the different countries according to their respective continents, Europe exceeds the number of publications when compared to America's (a 48.20% vs. 34.50%, respectively). At the same time, it was observed that Chinese publications have increased its contribution to the subject in recent years, resulting in about 13.70% of all articles have been published in that country. As what

comes to the authors, it was found that only 5% of them had published 3 or more times relating to the topic, and the majority (in particular 87.30%) had only published on one occasion. On the other hand, when analysing the articles that had received more citations, it was noted that 2008 was the year when more items of this type were published and that its origin was essentially the United States, but followed closely by Sweden. Finally, it was observed that approximately 58.20% of the journals in which articles were published on the topic were included in the ISI Journal Citation Report 2010, and mainly its impact indexes were above 2.00.

Then, based on the information contained in various publications recovered from the bibliographic research, it was carried out a qualitative analysis. This analysis allowed obtaining the information for describing the state of the art on the applicability of LCA to concrete structures. Looking at the state of the art, it can be appreciated the existence of a variety of methodological proposals for LCA studies, but it is emphasized the methodology offered by other ISO standards 14040 and 14044, due to its standardized and internationally compound. Then, with the aim of deepening in LCA' state of the art, a SWOT analysis was conducted contrasting its internal characteristics (opportunities vs. weaknesses) and external characteristics (strengths vs. weaknesses), respectively. Resulting from this contrast, three conclusions/proposals were extracted relating to: reduction of assumptions introduced by practitioners, measures to enhance accessibility to data needed when performing LCA studies, and development of the tool for incorporating to the methodology both economic and social considerations.

Once the state of the art and its analysis was developed, it was proposed a methodological guide for the application of LCA to concrete structures. Previously, an analysis of major studies for concrete structures found among scientific articles was performed, establishing for each of them (among others) the methodology used the scope of the study and the environmental impacts considered. This was followed by a description of the full life cycle of a concrete structure, and then passed to presenting the guide. This guide includes the conditions and constraints specific for the tool, identified during the development of state of the art, and to take into account when analysing a concrete structure with an LCA study.

For the practical application of the guide, it was set out a case study based on the comparison of two reinforced concrete structures of a building for residential use. This case study was obtained from the automatic designing module offered by the structural calculation software CYPE. Then each alternative's material requirements for the execution of the structure were quantified and it was proceeded to apply the proposed guide particularized for concrete structures. Given existing constraints in resources and accessibility, life cycle considered in the study was reduced (it was considered until the construction phase) and the assessed the impacts were the ones relating to energy consumption (MJ) and CO_2 emissions (kg). To this end, two databases were considered, one provided by the environmental impact assessment-ACV from the commercial software ARQUÍMEDES (CYPE) and the database BEDEC (ITeC). The results obtained show that the life cycle phase that produces more impact on the environment (as far as energy consumption and CO_2 emissions are concerned) coincide with the production phase of the materials used for construction of the structure, regardless of the alternative or database concerned. However, when assessing the alternatives it was noted that Alternative A (one-way slab) showed better performance than Alternative B (multi-way continuous slab) when considering data obtained from ARCHIMEDES but, when considering BEDEC, Alternative B offered best performance. Therefore the results throw inconstancy as, depending on the source of data considered, the results were directly opposite.

The work has helped providing a more accurate view of LCA's practice on concrete structures, noting the potential and problems existing within the tool. However, although it has been found that its implementation is feasible, the tool inevitably requires an increase and improved of construction related data relating, as well as the development of methods more specific of construction environment as also covering a broader spectrum of the life cycle of construction designs (raw materials extraction, production of materials, construction, operation/maintenance and demolition/reuse). Furthermore, among the different advantages that LCA counts with for its practice as more global decision-making tool, it is found its integration of both economic and social issues for, when selecting alternative during decision-making processes, it allows considering the triple-bottom objectives of sustainable development. This, as it has been observed during this work, is in very initial phases of development and still requires of great improvement and development to reach a complete integration and practice as a decision-making tool during decision-taking processes encounter on the life-cycle of a concrete structure.

C.2. RESUMEN EJECUTIVO.

La población mundial crece continuamente y, de un modo paralelo, su demanda tanto de recursos como de bienes de consumo y servicio. Está situación conduce a un progresivo agotamiento de los recursos naturales del planeta, así como a un incremento en la generación y emisión de contaminantes, que tienen como principal muestra de su repercusión el calentamiento global. Por su parte, según resultados aportados por diversos estudios, el sector de la construcción es responsable en los países desarrollados de aproximadamente un 40% de los recursos energéticos consumidos y residuos generados anualmente. Así pues, es patente la relevancia y contribución que tiene el sector de la construcción al marco medioambiental mundial.

Con la finalidad de alcanzar el objetivo de un desarrollo más sostenible, resulta indispensable acometer medidas encaminadas a la reducción de los impactos ambientales derivados de la industria de la construcción. Dicho objetivo puede ser alcanzado mediante la incorporación de nuevas metodologías y herramientas que tengan una mayor componente medioambiental, como es el caso del Análisis del Ciclo de Vida (ACV). El ACV es una herramienta de evaluación medioambiental que permitir calcular los impactos generados durante el ciclo de vida de un producto o servicio. A fecha de hoy, ya se ha integrado en otros sectores productivos con buenos resultados a la hora de valorar y elegir alternativas más sostenibles y, por lo tanto, reducir los impactos asociados. Con su incorporación al ámbito de la construcción se contaría con una herramienta capaz de identificar y evaluar aquellos procesos que más impacto medioambiental ofrecieran, o lo que es lo mismo, se contaría con una herramienta que mejoraría la eficiencia de las medidas de mejora medioambiental del sector de la construcción.

En este Trabajo Final del Máster en Planificación y Gestión en Ingeniería Civil se ha enfocado la atención en analizar la aplicabilidad del ACV a estructuras de hormigón, como herramienta para identificar los impactos ocasionados por su construcción. Igualmente se ha buscado proponer una guía para poder materializar su aplicación, teniendo en cuenta las características y limitaciones propias de la herramienta, a la hora de analizar los impactos ocasionado a lo largo del ciclo de vida del hormigón estructural (desde la obtención de las materias primas, pasando por su construcción y puesto en funcionamiento, hasta su demolición final).

Para ello, como primera fase se procedió a realizar una búsqueda bibliográfica de los artículos y documentación publicada hasta la fecha en relación a la aplicabilidad del ACV a estructuras de hormigón. Dicha fase se efectuó mediante la utilización de una estrategia de búsqueda que permitió recuperar los artículos y publicaciones científicas relacionadas con el tema, las cuales procedían de diferentes bases de datos (tales como IEEE Xplore, Science Direct or Scopus), y que posteriormente se analizaron cuantitativamente. De los resultados obtenidos tras dicho análisis, se observó que el tema resulta ser de una relativa actualidad, dado que la mayoría de las publicaciones se remontan unos 15 años (desde el año 1996). Por otro lado se observó también que el mayor número de publicaciones provienen de los Estados Unidos (en torno a un 28,60% del total). Sin embargo, al agregar los diferentes países según sus respectivos continentes, Europa rebasa el número de publicaciones que presenta América (un 48,20% frente a un 34,50%, respectivamente). A su vez, se apreció que las publicaciones provenientes de China han incrementado en los últimos años su aportación al tema, resultando que en torno al 13,70% del total de artículos han sido publicados en dicho país. En cuanto a los autores, se apreció que únicamente un 5% de los mismos habían publicado 3 o más artículos relacionados con el tema y que la mayoría (en concreto el 87,30%) sólo había publicado en una única ocasión. Por otro lado, al analizar los artículos que mayor número de citas habían recibido, se observó que el 2008 fue el año en el que más artículos de este tipo se publicaron y que su procedencia era eminentemente de Estados Unidos, pero seguida muy cerca por Suecia. Finalmente, se observó que aproximadamente el 58,20% de las revistas en la que se habían publicado artículos relacionados con el tema estaban incluidas en el ISI Journal Citation Report del año 2010, y que mayoritariamente sus índices de impacto eran superiores a 2,00.

A continuación, y partiendo de la información contenida en las diferentes publicaciones obtenidas tras la búsqueda bibliográfica, se procedió a realizar un análisis cualitativo de los mismos. Dicho análisis permitió obtener la información a exponer en la descripción del estado del arte sobre la aplicabilidad del ACV a las estructuras de hormigón. Al contemplar el estado del arte se aprecia la existencia de una gran variedad de propuestas metodológicas para la realización de un estudio ACV, destacando sobre el resto la metodología ofrecida por las normas ISO 14040 y 14044, dado su carácter estandarizado e internacional. Seguidamente, con el objetivo de profundizar en el estado del ACV, se llevó a cabo en el trabajo un análisis D.A.F.O. contrastando sus características internas (debilidades versus fortalezas) y sus externas (amenazas versus oportunidades), respectivamente. De ese contraste, se extrajeron un total de tres conclusiones/propuestas que inciden sobre aspectos como son: la reducción de la variabilidad de resultados introducida por los usuarios, medidas encaminadas a permitir la accesibilidad de datos necesarios para la elaboración de los estudios y desarrollo de la herramienta para que considere tanto aspectos económicos y sociales como medioambientales.

Una vez desarrollado el estado del arte, y efectuado un análisis del mismo, se pasó a proponer una guía metodológica para la aplicación del ACV a estructuras de hormigón. Previamente se realizó un análisis de los principales estudios en estructuras de hormigón encontrados entre los artículos científicos, estableciendo para cada uno de ellos (entre otros) la metodología utilizada, el alcance del estudio y los impactos medioambientales considerados. A continuación se efectuó una descripción del ciclo de vida completo para una estructura de hormigón, y seguidamente se pasó a la mencionada guía. Dicha guía incluye los condicionantes y limitaciones propios de la herramienta, identificados durante la elaboración del estado del arte, y a tener en cuenta a la hora de analizar una estructura de hormigón con la herramienta ACV.

Para la aplicación práctica de la guía se propuso un caso de estudio basado en la comparación de dos estructuras de hormigón armado de un edificio de uso residencial, elaborado a partir del módulo de pre-dimensionamiento ofrecido por un software comercial de cálculo de estructuras (CYPE). A continuación, se cuantificaron las diferentes cantidades de materiales necesarias para la ejecución de cada alternativa y se procedió a aplicar el método ACV particularizado a estructuras de hormigón propuesto en la guía. Dadas las limitaciones existentes en materia de recursos y accesibilidad a bases de datos, se efectuó una reducción de ciclo de vida considerando en el estudio (hasta la fase de construcción) y se valoraron los impactos relacionados con la energía consumida (MJ) y las emisiones de CO_2 (kg). Para ello, se recurrió a dos fuentes de datos diferentes, una ofrecida por el módulo de evaluación de impacto ambiental-ACV del software comercial Arquímedes (CYPE) y por la base de datos del BEDEC (ITeC). De los resultados obtenidos se observa que la fase del ciclo de vida que más repercusión produce en el medioambiente (en lo que a consumos energéticos y emisiones de CO_2 se refiere) coindice con la fase de producción de los materiales empleados para la construcción de la estructura, independientemente de la alternativa o base de datos considerada. No obstante, al valorar las alternativas se observó que la Alternativa A (forjado unidireccional) presentaba mejor comportamiento que la Alternativa B (forjado de losa maciza) cuando se consideraba la base del ARQUÍMEDES-ACV y que, al considerar BEDEC, la alternativa B era la que ofrecía mejor comportamiento. Es decir, se encontró con la incongruencia de que, dependiendo de la fuente de datos considerada, los resultados obtenidos eran opuestos.

El trabajo ha permitido ofrecer una visión más aproximada sobre la aplicación del ACV a estructuras de hormigón, observando las potencialidades y problemáticas de la herramienta. Sin embargo, a pesar de que se ha comprobado que su aplicación es viable, la herramienta ineludiblemente requiere un incremento y mejora de los datos relacionados con los impactos medioambientales del sector de la construcción, así como el desarrollo de la metodología para que resulte ser más específica del sector de la construcción y cubra un mayor espectro del ciclo de vida de los proyectos de construcción (extracción materias primas, producción de materiales/construcción, operación/mantenimiento y demolición/reutilización). Además, y entre los diferentes puntos con los que ACV cuenta para su aplicación más global como herramienta de decisión final, se encuentra su integración junto con aspectos de índole económico y social para que, a la hora de llevar a cabo la toma de decisiones, permita tener en cuenta las tres componentes del desarrollo sostenible. Esto mismo, tal y como se ha observado durante la realización de la tesina, está en fases aún muy tempranas y le queda aún evolucionar para alcanzar una completa integración y aplicación como herramienta de decisión final en procesos de toma de decisiones.

C.3. RESUM EXECUTIU.

La població mundial creix contínuament i, al mateix temps, la seva demanda tant de recursos com de béns de consum i servei. Està situació condueix a un progressiu esgotament dels recursos naturals del planeta, així com a un increment en la generació i emissió de contaminants, que tenen com a principal mostra de la seva repercussió l'escalfament global. Per la seva banda, segons resultats aportats per diversos estudis, el sector de la construcció és responsable en els països desenvolupats d'aproximadament un 40% dels recursos energètics consumits i residus generats anualment. Així doncs, és palesa la rellevància i contribució que té el sector de la construcció al marc mediambiental mundial.

Amb la finalitat d'assolir l'objectiu d'un desenvolupament més sostenible, és indispensable emprendre mesures encaminades a la reducció dels impactes ambientals derivats de la indústria de la construcció. Aquest objectiu pot ser aconseguit mitjançant la incorporació de noves metodologies i eines que tinguin una major component mediambiental, com és el cas de l'Anàlisi del Cicle de Vida (ACV). L'ACV és una eina d'avaluació mediambiental de permetre calcular els impactes generats durant el cicle de vida d'un producte o servei. A data d'avui, ja s'ha integrat en altres sectors productius amb bons resultats a l'hora de valorar i triar alternatives més sostenibles i, per tant, reduir els impactes associats. Amb la seva incorporació a l'àmbit de la construcció es comptaria amb una eina capaç d'identificar i avaluar aquells processos que més impacte mediambiental oferissin, o el que és el mateix, es comptaria amb una eina que milloraria l'eficiència de les mesures de millora mediambiental del sector de la construcció.

En aquest Treball Final del Màster en Planificació i Gestió en Enginyeria Civil s'ha enfocat l'atenció en analitzar l'aplicabilitat de l'ACV a estructures de formigó, com a eina per identificar els impactes ocasionats per la seva construcció. Igualment s'ha buscat proposar una guia per poder materialitzar la seva aplicació, tenint en compte les característiques i limitacions pròpies de l'eina, a l'hora d'analitzar els impactes ocasionat al llarg del cicle de vida del formigó estructural (des de l'obtenció de les matèries primeres, passant per la seva construcció i posat en funcionament, fins a la seva demolició final).

Per a això, com a primera fase es va procedir a realitzar una recerca bibliogràfica dels articles i documentació publicada fins ara en relació a l'aplicabilitat de l'ACV a estructures de formigó. Aquesta fase es va efectuar mitjançant la utilització d'una estratègia de recerca que va permetre recuperar els articles i publicacions científiques relacionades amb el tema, les quals procedien de diferents bases de dades (com ara IEEE Xplore, Science Direct or Scopus), i que posteriorment es van analitzar quantitativament. Dels resultats obtinguts després d'aquest anàlisi, es va observar que el tema resulta ser d'una relativa actualitat, atès que la majoria de les publicacions es remunten uns 15 anys (des de l'any 1996). D'altra banda es va observar també que el major nombre de publicacions provenen dels

Estats Units (al voltant d'un 28,60% del total). No obstant això, en agregar els diferents països segons els seus respectius continents, Europa sobrepassa el nombre de publicacions que presenta Amèrica (un 48,20% enfront d'un 34,50%, respectivament). Al seu torn, es va apreciar que les publicacions provinents de la Xina han incrementat en els últims anys la seva aportació al tema, resultant que al voltant del 13,70% del total d'articles han estat publicats en aquest país. Quant als autors, es va apreciar que únicament un 5% dels mateixos havien publicat 3 o més articles relacionats amb el tema i que la majoria (en concret el 87,30%) només havia publicat en una única ocasió. D'altra banda, en analitzar els articles que major nombre de citacions havien rebut, es va observar que el 2008 va ser l'any en què més articles d'aquest tipus es van publicar i que la seva procedència era eminentment dels Estats Units, però seguida molt a prop per Suècia . Finalment, es va observar que aproximadament el 58,20% de les revistes en què s'havien publicat articles relacionats amb el tema estaven incloses en l'ISI Journal Citation Report de l'any 2010, i que majoritàriament els seus índexs d'impacte eren superiors a 2,00 .

A continuació, i partint de la informació continguda en les diferents publicacions obtingudes després de la recerca bibliogràfica, es va procedir a realitzar una anàlisi qualitativa dels mateixos. Aquesta anàlisi va permetre obtenir la informació a exposar en la descripció de l'estat de l'art sobre l'aplicabilitat de l'ACV a les estructures de formigó. En contemplar l'estat de l'art s'aprecia l'existència d'una gran varietat de propostes metodològiques per a la realització d'un estudi ACV, destacant sobre la resta la metodologia oferta per les normes ISO 14040 i 14044, donat el seu caràcter estandarditzat i internacional. Seguidament, amb l'objectiu d'aprofundir en l'estat de l'ACV, es va dur a terme a la feina una anàlisi DAFO contrastant les seves característiques internes (debilitats versus fortaleses) i les seves externes (amenaces versus oportunitats), respectivament. D'aquest contrast, es van extreure un total de tres conclusions / propostes que incideixen sobre aspectes com són: la reducció de la variabilitat de resultats introduïda pels usuaris, mesures encaminades a permetre l'accessibilitat de dades necessàries per a l'elaboració dels estudis i desenvolupament de l'eina perquè consideri tant aspectes econòmics i socials com mediambientals.

Un cop desenvolupat l'estat de l'art, i efectuat una anàlisi del mateix, es va passar a proposar una guia metodològica per a l'aplicació de l'ACV a estructures de formigó. Prèviament es va realitzar una anàlisi dels principals estudis en estructures de formigó trobats entre els articles científics, establint per a cada un d'ells (entre altres) la metodologia utilitzada, l'abast de l'estudi i els impactes mediambientals considerats. A continuació es va efectuar una descripció del cicle de vida complet per a una estructura de formigó, i seguidament es va passar a l'esmentada guia. Aquesta guia inclou els condicionants i limitacions propis de l'eina, identificats durant l'elaboració de l'estat de l'art, i a que tenir en compte a l'hora d'analitzar una estructura de formigó amb l'eina ACV.

Per a l'aplicació pràctica de la guia es va proposar un cas d'estudi basat en la comparació de dues estructures de formigó armat d'un edifici d'ús residencial, elaborat a partir del mòdul de predimensionament influït a un programa comercial de càlcul d'estructures (CYPE). A continuació, es van quantificar les diferents quantitats de materials necessàries per l'execució de cada alternativa i es va aplicar el mètode ACV particularitzat a estructures de formigó proposat a la guia. Donades les limitacions existents en matèria de recursos i accessibilitat a bases de dades, es va efectuar una reducció de cicle de vida considerant en l'estudi (fins a la fase de construcció) i es van valorar els impactes relacionats amb l'energia consumida (MJ) i les emissions de CO_2 (kg). Per a això, es va recórrer a dues fonts de dades diferents, una oferta pel mòdul d'avaluació d'impacte ambiental-ACV del programari comercial Arquímedes (CYPE) i per la base de dades del BEDEC (ITeC). Dels resultats obtinguts s'observa que la fase del cicle de vida que més repercussió produeix en el medi ambient (en el que a consums energètics i emissions de CO_2 es refereix) coincideix amb la fase de producció dels materials emprats per a la construcció de l'estructura , independentment de l'alternativa o base de dades considerada. No obstant això, en valorar les alternatives es va observar que l'alternativa A (sostre unidireccional) presentava millor comportament que l'alternativa B (forjat de llosa massissa) quan es considerava la base del ARQUIMEDES-ACV i que, en considerar BEDEC, l'alternativa B era la que oferia millor comportament. És a dir, es va trobar amb la incongruència que, depenent de la font de dades considerada, els resultats obtinguts eren oposats.

El treball ha permès oferir una visió més aproximada sobre l'aplicació de l'ACV a estructures de formigó, observant les potencialitats i problemàtiques de la eina. No obstant això, tot i que s'ha comprovat que la seva aplicació és viable, l'eina ineludiblement requereix un increment i millora de les dades relacionades amb els impactes mediambientals del sector de la construcció, així com el desenvolupament de la metodologia perquè resulti ser més específica del sector de la construcció i cobreixi un major espectre del cicle de vida dels projectes de construcció (extracció matèries primes, producció de materials/construcció, operació/manteniment i retirada/reutilització). A més, i entre els diferents punts amb què ACV compta per a la seua aplicació més global com a eina de decisió final, es troba la seva integració juntament amb aspectes d'índole econòmic i social perquè, a l'hora de dur a terme la presa de decisions, permeti tenir en compte les tres components del desenvolupament sostenible. Això mateix, tal com s'ha observat durant la realització de la tesina, està en fases encara molt primerenques i li queda encara evolucionar per assolir una completa integració i aplicació com a eina de decisió final en processos de presa de decisions.

0. CONTENTS.

INTRODUCTION

1. INTRODUCTION.

In this first chapter of the master's work, a general introduction of its main contents will be exposed. It begins offering a background of nowadays society's environment problems, as the importance of implementing measures and practices (such as Life Cycle Assessment's results inclusion to decision-making processes) for achieving sustainability's goal in the future. Next, main characteristics of the work (object, objective, scope ...) and methodology for acquiring and analysing the recovered information will be introduced. Finally, at the end of the chapter, a description of the structure and sections the work is divided into will be presented.

1.1. Background.

World's population overpassed the seven billion people last October 2011, according to the latest report "*The State of World Population 2011*" by the United Nations Population Fund (UNFPA [199]). Moreover, the report establishes that population is expected to increase another billion in the next thirteen years. However, it is a fact that population growth is not directly attached to human development. If a look is taken to the "*Human Development Report 2011*" prepared by United Nations Development Programme (UNDP [193]), approximately 24% of the countries considered at the study are included in the Low Human Development Index group.

Therefore population growth has not agreed with improvement of well-being and poverty eradication in low developed countries. This trend is being modified by emerging countries, which are increasing their demand for resources and supplies as their economic growth and development maintains.

When considering future resource's consumptions, according to the "*Decoupling Report 2011*" by United Nations Environment Programme (UNEP [194]), it is estimated that by 2050 humanity will consume 140 billion tonnes per year of minerals, ores, fossil fuels and biomass (three times its current value). Furthermore, as it has been established in the "*International Energy Outlook 2011 (IEO2011)*" by the U.S. Energy Information Administrations (EIA [200]), nowadays world's marketed energy consumption (which amounts to 505 quadrillion Btu) is projected to increase by up to 53% between 2008 and 2035.

Energy consumption and resource depletion are not the only impacts humanity is causing to the Earth. By industry, transportation or construction activities (among others) carbon dioxide and other pollutants are being issued to the environment, as well as great amounts of waste production. Of all pollutants generated, carbon dioxide emissions (also called greenhouse gas) are the most important as being the main responsible of Global Warming.

According to the "*Special Report on Emissions Scenarios (SRES, 2000)*" published by the Intergovernmental Panel on Climate Change (Nakicenovic et al [189]), an increase of global GHG emissions (CO_2-eq.) in a 25-90% ranges is expected between 2000 and 2030, which will produce a temperature increase of 0.2ºC per decade.

So it can be stated that nowadays world's scenario of growth population, increase of resource consumption and emission of pollutants, is driving the planet resources to a critical situation. If a look is taken at "*Living Planet Report 2010*" World Wide Fund for Nature (WWF [203]), based on calculations of Global Footprint Network by 2007 humanity overpassed Earth's bio-capacity by 1.5 times. But most worrying, predictions for 2030 show that humanity will need two Earth's bio-capacity to provide its natural resource consumption and absorb all the CO_2 emissions produced.

At a first approach to the situation, there is no single solution to mitigate or prevent environmental problems caused by humanity, but the pursuit of Sustainable Development can be a proper start. Many policies and measures, coming both from public and private parties, have already been implemented to reduce environmental pressures (energy efficiency, environmental labelling, environmental management, etc.). At the same time different tools and methods have been released for equal purposes, as the environmental assessment tool Life Cycle Assessment (from now on referred as LCA) that, since its emergence in the mid 60's, has widespread its use (even its application is standardized by the ISO 14040).

In this work attention, from an environmental point of view, wants to be focused over the Construction Industry but more specifically over concrete structures. Applications of concrete in construction are wide and extensive (from piping, masonry or flooring to foundations), but the use by excellence in the construction sites is concrete structures. Main problem with concrete's production is it claims extraction of high quantities of raw materials and requires great energy supplies (mainly because of Portland's cement production). Moreover, nowadays practice by construction project designers is to overview environmental problems when taking decisions and alternatives, and focusing on different issues as durability, economic, performance, or even aesthetic criteria.

Hence, environmental improvement and development of more sustainable concrete structures for architecture and civil engineering designs is a must within the construction industry, objective than can be achieved by the inclusion of LCAs at the different stages of construction designs life cycle. A research about the state of the art related to the applicability of LCA to concrete structures will be elaborated, indicating its main characteristics and issues, and offering an example of its application for the environmental assessment of a concrete structure.

1.2. Research.

1.2.1. Object.

This work aims at analysing and establishing the state of the art relating the application of LCA technique in the construction industry, but more specifically to its application for environmental assessment of concrete structures. This paper wants to give a complete vision of LCA main strengths and disadvantages and, at the same time, offer a guide model for the application of LCAs to concrete structures, such as: building structures, bridges, power plants, etc.

1.2.2. Objectives.

There are, at least, six main recognizable objectives within the work at hand:

- Develop a bibliographic research related to the applicability of LCA on concrete structures.
- Set the theoretical framework about LCA and concrete structures in the construction environment.
- Analyse the state of the art about LCA applied to concrete structures, starting by the results obtained in the bibliographic research.
- Obtain the evolution of researching tendencies.
- Expose a methodological guide to practitioners of LCA in the construction environment for assessing concrete structures.
- Introduce a case study for the application of an LCA on a concrete structure following the methodological guide previously exposed.

But at the same time, it is also possible to point some other secondary objectives related to this work:

- Identify the actual framework about environment politics worldwide.
- Set the importance of construction industry, in relation to sustainability and environmental policies.
- Set the responsibility of energy consumption and environmental contamination by construction industry.
- Demonstrate the applicability and usefulness of LCA as a tool for assessing construction activities.
- Analyse pros and cons related to LCA applicability on assessing concrete structures.
- Expose future lines of work for the topic.

1.2.3. Justification.

Construction industry, as one of the most relevant economic sectors, high raw materials claimant, energy consumer and pollutant-emitting activity of today's worldwide society; must increase its environment-friendliness if sustainable development wants to be a feasible objective. Moreover, nowadays practice by construction project designers and constructors contractors is to overview environmental problems when taking decisions and alternatives, and focusing on different "more important" issues such as: durability, economic, performance, or even aesthetic criteria. As LCA is a tool that enables improvement of environmental issues by identifying highly pollutant products and services, its application and integration in the different phases of construction projects has to be reached by all the stakeholders included in the process.

1.2.4. Hypothesis.

The initial hypothesis, are the ones exposed as followed:

- LCA technique can be applied for the environmental evaluation of construction processes.
- Concrete structures life cycle is improvable from an environmental point of view.
- LCA is a competitive tool to identify deficiencies in construction processes.

1.2.5. Scope.

- Geographically: it is worldwide, as it can be applied in every country where a concrete construction is done.
- Language: it has been restraint to English, Spanish, Portuguese and French languages as are the ones that the writer of this work could manage. Obviously, English is the one predominant due to its worldwide diffusion for scientific knowledge.

1.3. Methodology.

The methodology followed to accomplish the document can be structured in six different phases:

1. Compilation.
2. Registry and storing.
3. Analysis of articles.
4. State of the art.
5. Guideline and case study.
6. Discussion and recommendations.

1.3.1. Compilation.

It consists on the research of scientific articles, conference proceedings, books and PhD thesis. Compilation is first performed by the use of a research strategy based on a mix of keywords that, in our case, were: “Life Cycle Assessment”, “structures” and “concrete”. Also, it was used the rules and standards related to the topic at a Spanish, European and International scope.

As the number of documents obtained from this research strategy was not enough for a later analysis of articles and the state of the art, it was needed to perform another research. This second research was made fixing on the references from articles acquired first.

1.3.2. Registry and storing.

All the references recover from the compilation, were organized and registered using the bibliography database manager RefWorks. Following this process, as a way to help later articles and information analysis, a spread sheet was prepared. It included useful information as: authors, date of publication, geographical allocation, keywords, etc. Finally, the information articles recovered from the research as the mentioned spreadsheet, were included in the online storage space Dropbox to allow future consultations by interested researchers and practitioners.

1.3.3. Analysis of articles.

Starting from the preceding spread sheet, an analysis of the articles recovered was performed taking into account aspects as: time-line evolution of publications, distribution of journals publication, distribution of authors, countries’ distribution of publications, quality of articles and publications (JCR-2010), or sub-topics treated (keywords). Then, graphical exposition of the information and conclusions reached was made.

1.3.4. State of the art.

To achieve an accurate state of the art about the topic, all information included on the articles recovered from the research was evaluated to determine the potential contribution to the study. This evaluation consisted on a review of their abstract and keywords, to quickly assess its relevance and adequacy on the topic treated at this work. Once the best articles related to the topic were identified (according to their relation to applicability of LCA to concrete structures), information was extracted and distributed into the four fields the state of the art was divided in:

- Life Cycle Assessment typologies and its practice on LCA concrete structures studies.
- Tools, software and databases and its practices on LCA concrete structures studies.
- Life Cycle Assessment's S.W.O.T. analysis.
- Life Cycle Assessment case studies on construction industry and concrete structures.

1.3.5. Guide and case study.

A guide for the application of LCA was developed at the work, basing on the information obtained from the state of the art performed, including the resolution of the methodological issues encountered within its practice. It was also focused for the exclusive appliance over concrete structures, it means, taking into consideration its special characteristics (materials, life cycle…) Next, in order to offer an example on how the guideline should be applied for practitioners of LCA on the field of concrete structure construction, a case study was performed comparing two types of residential concrete structures on the Spanish environment. For their assessment, it was required the use of two different databases (Arquímedes-ACV and BEDEC). Finally the results obtained were compared, in order to establish the grade of reliability of LCA results depending on the database selected and to extract conclusions.

1.3.6. Discussion and recommendations.

Finally, as last step of the methodology followed to complete this work, a discussion about the state of the art was carry out. The discussion was done in order to analyse the performed worked, from an objective point of view, and to establish the limitations and the recommendations for future researchers and practitioners of LCA methodology on concrete structures.

1.4. Structure.

This works is compound by an introduction, four body chapters, an ending chapter and one finally for references used, as it can be observed as followed:

1. Introduction.
2. Theoretical framework.
3. Research.
4. State of the art.
5. Guide and case study.
6. Discussion and recommendations.
7. References.

1.4.1. Introduction.

In the introduction chapter there are included four epigraphs: first the general background, secondly the research performed (which includes the statement of the problem: object of study, objectives, hypothesis and scope), third the methodology followed to accomplish the master's work and, finally, the structure of the work.

1.4.2. Theoretical framework.

In the second chapter it is included the theoretical framework, that compounds of four different epigraphs. First, the development of the sustainable thinking and the relation between sustainable development and the construction industry is analysed. Then a preliminary explanation of Life Cycle Assessment is exposed and finally an exposition of sustainable constructions or, more specifically, construction of concrete structures is established, as its potential utilization as a tool for turning construction industry into a more environmentally friendly activity.

1.4.3. Research.

In the third chapter, it is explained the research phase implemented to obtain the information for the later state of the art exposition and conclusions arrival. It is also displayed the different information achieved by the research.

1.4.4. State of the art.

The fourth chapter, which is divided in three epigraphs, includes the exposition of the state of the art developed from the analysis of articles carried out. It includes information about the different typologies of LCA that can be applied, the software and data resources available to the date and all from the point of view of its practice on concrete structures. Finally an S.W.O.T. analysis of the LCA is performed in order to identify its potential and its risky points to improve in the future.

1.4.5. Guide and case study.

The fifth chapter first offers some examples of Life Cycle Assessments already published that deal with the environmental assessment within the construction environment and, in a more accurate way, on concrete structures. Then a guideline and a case study for the use of Life Cycle Assessment to analyse the environmental performance of concrete structures are included on the work. Therefore it is divided in three paragraphs, one dedicated for the analysis of the published LCA studies on concrete structures, other for the exposition of the guideline and then another for the application of the case study.

1.4.6. Discussion and recommendations.

The sixth chapter includes a total of three paragraphs. First, a critical discussion on the results obtained from the state of the art and the appliance of the guideline on the case study is offered, which also includes the limitations encountered during the accomplishment of this work, as the recommendations for future researchers and practitioners (such as designers and construction managers among others) on the topic to avoid committing mistakes when performing an LCA. Finally, the review chapter ends by offering the conclusions of the work and, in addition, proposing future lines of research for the applicability of LCA technique to the construction industry.

1.4.7. References.

The last chapter of the work is for the exposition of the references used at the work. This is the part where all the articles recovered from the research phase are included. Moreover it contains literature related to the topic used for the state of the art, such as: scientific articles, conference proceedings, books, web pages, etc. This part of the work is mainly important for latter consultation on behalf of future researchers and practitioners interested on LCA applicability to concrete structures.

THEORETICAL FRAMEWORK

2. THEORETICAL FRAMEWORK.

In this second chapter of the work, there will be four lines of exposition. The first will deal with the topic of Sustainable Development, explaining first its appearance and evolution to actual dates, and then presenting some sustainable policies and measures already working on in public organizations. The second line will focus on the relation between construction industry and the environment, remarking the impacts due to construction all over the world, altogether with the introduction of some sustainable actions already taken into practice within the industry. After this an updated introduction to the situation of concrete and concrete structures within the construction industry (importance, environmental performance, etc…) and a connexion with the application of LCA will be established. Finally, at the last line of this chapter, the environmental tool LCA will be introduced, from the moment of its creation and evolution, as the most common methodology used for its practice (the standardized by ISO 14040 series).

2.1. Sustainable development.

2.1.1. Sustainable development: birth and evolution.

In 1987, under the charge of the World Commission on Environment and Development, took place the publication of "*Our Common Future*" or also known as the "*Brundtland Report*" (WCED [202]). This report was the first to introduce the concept of "*Sustainable Development*" (SD) as follows:

…"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"…

Latter in 1990, J.G. Speth (in his book "*Can the world be saved?*") and P. Ehrlich with A. Ehrlich (in "*The population explosion*"), established a connection between environment, economics and social goals of the world with the expression showed ahead (Van der Lugt et al [161]):

$$\boxed{EP = P \times W \times E} \tag{1}$$

In expression (1), EP stands for environment pressure (which had to be halved in a 50 years period starting from 1990), P stands for world population (which is predicted to double within 50 years), W stands for the average welfare rate of a world citizen (which is predicted to improve by 5 in 50 years) and E stands for environmental impact by welfare per citizen. The resolution of the expression (2) shows that for accomplishing a reduction of EP reduction by a half in 2040, the environmental load has to be decreased a factor 20 or, what is the same, a 95%.

$$1/2 = 2 \times 5 \times E \qquad (2)$$

Much discussion continued on years ahead relating the need of meeting with Sustainable Development aims. As an example, the United Nations Conference on Environment and Development (also called "*The Earth Summit*") that took place in 1992 at Rio de Janeiro accepted the Sustainable Development as a "triple-bottom-line" objective measurable by the consideration of three different values: social, economic and environmental (Reza et al [130]). Thereby, this conference was considered as a significant milestone that set a plan of action" for Sustainable Development, plan that received the name of "Agenda 21".

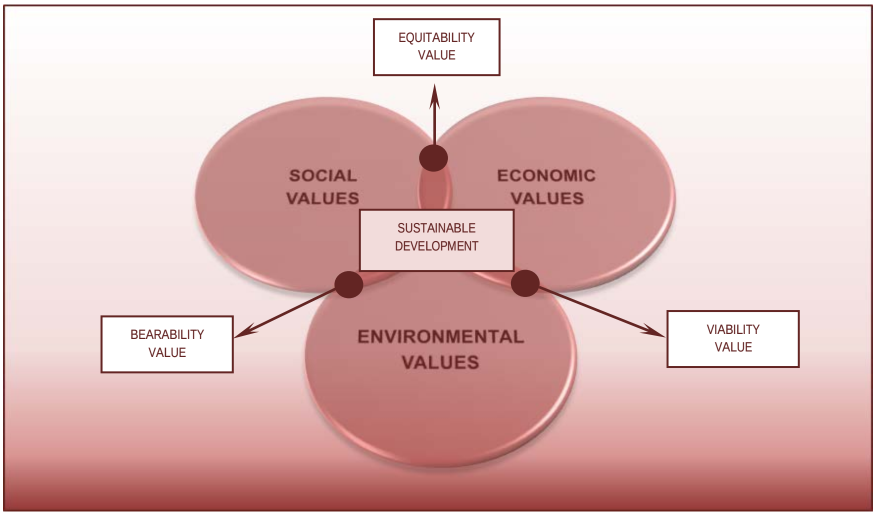


Figure 1: *Triple-Bottom-Line (TBL) of Sustainable Development. (Source: reproduced from Okon et al [110])*

Later, at the World Summit on Sustainable Development (WSSD) held in Johannesburg (South Africa) from 26 August to 4 September 2002 it is remarkable that the full implementation of "*Agenda 21*", the "*Programme for Further Implementation of Agenda 21*" and the "*Commitments to the Rio principles*", were strongly reaffirmed. In Johannesburg's meeting, leaders of many world national governments along with representatives from industry and civil society, took notice of the successes and failures of the past 30 years and looked at humanity's challenge in relation to Sustainable Development. Among others, the World summit led to a "*Plan of Implementation for Changing Unsustainable Patterns of Consumption and Production*" which main keys based on improving products and services without increasing the environmental and health impacts (Norris [107]).

Nevertheless, it was not until 1998 during the United Nations Framework Convention on Climate Change (UNFCCC) held in Japan, that an international agreement for environmental impact reduction became accorded. The major feature of the Kyoto Protocol (UNFCCC [195]), signed by 160 countries, was that established targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions. This amounts to an average of five per cent against 1990 levels, over a five-year period between 2008 and 2012.

As the first period of Kyoto's Protocol will end in 2012, its continuance was firstly treated at the Bali Climate Change Conference (UNFCCC [196]) in December 2007 and followed by the Cancun Agreements (UNFCCC [197]) Recently celebrated this past 2011, the Durban Climate Change Conference (UNFCCC [198]) remarked the importance of extending the period of validity for Kyoto's Protocol. However this extension was not finally accorded by the different parties related and a new end-of-line date has been delayed for 2015.

Next 20-22 of June 2012 it is expected to be held in Brazil the RIO+20 United Nations Conference on Sustainable Development (UNCSD [192]) which is expected to be the new milestone. During the conference, progressions done to the moment will be supervised, as future measures for accomplishing the goal of Sustainable Development. Mainly it will focus on two main themes:

- A green economy in the context of sustainable development and poverty eradication.
- The institutional framework for sustainable development.

YEAR	EVENT	DOCUMENT	ORGANIZER
1987	World Commission on Environment and Development	Our Common Future (also known as Brundtland Report)	UNCED
1992	Earth Summit in Rio	Agenda 21	UNCSD
1997	Kyoto Climate Change Conference	Kyoto Protocol	UNFCCC
2002	Johannesburg-World Summit on Sustainable Development	Plan of Implementation for Changing Unsustainable Patterns of Consumption and Production	UNCSD
2002	Bali Climate Change Conference	Bali Action Plan (also known as Bali Road Map)	UNFCCC
2007	Cancun Climate Change Conference	Cancun Agreements	UNFCCC
2011	Durban Climate Change Conference	Statements	UNFCCC
2012	RIO+20 United Nations Conference on Sustainable Development	-	UNCSD

Table 1: *Summary of relevant events relating sustainable development. (Source: own elaboration)*

2.1.2. Sustainable development: policies and politics.

Direct response to the *Kyoto Protocol* on behalf of the European Union took form in 1998 by the European Commission's communication "*Energy Efficiency in the European Community-Towards a Strategy for the Rational Use of Energy*" (EU Commission [213]). This communication reflected the European commitment to energy efficiency. Later in 2000 the European Commission would present the "*Action Plan to improve energy efficiency in the European Community*" (EU Commission [214]) aimed to meet the targets established by *Kyoto Protocol*. The Action Plan proposed a target of a 1% decrease per annum until 2010.

Five years after the Commission's action plan of 2000-06 on energy efficiency, it re-launched the debate at all levels of European society by the "*Green Paper on Energy Efficiency*" (EU Commission [216]). In 2006, based on the consultations of the "Green Paper", the European Commission adopted the "*Action Plan for Energy Efficiency (2007-2012)*" (EU Commission [217]). The Action Plan aimed achieving a 20% reduction in energy consumption by 2020, by improving (between other measures):

- Energy performance of products.
- Energy performance of buildings and services.
- Energy production and distribution.
- Rational energy consumption behaviour.

On the other hand, United States first position relating its ratification of the Kyoto Protocol was contrary. Nevertheless in 2002 took place the approval of the U.S. Climate Change Policy, with the objective to reduce the "greenhouse gas intensity" of the U.S. economy by 18% over a frontier period of 10 years (Kogan [85]). In order to meet the requirements established by this policy, the United States started diverse actions such as the ones offered ahead (Watson [247]):

- Design of more than 60 Federal programs (as for example the Nuclear Power 2010, Clean Air Rules…).
- Development of voluntary programs on behalf of US Department of Energy (DOE) and US Environmental Protection Agency (EPA) to supply guidance and advise both private companies and consumers.
- Incentives for carbon sequestration activities (as farms or forests).
- Finance for climate change programs and tax incentives for investing on science and technology.

On its behalf, although China ratified the Kyoto protocol in both 1997 and 2002, it was until 2007 that its position relating GHG emissions reduction did not take and official form. More accurately China's actual position has been established by the official documents National Climate Change Programme and China's Policies and Actions for Addressing Climate Change (Lo [93]). The first appeared in 2007 and, among the different strategies it contemplates, there are: decrease of R&D, energy efficiency (reduction of 20% by 2010), development of renewable and nuclear energy (increase its relevance into a 10% by 2010) or improvement of institutions and policies. The second was released in 2008 and is considered as a white paper and focused on China's position to address and cooperate on the international fight against climate change.

Regarding to the promotion and achievement of sustainability in all phases of product's life cycle, in 2003 the European Commission released the Integrated Product Policy (EU Commission [215]). As the complexity of the market is so wide, there is no single policy measure. On the contrary IPP includes include measures such as: economic instruments, substance bans, voluntary agreements, legislation or environmental labelling and product eco-design guidelines. Some more detailed examples of the application of IPP are offered next:

- The European Platform of Life Cycle Assessment project intends to promote life cycle thinking in business and in policy making in the European Union by providing data on products and services as well as consensus methodologies.
- As IPP is applied to all kind of products, no single policy tool is able to address all IPP aims. However, a combination of different policy instruments is needed: voluntary agreements, standardisation, environmental management systems, eco-design or eco-labelling and product declarations, etc.
- Work on identifying products consumed in the EU with greatest environmental improvements is carried in three phases (Kashreen et al [78]):
    - The Environmental Impact of PROducts (EIPRO) is the phase where products with the greatest environmental impact are identified.
    - Environmental Improvement of PROducts (IMPRO) is the second phase that attempts to identify different methods or production processes to reduce the environmental impacts.
    - In this third phase the European Commission will address policy measures for the products that are identified to have the greatest potential for environmental improvement at least socio-economic cost.

If a look is taken referring to product policies on other countries, one can find the Extended Producer Responsibility (EPR) policies in the United States and Canada. EPR is a policy that extends manufacturers responsibility over the whole life cycle of their product, but more especially on their end-of-life management (recovery and recycling). In the case of Canadian EPR regulations, according to an inventory conducted by the Canadian federal environmental agency in 2004, there were running a total number to 44 programmes. On the other hand, US state and federal governments EPR programmes continue focusing on voluntary initiatives but without a clear legislation support (Sheehan and Spielgeman [243]).

Furthermore, as a tool for implementing the IPP goals in the Europe context, in 1992 appeared the European Ecolabel program. Eco labelling consists on a voluntary testing procedure that awards the label to products and services that offer high environmental performance and quality, altogether allowing consumers to identify them on easy way (EU Commission [218]). On this same way works the Environmental Product Declarations is a procedure that lets quantifying environmental impacts of a product or service considering its whole life cycle. Summarising, environmental labels and declarations are the way to communicate information regarding the environmental aspects of products and services and that, at the same time, encourage the demand and supply of the ones with less environmental pressure.

On this sense, testing processes for acquiring Eco labels and performing product declarations were standardized in 1998 by the ISO 14020 series. According to the standard, environmental labels and declarations are divided into three types (Ritchie [132]):

- **Type I environmental labelling.** This environmental label (or "*Seal of Approval*") is awarded when a set of requirements is met, not just on the basis of a single attribute. The certification comes from a third party that authorizes the labelling basing on the mechanism provided by the ISO 14024:1999 "*Environmental labels and declarations--Type I environmental labelling--Principles and procedures*" (ISO [224]).
- **Type II environmental labelling.** Its procedure is standardized by the ISO 14021:1999 and consists of single-attributed self-declared environmental claims made by entities related to a product. It normally takes form as statements, symbols or graphics on product or package labels, product literature or technical bulletins (ISO [223]).
- **Type III environmental labelling.** This label is established by the ISO 14025:2006 "*Environmental labels and declarations--Type III environmental declarations--Principles and procedures*", and offers consumers a quantified environmental life cycle product information. The label is provided by the supplier and later verified by a third independent party (ISO [225]).

On its behalf, in 1992 the US Environmental Protection Agency (EPA) and the U.S. Department of Energy introduced the ENERGY STAR program, as a voluntary labelling program, with the objective of reducing GHG emissions by the identification and promotion of energy-efficient products. On its beginning, it started just on the computing sector, but nowadays ENERGY STAR label is applied to office equipment, lighting, home electronics, and even it covers new homes and commercial and industrial buildings (EPA [201]).

In the case of product labelling in China, it started in 1993 with the issue of the "*Circular Concerning the Establishment of the National Environmental Labelling Program*" by the State Environmental Protection Agency (SEPA). Later China's environmental labelling was officially launched by the creation of the Chinese Certification Committee for Environmental Labelling Products (CCEL) in May 1994 (CCICED [157])

Nevertheless work on product's environmental performance is one of the multiple trends and measures already put into practice. Green public procurement is one example for public authority's sustainable activities, which consists on a process to procure good, services or works with minimum environmental impacts all over their life cycle. As examples for this kind of procurement some examples are mentioned next:

- European Green Product Procurement (European Commission [219]) is an optional instrument for the Member States and public authorities. Since 2008, the Commission has developed 19 common GPP criteria, based on a life-cycle approach and scientific evidence base, for the selection of more environment-friendly optional products. Moreover, GPP implementation has been regularized by EU Directives 2004/17/EC (European Parliament [209]) and 2004/18/ED (European Parliament [210]).

- Environmentally Preferable Purchasing program is a US federal-wide program that encourages and assists federal governments purchasing environmentally preferable products and services. According to the US Environmental Protection Agency, EPP has five guiding principles (Fava [41]):
    - *Environment, Price, and Performance*. (EPP) Environmental considerations are to integrate as traditional criteria (cost, safety, availability, etc.) for selection of products.
    - *Pollution Prevention*. Consideration of environmental preference, emphasizing pollution prevention, should be included in the acquisition process.
    - *Life Cycle Perspective/Multiple Attributes*. Environmental preference of products and services should be examined from a life cycle perspective.
    - *Comparison of Environmental Impacts*. Determining environmental preference of products and services should pass by comparing their environmental impacts.
    - *Environmental Performance Information*. Including comprehensive, accurate, and meaningful information about the environmental performance of products or services is necessary in order to establish their environmentally preference.
- Policy on Green Procurement is a Canadian policy working since April 2006 with the objective of reducing the environmental impact of purchasing operations by Canadian public institutions. This is done by integrating environmental performance considerations into the procurement decision-making processes, all along the managerial phases (acquisition, use, operation and maintenance, and disposal or close-out activities), of goods and services acquisition (PWGSC [242]).

COUNTRY	GHG EMISSIONS	PRODUCT POLICY	ECOLABELLING	PROCUREMENT
EUROPE	Energy Efficiency in the European Community-Towards a Strategy for the Rational Use of Energy	Integrated Product Policy	EPD	European Green Product Procurement
USA	U.S. Climate Change Policy	EPR	Energy Star	Environmentally Preferable Purchasing program
CANADA	-	EPR	Energy Star	Policy on Green Procurement
CHINA	• National Climate Change Programme • China's Policies and Actions for Addressing Climate Change	-	Environmental Labelling Program	-

Table 2: *Summary of policies and politics related to sustainable development. (Source: own elaboration)*

2.2. Sustainable construction industry.

2.2.1. Construction industry impacts.

Construction environment activity is responsible for causing, on a directly or indirectly way, several worldwide environmental damages such as: raw materials extraction, pollutant emissions, waste generation, etc. This situation has been already studied and published in different reports, what has offered and allowed a better understanding of construction's responsibility on the environmental issues humanity is facing nowadays.

- According to data from the paper "*How ecology and health concerns are transforming construction*" of the Worldwatch Institute (1995), the construction of buildings consumes 40% of the stone, sand and gravel; 25% of timber and 16% of the water used annually in the world (Dimoundi and Tompa [32]).
- According to the Organisation for Economic Co-operation and Development, the building sector accounts for around 25-40% of final energy consumption in OECD countries (OECD [191]).
- Both in the European Union and the United States, construction and building sector have been estimated to be responsible a 40% of the whole environment impacts produced by their economies (Junilla et al [76]).
- Moreover, according to some studies, construction and demolition (C&D) waste may represent almost 40% of the total waste generations of a country (Vieira and Horvath [165]).

If we focus our attention to the European Union scope, we will be able to appreciate that…

- …aggregate consumption in Spain nowadays reached a total amount of 250 million tons, from which 220 million tons was directly due to construction environment (ACHE [240]).
- …the life cycle of buildings (construction, use and demolition) approximately contribute to 50% of energy consumption and GHG emissions to the atmosphere of all EU member states (Campogrande [20]).
- …, according to the final report of the SPAHOUSEC project conducted by "Instituto para la Diversificación y Ahorro de la Energía", Spanish building sector energy consumption represented in 2010 the 17% of the whole country energy demand (rate that rise to the 25% when looking at UE-27). (IDAE [188])
- …the construction and demolition wastes (C&DW) generated every year in the EU represent 31% of the total waste generation (Marinkovic [98]).

But, if we take a closer look at data coming from United States, it can be observed that…

- ….buildings in the US contribute to 36% of total energy use, 65% of electricity consumption, 30% of greenhouse gases emissions, 30% of raw materials use, 30% of output and 12% of potable water consumption (Mackley [41]).

- …consumption energy in 2006 by the residential sector was approximately 21% of the total energy consumption in the United States (Kahhat et al [77]).
- …54% of energy consumption in the United States is directly or indirectly related to buildings and their construction (Guggemos and Horvath [54]).
- …, at least every year 123 million tons of construction and demolition building related wastes are generated (Viera and Horvath [165]).

According to data related to Asian countries, it is possible to appreciate that…

- …building's energy consumption rate, when compared to complete energy consumption in China, has increased from a 10% at 1970s to 27.45% by 2007 (Xing et al [171]).
- …energy for the manufacture of building materials and construction phase in China amount each year close to the 25% of the national energy consumption (Ge [46]).
- …in 2008, consumption of cement, glass and steel for the construction of buildings in China accounted, respectively, for almost 40%, 45% and 30% of world's consumptions for this materials (Ge [46]).
- …building's energy consumption registered in China during 2005 generated approximately the 28% of all CO_2 emissions of the whole country (Yiewi et al [174]).
- …Japan's concrete production in 2000 accounted for 25% of the material input registered in that same year for the whole country (Noguchi and Fujimoto [106]).
- …Japan's waste totalled 458 million tons in 2000, of which demolished concrete accounted for 35 million tons (this is close to a 7.65%) (Noguchi and Fujimoto [106]).
- …primary energy demands registered by residential houses in Indonesia almost reach the 40%, mainly because of cooling (40%) and lighting (18%) (UTAMA and GHEEWALA [160]).

ISSUE	EUROPE	AMERICA	ASIA	WORLD
RESOURCE CONSUMPTION	88% aggregate (Spain)	30% raw materials 12% water	40% cement 45% glass 30% steel (2008 world's production)	40% aggregates 25% timber 16% water (1995)
ENERGY CONSUMPTION	50%	54%	25% (China, 2006) 40% (Indonesia, 2006)	25-40% (2003)
ENVIRONMENTAL IMPACTS	50% GHG emissions	30% GHG emissions	28% GHG emissions (China, 2005)	40%
WASTES	31%	123 million tonnes	Concrete wastes 8% (Japan, 2000)	40%

Table 3: *Summary of impacts due to construction industry activity. (Source: own elaboration)*

2.2.2. Sustainability in construction industry.

Since the 1990s, sustainability concern in construction industry has increased all over the world. Nowadays construction industry is interested in reducing the environmental impact of its products, as a consequence of global warming, and also due to its ability to contribute to sustainable development by finding more environmentally ways of construction and building.

By 1996, during the second United Nations Conference on Human Settlements (UN-HABITAT) that took place at Istanbul, it was declared accepted the existence of environmental problems related with society but specifically referred to the importance of the construction industry for achieving the Sustained Development. In its conference declaration it was stated (Peyroteo et al [123]):

> *"…encourage the development of methods that are economically and environmentally sane, as well as in the production and distribution of the materials used in construction, including the strengthening of the industries of traditional construction materials that use raw materials that are available as close as possible"*

Private companies have experienced an increase of their environmental concerns since sustainable thinking made its appearance. Over the world, as an example, there are already certified 40.000 companies by the ISO 14001 series for Environmental Management System (EMS). This certification includes, just not the environmental considerations of each own company activities, but has an indirect pressure over their purchases and supplies (Junilla et al [76]).

But attention has not just been focused on companies and suppliers of materials applied to construction projects. Many researchers have been interested in studying the environmental benefits of introducing more recyclable and reused or recycled materials in the building industry. As a study performed by Erlandsson and Levin (2008) showed, there is a potential environmental reduction close to a 70% by using reused-recycled materials, instead of using new ones, in building construction projects. This could be a doubled-profit situation, as not just environmental impacts are reduced but the use of this eco-materials, but wastes generated by construction and demolition activities can be reduce in quantity as well. According to some studies, construction wastes usually represent 10-20% weight of building materials delivered to a building site, and demolition wastes increase 10-20 times wastes generated during the construction phase (Yu et al [175]).

Therefore, sustainability in construction industry is an objective to accomplished search by the different parties involved within the construction industry. Nevertheless, when coming to ask what sustainable construction is, no clear answer is given as it includes a great number of issues. On this behalf, according to the article published in 2009 by Martínez et al [101] sustainable construction can be considered integrated by [Table 4]:

<table>
<tr><th colspan="3">LIFE CYCLE PHASE</th><th>CRITERIA</th><th>PRINCIPLE</th></tr>
<tr><td rowspan="7">DESIGN</td><td rowspan="7">PLANNING</td><td rowspan="7">CONSTRUCTION</td><td>Energy consumption and raw material extraction impact's reduction and minimization</td><td>• Consider material's reuse.
• Consider material's recycling.
• Use of renewable resources.
• Reduce the resource extraction.
• Efficiency on natural and energetic resources use.</td></tr>
<tr><td>Good construction conditions in order to assure user's commodity</td><td>• Reach energy efficiency satisfying user's requirements.
• Noise, pollution and smells reduction.
• Constrain the ground occupancy, for reducing territorial fragmentation.</td></tr>
<tr><td>Longer life span of the construction</td><td>• Use of materials and energy systems with long-term durability.</td></tr>
<tr><td>De-construction availability</td><td>• Use of precast and pre-assembly constructions, ...</td></tr>
<tr><td>Good construction site logistics</td><td>• Efficiency on transportation and supply of materials.</td></tr>
<tr><td>Improve work conditions</td><td>• Equipment, materials, security, …</td></tr>
<tr><td>Reduce pollution on construction site and surroundings</td><td>• Prevent toxic emissions as solid and liquid wastes.</td></tr>
</table>

Table 4: *Criteria and principles of sustainable construction. (Source: reproduced from Martínez et al [101])*

2.2.3. Sustainable construction industry: policies and politics.

As stated before, attempts to achieve the goals of Sustainable Development have turned the attention to construction industry. European Union, in order to reduce the negative impacts of the sector, has started to put into action different measure, such as the CPD and EPBD European directives.

- Construction Products Directive 89/106/EEC (European Parliament [207]) is a set of regulations relating to construction products and building industry in the European Union. The directive sets out the requirements regarding the materials and products used in terms of stability, health, safety or energy saving, among others. It introduces the assessment of sustainability of construction products for the intended use.
- Energy Performance of Buildings Directive 2002/91/EC (European Parliament [208]) introduces the requirements of an obligatory energy-certification of buildings. As it establishes, buildings are intended to be design and constructed for minimizing energy requirements during its operational phase, but taking into consideration local conditions and their resident's needs. Recently in 2010, a recast of the EPBD (Council Directive 2010/30/EU and 2010/31/EU) was adopted in order to clarify and reinforce some provisions of the latter version of the directive.

Spanish implementation of the EPBD was mainly carried out in 2006 by the "Technical Building Code" (TBC [239]). This code is compound of two sections: first part details the requirements relating to security and habitability to be fulfilled by a building; meanwhile second part is integrated by the called "Basic Documents", which develops the practice for the requirements exposed in the first part. Of all the Basic Documents there is the DB HE, which is focused on the procurement and exposition of measures to achieve building's energy savings. Nevertheless, the transposition was finally completed by two other measures: the "Regulations on Building Heating Installations" (RITE) and the "Regulation for energy efficiency certification in buildings of new construction".

But these are not the only actions taken into course, as the International Standardization Organization (ISO) and the European Committee for Standardization are currently developing standards to analyse and certify the environmental impact of buildings and infrastructures, and more specifically, enhance Environmental Product Declarations to play a crucial role in Business-to-Business communication (Oliver-Solà et al [111]).

Through ISO committee ISO/TC59/SC17, sustainability on construction wants to be standardized. One of the objectives within the activities of the committee is the promotion of EPD's use in the building environment. This is collected in the ISO 21930:2007 "*Sustainability in building construction--Environmental declaration of building products*" (ISO [235]) standard that provides a framework and requirements for type III environmental declarations of building products, as defined in ISO 14025. However this standard does not define requirements for developing type III environmental declaration programmes. Requirements for type III environmental declaration programmes are found in ISO 14025.

The EU Commission has mandated CEN/TC 350 to develop a set of horizontal European standards for sustainability construction work. The standards already under development in the field including framework for assessment of buildings (Vares and Hakkinen [164]):

- Assessment of environmental performance of buildings (calculation methods).
- Use of environmental product declarations.
- Environmental product declarations-product category rules.
- Environmental product declarations-communication formats.

Relating the disposal of Construction and Demolition wastes, in 2001 the Spanish Government approved the "National Plan for Construction and Demolition Wastes" (PNRCD 2001-2006). This plan aimed at, considering data from 2006, recovering at least 90% of C&D wastes, reducing 10% of wastes generated and achieving reuse and recycle rates for construction and demolition wastes close to 35%. The most important innovations it introduced to the scheme were: distinction of urban and non-urban waste and the responsibility of the production agent for the management of the wastes generated.

As the validity of the plan already expired, and the transposition of the European Directive 2008/98/EC was a must, in 2008 it was approved the "Integrated National Plan for Wastes"(PNIR 2008-2015). However, in this occasion, a unique plan for wastes generated from construction and demolition was not considered and, on the contrary, it was integrated as a chapter of the whole plan.

<table>
<tr><th>ISSUE</th><th>ENERGY</th><th>PRODUCTS</th><th>RECYCLING</th></tr>
<tr><td>EUROPE</td><td>Energy Performance of Buildings Directive
(EPBD 2002 and 2010)</td><td rowspan="2">Construction Products Directive
(CPD 1989)

CEN/TC 350

ISO 21930:2007</td><td>Directive 2008/9/EC</td></tr>
<tr><td>SPAIN</td><td>Technical Building Code
(TBC 2006)</td><td>National Plan for Construction and Demolition Wastes
(PNRCD 2001-2006)

Integrated National Plan for Wastes
(PNIR 2008-2015)</td></tr>
</table>

Table 5: *Summary of policies and politics for construction industry. (Source: own elaboration)*

2.3. Sustainable concrete constructions.

Construction industry, as previously indicated with some related data from the sector, is one of the most energy consuming, material using, waste generating and pollution emitting activities of humanity. On this sense, concrete is the most widely used building material in the construction industry. It is estimated that today's world concrete production is about 6 billion tons per year or the same, 1 ton per person/year (Marinkovic et al [98]).

As its largest component in quantity, consumption of natural aggregate is increasing solidary with production and utilization of concrete. Moreover, in addition to the large consumption of natural resources for concrete production, cement is the main raw material in concrete. Although the cement content in concrete is low (12-15%), it is an energy intensive substance. However concrete's consumption of natural resources, energy consumption and GHG emission to the atmosphere by cement production are not the only facts to face by the construction environment. On the other hand, waste arising from the sector is also a relevant concern in the protection of the environment. Whilst recycling and use of waste does occur within the construction industry (approx. 10% of materials used for construction in general are wastes), it is estimated that up to 25% by weight of the material ends up in landfill (Urie and Dagg [159]). Therefore improvement of existing and development of new state-of-the-art sustainable techniques are required by concrete constructions.

2.3.1. Concrete constructions impacts.

As indicated previously at this work, concrete constructions are one of the main and more ordinary elements in every building or civil construction project. Focusing on its environmental performance, among the main impacts that concrete generate over the environment all over its life cycle, we can find (O'Reilly et al [112]):

LIFE CYCLE PHASE		ENVIRONMENTAL IMPACTS
I	RAW MATERIAL EXTRACTION	• Energy consumption • Emissions of pollutant to the air (dust, GHG, …) • Noise • Soil contamination • Change in land uses • Affection to the biodiversity

LIFE CYCLE PHASE		ENVIRONMENTAL IMPACTS
II	RAW MATERIAL TRANSPORTATION	• Energy consumption • Emissions of pollutant to the air (dust, GHG, …) • Noise • Soil contamination (oils, lubricants, …)
III	MANUFACTURING	• Energy and water consumption • Emissions of pollutant to the air (dust, GHG, …) • Noise • Soil contamination (solid or liquid wastes)
IV	DISTRIBUTION TO PRODUCTION PLANTS OR CONSTRUCTION SITE	• Energy consumption • Emissions of pollutant to the air (dust, GHG, …) • Noise • Soil contamination (oils, lubricants, …)
V	DESIGN PROCESS	• Increase of paper wastes and other materials
VI	CONSTRUCTION	• Energy and water consumption • Emissions of pollutant to the air (dust, GHG, …) • Noise • Soil contamination (solid or liquid wastes) • Affection to the biodiversity and landscape • Occupation and change of land use
VII	OPERATIONAL	• Energy consumption • Noise • Soil contamination (solid or liquid wastes)
VIII	DEMOLITION/RE-USE/ REHABILITATION	• Energy consumption • Emissions of pollutant to the air (dust, GHG, …) • Noise • Soil contamination (solid or liquid wastes) • Affection to the people and landscape • Generation of solid and liquid wastes

Table 6: *Impacts generated over the life cycle of a concrete structure. (Source: reproduced from O'Reilley et al [112])*

Concrete is composed mainly by aggregates, cement and water. Nevertheless, it's mixing design and technologies have been developed to improve their properties and performance, so new different materials have been incorporated (as additives or recycled materials). The production and manufacturing of these different concrete compounds obviously endorsed different environmental burdens which we pass to treat ahead.

2.3.1.1. Aggregate impacts.

Aggregates are materials of inorganic nature which provide double utility to concrete: reduce concrete costs (their price is ten times lower than cement) and offer a smoothly longer durability than cement. On average, aggregates presence on concrete is constituted about 75% of concrete volume (ACHE [240]). Among the different environmental impacts generates during the extraction and processing of aggregates, we can find the next exposed:

- Energy consumption, which will consequently have endorsed the emission of air pollutants, such as CO_2, SO_2, etc.
- Water consumption. During the extraction and processing, there is a need for water in different processes. It is of great importance to follow a correct management process to prevent great environmental impacts, such as: uncontrolled river discharges, clogging recharge areas of underground water and excessive water consumption.
- Dust and gas emissions. The extraction and rock fragmentation, as well as its transportation to the processing plant, produce the expulsion of solid particles. On its behalf dust is deposited on soil, vegetation and buildings decreasing the quality of the landscape. On the other hand, engines generate sulphuric, nitrogen and oxide gasses that, when compared to dust production, represent a minor problem.
- Wastes. Although work performance for aggregate production offers high rates, generation of some wastes are inescapable. It is very important to establish a correct management process to reduce their potential environmental impacts, as it happened within the water consumption.
- Noise impacts are generated by almost all activities within an extraction site and processing plant.
- Vibrations are generated by explosives, jackhammer and the crusher machines, vibrating screen used at the raw material extraction site and processing plant, respectively. Although vibrations are the cause of disturbance to human and animals, they are not source of structural problems.
- Landscape impact. Although its relevance to sustainability does not have a great importance, it affects to the social acceptance of this kind of activities. Therefore, raw material extraction sites it requires of mitigation measures to accomplish minimal landscape impact.

2.3.1.2. Cement impacts.

During the manufacturing phase of cement, pollutants are generated and emitted to the atmosphere. Each produced ton of cement emits nearly 900 kg of CO_2, in addition to a number of other polluting constituents to the atmosphere (Vares and Hakkinen [164]). But CO_2 emissions are not the only derived from its production, these are exposed ahead (ACHE [240]):

- Carbon dioxide (CO_2) emitted during the production phase of cement comes from two different ways: limestone calcination and fuel consumption (such as coal).
- Nitrogen oxides (NO_X) are generated during consumption of fossil fuels, releasing more quantity as greater combustion temperatures are use during the process. Impacts subdued to its emissions are: island effect, reduce air quality and human health problems.
- Sulphur dioxide (SO_2) pollution can directly come from its presence on raw materials or from burning phases of the manufacturing process. Although nature alkaline materials tend to be “absorbed” between the 70 and 90% of it, the remaining is released leading to: reduction of air quality, production of “smog” acid rain and effect on human respiratory problems.
- Particles emission, such as dust, from raw material extraction activities to transportation or packaging, impacts are caused due to loss and release of particles to the environment. Particles smaller than 2.5 microns are mainly responsible for potential breathing problems, and offer great difficulty on its removal from the human body.
- Other harmful air pollutants are also produced when fuel is not completely consumed during combustion, such as carbon monoxide (CO) or VOC’s. Furthermore, clinker kiln generates metal compounds which also can be passed into the atmosphere.
- Water contamination is produced during the cement production processes because its demand on, as an example: dust emissions control, product cooling or gas cooling. The water used in the different processes contains large amounts of suspended solids, metals, dissolved organic matter, high levels of pH, …

2.3.1.3. Additive impacts.

Chemical additives are common components of nowadays concrete and cement, even essential in the case of self-compacting or high-strength concrete. It is to highlight that almost every concrete produced today in Europe has at least one type (ACHE [240]).

Main problem with chemical additives is the relatively high embodied content of CO_2, due to their organic origin. However, as its presence in a concrete mix design is low (rarely overpass 0.6% by weight of cement), its relevance on the environmental burden of concrete or cement is very small (less than 1% ratio). Even its contribution can be ignored, according to ISO 14000.

2.3.2. Concrete constructions sustainability improvement.

Environmental consciousness in the construction industry for a better utilization of concrete is already a relevant and challenging issue, as indicated by the "Lofoten Declaration" of 1998 (Gjorv and Sakai [49]). As conclusion of The Lofoten Workshop (a joint research program between Norwegian University of Science and Technology and Kagawa University), the next declaration was made:

> "*We concrete experts shall direct concrete technology towards a more sustainable development in the 21st Century by developing and introducing into practice*:
>
> 1. *Integrated performance-oriented life cycle design.*
> 2. *More environmental-friendly concrete construction.*
> 3. *Systems for maintenance, repair and reuse of concrete structures."*

In front of this scenario, numerous attempts to reduce environmental and socio-economic impacts due to construction activities have already been taken to the date. As an example, there is the Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD) that outlines a pathway towards a more sustainable cement sector by tracking action according to six main issues (Vares and Hakkinen [164]):

- CO_2 and Climate Protection
- Responsible Use of Fuels and Raw Materials
- Employee Health and Safety
- Emissions Monitoring and Reduction
- Local Impacts on Land and Communities
- Concrete Recycling.

Other identified measures for improving sustainability of concrete construction projects are through ISO committee ISO/TC59/SC14 that is developing, a part from EPD's promotion, the ISO 15686 series that deal with service life planning. This standards focus on the design life of structures, taking into consideration their life cycle cost, life cycle assessment, and service life care and end of life (Oliver-Solà et al [111]). On the other hand, ISO committee ISO/TC 71/SC 8 is developing an environmental management standard specific for concrete and concrete structures.

On the Spanish context, with the approval in 2008 of the "Instrucción de Hormigón Estructural" (EHE [238]) new environmental, social and economic criteria where introduced for the construction of more environmental structures. More specifically, in its 13th chapter it was incorporated the so called "Índice de Contribución de la Estructura" (ICES) that consist on an index that takes into consideration information (among others) related to resource depletion, pollutants emissions, energy savings and recycling.

Nevertheless, when considering construction project's life cycle, effectiveness or measures applied decrease as the project advances [Figure 2]. Therefore, to improve sustainability in construction there is a need for strong and complete decision-making tools to be implemented at primary phases of a projects life cycle (as the pre-design and design phases). Among the different environmental impact assessment (EIA) models or systems for buildings that have been developed to the date, LCA has already successfully been used to integrate issues like climate change and resource depletion in the decision-making process (from an objective point of view) and allow achieving sustainable development (Reza et al [130] and Zhang et al [177]). So, by the integration of LCA into the building design process, design and construction professionals are able to evaluate the life cycle impacts of building materials, components, and systems and choose the combinations that reduce the building's life cycle environmental impact.

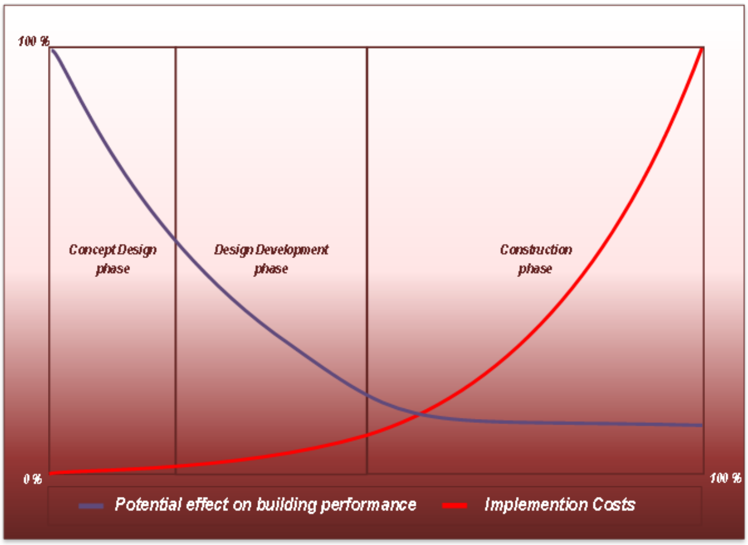


Figure 2: *Cost vs. effect of environmental measures over the life cycle of a project. (Source: elaboration from Strafaci [210])*

2.4. Life Cycle Assessment technique.

2.4.1. Life Cycle Assessment: birth and evolution.

At some point in the late 60's, two researchers at the Midwest Research Institute (William Franklin and Robert Hunt) began working on a technique for quantifying energy and resources, as well as environmental emissions, from the manufacture and use of products (Trusty and Deru [152]). Named as "*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 best environmental-friendly vessel material (glass of plastic) as whether disposable or recycled vessels produced less impact (Gerilla et al [47]).

LCA development first accelerated during the energy oil-crises of the 70s. 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 80s and early 90s, it gained importance to implement LCA for environmental marketing claims (Owens [116]). As the methods became wider, and studies performed for same products gave very different results, many initiatives to harmonise LCA methodology were taken. This tendency gave place to various methodological guidelines (as the Dutch and Nordic Guidelines) that 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 known "Code of Practice for Life Cycle Assessment". In addition, many different initiatives to standardize LCA methodology begun (as the LCA guideline Z-760 of the Canadian Standards Association), but the most recognized standardization process was the one started in the late 90's within the framework of the International Organizations for Standardization (Russel et al [136]).

During the 90s, first Japan and later Australia and Korea increased their LCA practice activity performing a wide number of environmental studies. However, until de 21st century, 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 the public and private sector, in different countries as Mexico, Argentina, Chile, Colombia or Peru. The African LCA Network recently hosted an LCA training workshop in which the participants began developing a life cycle inventory data with peculiarities of their respective countries (Norris [107]).

However, LCA practice on construction industry has started only in the last decade, but on the sense of environmental assessment of building and construction materials selection. A large study conducted by American Institute of Architect (AIA), and funded by US Environmental Protection Agency (EPA), created more than a decade ago LCA's for multitude of building materials (steel, wood, plaster, glass, etc.) (Kendall et al [80]). So, LCA in the construction industry is less developed nowadays than in other industries, but appears to be developing quickly (Scheuer et al [138]). Furthermore, at present, Life Cycle Assessment on buildings is a hot research theme in developed countries like Japan, North America or European Union (Ge [46]).

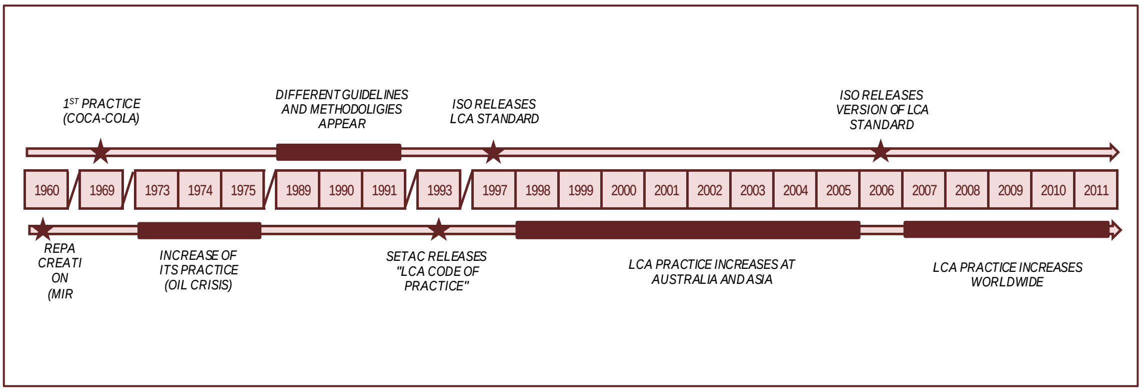


Figure 3: *Representation of the time-evolution experienced by LCA. (Source: own elaboration)*

2.4.2. Life Cycle Assessment: definition.

The International Standardization Organization (ISO) issued the relevant international standards in 1997, and defined LCA 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*" in the norms of the fourth series of ISO 14040 (ISO [227]). Therefore, LCA can be defined as a methodology for estimating the environmental burdens of processes and products (goods and services) during their life cycle from cradle to grave.

According to EPA, the life cycle of a product is divided in four main stages. But, some other establishes that the life cycle includes a total of five phases (raw materials extraction, production and transportation, use/maintenance, disposal and recycling/reuse or landfill). Notwithstanding, EPA's life cycle is exposed ahead (EPA [212]):

- Obtaining the raw materials. Includes the resources consumed, as well as the materials and energy spent, for the extraction and transport of the materials.
- Production. Includes the activities of raw materials transformation, product execution and its transport and conditioning to its destiny.

- **Use, reuse and maintenance.** Where the activities and consumptions resulting from the use and quality maintenance of the product are quantified.
- **Recycling and waste treatment.** Where the impact of the activities associated with destroying the product, as well as the impact of the resulting waste, are evaluated.

It is important to indicate that before products or services are processed or used by the consumers, they have already incorporated an amount of energy during for their production process. This same energy is named "**embodied energy**" and includes energy of the raw material extraction, production processes and transportation of raw materials to the factory and products to consumers. The assessment of this kind of embodied energy, that receives the name of LCA cradle-to-gate, was the main focus for the comparison between different materials and products, scope of the great majority of studies performed till the 90's. Nevertheless, nowadays LCAs expand the assessment to assess the operational and disposal phases of the product too (Junilla et al [75]).

2.4.3. Life Cycle Assessment: methodology.

Although there are different typologies for practicing a Life Cycle Assessment (which will be offered ahead in this work), a general view of the methodology will be offered mainly according to that offered by the ISO 14040 [Figure 4]. An LCA study compounds of four phases: **goal definition and scope assessment**, **inventory analysis**, **impact assessment** and **interpretation**. The second and the third are considered the active or dynamic phases of the assessment, as are the ones when data is captured and evaluated. Consequently the first and fourth phases are considered the static ones (Romero [133]).

First, the goal and scope of the assessment are established directly followed by the inventory analysis. As pointed out by the ISO standard, the LCA can finish at this phase an offer a view of the direct impacts derived from the system assessed but, if the assessment continues, then an impact assessment is performed. It is important to highlight that, even if it its and LCI or LCA study, a sensitive analysis of the assessment can be performed in order to identify mistakes or problems within the study. Depending on the observations and results reached whit this analysis, a revision of the previous steps can take place. Finally, al the impacts obtained from the LCI or LCA study, depending on the case, are gathered all together in the interpretation step, which offers a view of the study results.

Once the study is done, and according to ISO, a report has to be made. Nevertheless, there is a final step on the LCA methodology that is not usually included on the studies, known as **critical review**, but that is necessary to be performed when quality or credibility of the LCA study wants to be enhanced (Klöpffer [84]). Depending on the results of this critical review, that normally is done by a third party out of the LCA team, a revisions and improvement of the whole study can take place.

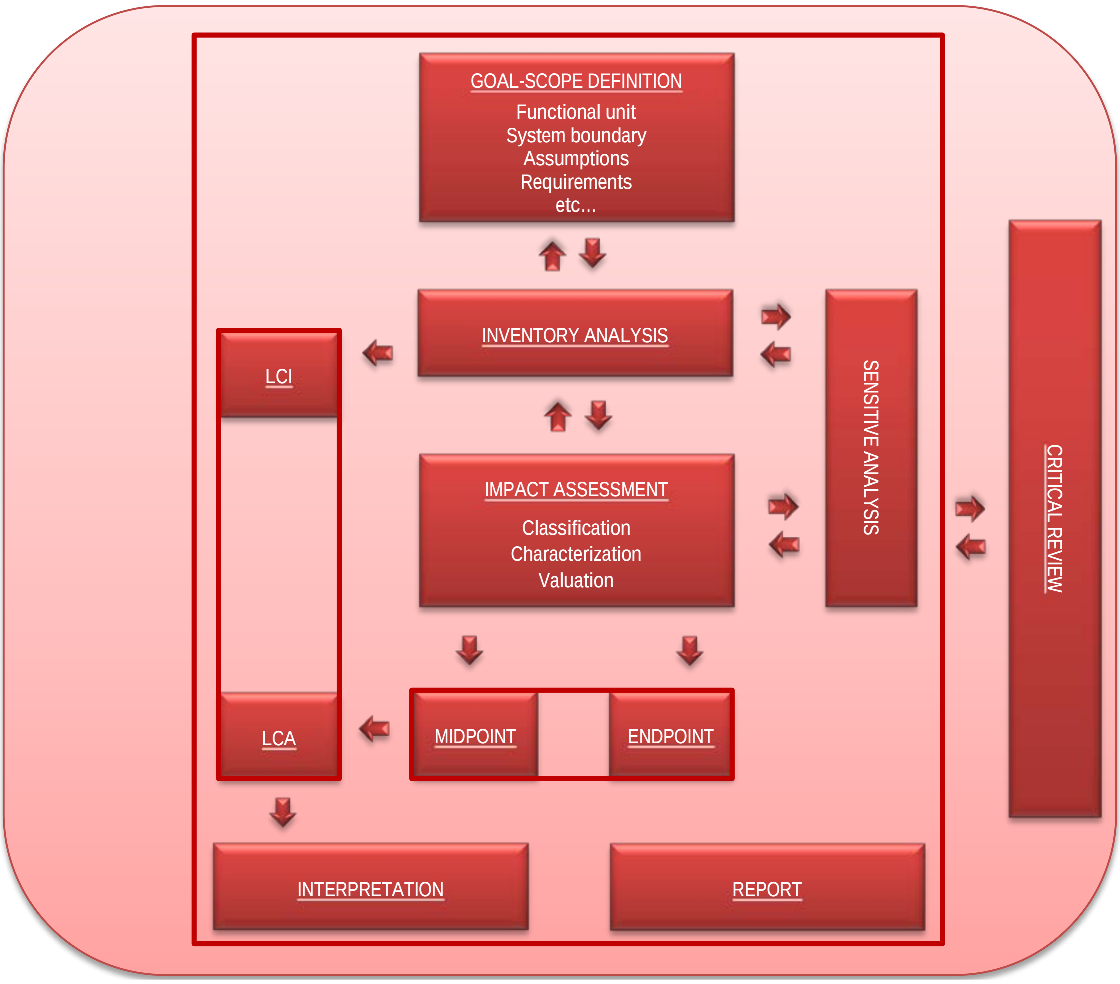


Figure 4: *LCA methodology flow-chart. (Source: Own elaboration)*

2.4.3.1. Goal definition and scope assessment.

The LCA phase for **goal definition and scope assessment** consists of two steps. First, purpose of the study is exposed indicating relevant information as: people in charge, team developing the study, company, case study, etc…it is the basic information of the study for achieve a correct presentation of the study. The second phase takes into consideration description of the characteristics and peculiarities existing within the methodology of the study, as it is the functional unit, sources of data, limitations of the study, methodologies or initial assumptions among others (ISO [227]).

- **Defining the purpose.** This step helps establishing the process/product basic information.
- **Setting the scope and depth.** This step would include, among others, the following items:
    - *Defining the LCA functional unit*. A measure of performance of the selected system needs to be defined. This is very important point, as latter comparison of the results with other studies will depend on the functional unit selected.

- *Establishing the system boundaries*. LCA requires a model for describing key elements and unit processes necessary to obtain the product or service assessed. This links of processes will be established before the analysis is performed.
- *Specify data quality requirements to be used at the assessment*.
- *Assumptions or limitations of the study, etc…*

2.4.3.2. Inventory analysis.

One of the fundamental parts of LCA is the undertaking of the life cycle inventory (LCI). **Inventory analysis** is the phase of the LCA involving the compilation and quantification of specific inputs and outputs (materials, energy, emissions) for a given system throughout the phases of the life cycle established previously at the goal and scope definition (Josa et al [74]). The LCI analysis requires collecting data for all process units and their associated energies and mass flows, as well as the data on emissions and discharges into the environment (Reza et al [130]). Usually the outcome of this phase is an inventory table that will be later used for the performance of the Impact Assessment phase. The life cycle inventory (LCI) phase will consist on the following (ISO [227]):

- **Quantifying** the materials, chemicals and equipment giving the reference flow for all inputs and outputs referred to the functional unit. This will also have to be done for wastes generated from the phases of the life cycle considered. If recycling and disposal are included in the life cycle considered for the study, it will be necessary to include information related to this processes.
- **Acquiring** environmental data of consumed materials, chemicals and equipment from the suppliers (specific data) or from database (generic data).
- **Indicating and assigning** environmental input and output flows quantified to each unit process or flow indicated in the model established.

After the identification and quantification is done, it's time for the "**allocation**" process. Allocation can be defined as the "*partitioning of environmental burdens and other material and energy flows to and from a technological activity between the products for which the activity is used*" (Russell et al [136]). According to ISO 14044, whenever several alternative allocation procedures seem applicable, a latter sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach. In some cases the results of this analysis will require a redefinition of the initial system boundary or even revision of the study's goal and scope (ISO [231]).

2.4.3.3. Impact assessment.

The **impact assessment** phase of an LCA, also called Life Cycle Impact Assessment (LCIA) is based on the LCI results obtained from the inventory analysis. In general, the process followed at the impact assessment consists on associating (or classifying) inventory data with different environmental impact categories and characterised by each category indicators. The results are then summarised into a list of impact categories with the objective of allowing a better understanding of the environmental burdens from the product/service life cycle (Reza et al [130]). The LCIA phase provides the information for the latter life cycle interpretation phase of the LCA.

Within the Impact assessment step, there are seven generally accepted elements in the process of conducting life cycle impact assessment, the first three elements are mandatory for ISO standard (ISO [231]).

- **Selection** of impact categories, category indicators and characterization models. For each impact category, the necessary components of the LCIA include:
    - Identification of the category endpoints.
    - Definition of the category indicator for given category endpoints.
    - Identification of appropriate LCI results that can be assigned to the impact category, taking into account the chosen category indicator and identified category endpoints.
    - Identification of the characterization model and the characterization factors.
- Assignment of LCI results to the selected impact categories (**classification**).
- Calculation of category indicator results (**characterization**). This element of the LCIA involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category by using specific characterization factors. The outcome of the calculation is a numerical indicator result. The method of calculating indicator results shall be identified and documented, including the value-choices and assumptions used, in all the process.
- **Normalization**. Calculation of the magnitude of the category indicator results relative to some reference information. The aim of the normalization is to understand better the relative magnitude for each indicator result of the product system under study.
- **Grouping**. Assignment of impact categories into one or more sets as predefined in the goal and scope definition, and it may involve sorting and/or ranking.
- **Weighting**. Process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results. Data prior to weighting should remain available
- **Data quality check**. This element brings to the LCIA step a better understanding of the significance, reliability and sensitivity of the collection of indicator results. In accordance with the iterative nature of LCA, the result of this data quality analysis may lead to revision of the LCI phase.

As it was said previously, the steps of normalization, grouping and weighting are not mandatory for the impact assessment phase. But, when performed in LCAs, their consistency must be established clearly in line with the goal and scope of the study as its transparency will have to be full for allowing future reviews and recalculations (ISO [231]). This transparency goes by the way of documenting and exposing every method and calculations used in the study.

Finally, there are identified two general approaches to categorize life cycle impacts: **midpoint** and **end point**. The midpoint approach starts from the emissions and resources identified in the LCI and then, take these data as input for the model that will take to its considered impact categories. In contrast, endpoint approach (or "damage assessment") uses models that link emissions and resources to endpoints indicators further more developed than that of the midpoint approach. Endpoint models typically offer a higher level of uncertainty, since they include more assumptions in the characterization impacts (Bare and Thomas [10]).

2.4.3.4. Interpretation.

The **interpretation** phase combines the information obtained from both the inventory and the impact assessment phases to identify, qualify, evaluate and present the findings reached by the practitioner after performing the LCA study. The final result may be displayed as impact categories or weighted to an environmental index (optional step of the LCIA) using value-choice factors based for example on political targets, as Kyoto Protocol among others (Arskog et al [7]). As pointed out by some studies, the purpose of this phase can also be to recommend improvements on the system assessed (Reza et al [130]).

The results included on the interpretation phase, as exposed previously at this work, may vary on the goal and scope of the study. As an example, if the scope of a LCA study is limited to the inventory analysis the results used for evaluating the environmental performance or burden of a system assessed, would be the impacts offered at the left column ahead. On the other hand, if the LCA study included an impact assessment, the results would depend on the LCIA methodology selected (which will be later exposed at this work). Nevertheless, a sample of most common impacts consider by all the methodologies is offered at the right column:

- Energy consumption: **J**, **MJ** or **GJ**
- Carbon dioxide (CO_2): **g**, **Kg** or **T**
- Nitrogen oxides (NO_X): **mg** or **g**
- Chlorofluorocarbons (CFCS): **mg** or **g**

- Global Warming (GW): **Kg CO_2 eq.**
- Acidification (A): **Kg SO_2 eq.**
- Eutrophication (E): **Kg PO_4 eq.**
- Ozone Depletion (OD): **Kg CFC11 eq.**

Nevertheless, it is also important to remark that on some LCA studies weightings steps are considered within the LCIA methodology. Some examples can be found at the LCA studies included at Arets et al [5], Gerilla et al [47] or Rosignoli et al [134]. These steps introduce relevant variations on the results obtained from the assessment, mainly due to the considerations within the weighting methodology, which can prevent form comparison with other LCA studies.

2.4.3.5. Report and critical review.

When finishing all LCA phases, after interpretation it is recommended to elaborate a **report** where all the different phases are included and described properly. This report will serve as later base for the critical review, in case it is necessary, and for other practitioners to replay the study in case comparison of products wants to be made. In the other hand, **critical review** is the tool to verify if an LCA study has met the requirements of the ISO according to: methodology, data and reporting. Although they are optional, they are to be conducted obligatory when LCA studies are used to make comparative assertion that will be disclosed to the public (Klöpffer [84]). The critical review ensures that (ISO [226]):

- Methods used to carry out the LCA are consistent with ISO standard.
- Methods used to carry out the LCA are scientifically and technically valid.
- Data used are appropriate and reasonable in relation to the goal of the study.
- Interpretation reflects the limitations identified and the goal of the study.
- The study report is transparent and consistent.

It can be carried by internal team or by external independent experts. It requires expert knowledge in the environmental sciences assessed and is by no means a routine work. There are two ways or kinds to do a critical review (Klöpffer [84]):

- Accompanying or interactive. The review team is part of the project team although reviewers can and do influence the study, except the goal itself.
- A posteriori. A review panel, team that is not a member of the overall project team, is confronted with the draft of the final report, where is too late to apply changes. This brings the possibility of incorporate a fresh look from outside and the lack of restraint to be critical.

The delay in the last type of critical review can be really risky, as it cannot be considered at the beginning of the project planning. The accompanying one may involve a few reviewer days more, but it can bring some “insurance” to a disastrous final phase (Klöpffer [84]).

RESEARCH PHASE

3. RESEARCH PHASE.

In this third chapter of the work, it will be exposed the methodology and findings of the research on LCA applicability to concrete structures performed. It will be divided in three different chapters, as followed described: description of the researching methodology, exposition of the organization of data recovered after the research and, finally, it will be shown the results of the analysis of articles done in the study.

3.1. Bibliographical research.

Within the objective of establishing the state of the art about LCA applicability to concrete structures, a research about the issue was conducted. More specifically, the research performed consisted of a bibliographical study about the subject. A bibliographical study is a methodology to acquire knowledge related to a topic, by researching information included in documents such as: books, scientific articles or conference proceedings (among others).

Main source for the research was poli[Buscador], the electronic portal for the UPV's Digital Library. This tool, a part of allowing access to primary and secondary data (articles, conferences books, meta-searchers, research databases etc.), offers some other services as personalizing the searches or exporting search results to bibliography database managers (like RefWorks or EndNote).

The success of the study mainly rests with the quality of the bibliographical research performed. So, due to the need to gain the most accurate information about the issue at hand, it was necessary to previously design and testing a research strategy.

Basically, the research strategy consisted on some chosen keywords about the topic related with Boolean operators. As the possibilities were so wide and non-numerical finishing, it was decided to design the research strategy by the next premises:

- Use of simple Boolean operators.
- Selection of directly representative Keywords.

Furthermore, it was also necessary to count on that the selected research strategy could be performed by different fields, as for example, authors, titles, keywords, etc. Therefore, it was decided to conduct some previous trials of different research strategies, to assure that the research strategy chosen was the best for the study.

3.1.1. Approximation research trials.

Although it was already quickly exposed before, it has been considered convenient to offer a more accurate view of the process followed to reach the research strategy used at this work. A total number of three trials were made, as it can be observed ahead:

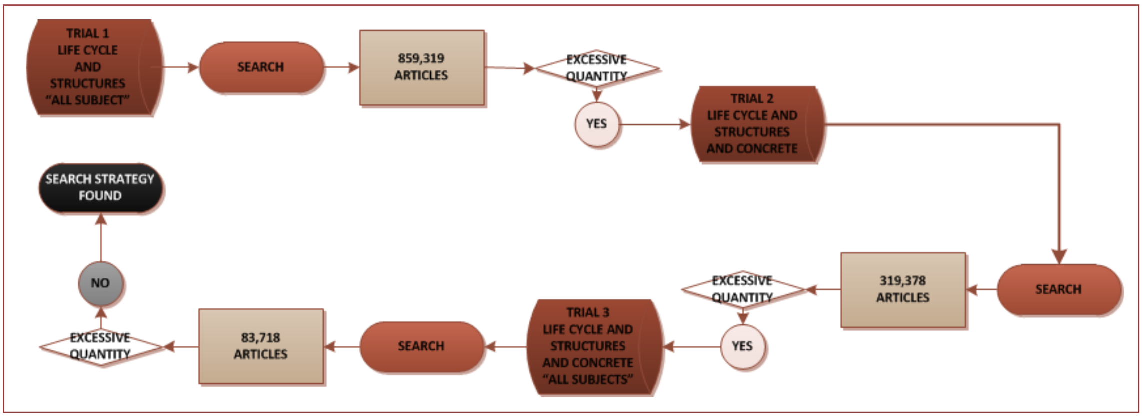


Figure 5*: Flow-chart for the trial research process. (Source: own elaboration)*

As the first research trial considered at the study, next strategy proposal was used:

<u>(LIFE CYCLE) AND (STRUCTURES) in "All subjects"</u>

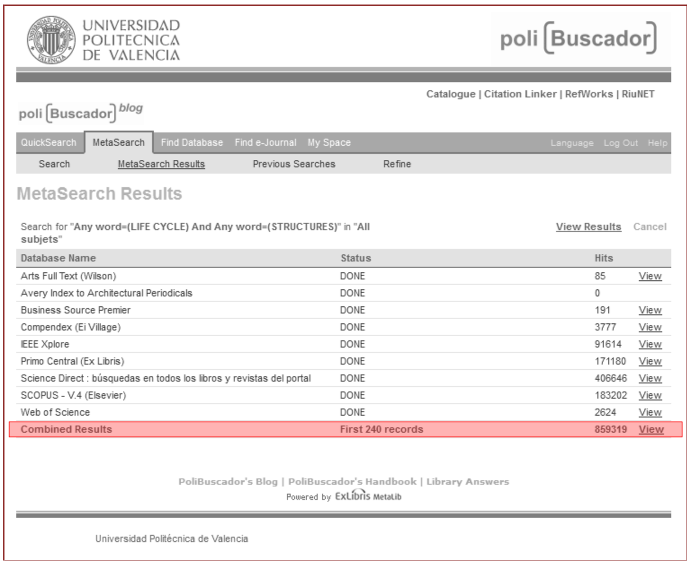
As it is shown ahead [Figure 6], the first attempt returned a total number of 859,319 documents. This result was considered too large, and obviously required a narrowing, so the first attempt was rejected. Therefore, a second trial was made but, in this occasion, adding to the search the keyword "CONCRETE":

<u>(LIFE CYCLE) AND (STRUCTURES) AND (CONCRETE)</u>

As it can be seen in [Figure 7], this second attempt returned a narrower result with a total number of 319,378 documents (almost 2.70 times less). However the searching strategy was once again considered too large and a third trial was required to narrow the results. In this occasion, the research strategy added the word "STRUCTURES", being the research strategy as follows:

<u>(LIFE CYCLE ASSESSMENT) AND (STRUCTURES) AND (CONCRETE) in "All subjects"</u>

In this occasion, it can be appraised [Figure 8] that the search narrowed considerably from the first trial (almost 10.30 times less), achieving a total number of 83,718 articles. Hence, the third strategy was finally the one selected for the research.



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MetaSearch Results

Search for "Any word=(LIFE CYCLE) And Any word=(STRUCTURES)" in "All subjets" View Results Cancel

Database Name	Status	Hits	
Arts Full Text (Wilson)	DONE	85	View
Avery Index to Architectural Periodicals	DONE	0	
Business Source Premier	DONE	191	View
Compendex (Ei Village)	DONE	3777	View
IEEE Xplore	DONE	91614	View
Primo Central (Ex Libris)	DONE	171180	View
Science Direct : búsquedas en todos los libros y revistas del portal	DONE	406646	View
SCOPUS - V.4 (Elsevier)	DONE	183202	View
Web of Science	DONE	2624	View
Combined Results	First 240 records	859319	View

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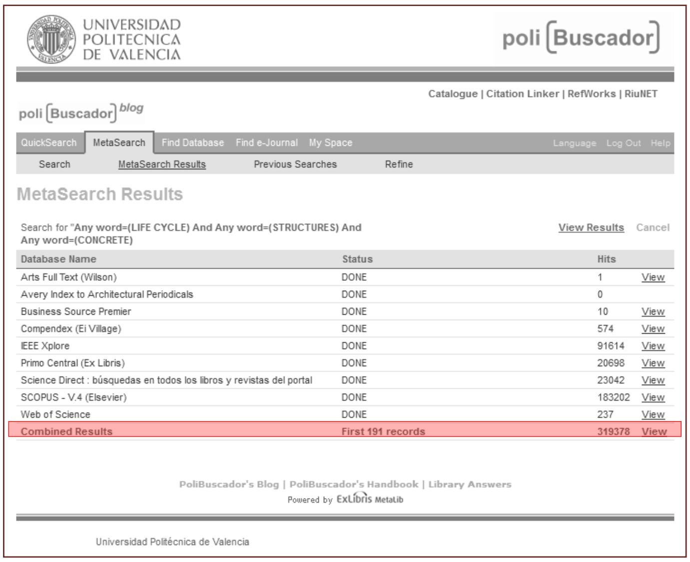
Figure 6*: UPV's poli[Buscador] first trial research results.*



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Search MetaSearch Results Previous Searches Refine

MetaSearch Results

Search for "Any word=(LIFE CYCLE) And Any word=(STRUCTURES) And Any word=(CONCRETE)" View Results Cancel

Database Name	Status	Hits	
Arts Full Text (Wilson)	DONE	1	View
Avery Index to Architectural Periodicals	DONE	0	
Business Source Premier	DONE	10	View
Compendex (Ei Village)	DONE	574	View
IEEE Xplore	DONE	91614	View
Primo Central (Ex Libris)	DONE	20698	View
Science Direct : búsquedas en todos los libros y revistas del portal	DONE	23042	View
SCOPUS - V.4 (Elsevier)	DONE	183202	View
Web of Science	DONE	237	View
Combined Results	First 191 records	319378	View

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Figure 7*: UPV's poli[Buscador] second trial research results.*

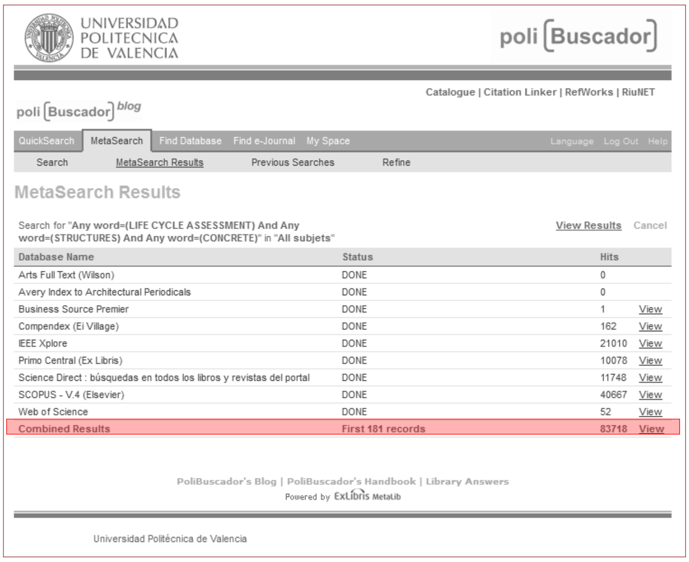


Figure 8: *UPV's poli[Buscador] third trial research results.*

3.1.2. Databases research recovers.

At the same time that trials were made to achieve the most accurate research strategy for the study, trials were used to see the most useful online research databases from poli[Buscador] for the study. These are ahead exposed:

- EBSCO HOST
- ENGINEERING VILLAGE
- IEE XPLORE
- SCIENCE DIRECT
- SCOPUS
- ISI WEB OF SCIENCE

In EBSCO HOST database, were found a total number of 197 articles [Figure 9], using the research strategy in the "*All Text*" field of search. Of the results recovered, in the study just were finally used 11 articles. By its behalf, in Engineering Village database were found 274 articles [Figure 10], by using the research strategy in the "*Keywords*" field. After checking the results given at the Referex database, due to their lack of relation to the search, it was decided to dismiss this database. A new search was done, this time using the research strategy in the "*Abstract*" field and just considering Compendex and Inspec databases. In this occasion, were given 129 (106+23) results and, after using the duplicate elimination tool offered by the database, the result decrease to 115 (106 + 9). Of these, just were finally used 31 articles.

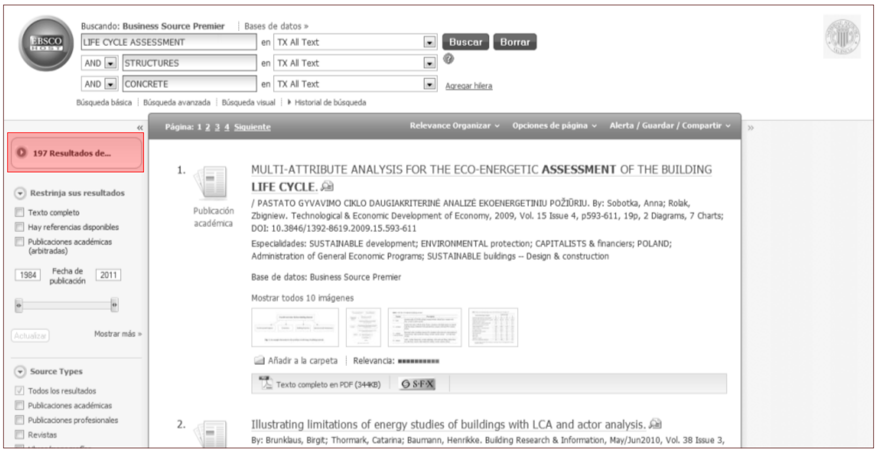


***Figure 9**: EBSCO HOST article's research results.*

***Figure 10**: Engineering Village article's research results.*

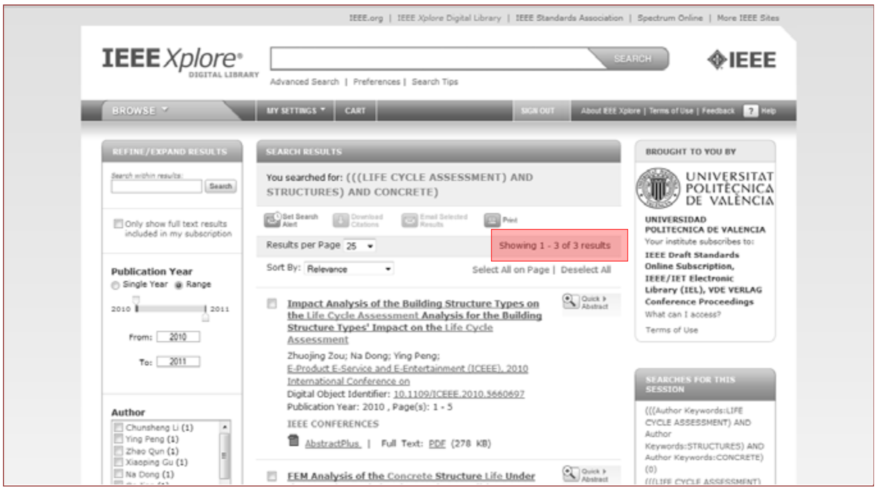


***Figure 11**: IEEE XPLORE article's research results.*

In IEEE Xplore database were found just 3 articles [Figure 11], by using the research strategy in the "*Metadata Only*" field. Of the three found, were finally used 2 articles. In SCIENCE DIRECT database were found 42 articles [Figure 12], using the research strategy in the "*Abstract, Title, Keywords*" field of search. Of the results found, were just used 8 articles. In SCOPUS database were found 171 articles [Figure 13], using the research strategy in the "*Article Title, Abstract, Keywords*" field of search. Of the results found, were used 49 articles. In ISI WEB OF KNOWLEDGE database were found 75 articles [Figure 14], using the research strategy in the "*Topic*" field of search. Of the results found, were finally used 25 articles.

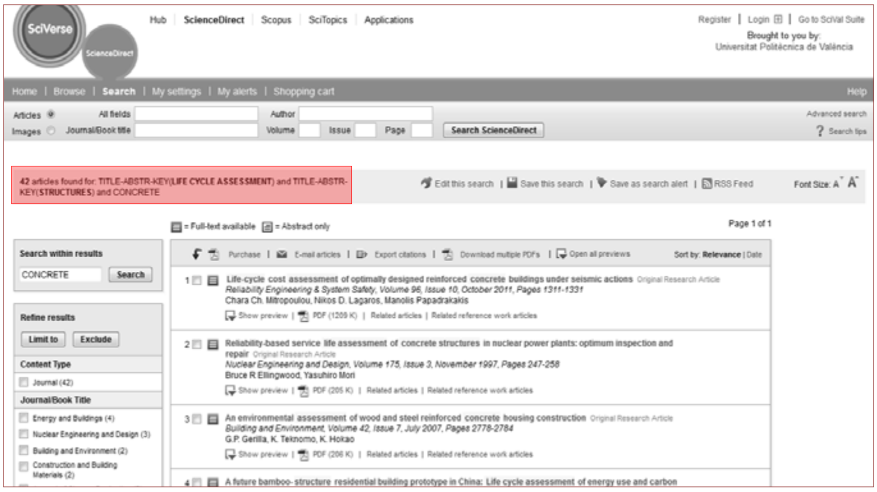


***Figure 12**: SCIENCE DIRECT article's research results.*

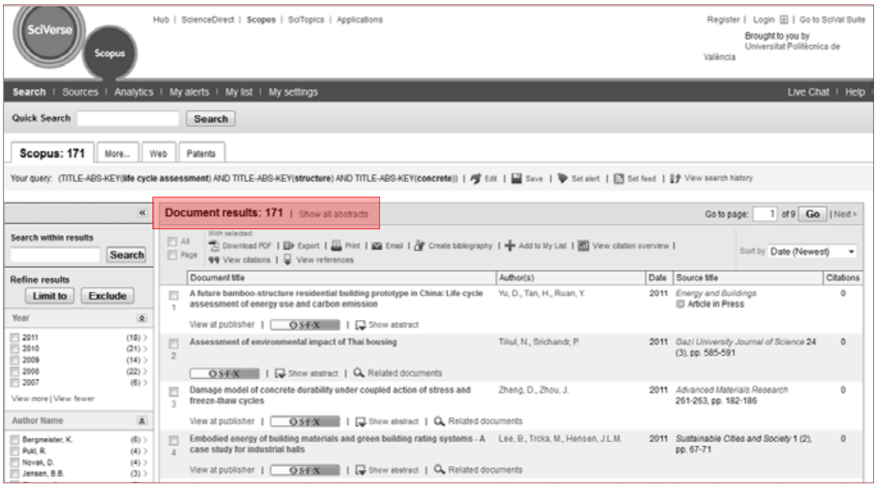


***Figure 13**: SCOPUS article's research results.*

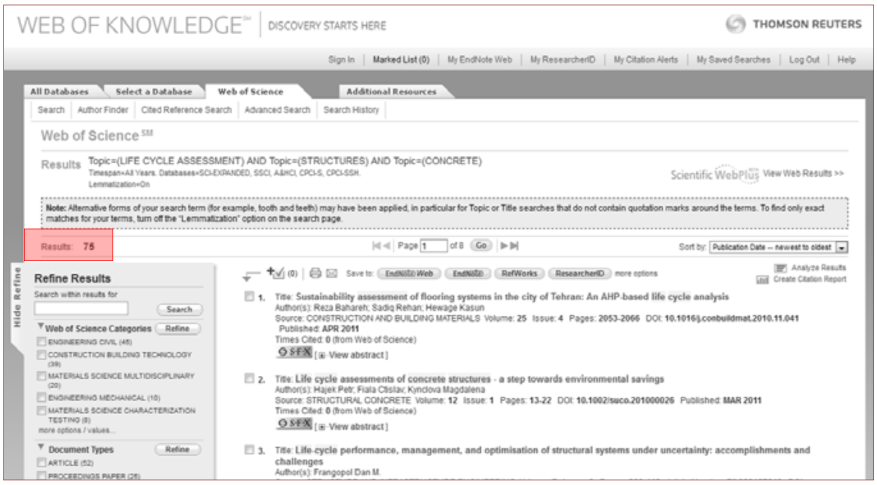


***Figure 14**: ISI WEB OF KNOWLEDGE article's research results.*

After recovering the articles from the different databases, their references were exported to RefWorks. Once all of them were exported (which rise to 129 articles references), the duplication tool offered by the soft was ran, finding that 46 articles had similar duplications between the different databases. So at the end, the number of articles finally was reduced to 76. Right ahead it can be seen the variation produced by the different filters of articles performed:

SOURCE	SEARCH RESULTS	FIRST FILTERING	SECOND FILTERING
EBSCO HOST	197	11	11
ENGINEERING VILLAGE	115	34	30
IEEE XPLORE	3	2	1
SCIENCE DIRECT	42	8	5
SCOPUS	171	49	20
ISI WEB OF KNOWLEDGE	75	25	9
TOTAL:	603	129	76

***Table 7:** Distribution of articles by source after each filtering process (%). (Source: own elaboration)*

SOURCE	SEARCH RESULTS	FIRST FILTERING	SECOND FILTERING
EBSCO HOST	32.67 %	8.53 %	14.47 %
ENGINEERING VILLAGE	19.07 %	26.36 %	39.47 %
IEEE XPLORE	0.50 %	1.55 %	1.32 %
SCIENCE DIRECT	6.97 %	6.20 %	6.58 %
SCOPUS	28.36 %	37.98 %	26.32 %
ISI WEB OF KNOWLEDGE	12.44 %	19.38 %	11.84 %

***Table 8**: Distribution of articles by source after each filtering process (%). (Source: own elaboration)*

Comparing the results after the filters, it is seen that EBSCO HOST suffers the most important reduction (passing from a representative 32.27 % to a final 14.47 %). By the other hand, Engineering Village database shows the opposite situation (increasing its representation from a 19.07 % to a 39.47 %). The rest of databases follow a similar representative distribution after the application of the filters.

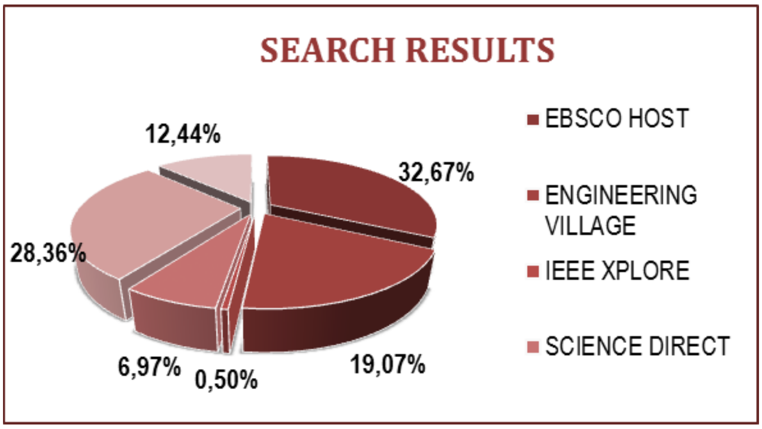


***Chart 1**: Distribution by database of recovered articles. (Source: own elaboration)*

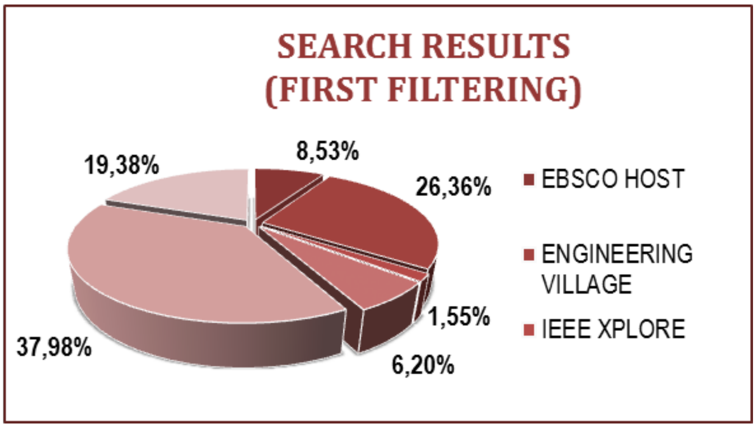


Chart 2: Distribution by databases of recovered articles after first filtering. (Source: own elaboration)

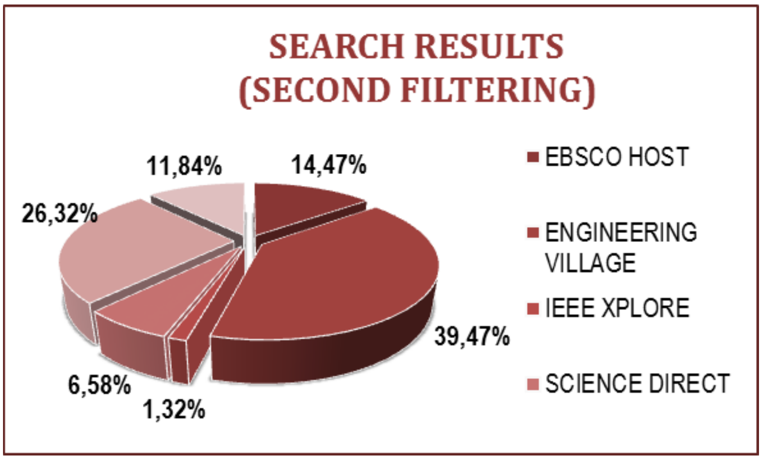


Chart 3: Distribution by databases of recovered articles after second filtering. (Source: own elaboration)

3.1.3. Research recovers expansion.

As the minimum number of articles for a good biographical study is recommended to be around 125-130 articles, it was necessary to expand the number of recovered articles after the performance of the research strategy. So, a second phase of research was needed, but this time it was done focusing on the bibliography of the articles recovered.

This second phase consisted on looking into each one of the recovered article's biography in the first phase. After choosing the ones close to the study from their titles, the articles were accepted or dismissed depending on the information contained in their abstract. This second phase research was performed twice, until recovering a total number of 168 articles for the study.

A simple flow chart of the process follow to complete the number of articles is right ahead attached:

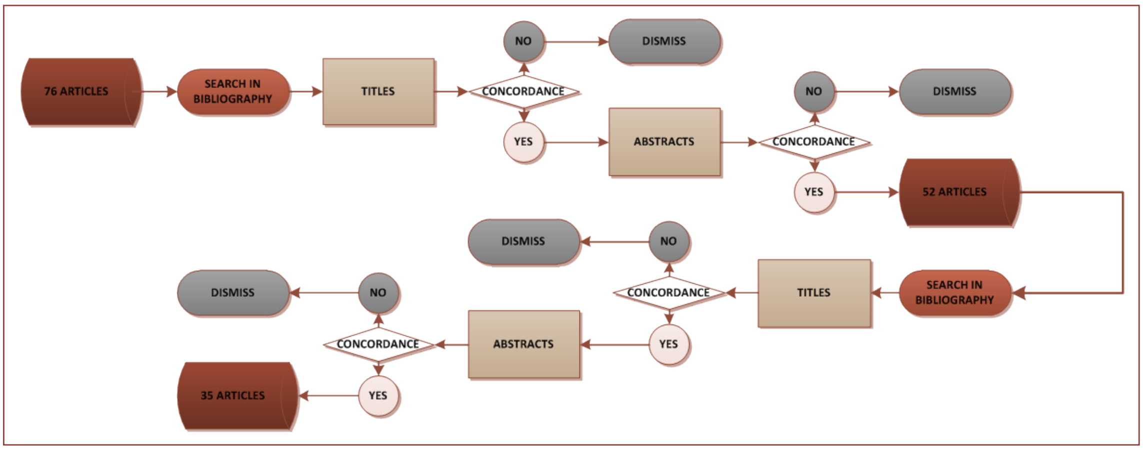


Figure 15: *Flow-chart for the second search process. (Source: own elaboration)*

It is remarkable that, if the results obtain by each research phase are compared, the second phase was more successful (almost the fifty four per cent of the articles used in the data mining came from this phase).

3.2. Data organization.

The amount of data that was acquired by the research was large. So, to simplify the rear data mining of the study, it was chosen which information would be useful and focused on its compilation. Mainly, the information considered was:

- Article's title
- Article's author/-s
- Article's journal
- Article's publishing year
- Article's origin (country and continent)
- Article's citation index
- Journal's impact and immediacy indexes
- Keywords

All this information was gathered, organized and included for each article in what was called an "article's sheet". Latter, the information was unified in a unique spread sheet that allowed and eased the following step of the work (analysis of articles recovered), exposed ahead.

TITLE:	*Inventory analysis of LCA on steel- and concrete-construction office buildings*				
AUTHOR 1:	*Xing, S.*	JOURNAL:	*Energy and buildings*	YEAR:	*2008*
AUTHOR 2:	*Xu, Z.*				
AUTHOR 3:	*Jun, G.*	COUNTRY:	*China*	CONTIENT:	*Asia*
AUTHOR 4:					
AUTHOR 5:		CITATIONS (WOK):	*7*		
IMPACT FACTOR:	*2,041*	5-YEAR IMPACT FACTOR:	*2,254*	INMEDIACY INDEX:	*0,273*
KEYWORDS:	*Life-cycle assessment; Inventory analysis; Emission; Energy consumption; Building materials*				

***Figure 16**: Example of articles sheet used at the research phase of this work. (Source: own elaboration)*

3.3. Analysis of articles.

Starting from the spread sheet, which compiled the most important information about the recovered articles, it was processed a data-mining focused on different aspects such as:

- Publishing time evolution
- Distribution of published articles by journals
- Indexes of journals
- Authors
- Origin of published articles
- Quality
- Issues by titles and keywords

This differences aspects are going to be developed as followed using graphical representations of the data acquired.

3.3.1. Article's time analysis.

In a first stage it was looked into the evolution of articles during the last thirty years. It can be seen that this topic has become trendier during the last fifteen years.

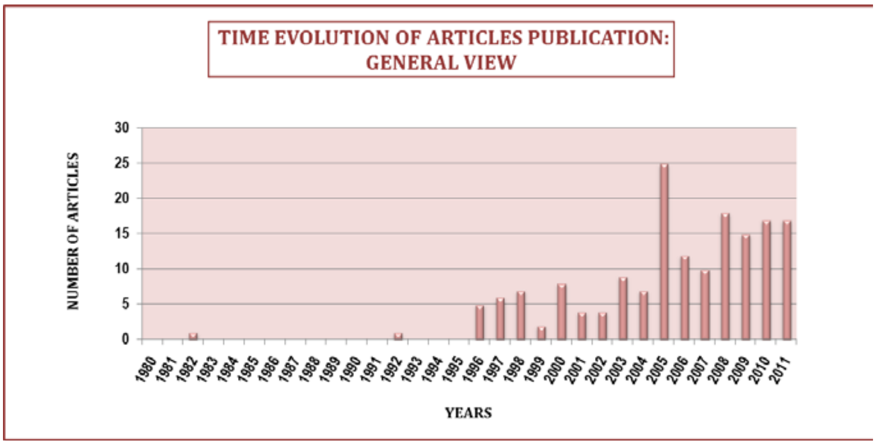


***Chart 4**: Distribution of published articles by time (time evolution). (Source: own elaboration)*

If an evolution trend line is draw, considering the last fifteen years of published material, it can be appraise that the topic offers a clear growth projection [Chart 5].

Of the last fifteen years, 2005 was the year with more articles published about the topic. Is also necessary to point that, due to the study was made during August-September 2011, for that same year the data is biased. In any case, the trend line show that publications for this year were supposed to be larger, as the years to follow [Chart 6]. So, basing on the time analysis, the topic of LCA applied to construction environment is one of current interest for the scientific world.

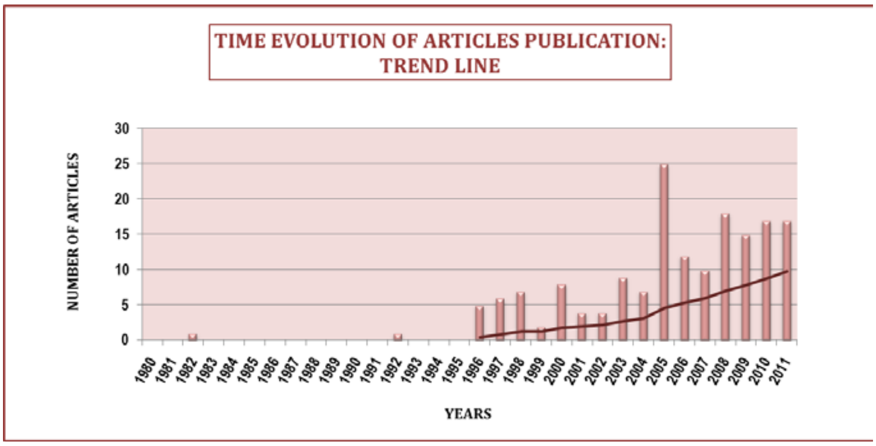


Chart 5*: Distribution of published articles by time (trend line). (Source: own elaboration)*

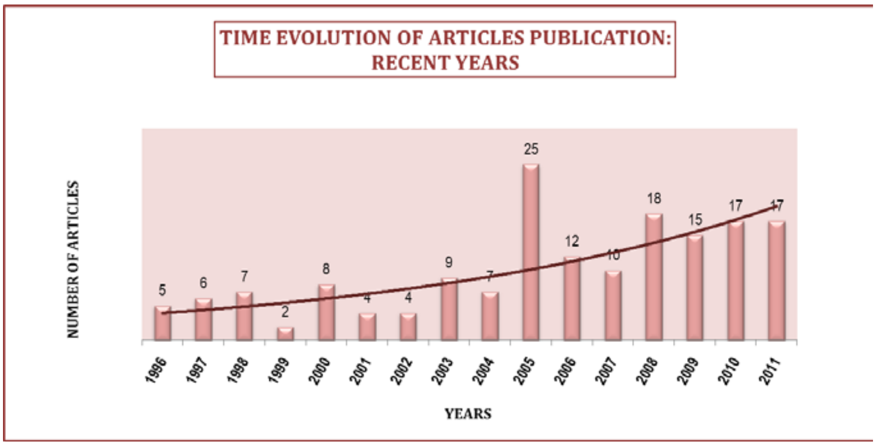


Chart 6*: Distribution of published articles by time (recent years). (Source: own elaboration)*

3.3.2. Article's geographical analysis.

The first impression, which latter was proved [Chart 7], during the analysis of the article's geographical origin, was that United States of America was the country where most publications came from. In a following stage after U.S.A., it can be found: Sweden, China, Germany and United Kingdom. It is to stand out that Spain is located in the sixth position in number of articles recovered about the topic, as Canada.

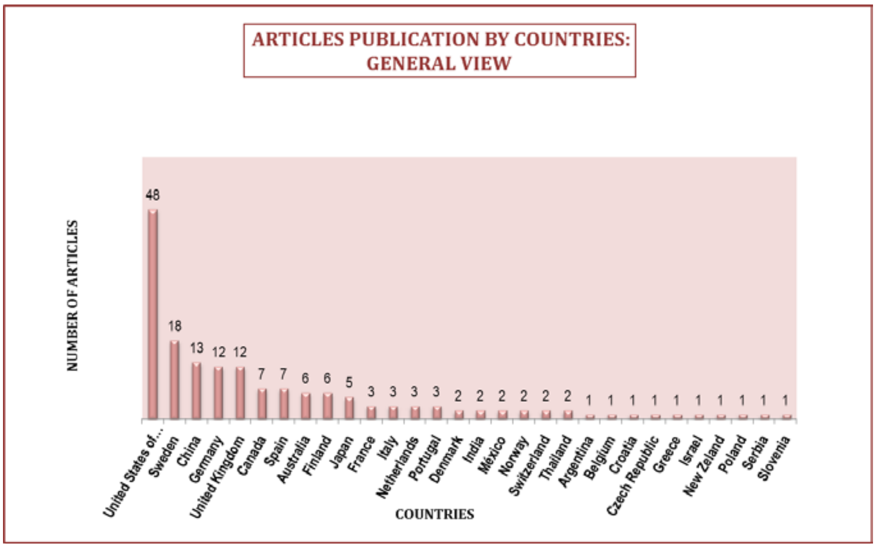


__Chart 7__: Distribution of published articles by origin (countries). (Source: own elaboration)

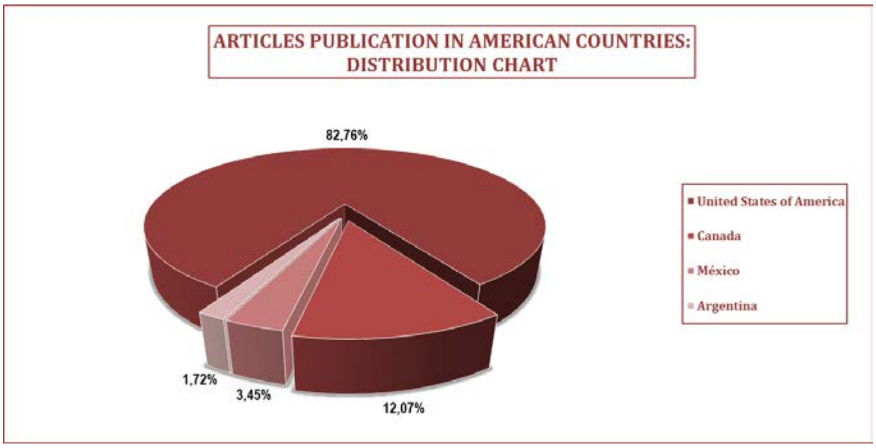


__Chart 8__: Distribution of published articles by origin (American countries). (Source: own elaboration)

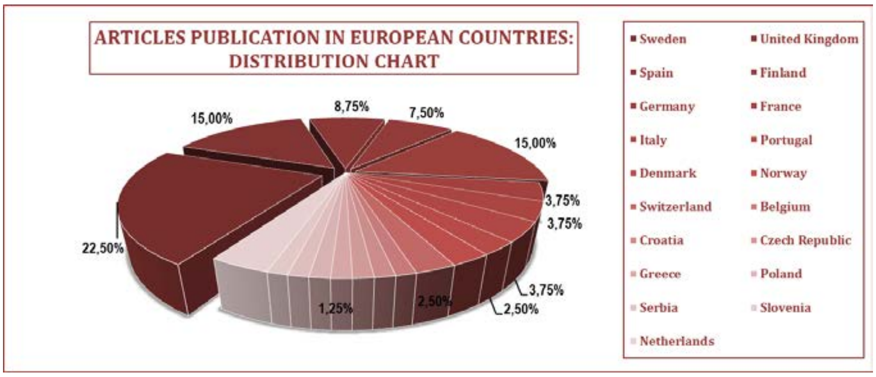


__Chart 9__: Distribution of published articles by origin (European countries). (Source: own elaboration)

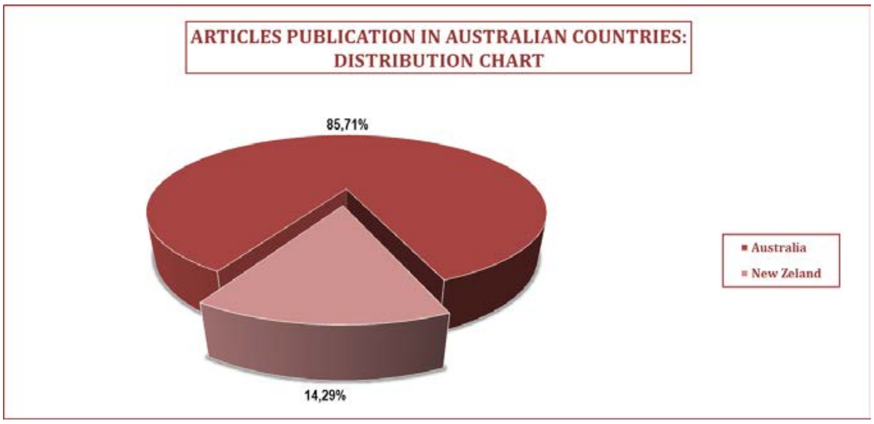


Chart 10: Distribution of published articles by origin (Australian countries). (Source: own elaboration)

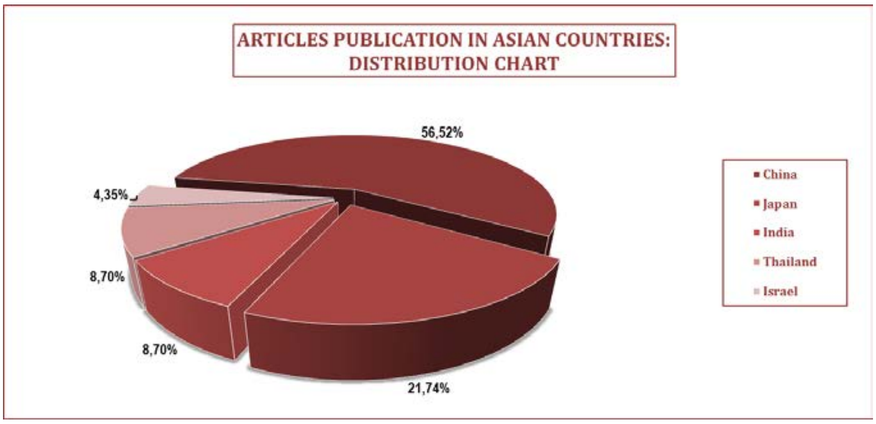


Chart 11: Distribution of published articles by origin (Asian countries). (Source: own elaboration)

Chart 12: Distribution of published articles by origin (continents). (Source: own elaboration)

If a look is taken into the distribution of articles recovered by continents, the sum of publications from European countries overcome publications from United States of America. It is also remarkable the presence of China, as the third country with more publications recovered in the study, and that no publication has come from Africa (shows the underdevelopment that the countries of this continent are suffering nowadays).

3.3.3. Article's time and geographical analysis comparison.

After the analysis performed on the time evolution and its geographical distribution, it was considered necessary to compare the relevance of the most important countries with the continent they were in. This led us know their progression and the importance they had in our topic's development.

First, it was analysed the representation of articles published in United States of America, comparing to articles published in all the American continent. It can be seen [Chart 13] that the relative importance is high and that there is an incremental trend for the topic.

Then it was the turn to take a look at the European country, and more specifically to Sweden, as the most important country related to our topic. It can be said, and appraise [Chart 14], that the importance of the published article's contribution in Sweden is dilute by the number of articles published in other countries from the same continent. Also, it is seen that the tendency is taking a decreasing trend from 2009 to now.

Finally, it was analysed the Asian continent [Chart 15] taking into consideration and contrasting the evolution for China. It was observed that China, its articles publication, shows an increasing trend for the last six years and that it is importance into the published articles is elevated.

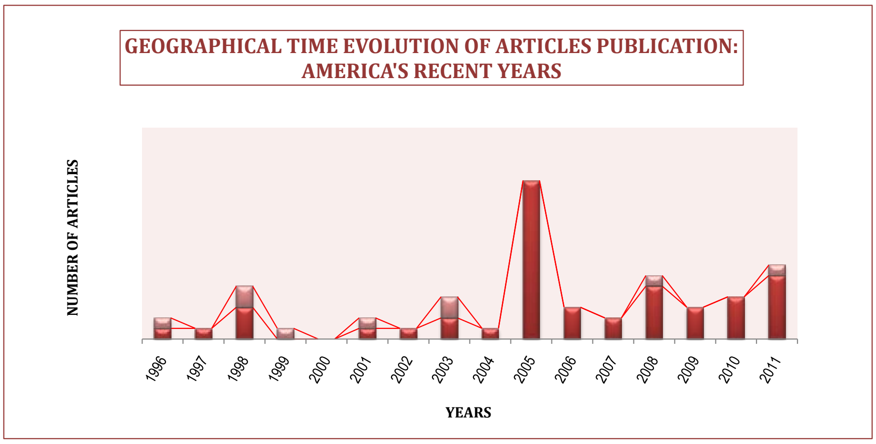


***Chart 13**: Contrasted publication's time evolution between USA and total in America. (Source: own elaboration)*

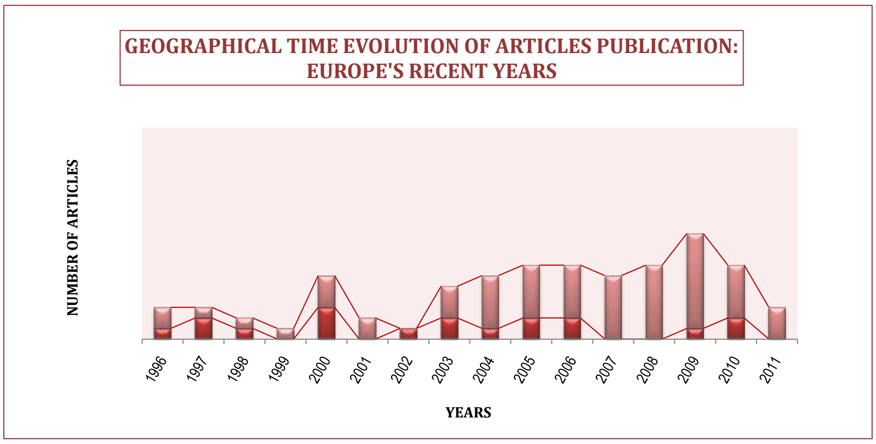


Chart 14*: Contrasted publication's time evolution between Sweden and total in Europe. (Source: own elaboration)*

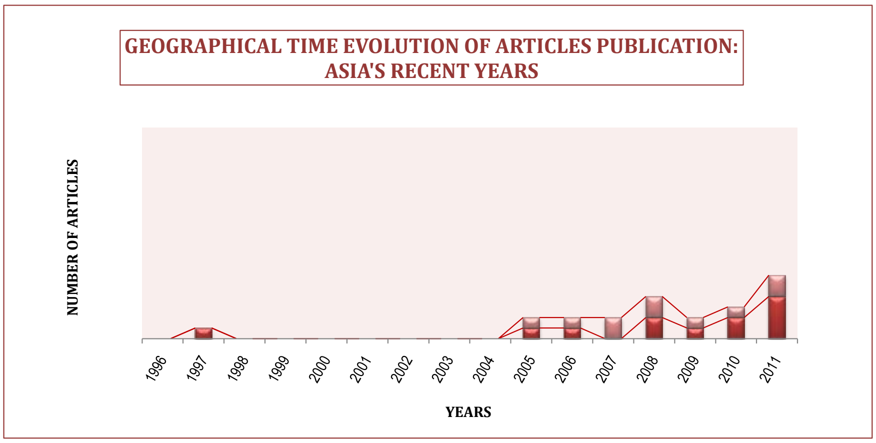


Chart 15*: Contrasted publication's time evolution between China and total in Asia. (Source: own elaboration)*

3.3.4. Article's authors analysis.

During the analysis of the author's number of publications, it was appraised that less than five per cent of the authors had published three or more articles about the topic. The most of the authors just had published a single article.

Afterwards it was studied the average of citation received by the articles published by the five per cent of authors mentioned before. From this study was observed [Chart 17] that the five most cited authors were: Björklund, Althaus, Joshi, Adalberth, Heijungs, Hendrickson and Cole.

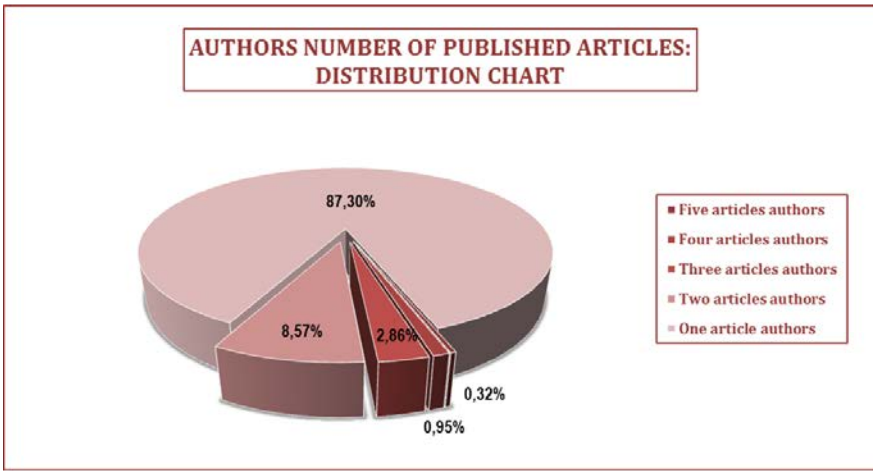


***Chart 16**: Distribution of published articles by authors. (Source: own elaboration)*

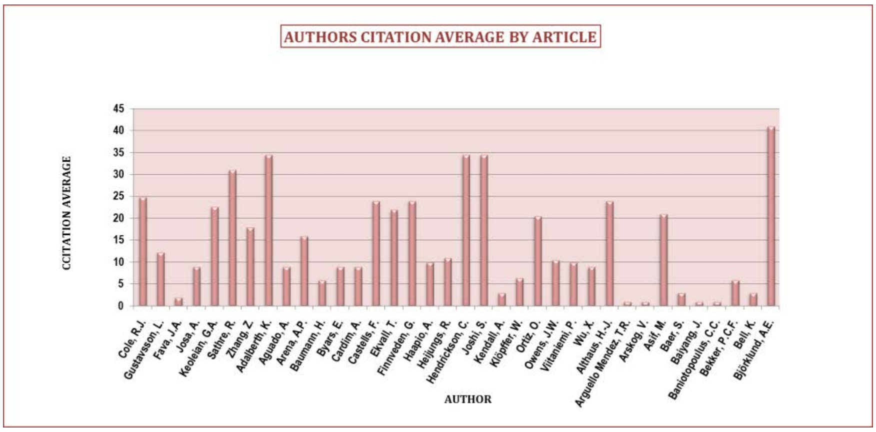


***Chart 17**: Distribution of average author's citation (authors with more publications). (Source: own elaboration)*

3.3.5. Journal's distribution analysis.

From the analysis of journals, it was seen that the journals with most number of articles published were: Building & Environment (B&E), International Journal of Life Cycle Assessment (IJLCA), Building Design & Construction (BD&C), Energy & Buildings (E&B) and Journal of Infrastructure Systems (JIS). Then there is a group of journals between 2 and 4 articles, but the biggest amount has just an article published.

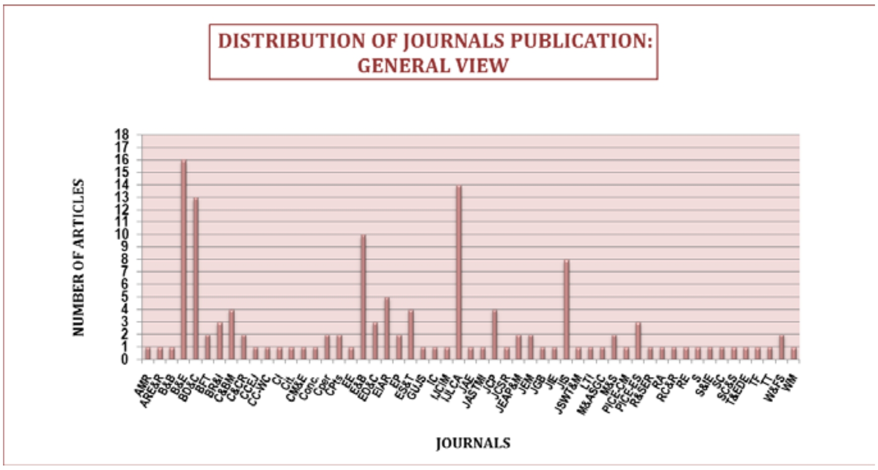


Chart 18: *Distribution of published articles by journals. (Source: own elaboration)*

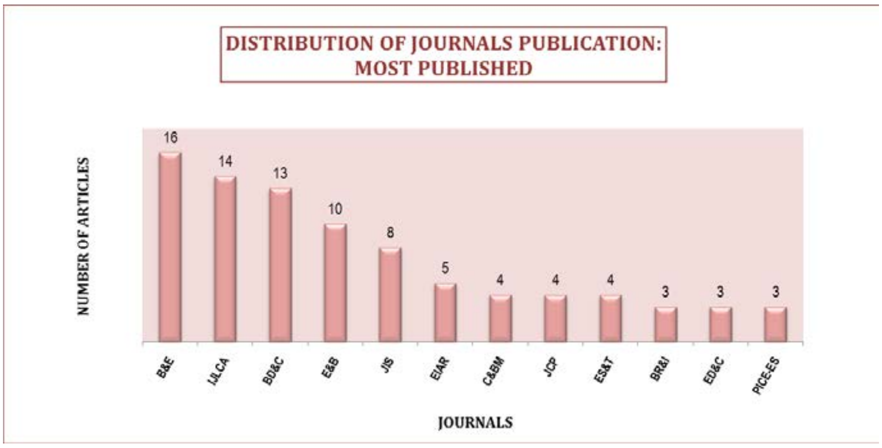


Chart 19: *Distribution of published articles by journals (most published). (Source: own elaboration)*

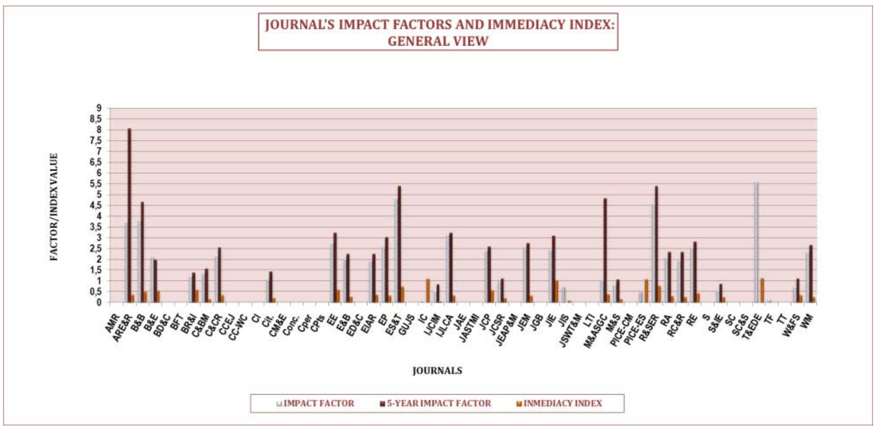


Chart 20: *Distribution of impact factors and immediacy index of journals. (Source: own elaboration)*

If an accurate look is taken to journal's impact factors and immediacy index, it is possible to conclude that the journals with more articles published do not match the best rated journals [Chart 21; Chart 22; Chart 23]. It is also possible to see that just International Journal of Life Cycle Assessment (IJLCA) has rates that located it at head positions, close to journals as Technological & Economic Development of Economy (T&EDE) and Environmental Science & Technology (ES&T).

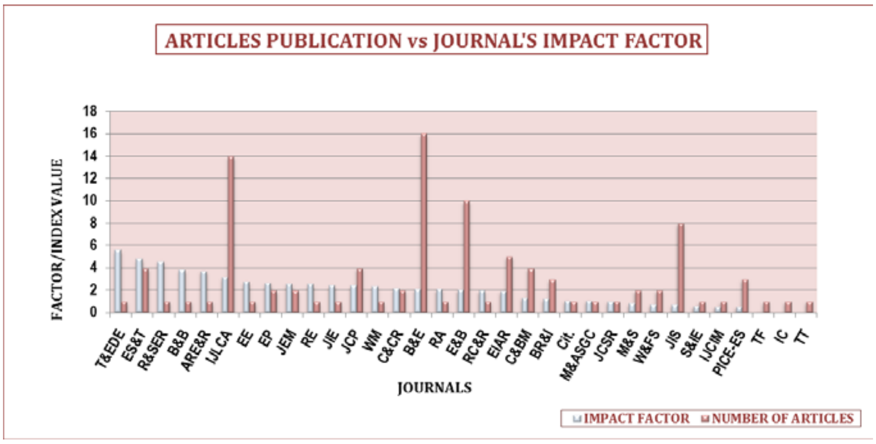


***Chart 21**: Distribution of impact factors of journals and articles published. (Source: own elaboration)*

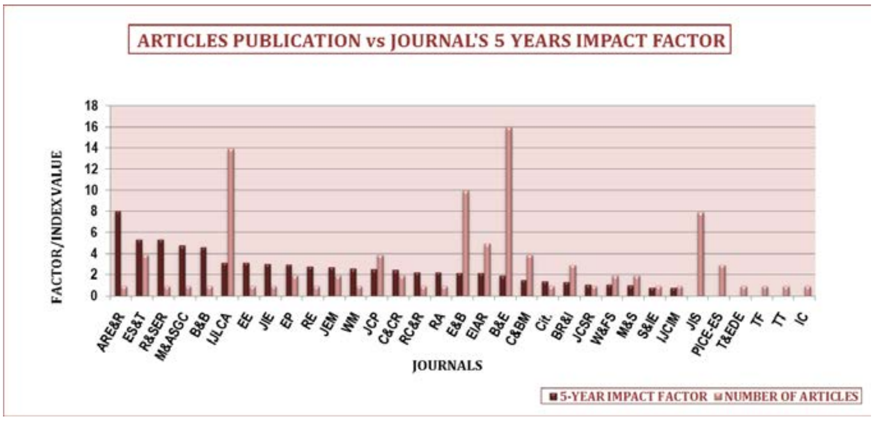


***Chart 22**: Distribution of 5years impact factors of journals and articles published. (Source: own elaboration)*

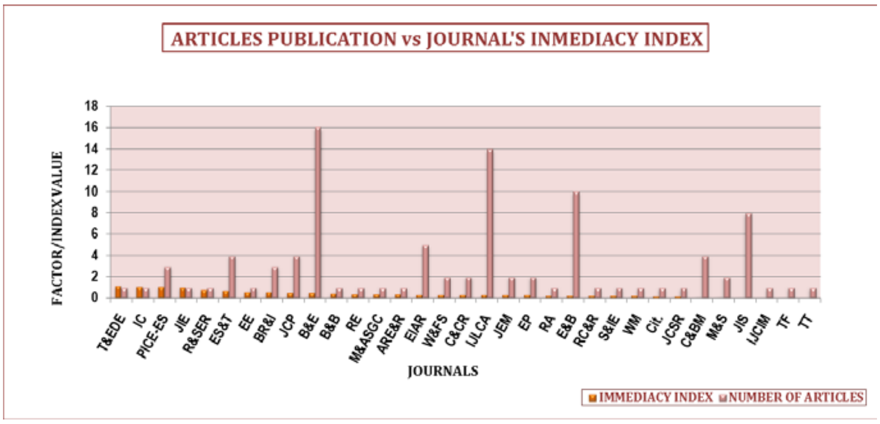


***Chart 23**: Distribution of immediacy index of journals and articles published. (Source: own elaboration)*

3.3.6. Best quality articles analysis.

The quality in articles for this study was mainly based on the citations received by other scientific articles. Of this kind of articles it was taken a tighter look, focusing on aspects as: publication years, their origin and their authors. If years that most cited articles were published is considered, it is appreciated that 2008 (twenty-one per cent) was the year when more quality articles were published [Chart 21]. Directly followed by 2008 are 2009 and 2005 (thirteen and eleven per cent respectively).

Relating to the origin, it is appraised that United States of America (with a seventeen per cent) and Sweden (with a fifteen per cent) are the countries where more quality articles were published [Chart 25]. But, it is also to point the fact that Canada, Germany and Spain are following this countries (eight and seven per cent of representativeness), even taking into account that this same countries generally count on a fewer rate of articles published [Chart 7]. Anyway, if a look is taken to continent origins, Europe agglutinates the biggest percentage (fifty-three per cent). So it is that Europe publishes more than USA altogether as the high quality (citation) of their articles.

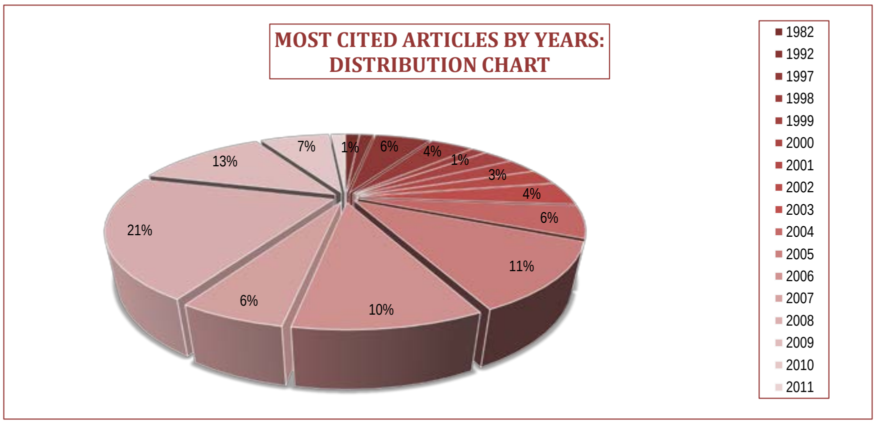


***Chart 24**: Distribution of most cited articles per year. (Source: own elaboration)*

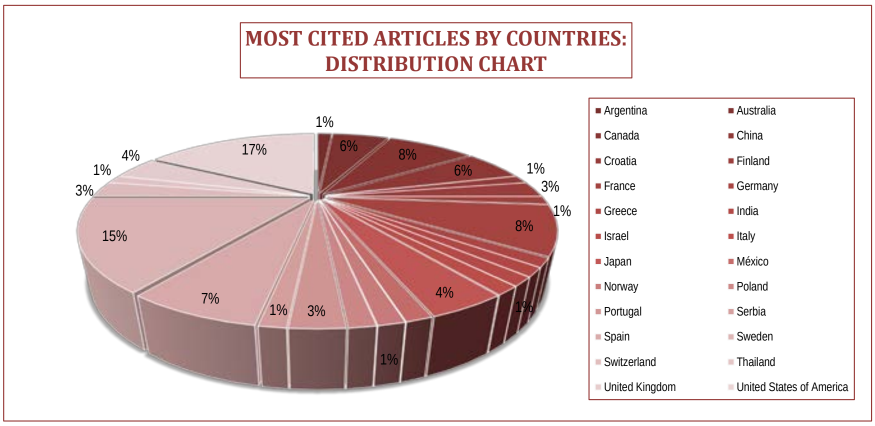


***Chart 25**: Distribution of most cited articles by country. (Source: own elaboration)*

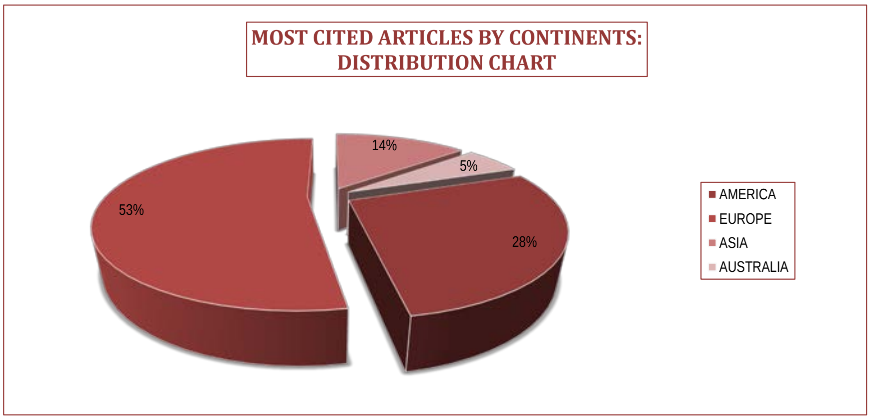


***Chart 26**: Distribution of most cited articles by continent. (Source: own elaboration)*

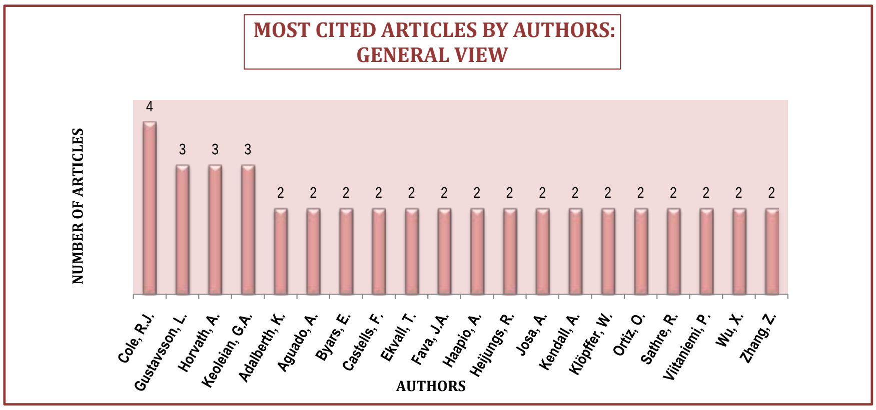


***Chart 27:** Distribution of most cited articles by authors. (Source: own elaboration)*

As it was studied the average of citation by articles published by authors, now it is time to look which authors publish the most cited articles. As it is seen at the chart below [Chart 27], the authors can be grouped into three, depending on the number of the most cited articles published. In the first group, it is found alone Cole, but in the second are located: Gustavsson, Horvath and Keolelan. The rest of the authors, as Adalberth or Ortiz, are included in the third group.

With the objective of establishing the quality of the journals where the most articles related to the topic were published, a look was taken to the Thomson Reuters Journal Citation Reports of 2010 (JCR-2010). The information obtained has been exposed at the table offered ahead:

JOURNAL	ARTICLES	IF	Q1	Q2	Q3	Q4
Building and Environment	16	2,131	X			
International Journal of Life Cycle Assessment	14	3,148	X			
Energy and Buildings	10	2,046	X			
Journal of Infrastructure Systems	8	0,74		X		
Environmental Impact Assessment Review	5	1,944	X			
Construction and Building Materials	4	1,366	X			
Environmental Science and Technology	4	4,827	X			
Journal of Cleaner Production	4	2,43	X			
Building Research and Information	3	1,25	X			
Proceedings of the Institution of Civil Engineers: Engineering Sustainability	3	0,522			X	
Cement and Concrete Research	2	2,187	X			
Energy Policy	2	2,629	X			
Journal of Environmental Management	2	2,597	X			
Materials and Structures	2	0,85		X		
Wood and Fiber Science	2	0,752		X		

Table 9: *Impact factors and distribution quartiles for journals with more articles published JCR-2010. (Source: own elaboration)*

3.3.7. Article's titles and keywords analysis.

Finally, for the ultimate step of the data mining phase of the study, it was conducted an analysis of titles and keywords of the articles recovered. The results obtained are reflected ahead:

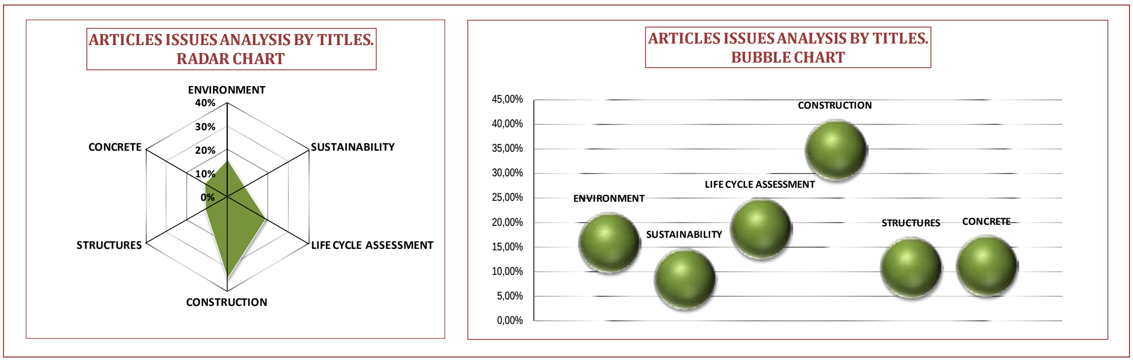


***Chart 28**: Distribution of articles titles. (Source: own elaboration)*

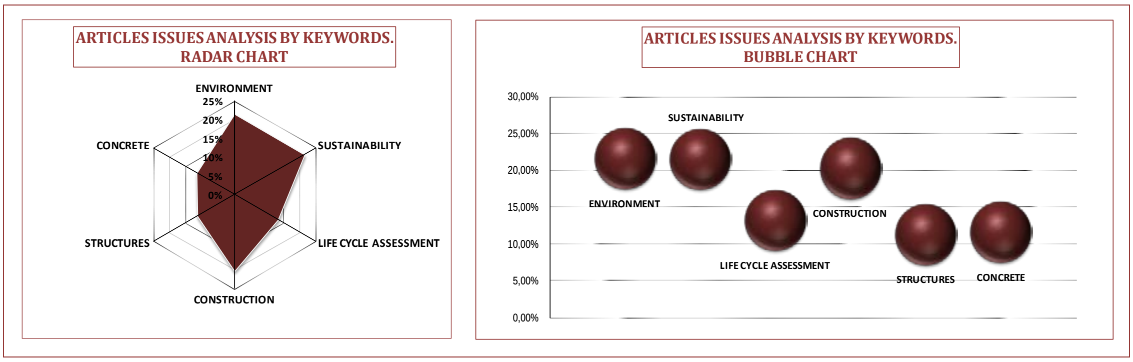


***Chart 29**: Distribution of articles keywords. (Source: own elaboration)*

3.3.8. Article's titles and keywords analysis comparison.

Afterwards the analysis of titles and keywords of the articles recovered was conducted; the results between titles and keywords were compared to locate differences and similarities.

The main singularity of the results of this study are that the title emphasized words related to constructions but, in other hand, keywords focus more on environment and sustainability related words. In regard to words related to structures and concrete, both (titles and keywords) show an equal rate.

On his behalf, Life Cycle Assessment terms show more importance at the articles titles, but more or less the have a similar rate for articles titles and keywords.

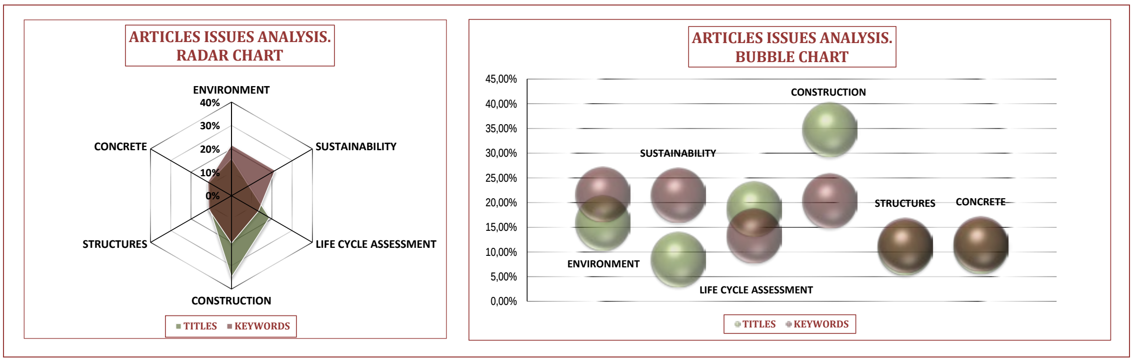


***Chart 30**: Distribution of articles by titles and keywords. (Source: own elaboration)*

3.3.9. Articles analysis main observations.

As it was already exposed at this work, a literature search of articles and documents published to date regarding the applicability of LCA to concrete structures was performed. After reaching a volume of 168 articles and scientific publications, obtained from different databases (such as IEEE Xplore, Science Direct or Scopus), we proceeded to analyse them in a quantitative way. From the results obtained from this analysis, we observed that the issue turns out to be relative present, since most of the publications date back 15 years (since 1996). On the other hand it was also observed that the greatest number of publications came from the United States (around 28.60% of the whole). However, by adding the different countries according to their respective continents, Europe exceeds the number of publications when compared to America's (a 48.20% vs. 34.50%, respectively). At the same time, it was observed that Chinese publications have increased its contribution to the subject in recent years, resulting in about 13.70% of all articles have been published in that country. As what comes to the authors, it was found that only 5% of them had published 3 or more times relating to the topic, and the majority (in particular 87.30%) had only published on one occasion. On the other hand, when analysing the articles that had received more citations, it was noted that 2008 was the year when more documents with this particularity were published and that its origin was essentially the United States, but followed closely by Sweden. Finally, it was observed that approximately 58.20% of the journals in which articles were published on the topic were included in the ISI Journal Citation Report 2010, and mainly its impact indexes were above 2.00.

LCA STATE OF THE ART

4. LCA STATE OF THE ART.

In this fourth chapter of the work, there will be included a thorough exposition of the up to date knowledge related to LCA. Within this part, all relevant information related to LCA will be exposed, offering a view of the different points of its application to concrete structures, as it can be: existing methodologies, types, available software, databases… First, a description of the different methodologies and typologies existing will be done. Next, it will be offered a relation of the different software and databases that there are to help during the practice of LCA studies. Finally it will be introduce an S.W.O.T. analysis of LCA to establish different and important aspects of the tool for its practice on concrete structures and future developments.

4.1. Life Cycle Assessment typologies.

4.1.1. Depending on the standard/guideline.

Until present time, different standards and guidelines for LCA framework have been provided by various organisations. Some examples are ISO's 14040 standard, SETAC's "Code of Practice for Life Cycle Assessment", CML's "Environmental Life Cycle Assessment of Products" guideline, ASTM's E1991-05 standard, EPA's LCA101 "Life Cycle Assessment: Principles and Practice" or CAN/CSA-Z760 standard, among many others. Introduction of nowadays most relevant standards and guidelines is then exposed, focusing on each proposed methodology for conducting Life Cycle Assessments and pointing out main differences existing between them.

4.1.1.1. International Organization for Standardization.

International Standard ISO 14040:1997 "*Environmental management--Life cycle assessment--Principles and framework*" was prepared by Technical Committee ISO/TC 207/SC5, formed by 24 delegates and 16 further observers from different countries each (Klöppfer [83]). ISO 14040:1997 was later complemented by the publication of the next standards:

- ISO 14041:1998 "*Environmental management--Life cycle assessment--Goal and scope definition and inventory analysis*"
- ISO 14042:2000 "*Environmental management--Life cycle assessment--Life cycle impact assessment*"
- ISO 14043:2000 "*Environmental management--Life cycle assessment--Life cycle interpretation*"

With the objective of easing and enhancing its practice, ISO published different standards with examples for applying LCI and LCA studies. First of them was ISO/TR 14049:2000 "*Environmental management--Life cycle assessment--Examples of application of ISO 14041 to goal and scope definition and inventory analysis*", that shows considerations to be taken when doing the goal and scope definition and the Life Cycle Impact (LCI) phases.

The other standard released by ISO was ISO/TR 14047:2003 "*Environmental management--Life cycle impact assessment--Examples of application of ISO 14042*", which provides examples to illustrate practice in carrying out the Life Cycle Impact Assessment (LCIA) phase of LCI and LCIA studies. Later in 2006 a second edition of ISO 14040 standard was published (ISO 14040:2006), together with ISO 14044:2006 "*Environmental management--Life cycle assessment--Requirements and guidelines*", that cancelled and replaced previous ISO standards 14040:1997, 14041:1998, 14042:2000 and 14043:2000. According to ISO 14044:2006, already exposed previously at epigraph "*2.3.3. Life Cycle Assessment method*", a LCA study comprehends four phases: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation.

***Figure 17**: Life Cycle Assessment procedure according to ISO 14040. (Source: reproduced from Guinée et al [208])*

Notwithstanding LCA studies based on ISO 14044 are the most common and typical. These types of LCAs are not free of some peculiarities that must be taken into account once an assessment is performed:

- Depending on if considering or not inventory analysis phase, the assessment can be called Life Cycle Inventory study (LCIA is excluded) or Life Cycle Assessment study (when LCIA is included) (ISO [227]).
- A distinction is made at the Life Cycle Impact Assessment (LCIA) phase when considering mandatory and optional elements. According to ISO, every LCA must at least include an impact categories selection, a classification step and a characterization procedure (ISO [227]).
- Critical reviews are considered as optional, except when LCAs contain comparative assertions intended to be disclosed to the public. In those cases, critical review must be conducted according to panel method (Klöppfer [84]).

As it was indicated previously, this methodology is the most practiced for LCA studies. As an example, for a product to publish its EPD or to be certified with an environmental label, it is necessary to perform the LCA methodology established by the ISO standard. Moreover, when taking a look at the LCA studies on concrete studies, it has been observed that process methodology (the one established in ISO) has been the most common for conducting the assessments (this will be later exposed at this work). Some examples of this are the study performed by Lopez-Mesa et al [94], comparing two types of structural concrete slabs in a Spanish context, and the comparison of steel with a reinforced concrete structure in Greece performed at the study by Dimoundi and Tompa [32].

4.1.1.2. Society of Environmental Toxicology and Chemistry.

The Society of Environmental Toxicology and Chemistry (SETAC), according to Klöpffer [83], is a worldwide professional society composed equally by researchers coming from the academia, industry and governmental fields. This fact gives SETAC authority and credibility to prescribe behaviour for LCA commissioners as well as practitioners. In 1993 it released the "*Code of Practice for Life Cycle Assessment*", as indicated previously in the present work at epigraph "2.3.1. Life Cycle Assessment birth and evolution". According to the 69-page SETAC's guideline, LCA studies are composed of three stages:

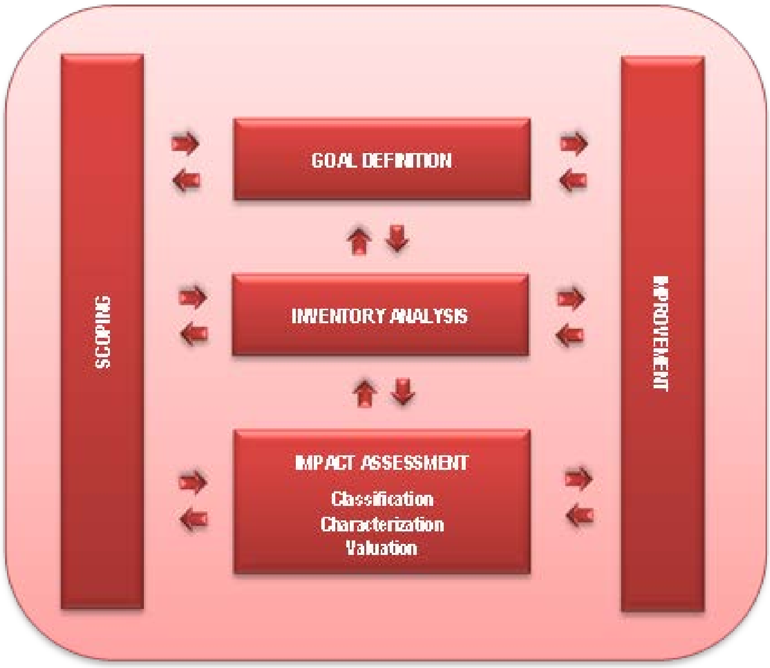


***Figure 18**: SETAC's LCA methodology graph. (Source: reproduced from Cole [23])*

1. Goal Definition and scoping. A clear statement of the primary purpose of the assessment, for whom and to what end, together with a clear definition of the functional unit, including both a description of the elements and its expected life-span.
2. Inventory analysis. The calculation of the energy and raw material inputs and air emission, liquid effluents and solid waste associated with the acquisition, production, use and disposal. A clear declaration of the system boundaries is central to this stage of the process.
3. Impact assessment. The classification of the inventory data into relevant impact categories and identification of the impacts on natural systems.

When compared with the ISO standard, SETAC's "Code of Practice shows the same first three steps. Nevertheless, within the impact assessment stage of the study, a new component named "valuation" is included after the "classification" and "characterization" elements. When taking a look at the "interpretation" step, SETAC's methodology considers it as an "improvement assessment" and the final critical review is more strictly recommended, even proposing an interactive or accompanying review.

4.1.1.3. Centre of Environmental Science.

In October 1992 was published the report of the study "Towards a method for comparative product assessment on environmental effects", mainly carried out by the Centre of Environmental Science (CML) at Leiden University. The framework for LCA in this report consists of five components: goal definition, inventory analysis, classification, evaluation and improvement analysis.

1. Goal definition. Includes the purpose of the Life Cycle Assessment, but also other aspects as: the target group, desired application, etc. Limitations of the study due to available resources (time, money of data) will also be viewed in this part of the study.
2. Inventory analysis. Is the part of the LCA when the system of the product is analyzed: system boundaries, allocation and the inputs/outputs
3. Classification. Is the part of the LCA when quantification of the environmental interventions of a product system is used.
4. Evaluation. In this step, the environmental effects quantified are scored. This scoring, according to the guide will have to be rated in order to make an assessment.
5. Improvement analysis. During the improvement analysis information about the life cycle of a product is used to make recommendations for the redesign or a different process operation, it means that this step is taken when product innovation is the aim of the study.

At the evaluation step, the guideline proposes the use of a Multi-Criteria Analysis (MCA) with the objective of allowing a comparison between products assessed. Moreover, for gaining information from the process tree to latter make recommendations for the redesign of a product or changes in the improvement assessment, two analytical techniques are distinguished:

- Dominance analysis. In this technique the entire process tree has to be traced to find the ultimate cause of a given dominant element in the inventory table, environmental profile or environmental index. However, such dominant elements may be due to many causes
- Marginal analysis. Provides information about individual changes in all process data provided when all other process data remains constant.

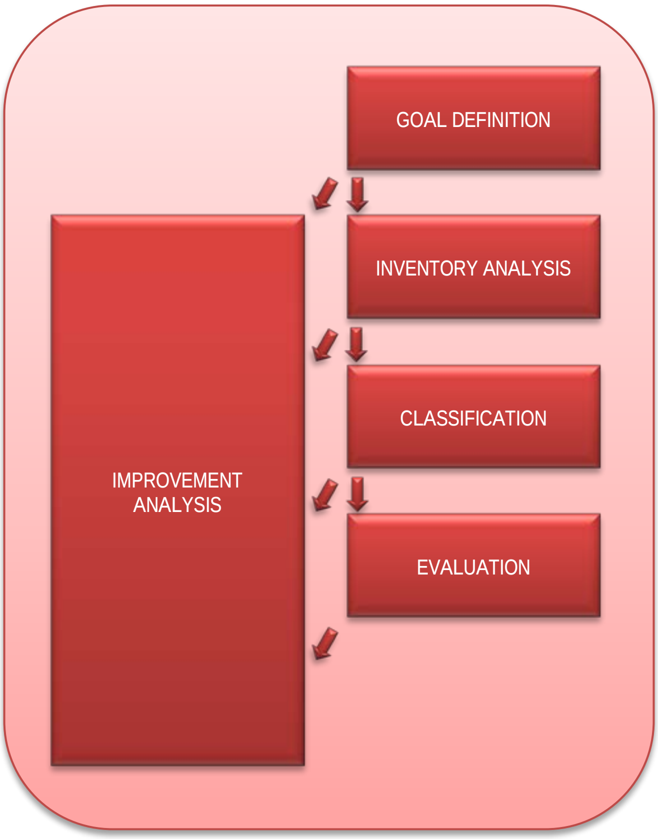


***Figure 19**: CML's LCA methodology graph. (Source: reproduced from Guinéé et al [186] and Guinée et al [187])*

4.1.2. Depending on the functional unit/system boundary.

LCA's results are directly linked to the functional unit a system boundary established for the product or service assessed. So, depending on the combination of these two concepts, the results of the LCA performed will vary. According to Khasreen et al [78], focusing on the construction industry, when the functional unit considered in the

LCA study is a whole building or infrastructure then the assessment will be defined to a certain level and will contain all materials and construction processes necessary for the project to accomplish. This level could be called "Whole Construction Process" (WCP). On the other hand, if the LCA is concerned with a part of the building, building component or material, the level would be called "Building Material and Component Combination" (BMCC).

Depending on the life cycle stage considered in the study, there different system boundaries are to be considered:

- Cradle-to-grave. It considers the full life cycle of the product from the point of raw materials extraction to the disposal stage. For example, in the case of a concrete structure, this would be from the extraction of aggregates, production of concrete mixing compounds, construction of the structure, operational and managerial phases and finally the demolition of the structure [Figure 23]. One example of a LCA study for a concrete structure considering the whole life cycle is found on that published by Bouhaya et al [15].
- Cradle-to-gate. Terminate at an intermediate stage of the life cycle, as it can be an assessment till the construction of a building or an infrastructure. An example for this kind of assessment is found on the one performed by Bilec et al [12], that considered the construction phase for a precast parking garage in United States.
- Cradle-to-cradle. Also known as open loop life cycle, considers the full life cycle, as that of the cradle-to-grave, but also including the secondary life cycle of the products or, what is the same, the reutilization or recycling of the disposal wastes. In the case of a concrete structure, this assessment is found on that published in 2009 by Gian Andrea [50] which included the reutilization of the demolished concrete from a building frame in the Italian context.

4.1.3. Depending on the allocation method.

Results obtained from LCA studies can vary depending on the loop of the inner life cycled considered for the product or service assessed, and on the elections taken and their effects. Also is important taking into account the time, the future time, and evolution. According to Viera and Horvath [165], there are two existing methods to conduct the allocation of the LCI phase of the study:

- Attributional. Aims at describing the environmentally relevant flows of the life cycle considered, excluding unit processes outside the lifecycle investigated.
- Consequential. Aims at describing environmental relevant flows change in response to possible modifications in the life cycle of the system. It includes unit processes that are affected whether they are inside or outside the life cycle.

The different results obtained with both methodologies is analysed by the same study published by Viera and Horvath [165] for the assessment of an office building with a concrete structure focusing mainly on the end-of-life phase of the life cycle and integrated in an American context.

4.1.4. Depending on the Life Cycle Impact.

According to the LCI approach considered, it can be distinguished two types of LCA methods: the **process analysis** and the **input-output analysis**. Nevertheless, as each method disposes its own disadvantages, a hybrid method integrating the strengths of both has been developed. The three of them will be explained as followed:

4.1.4.1. Conventional LCA.

This method, also named by other authors as process or traditional method is the one implemented by the ISO 14040 series. As it was pointed out in the paper by Bilec [12]), the environmental inputs and outputs within the life cycle of a product or service are established by following a process flow diagram. This representation, and consequently the calculations, usually begin in the final stage of the system assessed and directs backwards until reaching the point of raw material extraction. The main advantage that the method offers is its high accuracy.

Among the disadvantages the method includes, it requires data collection from multiple sources, as it could be: public organisations, private companies, manufacturer's product declarations and researcher's publications. Furthermore, and depending on the system assessed, the process offers such a difficulty in their flow diagram representation and understanding that problems during the calculation phase can arise. This situation, already considered by the research performed by Khasreen et al [78], can drive the study to a significant incompletes and therefore wrongness. So, if this is altogether considered, the method suffers from variability and consequently different results depending on the data and the flow diagram considered.

This variability previously mentioned, was studied by Lenzen and Treolar [87] for the production processes and defined as a "…*systematic truncation error*…" which mainly derived from the finite system boundary established in the process flow diagram. Its magnitude was also measured in the referred study, and it amounted to a 50%. Moreover, it was remarked the impossibility to be reduced to acceptable levels by the enlargement of the diagram as this would mean an increase of the system and consequently increase of calculations difficultness.

4.1.4.2. Input-Output LCA.

Input-output (I-O) analysis was developed, in terms of economics, in 1936 by Wassily Leontief. I-O LCA model combines national sector-by-sector economic data, quantifying economic dependencies between sectors, and links it to resource use and environmental effects. The model using matrix operations as a base lets the practitioner to identify and quantify environmental impacts when a change in economic demand from a sector is generated. Nevertheless, and as pointed out by Khasreen et al [78], it is "…*generally used as a black box*…" what makes practitioners do not understand completely the real values applied to the model in each process of the life cycle. Even so, it is considered to be more comprehensive than process method, as it can give direct and valuable estimates of embodied energy.

In recent years, the Green Design Institute from Carnegie Mellon University has developed an I-O based LCA tool, economic EIO-LCA (Lave et al 1995; Hendrickson et al 1998; Green Design Institute, Carnegie Mellon University 2004). This tool considers not just the direct impact, but the indirect impact on different sectors from economic data sources coming from the United States.

Some examples of I-O LCA for concrete structures, although are not wide in number, are found on the paper published by Ge [46] in 2010 comparing a steel against a concrete structure for a residential building in China and the one published by Horvath and Hendrickson [68] in 1998, also comparing a steel and concrete structure, but in this case for a bridge in the United States.

4.1.4.3. Hybrid LCA.

Process-based LCA uses data on direct environmental impacts just for the system assessed, while EIO-LCA provides environmental impacts both from the system and the supply-chain from a national perspective. These two methods, used together in a hybrid approach, provide an accurate picture of total life-cycle emissions. So, the goal of a Hybrid LCA is to combine the advantages of both approaches. There are several types of hybrid models, which we pass to treat ahead:

- **Tiered hybrid analysis** was developed in 1978 by Bullard et al. This type of hybrid analysis uses Input-Output data to quantify economic inputs and output flows from a process-model-flow diagram. This means that the method applies I-O analysis in each step of the process model, what offers an increase perspective of the process method. It has two phases of approach; the first that include a whole economy level and a second more sector-specific allowing the method assess atypical products. This last approximation, to assure correctness of specific data introduced in the model, is previously made by introducing factors.
- The **Input-Output based hybrid analysis method** focuses on specific sectors, according to detailed economic information, and not gross national data. This allows assessing products or services that are not well described in I-O economic data sources; such is the case of new product releases.
- The third method, **integrated hybrid analysis**, was developed by Suh 2004. This model integrates process LCA with I-O in a mathematical framework. Its main advantages are consistency (by mathematical framework) of the entire life cycle calculation, avoidance of double counting, and easiness for its latter application in analytical tools. On the contrary, its disadvantages are that it is data and time intensive.
- **Augmented process-based hybrid model** combines both economic IO-LCA data and environmental process data for the assessment of the complete life cycle of a product or service. It also allows including sector specific information when data is available.

Examples of Hybrid LCAs on concrete structures are more numerous than that performed using I-O analysis. As examples, we have the paper published by Gerilla et al [47] comparing a wood versus a reinforced concrete structure for a residential building in the Japanese context, but also the one by Guggemos and Horvath [54] published in 2005 assessing and comparing a steel and a cast-in-place concrete office structure in the United States.

4.1.5. Depending on the Life Cycle Impact Assessment.

There are essentially two types of methods for conducting the Life Cycle Impact Assessment in a LCA study:

- Problem-oriented methods (mid-points) do contemplate the conversion of impacts obtain from the LCI to environmental themes, such as: climate change, acidification, human toxicity, etc. As indicated by Josa et al [74], when compared to end-point approach, it reduces the assumptions/complexity of the modelling and results. However, interpretation results are more difficult, since they don't refer directly to damages.
- Damage-oriented methods (end-points), on the other hand, classify the flows into various issues of concern, modelling each issues damage caused to human beings, natural environment and resources. Endpoint results have a higher level of uncertainty compared to midpoint results but are easier to understand by decision makers.

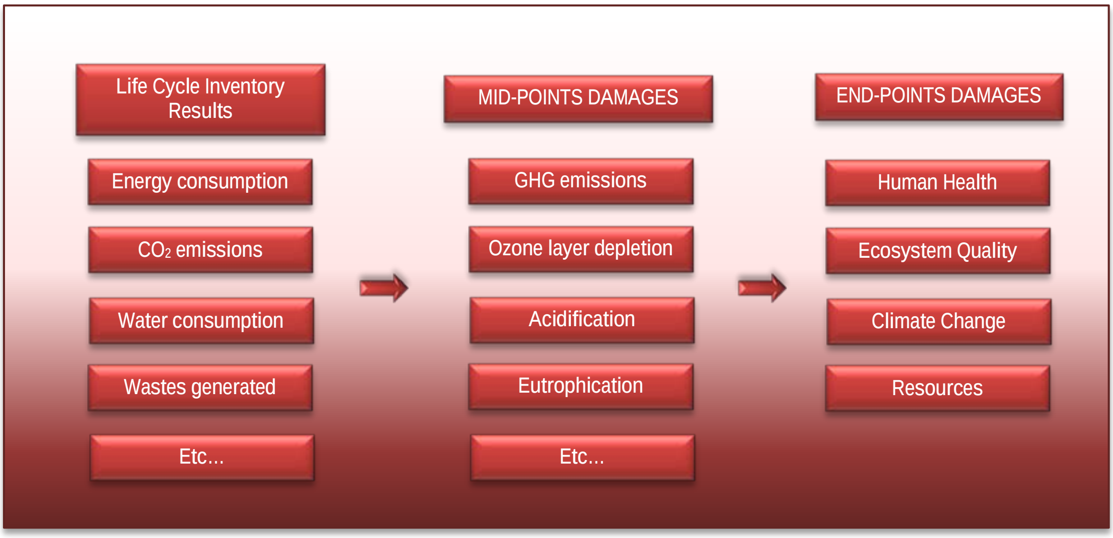


***Figure 20**: LCIA mid/end-points graphical representation. (Source: own elaboration)*

Selection between mid-point or end-point methodologies in an assessment is a decision to be taken by LCA practitioners. According to some authors (Bare and Thomas [10]) the first methodology enjoys of wider consensus than end-point method. On the other hand, it is also important to consider the objective of the assessment as, for example, if it is comparison between products, results will have to be given in the same measures or indicators.

4.1.5.1. CML.

The CML methodology was developed and firstly presented in 1992 by the Institute for Environmental Sciences of the Leiden University (Holland). In 2001 the IES published its last update, the CML 2 baseline 2000. CML is an end problem–oriented method that considers ten different impact categories (Klöpffer [83]):

- Abiotic depletion
- Acidification
- Eutrophication
- Global Warming (GWP 100)
- Ozone layer depletion (ODP)
- Human toxicity
- Fresh water aquatic eco-toxicity
- Marine aquatic eco-toxicity
- Terrestrial eco-toxicity
- Photochemical oxidation

Furthermore, as pointed out by Josa et al [74], the method includes a characterization and normalization process according to bot Dutch and European references, but does not include a weighting step. The CML guide groups the impacts considered into three broad categories, as are the next (Klöpffer [83]):

- Obligatory impact categories (indicators used in most LCAs)
- Additional impact categories (operational indicators exist, but are not often included in LCA studies)
- Other impact categories (no operational indicators available)

As an example of its practice on the building environment, it has been found that the paper published by Evangelista and De Brito [39] in 2007 considered if in the impact assessment step of the LCA performed to compared different mixing designs with diverse rates of recycled fine aggregates. Nevertheless, it was not the only, as in 2006 Rosignoli et al [134] considered this LCIA methodology for the analysis of a concrete bridge and different repair measures.

4.1.5.2. Eco-indicator.

Eco-indicator is a damage-oriented approach method, which first version appeared in 1995. Last version, Eco-indicator 99 includes data for the impact categories according to information from Pre Consultants, which are collected and published in a spreadsheet by the Institute of Environmental Sciences of Leiden University (The Netherlands). Eco-indicator is supposed to be a final analysis procedure, giving an environmental score to a product or process. It is obtained by evaluating the environmental damage in Human Health (HH), Ecosystem Quality (EQ) and Resources (R). Damages to public health and ecosystems have the same weight; damage to natural resources has a weight sensibly half of the previous ones. According to Marceu and Vangeem [97] it is based on how a panel of experts weighted the different types of damage caused by the impact categories.

As an example of its wide applicability, in 2008 it was conducted a multi-objective comparison of a reinforced concrete building frame, that included among other consideration, the embedded CO2 emission normalized using this endpoint LCIA methodology (Paya et al [120]). But focusing on is practice on concrete structures LCA studies, it has been incorporated among others in papers published in 2007 by Evangelista and De Brito [39] and in 2006 by Marceau and Vageem [97].

4.1.5.3. EDIP.

The EDIP "Environmental Development of Industrial Products" is a method that was developed by the Institute for Product Development (IPU) at the Technical University of Denmark. EDIP was first released in 1997, although there is an update for 2003. As indicated in Marceu and Vangeem [97], the methodological approach for EDIP 2003 lies closer to a damage-oriented approach. It investigates the possibilities for inclusion of exposure in LCAs of non-global impact categories. EDIP considers a total number of impact categories of eighteen, which are:

- Global Warming (100a)
- Ozone depletion
- Ozone formation (Vegetation)
- Ozone formation (Human)
- Acidification
- Terrestrial eutrophication
- Aquatic eutrophication EP (N)
- Aquatic eutrophication EP (P)
- Human toxicity air
- Human toxicity soil
- Eco toxicity water chronic
- Eco toxicity water acute
- Eco toxicity soil chronic
- Hazardous waste
- Slags/ashes
- Bulk wastes
- Radioactive waste
- Resources (all)

EDIP methodology, when taking a look at concrete structures LCA studies recovered from the bibliographic research, has been used by Marceau and Vangeem [97] in 2006 for the comparison or a wooden and a concrete isolations wall for a single-family house, considering its construction on five different location of the United States. Nevertheless, it was not the only, as it was also applied for the comparison of different mixing designs in the paper by Evangelista and De Brito [39] (paper where CML and Eco-indicator were used, as indicated previously).

4.1.5.4. ReCiPe.

The ReCiPe method was created by RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft. It is a midpoint and endpoint LCIA methodology, as it includes a normalization step, depending on the election of the practitioner. The method considers three different perspectives of human behavior (Goedkoop et al [185]):

- Individualist (I). Based on short-term interest, impact types that are undisputed, technological optimism.
- Hierarchist (H). Based on the most common policy principles with regards to time-frame and other issues.
- Egalitarian (E). Based on long time-frame impacts which aren't fully established but indication is available.

The methodology groups in eleven environmental issues (which are shown ahead) the different mid-point and end-point damages (eighteen and three respectively) resulting from its characterization and normalization factors:

- Climate change
- Ozone depletion
- Acidification
- Eutrophication
- Toxicity
- Human health damage
- Ionising radiation
- Land-use
- Water depletion
- Mineral resource depletion
- Fossil fuel depletion

This methodology has been found to be used in the master thesis by Boulenger [16] for the assessment of a concrete bridge and tunnel, which was released in 2011, by using public databases as sources for the inventory.

4.1.5.5. IMPACT 2002+.

The Life Cycle Impact Assessment methodology IMPACT 2002+ was developed by the Center for Risk Science, integrated in the University of Michigan. The methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories:

- Carcinogens
- Non-carcinogens
- Respiratory inorganics
- Ionizing radiation
- Ozone layer depletion
- Respiratory organics
- Aquatic eco toxicity
- Terrestrial eco toxicity
- Land occupation
- Aquatic acidification
- Aquatic eutrophication
- Global worming
- Non-renewable energy
- Mineral extraction

For IMPACT 2002+there are four damage categories: human health, ecosystem quality, climate change and resources. In the methodology, both human toxicity and eco-toxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from existing characterizing methods (Eco-indicator 99 and CML 2002). All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint or at damage level. The IMPACT 2002+ method provides characterization factors for almost 1500 different LCI-results (Goedkoop et al [182]).

4.1.5.6. TRACI.

For the past 10 years, the U.S. Environmental Protection Agency has focused on developing an impact assessment tool for life cycle impact assessment. This research is called TRACI, which stands for Tool for the Reduction and Assessment of Chemical and other Environmental Impacts. The TRACI is primarily a midpoint approach, which methodology draws simple cause-effect chains to show the point at which each impact category is characterised. TRACI methodology reflects current state of developments, consistency with EPA regulations and policy as well as best-available practice for life-cycle impact assessment (LCIA) in the United States. The impact categories used in the TRACI methodology are listed then (Bare and Thomas [10]):

- Acidification.
- Eco-toxicity
- Eutrophication
- Fossil fuel depletion
- Global worming
- Human health cancer
- Human health criteria pollutants
- Human health non-cancer
- Ozone depletion
- Smog formation
- Land use
- Water use

4.1.6. Depending on the weighting/valuation process.

The valuation (or also called weighting) process of the Impact Analysis step in LCA, as exposed before, is the part of the LCA where seriousness of the impacts considered in the study are weighted or valued. As the more subjective and controversial point of the LCA technique, the final study performed can vary depending on the hypothesis taken in this part. Weighting approaches can be either quantities or qualitative. According to the study done on this topic by Wu et al [201], other authors have classified them into five main groups exposed ahead:

4.1.6.1. Proxy or damage function method.

This approach uses a few quantitative measures, stated to be indicative for the total environmental impacts. Weighting factors are based on the relationship between environmental interventions and the damage they cause to ecosystems and human health. Environmental cost methods are more objective than Delphi and Distance-to-target ones, but he problem with this method is that is not integrated into standard welfare economics. Although the damage function approach has its limitations, as indicated by Lopez-Mesa et al [94] it continues to be used on a selective basis. This approach can't be taken as a professional weighting method and with little application.

4.1.6.2. Technology method.

For estimating the biologically productive area necessary to support current consumption patterns. The ecological footprint would be a typical example. As it happens with Proxy or damage function method before, it has scarce application (Lopez-Mesa [94]).

4.1.6.3. Delphi or panel method.

People are asked to judge seriousness across categories subjectively and empirically through questionnaires or face-to-face communications, and the applications are then done in the Delphi or Analytic Hierarchy Process. Internal or external experts, or representatives of societal organisations, are asked to decide on weighting factor for every environmental effect. This method is relatively quick and easy, but it strongly depends on the constitution of the panel (Lopez-Mesa [94]).

4.1.6.4. Distance-to-target method.

This is applied in many well-known LCA methods, as EDIP or Eco-indicator. For each category, an administrative or sustainable target is defined and the distance from the current level to the target is simply thought to be the weighting factor. However it just reveals the inner-seriousness within a category instead of the inter-seriousness across categories. So it, essentially, is not a real weighting approach. The weighting factor for each environmental effect depends on the difference between the present performance and the level required for sustainability. This method is objective in principle, except for the fact that there is no clear-cut objective way to define sustainable target levels (Lopez-Mesa [94]).

4.1.6.5. Monetization method.

This weighting method is based on the idea that seriousness across categories can be measured by money. This considers the costs of society need to pay to avoid environmental damage and restore deteriorated areas. These are also reasonably objective methods. The source of the data used for the weighting can come from the market prices, and in case they are not available, they can be obtained using some other methods like: the travel cost method, the hedonic pricing method or the contingent valuation method. As an example for the appliance of this weighting factor, we have the willingness-to-pay (WTP) of today's OECD inhabitants to restore impacts of each category or the WTP to avoid changes (Lopez-Mesa [94]).

4.2. Tools, software and databases.

The field of building environmental assessment tools is vast and many different tools have already been launched around the world. Most of the tools are software programs, which require information for supplying and basing the evaluations and calculations they perform.

4.2.1. Typologies of tools.

Existing tools cover different life cycle phases of the building and take into consideration different environmental impacts. Moreover tools have been developed by various institutes and for different. There are two well-known classification systems for environmental assessment tools, but in this work we are going to consider three, which are (Haapio and Viitameni [60]):

- ATHENA Institute classification system.
- IEA Annex 31 classification system.
- Complementary classification system

4.2.1.1. Athena classification system.

According to Athena Sustainable Materials Institute's tool classification system, three levels of tools can be distinguished (Trusty and Horts [153]):

- **Level 1 tool** focus on construction products and are used to make environmental /economical (or both) comparisons between them. They can be further grouped in two:
    - Level 1A tools are intended for use by LCA practitioners.
    - Level 1B tools are for those who simply want the results, with the detailed LCA work done in the background.
- **Level 2 tools** focus on whole buildings, providing decision support. These tools tend to be data-oriented and objective, and applied from the early conceptual through detailed design stages.
- **Level 3 tools** are whole building assessment frameworks or systems that include a broader range of environmental, economic and social concerns relevant to sustainability. They use a mix of objective and subjective inputs, leaning on Level 2 tools much for the objective data. All use subjective scoring or weighting systems to distill the information and provide overall measures, latter used to inform or guide the design process.

Although Level 1A tools are able to be used at whole building levels, first they are not design for difficult systems and second require great efforts on behalf of its practitioners in that case. Level 2 tools use data and typically incorporate building systems specific to the region for which they are built, but they can be modified or adapted for use in other regions but only with great care. Some are supported by robust life cycle inventory data, but other is not (Trusty and Horts [153]). Available Level 3 tools may apply to new projects, to existing buildings, and to major renovations or retrofits, a wide range of building types. Some require external auditors.

4.2.1.2. IEA Annex 31 classification system.

In the project IEA Annex 31 "*Energy related environmental impact of buildings*" assessment tools are categorized into five classes (Haapio and Viitameni [60]):

- Energy modeling software.
- Environmental LCA Tools for Buildings and Building stocks:
- Environmental Assessment Frameworks and Rating Systems:
- Environmental Guidelines or Checklists for Design and Management of Buildings.
- Environmental Product Declarations, Catalogues, Reference Information, Certifications and Labels.

In addition to Athena classification, the IEA Annex 31 includes on the classification system: energy modeling software, different environmental guidelines, checklists, product declarations and certifications (Haapio and Viitaniemi [60]).

4.2.1.3. Complementary classification system.

Reijnders and Van Roekel [128] made a rough division of LCA tools in two classes: qualitative tools based on scores and criteria and quantitative tools using a physical life cycle approach with quantitative input and output data on flows of matter and energy (Forsberg and Von Malmborg [45]).

- **Qualitative** methods are often based on auditing of buildings, putting score to each investigated parameter, resulting in one or several overall scores of a building. Some parameters are quantitative, like energy use, while others are entirely criteria based.
- The second group takes all tools based on **quantitative** data pending form LCI or production data of material or energy flows.

First have been used in the market during the past ten years, but the latter have only existed for the past six years on the official market and as a result they have not been applied as extensively on various objects as the tools mentioned above (Forsberg and Von Malmborg [45]).

4.2.2. Main LCA tools.

A thorough study and comparison of different LCA tools was performed in 2007 by Haapio and Viitaniemi [60]. The study categorized in five groups, taking into consideration these different criteria:

- Assessed building.
- Users of the tools.
- Phases of the life cycle.
- Databases of the tools.
- Forms of the results used.

In the study, a total of sixteen tools were compared, which are related at the table ahead. The building environmental assessment tools included in the study were normally used at a national level. In addition to this, seven of them showed the possibility of being used globally, which were: BEES, TEAM™, ATHENA™, BEAT, Envest 2, BREEAM and LEED (Haapio and Viitaniemi [60]).

NAME	DEVELOPER (COUNTRY PROCEDENCE)	C.S. APPLICABILTY	NAME	DEVELOPER (COUNTRY PROCEDENCE)	C.S. APPLICABILITY
ATHENA™	ATHENA Sustainable Material Institute (Canada)	HIGH	Envest 2	BRE (UK)	LOW
BEAT 2002	SBI (Denmark)	MEDIUM	Environmental Status Model	Association of the Environmental Status of Buildings (Sweden)	MEDIUM
BeCost	VTT (Finland)	LOW	EQUER	CEP (France)	MEDIUM
BEES 4.0	U.S. NIST (USA)	LOW	ESCALE	CTSB and the University of Savoie (France)	MEDIUM
BREEAM	BRE (UK)	HIGH	LEED	USGBC (USA)	HIGH
EcoEffect	KTH (Sweden)	HIGH	LEGEP	University of Karlsruhe (Germany)	MEDIUM
EcoProfile	NBI (Norway)	MEDIUM	PAPOOSE	TRIBU (France)	MEDIUM
Eco-Quantum	IVAM (the Netherlands)	LOW	TEAM™	Ecobilan (France)	MEDIUM

***Table 10**: Worldwide existing LCA tools. (Source: own elaboration based on Haapio and Viitaniemi [60])*

According to classifications showed in previous epigraphs of the study, a quick classification (mixing both ATHENA and IEA Annex 31) of the related tools assessed in the study is done ahead (Haapio and Viitaniemi [60]):

- LCA tools.
  - Level 1 tools: BEES 4.0 and TEAM™.
  - Level 2 tools: ATHENA™, BEAT 2002, BeCost, Eco-Quantum, Envest 2, EQUER, LEGEP and PAPOOSE.
  - Level 3 tools: EcoEffect and ESCALE.
- Rating systems.
  - Level 3 tools: BREEAM, EcoProfile, Environmental Status Model and LEED.

As tools have their own related software developed, and depth analysis of present-available market tools is not the objective of the present work, we will later develop most relevant LCA-tools when describing the main LCA software existing nowadays.

4.2.3. Main LCA software.

According to a study performed in 1997 by Rice et al [131], which review and compared 12 of the main European LCA software packages available at the time, all software were essentially similar in their aims. The basic function of any of them was to complete energy and mass balances on an item specified by the user and then allocate emissions, energy uses, etc. normalized on some common basis. The software examined was:

NAME	DEVELOPER	C.S. APPLICABILITY	NAME	DEVELOPER	C.S. APPLICABILITY
The Boustead Model	Boustaed	LOW	EcoPro 1.3	EMPA	MEDIUM
Gabi 2.0	IKP	HIGH	KCL-ECO	KCL	LOW
LCAiT 2.0	Chalmers Ind.	LOW	LMS Eco-Inventory Tool	LMS Umweltsysteme	LOW
Oeko-Base	MGB	MEDIUM	PEMS 3.0	Pira International	MEDIUM
PIA	TME	LOW	SimaPro 3.1	PRé	HIGH
SimaTool	CML Leiden	HIGH	TEAM™	The Ecobilian Group	MEDIUM

***Table 11**: European LCA software. (Source: own elaboration based on Rice et al [131])*

According to considerations set in this study, and considering the software available at the time, there are four major packages for LCA soft in Europe. These were: Boustead's model, Ecobalance UK's TEAM™, PEMS 3.0 and SimaPro 3.1 (Rice et al [131]). Notwithstanding, of all the software nowadays available on the market, the next will be treated ahead:

- Athena (EcoCalculator/Impact Estimator).
- ARQUIMEDES-ACV
- BEES
- GaBi Software
- SimaPro
- TEAM™

When focusing on published LCA studies practiced over concrete structures, it could be observed that the most used software by practitioner where SimaPro and Athena. For the first software tool, it was encountered that in 2006 Bilec et al [12] published a Hybrid LCA for the assessment of the construction phase of a precast concrete structure helping its calculation with SimaPro. Moreover, the study by Gian Andrea [50] for the assessment of a reinforced concrete structure on the Italian context was performed by using this same software. On the other hand, for Athena software just one paper was published comparing the impacts due to the on-site construction of three different structures (wood, steel and concrete) in the Canadian construction context (Cole [25]).

4.2.3.1. ATHENA.

The Athena Sustainable Materials Institute offers two software tools which are related but different at the same time:

- On one hand there is the Athena EcoCalculator, a tool very fast but limited in design options.
- On the other there is the Athena Impact Estimator, a program that provides users with more flexibility in proposed designs and existing buildings.

These tools are whole building systems and tend to be used in building design, as pointed out by Cooper et al [28]. Both are customized for North American regions, and take into account the following impacts: primary energy consumption, acidification, global warming, human health respiratory effects, ozone depletion, photochemical smog, eutrophication and weighted raw resource use.

4.2.3.2. ARQUÍMEDES-ACV.

ARQUIMIDES is a program for project management, developed by CYPE S.A., that allows users to bill, certificate and introduce specifications of their projects. Recently the company has developed and integrated into ARQUIMEDES a new module named "Impacto Ambiental-Análisis del Ciclo de Vida" that offers the chance to calculate the environmental impact due to the construction process of a building of engineering project.

The new development permits LCA practitioners to obtain the energy consumption and CO_2 emissions to the air during the life cycle of a project till its construction, but not the operational/maintenance and end-of-life phases. The results obtained by the use of the software are available in a document where the practitioner is showed the impacts caused by each chapter of the project bill and, therefore if considered necessary, apply the opportune changes. Moreover, this document incorporates an annex explaining and justification the: initial assumptions, calculations processes and the data source consulted.

4.2.3.3. BEES.

BEES (Building for Environmental and Economic Sustainability) goes by its third edition, and is a product-to-product comparison tool developed by the National Institute of Standards and Technology. This software measures environmental performance of building products by using the ISO 14040 series of standards and the US TRACI LCIA method. Environmental and economic performance is combined using the ASTM standard for Multi-Attribute Decision Analysis.

4.2.3.4. GaBi Software.

GaBi Software is a sustainability software solution for Life Cycle Assessment developed by PE INTERNATIONAL. This tool enables the users to introduce LCC (Life Cycle Costing) and LCWE (Life Cycle Working Environment) information and all databases include DQI's (Data Quality Indicators). Moreover, it allows transfer data into the software as it's in accordance with the International Life Cycle Database (ILCD) format (Haapio and Viitaniemi [60]).

4.2.3.5. SimaPro.

SimaPro, developed by PRé Consultants in the Netherlands, is a widely used process based LCA software program. With SimaPro, the LCA practitioner develops an LCA by using the software's existing processes or creating new ones (Bilec et al [12]). It allows life cycle impacts to be modelled and analysed following ISO standard, containing 9 inventory databases supplied by other organisations (such as ecoinvent v.2, US LCI, ELCD, US Input Output, etc.) and 17 impact assessment methods (such as Eco-indicator 99, USEtox, IPCC 2007, Impact 2002+, Traci 2, etc.). It allows:

- Making assessments using process, Input-Output or Hybrid analysis methods.
- Data is transparent and it can be shared with other practitioners.
- Evaluate uncertainty in parameter values.
- Set switches between different parameters in a sensitivity analysis.

4.2.3.6. TEAM™.

TEAM™ 4.0 (Tools for Environmental Analysis and Management) is an integrated suite of software tools developed by Ecobilian S.A. (member firm of PricewaterhouseCoopers). TEAM allows its users to model their own system boundary, build a large database and calculate its associated Life Cycle Inventory. It too includes a set of predefined impact assessment and valuation methods, according to the ISO 14040 series of standards, for applying to the resulting inventories (TEAM [246]).

TEAM™ has been designed in order to be able to handle a variety of methodological rules, such as:

- Defining system boundaries.
- Choosing allocation rules.
- Taking into account recycling.
- Allowing different scenario and sensitive analysis.
- Performing uncertainty analysis (check data uncertainty influence on the inventory) by two available different testing methods: min-max values of variables (Min-Max analysis) or statistical distribution of variables (Monte-Carlo analysis).

4.2.4. Main LCI and LCIA databases.

There are a large number of databases which provide data about several materials, usually included in software packages that allow practitioners to assess their systems under study. As indicated at Kashreen et al [78], available databases nowadays fit four different categories: public database developments, academic, commercial and industrial. Moreover, in a growing number of countries, there are national projects (planned, under way or completed), whose purpose is to develop publicly available LCI data. Some examples are:

- U.S. LCI Database Project
- U.S. Input Output 2002
- IO-database for EU-27 2000
- IO-database for Denmark 1999
- Dutch Input Output
- Japanese input-output
- Industry data v.2
- Ecoinvent v2 Database
- BEDEC
- CORRIM
- ELCD core database v2
- E3IOT
- DEAM ™ Database
- GaBi Databases

When considering data sources used by practitioners of LCA studies on concrete structures, it can be observed that there is several numbers of them integrated in the assessment such as: on site data (Bouman et al [17]), own countries published data (Ge [46]), other LCA studies (Guggemos and Horvath [55]) or, even own authors experience/knowledge (Gian Andrea [50]). Furthermore, in the cases when practitioners made used of LCA software, they based their calculations on databases provided by this same software. As an example, we have the study performed by Lopez-Mesa et al [94] that used Ecoinvent database (one of the several databases included in SimaPro) for the comparison of two concrete slab systems for a structure in the Spanish environment. Another example, also with databases included in SimaPro (CORRIM and U.S. LCI), is offered by the study published in 2005 by Winistofer et al [168] for the comparison of a wood and concrete frame in the Canadian context.

4.2.4.1. US LCI Database Project.

The U.S. LCI Database Project, owned and managed by the National Renewable Energy Laboratory (NREL), is a public/private research partnership to develop a publicly available life cycle inventory database for commonly used materials, products and processes. The database provides LCI data to support public, private, and non-profit sector efforts to develop product life cycle assessments and environmentally oriented decision-support systems and tools (Trusty and Deru [152]).

- NIST is using U.S. LCI Database Project in its BEES software tool.
- Athena Institute is also doing the same in its Impact Estimator software.

4.2.4.2. Ecoinvent.

Ecoinvent database developed by the Swiss Centre for Life Cycle Inventories, releases in fall 2003, contains over 2500 background processes, with focus primarily on the Swiss and European contexts. It has a data exchange format that can be used to integrate data contained in the database into other databases and software (Russel et al [136]).

4.2.4.3. BEDEC.

BEDEC “Banco Estructurado de Datos de Elemento Constructivos” is a database developed by the ITeC that contains 550.000 construction elements with, among other, economic and environmental data. The environmental data includes information as: construction wastes, energy consumptions and CO_2 emissions. This database is periodically updated and offers both visualization and use of the information it contains (Arguello and Cuchi [6]).

4.2.4.4. Environmental Profiles Database.

The Building Research Establishment (BRE) publishes the web-based Environmental Profiles Database, which holds the Environmental Profiles of 18 materials from LCAs carried out to ISO standards. More Environmental Profiles are proposed, and BRE plan to develop the database to include social and economic impacts (Goedkoop et al [182]).

4.2.4.5. CORRIM.

The results of the Consortium for Research on Renewable Industrial Materials (CORRIM) program provide information to develop estimations. In 1996 it was formed by 15 research institutions as a non-profit entity that would undertake research on the use of wood as a renewable material. It has produced to the date LCIs from forest regeneration, product manufacturing, construction, etc. for different residential structures (Upton et al [158]).

4.3. LCA S.W.O.T. analysis.

With the objective of presenting a general vision of advantages and disadvantages in LCA studies, a simple S.W.O.T. analysis was performed at this work extracting the main characteristics of the tool from the articles and scientific publications recovered on the previously performed research. The SWOT analysis (alternatively named SLOT analysis) is a strategic planning method used to evaluate a project or business venture, but also serves as a tool for identifying potential areas of development or improvement for a product, service or even wider scopes as whole economic sectors. The procedure that has been followed to establish the SWOT analysis at the present work first passes by the identification of the object analysed and then specifying the issues related ahead (Zamora [176]):

- Strengths. Characteristics of the object analysed that bring competitive advantages when compared to others and that allow exploiting opportunities.
- Weaknesses. Characteristics that place the objet at a disadvantage when compared to others.
- Opportunities. External environmental conditions that bring competitive advantages to the object of analysis (e.g. make greater profits).
- Threats. External environmental elements that could cause limitations, risks or decrease benefits for the object assessed.

It is to remark that SWOT analysis can be considered as counting with two different parts [Figure 21], establishing a relationship between strengths/weaknesses and opportunities/threats, as it is showed ahead (Zamora [176]):

- Internal. It is related to strengths and weaknesses of the studied object, aspects that can be modified or improved as there is a certain control under them.
- External. It includes the opportunities and threats of the environment the object of study is surrounded by. Generally speaking, external factors are all the circumstances which do not offer a direct control.

On the other hand, a second group of the issues can be considered when performing a SWOT analysis. This second group classification is directly related to negative or positive [Figure 21]. It can be considered that strengths and opportunities are positive characteristics or elements that promote the development and success of the studied object. On the contrary, weaknesses and threats are the negative characteristics or elements that expose the object to limitations of development and success.

In order to increase the depth of the analysis, after organizing the different issues of LCA following the SWOT classification introduced before, a selection of the main or more important will be done (based on subjective criterion). Then these will be contrasted on an internal and external level, to finally extract some conclusions or proposals to improve LCA general practice, which includes practice on the construction industry and, more specifically on concrete structures (work's scope).

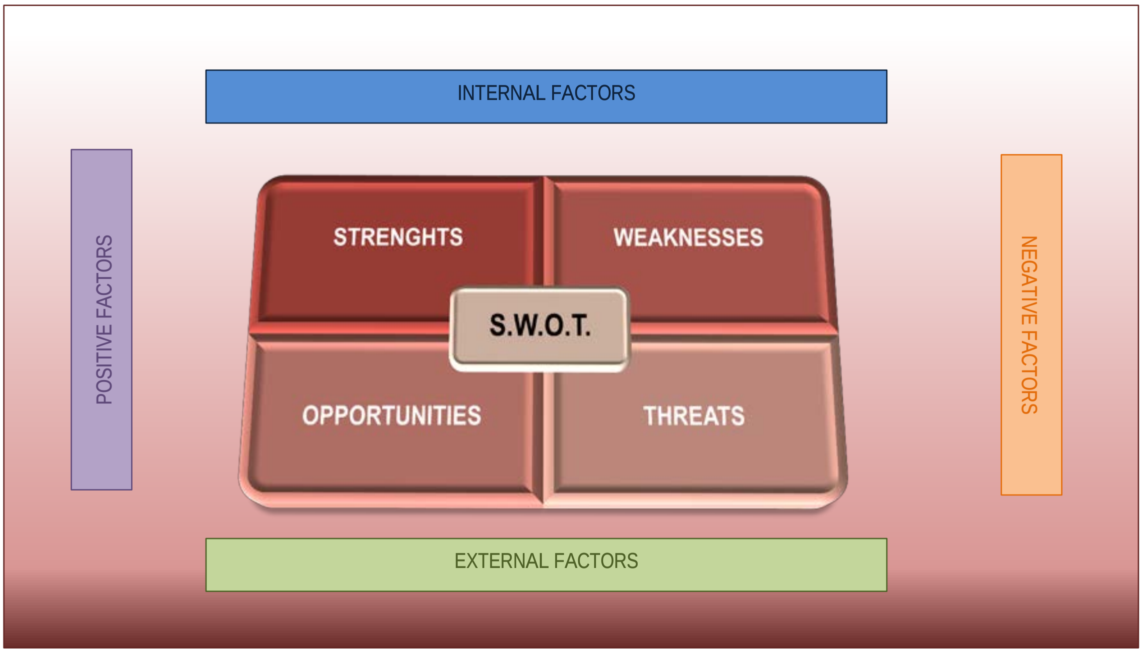


***Figure 21**: Graphical representation of a SWOT analysis. (Source: own elaboration)*

4.3.1. LCA strengths.

Life Cycle Assessment is an environmental evaluation tool that can be applied to a very wide range of issues, from the assessment of a single product (or part of it) to a whole sector or industry. Considering the positive characteristics it offers LCA has the strong points related ahead:

- LCA has its own international standard, what makes it a method with clear structure and rules for its practice (Hunkeler and Rebitzer [71]).
- LCA is intended to be an objective evaluating method (Hunkeler and Rebitzer [71]).
- LCA is transparent, as the methodology and assumptions can be consulted by every interested party (Klöpffer [84]).
- As all forms of production can be evaluated equally on a scientific basis, it can be considered that the studies are technological neutral (Ritchie [132]).
- Its results are not intended to be prescriptive; on the contrary LCA provides flexibility to determine improvements to be applied (Ritchie [132]).
- The methodology can be applied by a wide range of practitioners from very different sectors (Ritchie [132]).
- LCA is a thorough method, as the process can address full spectrum of relevant environmental impacts (Ritchie [132]).

4.3.2. LCA weaknesses.

Weaknesses can be defined as the inherent and internal negative characteristics of the object assessed at the SWOT analysis. Then it is going to be exposed a relation of the different weak points that Life Cycle Assessment contains within its methodology:

- LCA is inherently complex and its practice can be expensive and highly time consuming (Horvarth and Hendrickson [68]).
- Risk of committing mistakes increases with the degree of complexity of the functional unit and system boundaries considered in the study (Jönsson et al [73]).
- Objectiveness on Life Cycle Assessment is affected by practitioner assumptions, such as: election of the functional units, system boundaries, allocation, selection of data sources and impact categories. These subjective choices can lead to different outcomes for a same product depending on the LCA practitioner (Klöpffer [83]).
- If the functional unit of the study is not well chosen or it is not standardized, it is impossible to perform studies comparison analysis to choose the best environmental option (Khasreen et al [78]).
- Allocation can drive to result mistakes, as when assigning parts of an environmental impact to an activity which provides different functions for different products, assumption can be wrong (Russell et al [136]).
- LCIA aggregation is another classical problem of LCA that can drive to results mistakes due to bad praxis (Russell et al [136]).
- Impact analysis methodology has no widespread practice or specific agreement (Marceau and Vangeem [97]).
- LCIA for some impacts considered at the study are especially difficult to perform, mainly due to lack of appropriate scientific data (Horvarth and Hendrickson [68]).
- Lack of spatial and temporal distribution of environmental impacts introduces uncertainties in the impact assessment (Junilla et al [76]).
- Interpretation of results is controversial, as it depends on the objectives of the practitioner and on the weight assigned to each of the environmental effects quantified (Junilla et al [76]).
- A lack of transparency between data centres (data or data origins and references are not accessible) make it difficult for comparing results (Jönsson et al [73]).
- Inclusion of spatial and time effects into LCA is neglected in most LCAs (Klöpffer [83]).
- LCA does not consider social concerns, just environmental and economic ones (Norris [107]).

Still there are also other weak points that do not depend directly within Life Cycle Assessment's own methodology, but with variations introduced by other factors (as nowadays misuse or bad practice). These are shown ahead:

- There is little standardization, as each building is unique and is designed as such, so new choices have to be made for each specific situation. Moreover, production processes in construction are very complicated and different (Khasreen et al [78]).
- When assessing a product or service, the whole life cycle has to be considered, other way it can drive to mistakes and bad results (Yu et al [175]).
- During its life span, a construction may be subject of variations in its function or components, which can suppose significant (or even more) impact than the original. Prediction of this modification during whole life-cycle of a construction is a very difficult task (Khasreen et al [78]).
- Environmental impacts depend not only on the building system, but also on its interaction with their natural environment and its users (Lloyd et al [92]).
- Local conditions of the functional unit assessed may not be identified or adequately reflected by regional or global conditions (Junilla et al [76]).
- Increased LCA activity in new regions is bringing new impact categories, such as soil salinization from irrigation which are not studied (Norris [107]).
- Maintenance and replacement activities are very difficult to estimate in the design phase of a construction, what introduces uncertainty to the results of LCAs (Malin [96]).
- Data are collected from a wide variety of resources: either directly from participants in the life cycle, production sites, engineering texts, regulatory reports for industries, or industry literature or past LCAs. This generates considerable variation in accuracy among data points and holds the potential for out-of-date entries (Horvarth and Hendrickson [68]).
- Quality of data is very important for LCA's results correctness, as data usually contains uncertainties. This drives LCA to depend on the sources used in LCI (Horvarth and Hendrickson [68]).

4.3.3. LCA opportunities.

As it has been observed, Life Cycle Assessment studies can be used for a wide range of environmental purposes. But the main advantage for its use has not been pointed yet, as well as new chances for the future. Then, opportunities offered by Life Cycle Assessment studies are presented ahead.

As an assessment tool, it can give **decision-making basis** from an environmental point of view for (Malin [96]):

- Developing policy and regulations.
- Purchases or public procurement.
- Project or investment selection.

Life Cycle assessment can be integrated into the **design processes**, for including environmental criteria on the development of products or services:

- Environmentally sound product development (Romero [133]).
- Following the methodological stages of the LCA, it is possible to identify points to improve of the product over design process, as minimal energy consumption during its whole life cycle (Huberman and Pearlmutter [70]).
- It can also be helpful to reduce production costs as the new designs and production processes, transportation and distribution, among others, promote a bigger efficiency at raw materials, energy consumptions (Romero [133]).
- It can be connected with and linked to BIM software (3D-CAD program), which is most used widely at the early design stage, to estimate different aspects of the building (Cooper et al [28]).

It can also be used as a **rating or certification tool** of environmental good use and behaviour. Documenting environmental good performance can be used by companies for communications and marketing purposes (Malin [96]). As examples we can find next exposed:

- Certification of products under eco-labelling programs (or green labelling) and Environmental Product Declarations (ISO 14025:2006 "*Environmental labels and declarations—Type III environmental declarations—Principles and procedures*" and ISO 21903:2007 "*Sustainability in building construction—Environmental declaration of building products*") (Romero [133]).
- The U.S. Green Building Council (USGBC) is preparing to the integration of LCA based credits into its Leadership in Energy and Environmental Design (LEED) rating systems (Howard and Dietsche [69]).

Life Cycle Assessment can be used for **basing environmentally** a **Life Cycle Management** (LCM). It can help as a tool to analyse and identify environmental improvements during the operational phase of the product or service assessed.

- Evaluating environmental performance to document improvement for environmental management systems. This means integrating LCA with environmental management methods (Malin [96]).
- It gives competitive advantages as giving analysis element for the companies for improving and developing their products (Romero [133]).
- Using whole life cycle assessment studies to establish the effect of alternative materials on the energy performance of the buildings (Khasreen et al [78]).
- It can give information about repairing activities, from an ecological point of view, when choosing carry out preventive maintenance or just when repairs may be necessary (Arskog et al [7]).
- It can be used for applying strategies during the operation phase, such as making changes in consumption patterns, therefore improving environmental performance (Ortiz et al [113]).

Practice of LCA and its integration into decision-making processes for organizations is far from being standard practice. Nevertheless, there are some leading multinational firms, who have already embraced life cycle thinking and LCA (Lopez-Mesa et al [94]). Companies will be able to apply LCAs to their product lines, both in terms of achieving a better understanding of their own systems, and in promoting their ecological and economic benefits (Graveline [52]). Furthermore it can be used by companies to understand and know the effects of their products or activities caused on environment to attend the legal, social and political responsibilities implicated, as well as the economical and image loses (Romero [133]).

4.3.4. LCA threats.

First of all threats to be considered for LCA, the most relevant are the technique's weaknesses previously identified. If these weak points of the methodology are not improved by researchers and users, there is a potential risk for the tool to be dismissed. Moreover, as exposed by Arena and de Rosa [4], there are a number of difficulties for using LCA, among them: lack of expertise, high costs, complexity and lack of local data, being the last one of the most costly aspects of LCA.

The high time, cost and resource demanding process of performing a LCA can prevent it to be a tool, actually rather academic, widely used by design professionals from all types of companies (Urie and Dagg [159]) What is more, a study performed by EPA between 1970 and 1974 pointed LCA as a far too complicated tool to be used by small and medium companies (Romero [133]).

Additionally, as indicated at Graveline [52], in there is a limited demand for these studies on the market. So public policies, rules and laws are mandatory to draw attention and necessity for the application of environmental tools. Furthermore, there already other tools located in the market to analyse and assess environmental issues.

Another importer fact comes from product manufactures, as companies should supply all the information regarding their products (publishing LCAs or providing data on LCI databases) on a voluntary way (Graveline [52]). But, on the contrary, manufacturers are not likely to publish detailed LCAs on their products for several reasons (Malin [96]):

- Publishing underlying data might reveal trade secrets to competitors.
- Publishing results may be taken or used against the company by competitors or environmental activists¡.
- The published study might show their product is not best choice environmentally.

4.3.5. S.W.O.T. matrix, analysis and proposals.

As it was already pointed out, after establishing the different issues of LCA, it has been made a subjective selection of the most important. Then, this issues are integrated in the analysis, which will be performed right ahead, and some proposals to improve practice of LCA are also established. The issues considered at the analysis are included at [Figure 22] and have been limited to four to each SWOT issue. Then, they are contrasted in an internal and external level, or what is the same, a direct comparison between strengths and weaknesses (internal level) and opportunities against threats (external level). The results are exposed ahead:

- Internal.
    - LCA methodology is standardized and aims to provide objective results in its assessment, but still there are gaps in its practice usually covered by practitioner's assumptions, which introduces subjectivity and therefore affects its results comparison and reliability.
    - Its applicability is worldwide and general, so it is able to cover a great number of case studies. Nevertheless it is a tool that requires a high quantity of resources in its practice such as: time, funds, data, personnel...
    - Although it is limited by the demands of its methodology and by the issues observed in its analysis (environmental), its flexibility and transparency can be exploited by researchers to develop the tool for new field's practice and issues (economic and social).
- External.
    - LCA can be used as a tool for decision-making at any circumstance or moment of the life cycle of a product or service, but it inescapably requires the improvement and development of its internal weaknesses.
    - It can be integrated in the environmental management system of companies, but it requires transparency and interoperability of data used for the assessments to be reviewed by certification organizations.
    - Companies can take service of LCA to improve environmentally their products, and even economically by reduction of wastes or energy consumptions. Nevertheless, there are already some other assessment tools on the market that provide equal or close results as that provide by LCA.
    - It can provide environmental results to use for commercial purposes, but this requires that manufacturing companies provide published data related to their products (which they are reluctant).

After the internal and external comparison is performed three subjective conclusions/proposals, integrating both internal and external perspectives, are established about LCA methodology practice. These are exposed ahead:

- LCA practice's enhancement passes by its development on a more ferrous-methodology tool. On this sense, it would contribute on more reliable and objective results for companies to use on decision-making.
- For the integration of data with high quality and reliability, there is a need for manufacturers and companies data publishing. This would decrease the need for resources, as practitioner would have access to up-to-date and reliable data. This would become real by more regulation and political measures.
- LCA offers great potential to become a final decision-making tool for different typologies of organizations (companies, governments, purchasers…) integrating the three concepts of sustainable development. Notwithstanding this passes by the collaboration of different stakeholders: (researchers, politicians, manufacturers) from the point of investment, regulation and active development.

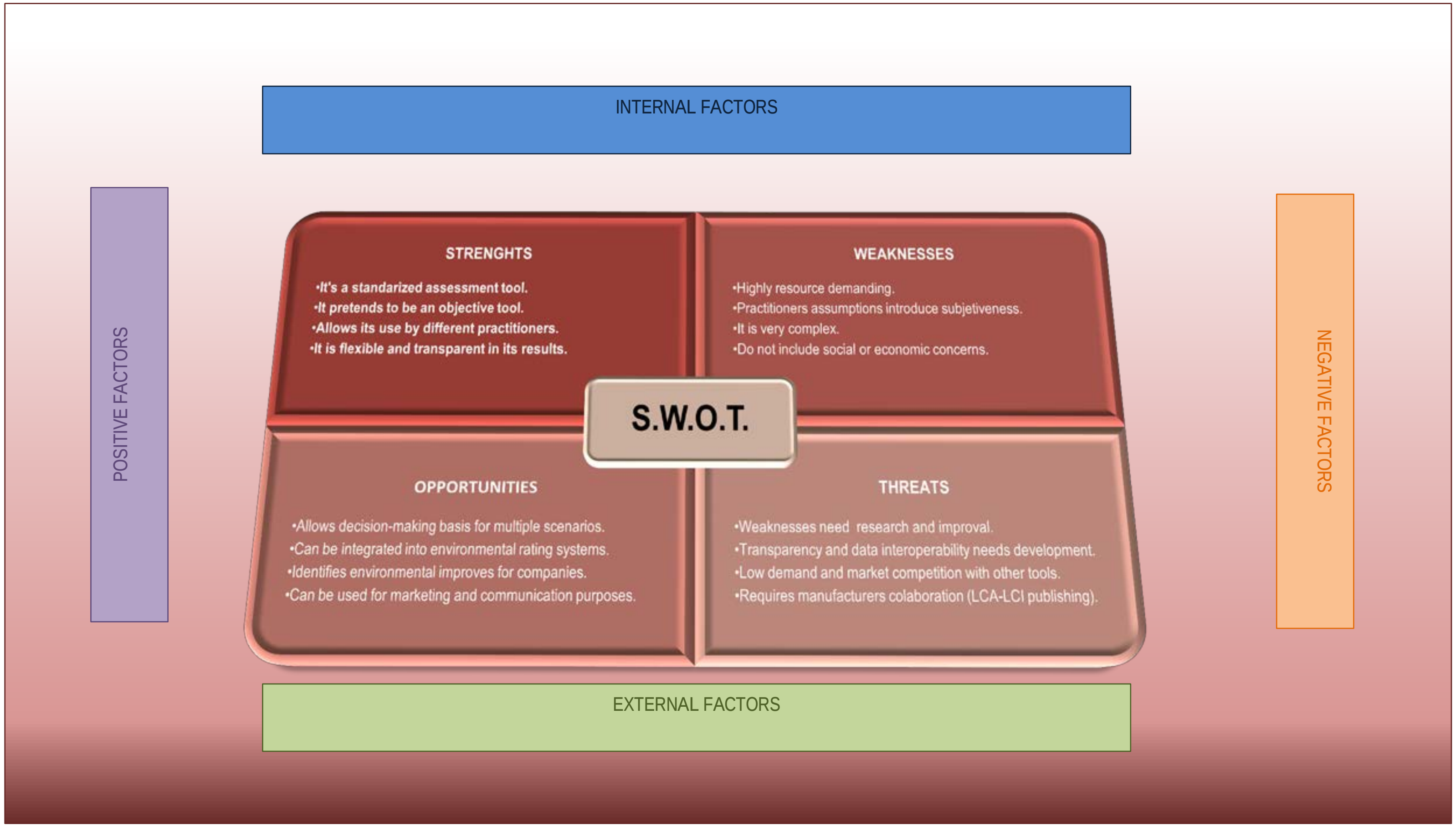


Figure 22: *SWOT analysis of LCA. (Source: own elaboration)*

LCA REVISION ON CONCRETE STRUCTURES

5. LCA REVISION ON CONCRETE STRUCTURES.

In this fifth chapter of the work, a more direct and focused attention to the application of LCA on concrete structures will be developed. First, a list of published LCA studies on concrete structures will be offered, taking into consideration subjects within them such as: methodology used, system boundary, scope of the study, impacts considered or conclusions reached. Then, a guideline for stakeholders within the construction environment will be exposed for LCA practice on concrete structures. Finally, a case study to compare environmental performance of two concrete structures will be performed, making use of the exposed guide, as well as for the extraction of conclusions and impression from the results obtained.

5.1. LCA studies analysis.

5.1.1. LCA studies on construction industry.

Research on LCA has history of more than 40 years, but the practice of the method on the construction field is carried out in the late 20 years (Yiwei et al [174]). Life Cycle Assessment technique can be used to assess the environmental impact of a product all along its life cycle, but it can also be applied for the assessment of whole buildings/infrastructures or even an economic sector to establish which are more energy demanding or pollutant emitting. Right ahead we are going to offer a review of different application of this technique in the construction environment, enabling to see the broad potential usage of this tool.

5.1.1.1. Comparison and evaluation of building materials.

Life Cycle Assessment has usually been used for comparing environmental burdens of different products. Some examples are offered then:

- A partial environmental LCA of concrete made with fine recycled aggregates (FRA) in a Portuguese context, focusing on the embodied energy and on site construction, was performed by Evangelista and Brito [39].
- In 1998, a paper by Horvath and Hendrickson [68] presented results of a Life Cycle Inventory Analysis comparison between steel and steel-reinforced concrete bridge girders.
- A study performed in 2009 by Kahhat et al [77]calculated the environmental impacts of six types of exterior wall systems (concrete block, poured in-place concrete, insulated concrete, two types of traditional wood framing and steel stud framing) for a single-story residential building.
- Kendall et al [80] performed in 2008 an integrated Life Cycle Assessment and Life Cycle Cost Analysis model to compare alternative bridge deck designs: a conventional concrete bridge deck and an alternative engineered cementitious composite link slab design.
- A study, combining the use environmental profiles with LCA framework, was performed by Wu et al [170] in 2004 to assess the environmental impact of cement and structure steel, two major building materials.

5.1.1.2. Comparison and evaluation of whole buildings.

However, not just comparison and assessment of building materials has been the scope of LCA on last years. Instead behaviour assessments for buildings have been already performed, analysing various issues of their whole life cycles such as: energy use during use phases, environmental burdens, pollutant emissions, etc. Some examples are offered right away:

- A study comparing the energy use during the life cycle of three single-unit dwellings built in Sweden was done by Adalberth [2] in 1996.
- In a paper by Ge et al [46] published in 2010 a Chinese residential building was assessed by an EIO-LCA. In the study three types of impacts relate to two different structures were taken into account (one made of steel and the other of concrete).
- A paper published in 2005 by Guggemos and Horvath [54], identified and quantified the energy use and environmental emissions of two five-story office buildings during their life cycle. Both of them were located in the United States and had an expected life span of 50 years, but one was a structural steel frame building and the other had cast-in-place concrete frame.
- A study by Haapio and Viitaniemi [61] in 2007 aimed to analyse how different structural solutions and building materials (wall insulations, cladding materials, window frame materials and roof materials) affected the environmental assessment of 78 single-family buildings over their life cycle. In addition, it was analysed how the length of the building's service life affected the results of their Life Cycle Assessments.
- A study by Junilla et al [75] assessing the environmental aspects of two new office buildings, one from Europe (Finland) and the other from United States (Midwest region), considering all their life cycle was published in 2006.
- In the study performed by López-Mesa et al [94], undertaking a life cycle assessment approach, two types of slab systems used for internal floor structures (a concrete based one-way spanning slab and a hollow core slab floor) were studied and compared, taking into consideration the use of precast and on sited installed concrete.
- In 2001 Peuportier [121] applied a life cycle simulation tool to compare three types of single family houses in the French context.
- In 2009, a study performed by Utama and Gheewal [160], took as object of study the life cycle energy consumption of buildings in Indonesia, focusing mainly in their envelope materials (walls, window-doors frames, glass and ceiling) and their performance relating to air-conditioning.

But moreover, LCA can also be used as a tool for management purposes. It can give basis to decisions in management and reparation activities during the use/maintenance phase of a building:

- A paper published by Arskog et al [7] focused on introducing a framework and methodology for quantifying the environmental burden of various repair materials and systems for maintenance of concrete structures. In the study, materials and energy consumptions, waste generation and emission to the environment were included.
- A study by Ortiz et al [113] applied a Life cycle Management (LCM) approach to a typical Spanish Mediterranean house, evaluating building materials that were more environmentally efficient and the impact of energy consumption during the operation phase.
- Rosigonli et al [134] performed and published in 2006 an environmental assessment of different repair techniques for a concrete structure, more specifically a bridge. In this paper production and restoration of a reinforced concrete pier is analysed for the four different technological variants to finally select the most environmental-friendly ones.
- In 2011 Yiwei et al [174] conducted a study related to buildings energy efficiency design and old buildings energy saving renovation work, selecting as cases of study: an office, a health care and campus buildings.

5.1.1.3. Design supporting tool.

But previous applications, material and whole buildings assessments/comparison, are not the only applications for LCA. As in many papers it is pointed out, Life Cycle Assessment is an environmental tool to be used during construction designing process. Many studies have been conducted on this topic, as it is shown within some examples offered right ahead:

- A research conducted by Gu et al [53] adopted a Life Cycle Costs Analysis (LCCA) and a hybrid Life Cycle Assessment (LCA) method to base economically and environmentally the selection of a large-scale hydropower project against a small-scale one.
- A study performed by Myer et al [105], on the basis of LCA, compared three different alternatives for the design of 2000 Sidney Stadium. The first alternative, called “Base Case”, assumed ordinary building practice with little environmental innovation. The second alternative (named “The Offer” was an improved designed that included reduced-impact components and technologies already available on the market. Finally, the “Enhanced Environmental Case” included the most updated technologies which were expected onto the market within the development programed.
- A case study for the selection of flooring systems in Tehran was done by Reza [130] using LCA an integrating AHP to make a decision on the best system based on a single measure called sustainability index (SI) counting social, political and economic impacts associated to the construction process.

5.1.1.4. End of life evaluation.

But the recycling and final disposal is also a topic assessed by this studies LCA:

- In 2009 Blengini [50] presented a paper offering the results from a research based on comparison of alternative waste disposal scenarios from the demolition process of a residential block of flats in Italy. The research paid special attention on waste recycling processes and the recycling potential of materials recovered from the demolition.
- A paper published by Vieria and Horvath [165] in 2008, presented a hybrid LCA method applied to an office building with a RSC frame, focusing on end of life recycling policies and environmental decision making.

5.1.2. Results and observations of LCA studies.

As is has been previously reported, Life Cycle Assessment is a tool that shows a wide and feasible applicability to the construction industry. Moreover, from the different studies performed to the date, some general conclusions can be drawn. Right ahead, the commonly accepted results and observations exposed in the different studies analysed have been collected and introduced then:

- Commonly-accepted results and observations gained from the assessment of building materials:
    - When comparing wood to concrete as material for a building frame (as the studies by Gerilla et al [47] and Gustavson et al [59]), wood shows a lower environmental impact for the construction phase than concrete. Even though, when considering the whole life cycle of the building, the differences noted in the construction stage disappear and the concrete frame appears to be a preferable environmental choice.
    - When comparing steel to concrete as material for a building frame (as the study by Guggemos and Horvath [54]), steel shows a lower environmental impact for the construction phase than concrete. Even though, when considering the whole life cycle of the building, the differences noted in the construction stage disappear and the concrete frame appears to be a better environmental choice.
    - Concrete as a material has smaller values of embodied energy and environmental impacts as compared to other construction materials (such as glass, aluminium and ceramic tiles). However, since concrete is used in very large quantities, it becomes responsible for a large share of gross embodied energy and environmental impacts (Asif et al [8]).
    - According to a study assessing bamboo as a material construction for building frames by Van der Lugt et al [161], it can be said that is a more friendly environmental material than wood, steel or concrete.

- Commonly-accepted results and observations gained from the assessment of whole buildings:
  - Embodied energy from building materials, when compared with a whole building's life cycle, accounts on an average range of 10-20% (Adalberth [2]).
  - The supporting structure is responsible for almost 60% of the environmental load caused by building materials. Therefore the supporting structure is responsible for about 12% of the whole environmental load of the buildings construction (López-Mesa et al [94]).
  - The construction phase impacts represent a relatively small part (0.4%-11%) of the overall building life-cycle energy use and emissions (Guggemos and Horvarth [54]).
  - Several studies have shown (as the performed by Junilla et al [160] and Utama and Gheewala [75]) that impacts and energy consumption for material production and construction phase; account less when comparing to that of the operating/maintenance phase. It has been accounted for approximately 70-80% of the total energy use of a building's life cycle.

- Commonly-accepted results and observations gained from the assessment of maintenance activities during building's operational phase:
  - Use of "alternative" building materials, as indicated by the study of Huberman and Pearlmutter [70], can reduce for reinforced concrete buildings the equivalent of 25-30 years of operational energy.
  - Embodied energy, as indicated by Junilla et al [75], can be 20-50 times the annual operational energy of commercial buildings or as much as 67% of use phase energy over a 25-year period.

- Commonly-accepted results and observations gained from the assessment of building's end-of-life:
  - Environmental benefits obtained from proper management of the end-of-life cycle phase are relative small (0.2-2.6%) compared to the full life cycle impacts of a conventional building (Gian Andrea [50]).
  - The recycling potential is accounted to be around a 29% of the energy used for manufacturing and transporting the building materials (Gian Andrea [50]).
  - A study by Gian Andrea B. [50] reported a potential for recycling construction demolition waste estimated between a 35% and 40%.
  - Steel structures have a higher reuse rate than steel-reinforced concrete, as pointed by a study of Horvath and Hendrickson [68].
  - It has been estimated by Khasreen et al [78] that the end-of-life treatments in conventional building represent less than 1% through the life-cycle energy use.
  - Increasing the recycling of concrete from deconstructed buildings, as indicated by Vieira and Horvath [165], to 50% rate could yield a 2-3% reduction in buildings' greenhouse gas emissions (2.7-5.6 million metric tons of CO_2 equivalent).

	BUILDING MATERIAL	CONSTRUCTION	OPERATIONAL/MAINTENACE	END OF LIFE
WHOLE BUILDING	Building materials account for 10-20% of the embodied energy of a building	It account for 0,4-11% of the whole energy and emission of the whole life cycle	70-80% of the energy used for all the buildings life cycle	Environmental benefits from correct en-of-life management account for 0.2-2.6% impact savings.
STRUCTURE	Account for 60% of the embodied energy of all the building materials	The supporting structure is responsible of 12% of the whole construction	Use of greener materials in reinforce concrete structures decrease consumptions as that of 25-30 years of operational use	Steel structures offer a higher level of recyclability than that of reinforced concrete
CONCRETE	When considering its full life cycle, concrete shows the best environmental performance as structure material	-		A 50% rate of recycling in a concrete structure can achieve a reduction of 2-3% of whole life cycle energy consumption

***Table 12**: Summary of conclusions on LCA studies. (Source: own elaboration)*

5.1.3. LCA studies on concrete structures.

Right ahead we are going to offer a review on published LCA studies performed on concrete structures. Even though the objective has been always the same (to evaluate environmental performance of concrete structures) each study has applied different assumptions, methodologies, databases, etc. that have driven to different results. Ahead a table with a list of different LCA applied to concrete structures will be incorporated, indicating characteristics such as: year of publication, scope of the study, methodology used, LCI/LCIA performed or databases/software used.

Taking a closer look at the listed studies shown ahead, it has been observed that their publication has taken place from 1998 to 2011. Notwithstanding, half of its publication (more specifically the 59.26% of them) have concentrated on the range of years comprehend between 2005 and 2009, so it can be considered as a current issue.

On the other hand, when focusing on the methodology used for LCA practice, it can be drawn that process method is the trendy methodology used by practitioners (67.34%) followed by hybrid LCA (14.82%). Furthermore studies that reached LCI and LCIA steps are half distributed: some just stay to the LCI inventories and remained on the analysis of impacts such as energy consumption and emissions to the air (such as CO_2, SO_2 and CH_4 gases) and others reach the LCIA step (51.85%), but just two studies reach further to normalization step. Finally, according to databases and software, it has been appreciated that studies do not usually make use of them.

Little amount of them perform a sensitive analysis or data quality assessment (Börjesson and Gustavsson [14] point their importance), situation that drives studies to uncertainties and lack of transparency on their assessments. Just two case studies perform a sensitive analysis (Bouhaya et al [15] or Gerilla et al [47]) and are considering more as different scenarios than sensitive analysis.

REF.	AUTHORS	YEAR	GOAL AND SCOPE	FUNCTIONAL UNIT	METHODOLOGY	LCI	LCIA	DATABASES SOFTWARE	SENSITIVE ANALYSIS	DATA QUALITY ASSESSMENT
[5]	Arets et al	2003	Comparison of 7 usual types of floors in Dutch buildings	1 m² of floor for a lifespan of 75 years	Conventional LCA	**	Normalization to environmental cost	GreenCalc	*	*
[7]	Arskog et al	2004	Compare two types of concrete repair and maintenance systems (shotcrete patch vs. surface protection)	1 m² of repaired or protected concrete surface for a period of 10 years	Conventional LCA	**	• Energy • Global Warming • Acidification • Eutrophication • Photo-oxidant • formation	• IPPC (Montreal Protocol) • Article data (Heijungs, 1999)	*	*
[12]	Bilec et al	2006	Assessment of the construction phase for a precast parking garage located in Pittsburgh	Construction phase of a five-level precast parking structure	Hybrid LCA	• CO_2 • CH_4 • N_2O • CF • SO_2 • CO • NO_2 • VOC • PM_{10}	*	• SimaPro • U.S. Department of Commerce EIO-LCA database1992	*	*
[14]	Börjesson and Gustavsson	2000	Comparison of the construction phase for a wood vs. concrete frame of a multi-storey building	Whole structure materials manufacturing and end-of life management	Conventional LCA	• Energy • CO_2 • CH_4	*	Other authors	*	Points its necessity but avoids its performance as it is out of the scope
[15]	Bouhaya et al	2009	Assessment of an innovative bridge structure, made of wood and ultra-high performance concrete	25 m span bridge deck for a lifespan of 100 years	Conventional LCA	• Energy • CO_2	*	• Product's EPD • French Civil Engineering Association (AFGC) • Manufacturer's information	Considers three different scenarios for end-of-life treatment	*

***Table 13**: Main characteristics of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	GOAL AND SCOPE	FUNCTIONAL UNIT	METHODOLOGY	LCI	LCIA	DATABASES SOFTWARE	SENSITIVE ANALYSIS	DATA QUALITY ASSESSMENT
[17]	Bouman et al	2000	Comparison of different concrete mix designs	1 m³ of concrete from raw material extraction to on-site supply	Conventional LCA	• Energy • CO_2	*	• On site data • Other authors	*	*
[25]	Cole	1999	Comparison of the on-site construction for wood, steel and concrete structural assemblies	1 m² of either wall or floor area	Conventional LCA	• Energy • CO_2 • CH_4 • CO • NO_2	*	Athena	Performed by introducing workers transportation	*
[30]	Courard et al	2001	Comparison of steel, concrete and wood-concrete concrete structure for an industrial hall in Belgium	1 m³ of each material considered from raw material extraction to demolition and recycling	Conventional LCA	Unexposed	Eco-factors and Eco-points	• CORINAIR • European studies • Manufacturers information	*	*
[32]	Dimoundi and Tompa	2008	Comparison of materials from two office building, with a reinforced concrete structure, in Greece	1 m² of floor area	**	• Energy • CO_2 • SO_2	*	• SIA • CBPR • Other authors	*	*
[39]	Evangelista and De Brito	2007	Comparison of different concrete mix designs, using diverse rates of fine recycled aggregates	1 m² of reinforced concrete slab	Conventional LCA	Unexposed	• CML • EDIP • Eco-indicator	EcoConcrete	*	*
[46]	Ge	2010	Comparison of a steel vs. concrete structure for a building in China	Whole building during complete life cycle	Input-Output LCA	• Energy • CO_2	• Resource consumption • Energy consumption • CO_2 emissions	• China Environment Yearbook 2002 • National Bureau of Statistics of China 2002	*	*

***Table 13**: Main characteristics of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	GOAL AND SCOPE	FUNCTIONAL UNIT	METHODOLOGY	LCI	LCIA	DATABASES SOFTWARE	SENSITIVE ANALYSIS	DATA QUALITY ASSESSMENT
[47]	Gerilla et al	2007	Comparison of wood vs. reinforced concrete residential houses in Japan	1 Kg of emission per year per square meter	Hybrid LCA	• CO_2 • N_2O • SO_2 • PM_{10}	Global Warming Potential, and later normalized by 1998 European Study ExternE	• Japan public information • Questionnaire survey	• Increasing life span • Introducing alternative energy sources • Combination of the previous	*
[50]	Gian Andrea	2009	Assessment of a reinforce concrete structure focusing on the end-of-life phase	1 m² floor area, over a period of 1 year	Conventional LCA	Unexposed	• Energy resources • Global warming • Ozone depletion • Acidification • Eutrophication • Photochemical smog	• Field measured data • Author's data • SimaPro • Bousted Model	Recalculation of impacts for the two most important materials with other database (ecoinvent)	*
[54]	Guggemos and Horvath	2005	Comparison of steel vs. cast-in-place concrete for typical offices in United States	Whole building for a lifespan of 50 years	Hybrid LCA	• Energy • CO_2 • CO • N_2O • SO_2 • PM_{10}	*	• IPPC • US EPA • Other authors	*	*
[58]	Gustavsson et al	2006	Comparison of wood vs. concrete framed buildings in Sweden and Finland	Whole structure for a life span of 100 years	**	• Energy • CO_2	*	Other authors	*	*
[68]	Horvath and Hendrickson	1998	Comparison of steel vs. reinforced concrete bridges	**	Input-Output LCA	*	*	• US EPA TRI • Air Chief 1995 • US GAO 1994	*	*

***Table 13**: Main characteristics of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	GOAL AND SCOPE	FUNCTIONAL UNIT	METHODOLOGY	LCI	LCIA	DATABASES SOFTWARE	SENSITIVE ANALYSIS	DATA QUALITY ASSESSMENT
[73]	Jönsson et al	1998	Comparison of 7 steel vs. concrete framed (office and dwelling) buildings in Sweden	1 m² of floor area for a lifespan of 50 years	Conventional LCA	• Energy • CO_2 • NO_2 • SO_2 • COD • Waste	• EPS • Environmental theme method • Ecological scarcity method	LCAiT	*	*
[87]	Lenzen and Treloar	2002	Analysis of the study, in the Australian context, published by Börjesson and Gustavsson [14]	Whole structure materials manufacturing and end-of life management	Hybrid LCA	• Energy • CO_2 • CH_4	Greenhouse gas emissions	• Australian public information • Other authors	*	*
[94]	Lopez-Mesa et al	2009	Comparison of two systems of reinforced concrete structure slabs in Spain	1 m² of floor area for a lifespan of 50 years	Conventional LCA	Annexed	EPS 2000 method	SimaPro Ecoinvent	*	*
[97]	Marceau and Vangeem	2006	Comparison of wooden vs. concrete isolation wall for a single-family house in five different cities of US	Whole single-family house for a lifespan of 100 years	Conventional LCA	Unexposed	Eco-indicator 99 EDIP 96 EPS 2000	• SimaPro • US data • Products EPD	*	*
[123]	Peyroteo et al	2007	Comparison of steel vs. reinforced concrete structures in Portugal	Material production and construction phase for a portico	Conventional LCA	• Energy • CO_2 • SO_2 • NO_2 • Water	*	Own database	*	*
[134]	Rosignoli et al	2006	Analysis of four techniques for a concrete bridge and comparison of different repair measures in Switzerland	Whole bridge for a life cycle of 100 years	Conventional LCA	**	CML method with a later Eco-indicator normalization	**	*	*

***Table 13**: Main characteristics of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	GOAL AND SCOPE	FUNCTIONAL UNIT	METHODOLOGY	LCI	LCIA	DATABASES SOFTWARE	SENSITIVE ANALYSIS	DATA QUALITY ASSESSMENT
[141]	Selih and Sousa	2007	Comparison of materials for a concrete wall	Material production and on-site construction of 1 m² of insulating material	Conventional LCA	Unexposed	CML	ERMCO	Includes two: one considering different cements and other with different reinforcements	*
[149]	Tikul and Srichandr	2011	Assessment of reinforced concrete structures residential buildings in Thailand	Whole building with a lifespan of 50 years	Conventional LCA	Unexposed	• Global Warming Potential (GWP) • CO_2-eq. emissions	Ecoinvent	*	*
[165]	Vieira and Horvath	2008	Assessment of a concrete structured office building in US focusing on the end-of-life phase	**	Conventional LCA	• Energy • CO_2 • CO • NO_2 • SO_2 • PM_{10}	*	US data average data	*	*
[168]	Winistorfer et al	2005	Comparison of energy use of wood vs. concrete framed buildings in Atlanta	Whole building for a lifespan of 75 years	**	• Energy • CO_2	*	• SimaPro • CORRIM • US EPA	*	*
[171]	Xing et al	2007	Comparison of steel vs. concrete framed buildings in China	1 m² of building are for a lifespan of 50 years	Conventional method	• Energy • CO_2 • CO • CFC • NO_2 • SO_2 • PM_{10}	*	BESLCI	*	*

***Table 13**: Main characteristics of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

(*) Item not included at the scope of the study.

(**) Item not exposed at the study, even being included at its scope.

Once LCA studies on concrete structures recovered from the research have been introduced, an analysis of the limitations pointed within them and observed after its reading will be exposed ahead. As first approach, limitations indicated by the authors themselves are grouped and presented to offer an objective vision of problems within LCA practice on concrete structures. Secondly, this objective vision will be complemented by a subjective analysis of problems and limitations observed.

First limitation established by the own practitioners of LCA is found on the definition of the system boundary to be considered. As pointed out by Börjesson and Gustavsson [14] during the performance of the assessments, whole life cycles are not usually considered, and even in some cases materials, construction processes or deliveries are considered out of the scope of the assessment (Bilec et al [12]). On the other hand, when defining the functional unit and system boundary on a LCA studies, Jöhnsson et al [73] points out that the more difficult they are the more unreliable the results become. Furthermore, as this two concepts increase their difficulty, sensitive analysis therefore increases its complexity.

Problems with data are also addressed by many authors, as related construction data is considered to be: scarce, uncertain and obsolete (Bouhaya et al [15], Courard et al [30], Horvarth and Hendrickson [68]). This exposed problem with data, carry most of practitioners to introduce assumptions for solving data gaps encountered during the performance of their studies (Evangelista and De Brito [39]). Therefore assumptions, all together with selected software and bad quality data included at the study, make the results of LCA studies on concrete structures to be different depending on its practitioner and, consequently, decreasing the reliability of the study (Bilec et al [12], Bouhaya et al [15] and Gian Andrea [50]). If the consideration established by Borjesson and Gustavsson [14] is taken into account, the data and assumptions introduced in the study require of a complete review for assuring its reliability.

Furthermore, geographical location of data is indicated by many authors (Tikul and Srichandr [149], Peyroteo et al [123] or Dimoundi and Tompa [32]) as a factor that introduces wrongness on the assessment due to, as an example, different energy sources needed for the manufacturing of products. As a potential solution for this issue, Tikul and Srichandr [149] propose a detailed decomposition of related data for practitioners to modify depending on the location of the study performed.

In other studies, impacts considered in the LCA study resulted limited by the scarcity of impact data (Tikul and Srichandr [149] and Jönsson et al [73]).

So according to all previously exposed limitations, and more precisely according to Viera and Horvarth [165], there is a high need for improving construction related data to reduce uncertainty and improving LCA reliability.

Finally, according to Marceau and Vangeem [97] and Rosignoli et al [134], a relationship between system boundary, scarcity of data and assumptions is established. As data related to operational and maintenance life cycle phases are completely defined, practitioner must incorporate assumptions or limit their studies to the phases they count data with. One possible solution for this methodological and source problems could pass by the development of new construction related and specific LCA software (Peyroteo et al [123]).

The personal analysis of the LCA studies has been performed mainly focusing on aspects of its methodology, such as: data used for the assessments (source and uncertainty), the considered system boundary, assumptions and limitations introduced by practitioners, or even the exposition grade of the assessment performed. It has been observed that these studies normally fail on issues like the ones related ahead:

- When **defining the functional unit** of the study, this is scarcely defined or is considered one that differs from ordinary functional units observed in studies. This wrong definition can take the study to results difficult to compare with other studies, as they differ in their functional unit.
- When **establishing the basic information of the study** related to **limitations and assumptions** considered in the study, the practitioners do not expose them on a clear manner. This situation prevents the study from review or reproduction on behalf of other practitioners.
- As it was already exposed at this work, practitioners of LCA studies on concrete studies recommend to **consider the full life cycle** of the structure assessed. Therefore, concrete can be affected by this limitation and when compared to other structural materials it can be in disadvantage (even being the optimal material).
- It has been observed that there are a scarce number of studies which include a **flow diagram of the system boundary** exposed at the study.
- As the limitations and the assumptions of the studies, the impact data to include on the **inventory phase is not exposed** or even, in some cases, no mentioning of its source is done. On the same way, the impact assessment is not exposed. So, it can be said that almost all the LCA studies do not make an exposition of their calculations (studies low transparency).
- When performing **data quality or sensitive analysis**, it has been observed that none of them are included in the studies. Therefore, the results of the studies performed suffer from unreliability.
- Finally, the **graphical representation** of the results obtained in the studies is not normally included on the interpretation of the results obtained.

Therefore, it can be extracted that LCA studies on concrete structures performed to the date offer great number of deficiencies. Among the most relevant are identified the transparency, reliability and certainty of the LCA study performed. These issues will be treated ahead at this work with the exposition of a guide for the practice of LCA on concrete structures, and the performance of a simplified LCA comparison of two typologies of concrete structure.

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[5]	Arets et al	2003	x	x	• Unusual functional unit (difficulty for latter comparison with other studies). • Limitations of the study unexposed. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • Source and LCI data unexposed. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability).
[7]	Arskog et al	2004	x	• Assessment of environmental burden during the life cycle of a product is a difficult task. • LCA practice easiness passes by development of an international database.	• Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • Source and LCI data wide and unexposed. • LCIA calculation process unexposed. • No data quality assessment process included (unreliability).
[12]	Bilec et al	2006	• Does not include all construction processes, materials and deliveries. • Assumptions introduced. • System boundary includes transportations limitations.	• Process assessed and software selected varies the results of the studies. • Inclusion of construction of service sectors is necessary to perform good assessments. • More on-site construction information/data is required. • Current Input-Output data on construction industry is not completely developed, assumptions are required.	• Unusual functional unit (difficulty for latter comparison with other studies). • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • Source and LCI data wide and old. • No data quality assessment process included. • No graphical representation of results.
[14]	Börjesson and Gustavsson	2000	• Does not include operating phase. • Uncertainty of data used at the study.	Input data and assumptions need further analysis to ensure accurate results.	• Unexposed functional unit (difficulty for latter comparison with other studies). • System boundary limited (no operating phase). • LCA calculation process unexposed. • Process of the LCA is not clearly exposed. • No data quality assessment process included (unreliability).

***Table 14**: Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[15]	Bouhaya et al	2009	• Assumptions introduced for different phases. • Do not include structure foundations.	• Impacts on raw material extraction and water wastes consider at the study are to be extended. • Data for allocation process is scarce.	• Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Source and LCI data unexposed. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).
[17]	Bouman et al	2000	• Assumptions introduced at the study. • System boundary to construction phase. • Just fuel and operational energy are considered. • Data from on-site construction was not enough.	Companies' activities are recommended to be included on data sources to improve LCA results accuracy and objectivity.	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • Source and LCI data unexposed. • Allocation assumptions unclear. • No data quality assessment process included (unreliability). • No graphical representation of results.
[25]	Cole	1999	x	Transportation of workers to the construction site should be included on the calculations of LCA, as depending on the task assessed, more resources will be needed and, therefore requiring more transport and emissions to the air.	• Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Source and LCI data unexposed. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[30]	Courard et al	2001	x	• Results obtained from one study cannot be directly taken for other studies assessing systems of different countries. • Obtaining related data on construction industry for the performance of LCA on buildings is one of its main problems.	• Unusual or scarcely defined functional unit (difficulty for latter comparison with other studies). • Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • No flow diagram of the assessed processes. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability).
[32]	Dimoundi and Tompa	2008	x	• As data used at the study came from international sources, results have integrated a degree of inaccuracy • Studies on energy lack of detailed information relating the process followed for their results. • Comparison between studies is not direct due to the functional unit selected and assumptions introduced on each study.	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Source and LCI data unexposed. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).
[39]	Evangelista and De Brito	2007	Limited database of the tool used for the assessment, drove to introduction of assumptions for: recycling process, cement of the concrete mix design.	LCA results have to be based on wide, accurate and reliable databases.	• No clear exposition of the study background. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Source and LCI data unexposed. • Allocation assumptions unclear. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability). • No graphical representation of results.

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[47]	Gerilla et al	2007	x	x	• No clear exposition of the study background. • Unusual or scarcely defined functional unit (difficulty for latter comparison with other studies). • Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • LCI data unexposed. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).
[50]	Gian Andrea	2009	x	• LCA results are very influenced by the assumptions taken by their practitioners. • Incorporation of indicators for use of land is a source for future researching. • All phases, from cradle-to-grave have to be considered.	• Limitations of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability).
[54]	Guggemos and Horvath	2005	x	• The operation phase, when compared to the other phases of the life cycle, reduces their relative impact. • Comparison with other studies must be done on a carefulness basis, due to differences on system boundaries and data used for each study.	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • Source and LCI data unexposed. • No data quality assessment process included (unreliability).
[58]	Gustavsson et al	2006	Uncertainties of the study due to measurements, place, time and process technology.	The results of the study are affected by, among others, by uncertainties on primary energy of materials.	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[68]	Horvath and Hendrickson	1998	• Environmental burdens on the study were not wider due to lack of data and acceptable metric. • Data used in the study suffers from uncertainty, as its data with certain obsolescence. • Data not available for certain materials and processes.	Data obsolescence for material manufacturing is not a problem, as they are design for a long life-cycle.	• Scarcely defined functional unit (difficulty for latter comparison with other studies). • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • No flow diagram of the assessed processes. • Allocation assumptions unclear. • No data quality assessment process included (unreliability). • No graphical representation of results.
[73]	Jönsson et al	1998	x	• The risk of committing mistakes increases with the complexity of the functional unit selected. • System boundaries for complex studies are more difficult to process and calculate. • Impacts are wider than the selected system boundary. • Transparency of studies is a must. • Sensitive analysis of complicate LCA studies is a hard task. • Use of computational software can help easing LCA practice.	• Limitations of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • Source and LCI data unexposed. • Allocation assumptions unclear. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability).
[87]	Lenzen and Treloar	2002	x	x	• Unusual or scarcely defined functional unit (difficulty for latter comparison with other studies). • Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Allocation assumptions uncleared. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability). • No graphical representation of results.

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[94]	Lopez-Mesa et al	2009	• Excavation and walls are out of the study. • Use and operational phase are excluded.	x	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability).
[97]	Marceau and Vangeem	2006	• Assumptions introduced on occupant behaviour and house performance. • No data related to some materials produced its extraction from the study.	x	• Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited. • LCA calculation process unexposed. • Source and LCI data unexposed. • Allocation assumptions unclear. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability). • No graphical representation of results.
[123]	Peyroteo et al	2007	Data is not established for the country where the assessment is performed, so average of European data was extracted.	There is not specific software on construction industry to base decisions during building processes.	• Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).
[134]	Rosignoli et al	2006	Assumptions for the maintenances phase are extracted from experiences and literature of other authors.	x	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Source and LCI data unexposed. • Allocation assumptions unclear. • LCIA and normalization process unexposed. • No data quality assessment process included (unreliability).

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[141]	Selih and Sousa	2007	x	x	• No clear exposition of the study background. • Limitations and assumptions of the study unexposed. • LCA calculation process unexposed. • Source and LCI data unexposed. • Allocation assumptions unclear. • LCIA process unexposed. • No data quality assessment process included (unreliability). • No graphical representation of results.
[149]	Tikul and Srichandr	2011	• Data used is not correct due to its geographically deviation. • Impacts consider at the study are reduced due to the scarcity of data.	Developed countries with databases available should offer a break down for other countries to adapt this data.	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • System boundary limited (no end-of-life phase). • LCA calculation process unexposed. • No flow diagram of the assessed processes. • Allocation assumptions unclear. • No data quality assessment process included (unreliability).
[165]	Vieira and Horvath	2008	x	• By the inclusion on Hybrid LCA studies of specific allocation boundaries, uncertainty with technological forecasting can be diminished. • Data on impacts is needed to reduce uncertainty of studies. • Further research on its applicability and development of databases for the construction industry is needed.	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA calculation process unexposed. • Data quality assessment process is unexposed. • No graphical representation of results.

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

REF.	AUTHORS	YEAR	STUDY LIMITATIONS	APPLICABILITY CONCLUSIONS OF THE STUDY	PERSONAL OBSERVATIONS
[168]	Winistorfer et al	2005	Impacts consider at the study are reduced due to the scarcity of data.	• Difficulty for assessing complex structures is based on the collection of data necessary. • Due to the different sources of data for processes and phases, the results of the assessment will include uncertainties.	• Unusual or scarcely defined functional unit (difficulty for latter comparison with other studies). • Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • LCA methodology and calculation process unexposed. • No flow diagram of the assessed processes. • Allocation assumptions unclear. • No data quality assessment process included (unreliability). • No graphical representation of results.
[171]	Xing et al	2007	x	x	• Limitations and assumptions of the study unexposed. • Assumptions introduced prevent results obtained (inaccuracy) to be used for other studies. • Allocation assumptions unclear. • No data quality assessment process included (unreliability). • No graphical representation of results.

Table 14: *Main applicability issues of LCA studies on concrete structures recovered from bibliographic research. (Source: own elaboration)*

(x) Item not exposed at the study, even being included at its scope.

5.2. LCA guide for concrete structures.

When focusing on environmental loads and impacts within the construction industry, attention is directly focused on concrete as one of the most used construction materials. It has already been indicated in the present paperwork that use of concrete in the construction industry has a vast wideness, but the most common (together used with steel) is as reinforced steel concrete (RSC) for the construction of bearing structures.

Some studies on the topic, more specifically one developed by Arets et al [5], concluded that in building constructions bearing structures are responsible for the greater part of the environmental load/cost in comparison with all building materials. Thus, if sustainability in construction wants to be achieved, one option would pass by focusing on improving bearing structure environmental performance. To decrease the environmental load of bearing structure, attention should be focused on issues as: selection of materials, efficient design and prolonging the lifespan. Therefore, a powerful tool able to integrate these choices is needed within the industry.

These demands can be supplied by LCA practice, tool which do not even include issues indicated before, but can be used and developed for further more. Then, a methodological guideline for the assessment of environmental performance of concrete structures, indicating main practice problems and solutions, will be exposed ahead.

5.2.1. Life cycle of concrete structures.

Life cycle of a product or service includes phases from acquisition of raw materials to the end of its life span and disposal. According to this, and taking into account concrete structures main characteristic, its life cycle [Figure 23] can be divided in the next phases:

- Raw material extraction
- Manufacturing, production and transportation
- Use and maintenance
- End of life and demolition
- Landfilling, reutilization or recycling

First phase of concrete's life cycle corresponds to "raw material extraction", phase that includes the procedures and works aimed at obtaining the basic mixture components for concrete's manufacturing. When the unprocessed raw materials are already extracted, then comes second phase of the life cycle "manufacturing" where these raw materials are exposed to different treatments at the production plant to obtain the final mixture materials for concrete. Although nowadays concrete`s technology has developed a wide range of typologies and mixture designs, the most widespread materials are: water, aggregates, binder/cement materials and chemical mixtures (fly ash, fluidity additives, curing retardants, etc.).

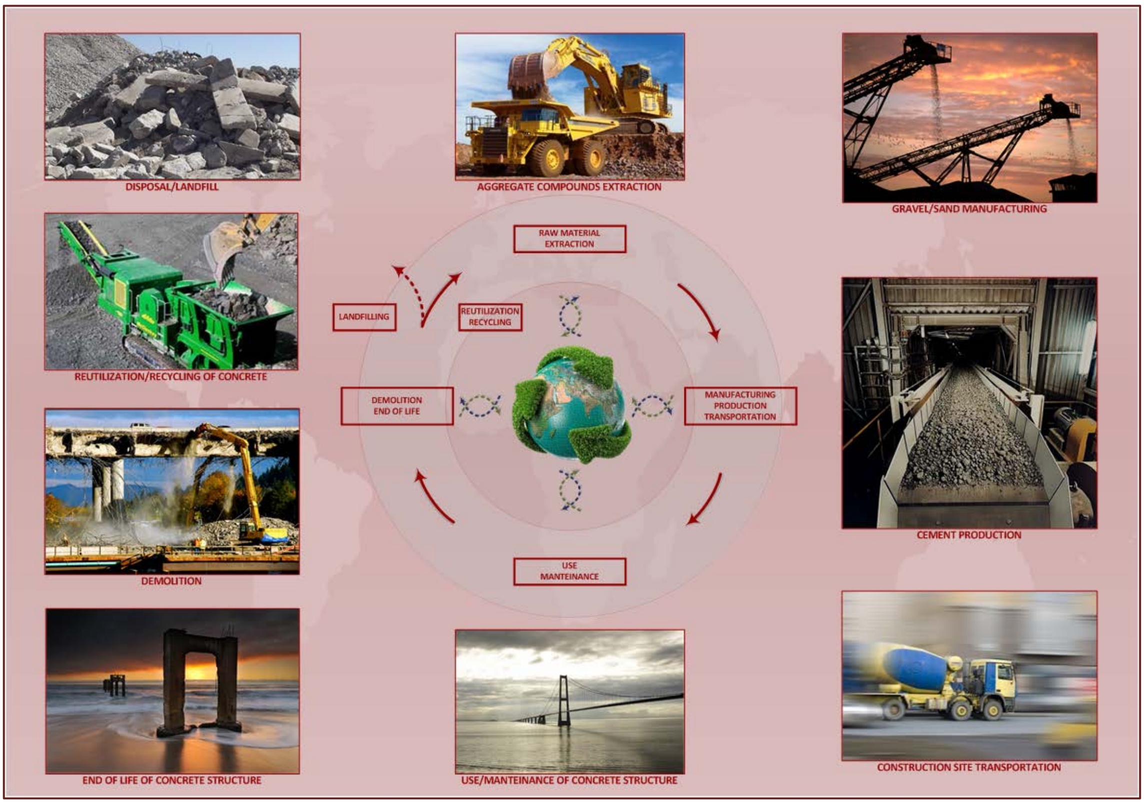


***Figure 23**: Common life cycle for a concrete structure. (Source: own elaboration and images extracted from the internet)*

Within the complete production process of concrete aggregates there are four main phases [Figure 24], which are: raw material extraction, load/transport to treatment plant, scalping/crushing and finally separation/washing (ACHE [240]).

- Raw material extraction. Aggregates come from bedrock or unconsolidated deposits that have to be quarrelled to obtain the mineral aggregate. There are different techniques for materials extraction, and their quality will be directly related to this ways of extraction. Most important extraction techniques are:
  - Strip mining. Consist on surface extraction of materials by excavating the earth, rock or other materials.
  - Drilling. It is based on the use of drilling machines to obtain mineral materials under the surface.
  - Blasting. By the use of explosives, mass rock formations are reduced to smaller portions that can be later extracted by strip mining methods.
- Load and transport phase consist on the load of trucks and dumpers with the material extracted for its transportation to the treatment plant.
- Crushing is the phase when the material is reduced by mechanical actions to the sizes the aggregates is needed for. There are a wide types and systems for crushing, which will not be treated here, and their election depends on issues such as: aggregate's mineral characteristics, machine's performance, sizes required, economy, etc.

- Separation and washing are the last process aggregates are exposed to and consist, as their names indicate, on the classification by size and later washing of the resulting aggregates from the processes before explained.

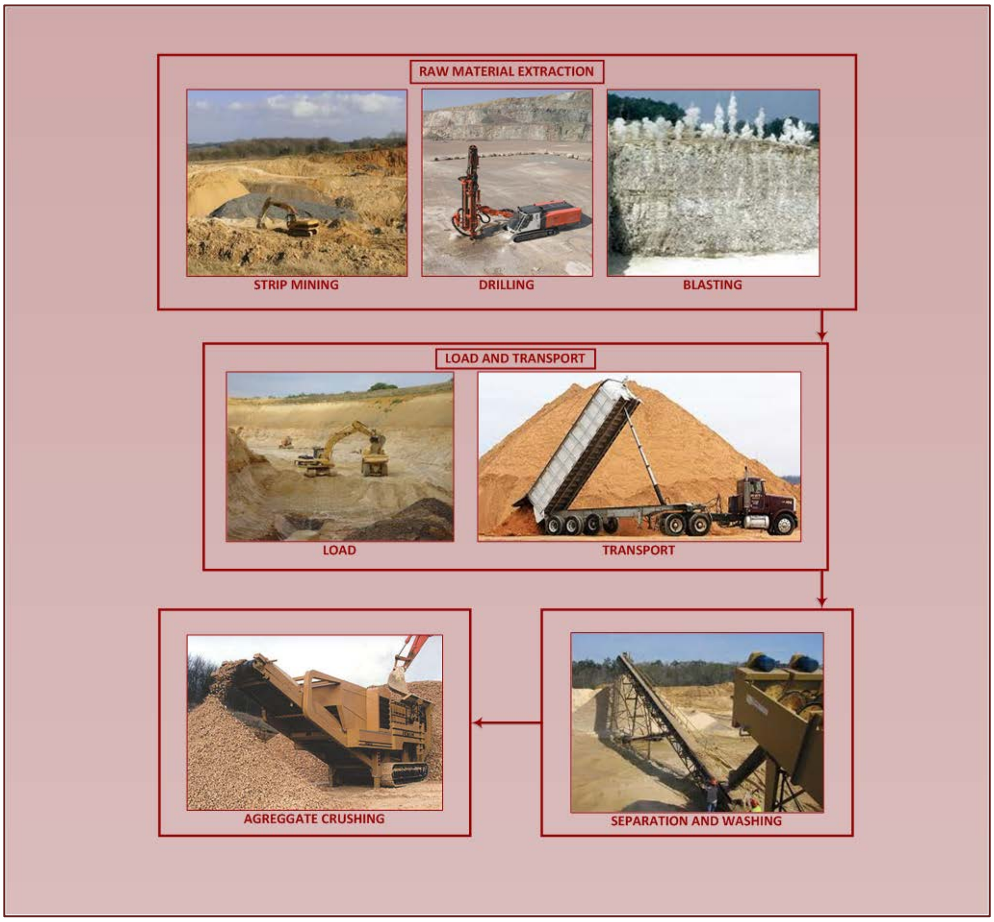


Figure 24*: Production process of concrete aggregates. (Source: own elaboration and images extracted from the internet)*

So, generally speaking that is the process for the production of concrete's aggregates. Ahead, production process for cement [Figure 25] will be exposed which is mainly formed by four steps: raw materials extraction, raw materials preparation, raw materials grinding and pyro processing (ACHE [240]).

- Raw materials extraction. Main raw materials in for cement are: limestone, sand, shale, clay, and iron ore. Of this, limestone is considered the main and is usually mined on site while the other materials can be mined either on site or in nearby quarries. Another source, instead of using raw materials, can be introduction of industrial by-products.

- Raw material preparation for cement production follows the same line as that for lately explained mineral aggregates: drilling and blasting extraction techniques, load of trucks to transport at the crushing plant, crushing and washing to right sizes (>100 mm) and finally stored until its use.
- Raw grinding. There are two types of process: the wet and the dry.
  - In the wet process, the raw materials are introduced, altogether with water, in a rotating ball mill until grounded to a fine powder size (<75µm). The obtained material is called “slurry” and is then pumped to blending tanks for its homogenization, to insure its chemical composition.
  - In the dry process raw materials are dried and size reduced as in the wet process. When they exit either the rotating ball mill or the vertical roller mill, are then pneumatically blended and stored into silos.
- Pyroprocessing. Whether the raw material grinding process is wet or dry, same reactions take place during this phase: moisture is completely eliminated, the limestone is calcinated to produce free calcium oxide and this same calcium oxide react with other minor materials (such as sand, shale, clay or iron). The resulting product, known as "clinker", offers the desired hydraulic properties for the binder.
  - The slurry obtained from the wet grinding process is fed to a large rotary kiln that can reach during the process temperatures as high as 1450ºC.
  - Dry material is fed to a preheater tower and then discharged to a rotary kiln, which is fired with an intense flame, produced by burning coal, coke, oil, gas or waste fuels.

  Then, the heated clinker exiting the rotary kiln is introduced into a clinker cooler that recovers the heat and returns it to the process. Clinker leaving the clinker cooler is handled on standard conveying equipment.
- Finish grinding and distribution. Gypsum is finally added during the grinding process and then the clinker obtained is stored in silos or clinker domes until needed for cement production.

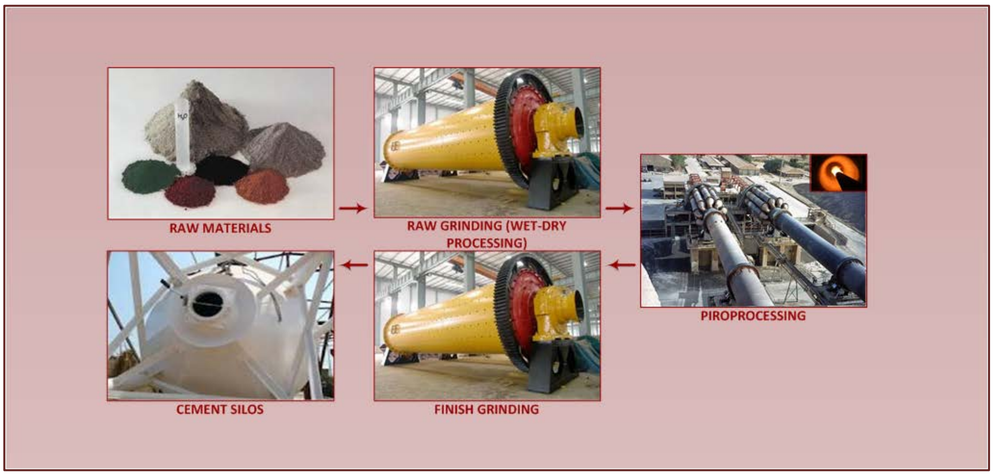


***Figure 25**: Production process of concrete cement. (Source: own elaboration and images extracted from the internet)*

Once cement and aggregates are manufactured, they are delivered to batching plants for concrete production. The manufacture of concrete is fairly simple: first, the cement (usually Portland cement) is prepared, and then the other ingredients (aggregates, admixtures, fibers and water) are mixed together with the cement to form concrete. The mixing operation, which uses a variety of batch and continuous mixer, uses rotation or stirring to impregnate the surface of the aggregate with cement paste and to blend uniformly the other ingredients. Moreover, if desired, fibers can be added by a variety of methods including: direct spraying, premixing, impregnating, or hand laying-up. Silica fume is often used as a dispersing or densifying agent (ACHE [240]).

Once concrete mixture is ready, it is transported to the work site. There are many methods of transporting concrete, but most used for long distances are truck mixers. At the construction site, concrete would be directly poured or pumped to the place where the steel and formwork would be prepared and already arranged. During placing, segregation of the various ingredients must be avoided so that full compaction (elimination of air bubbles) can be achieved. Compacting process by the use of vibrators would take then place and, once finished, concrete's curing process would take its start. When the curing process is finished, operational phase of the structure begins. At this point of the life cycle of a concrete structure would be considered the **embodied energy**, as it includes: energy in the processing of raw materials, manufacturing of concrete and its installation in the construction site.

***Figure 26**: Concrete on-site placing. (Source: own elaboration and images extracted from the internet)*

The operational phase of a concrete structure will last depending on the life cycle span established at the designing phase of the project. During the operational phase, different maintenance activities will be done for ensuring the correct functionality of the structure and for preventing concrete deterioration. Some maintenance activities of concrete are offered ahead (USACE [245]):

- Cleaning. Stains on the surface of concrete do not normally affect its service life, but its recommend to be removed to prevent further penetration or future removal difficulties. Some of technique for this purpose are:
    - Water washing. Consist of a fine mist of water applied from top to bottom of the structure.
    - Steam cleaning. Consist of a hot steam jet applied over the surface of concrete.
    - Water/abrasive blasting. Consist on the elimination of part of the affected surface of concrete by the blast of water or sand from a distance.
    - Flame cleaning. By the heating of the affected zone, biological presence is eliminated but the operation is not free of generating fumes.
- Coating and sealing. These techniques are usually used to protect concrete surfaces from chemical attacks, but it can also be for: reducing water's penetration, physical protection or, even, decorative purposes. Some coating materials normally used are:
    - Silicones, siloxanes and sinales are indicated as water repellents.
    - Cementitious coatings are used for decorative purposes, but modified can serve another functions.
    - Urethanes films are used for seal chemically concrete.
    - Epoxy polyesters are thin film coatings for interior or exterior exposures on wall with little physical abuse.
    - Latexes are also applied as coatings. Elastomeric formulations provide very good properties.

***Figure 27**: Concrete end-of-life treatment. (Source: own elaboration and images extracted from the internet)*

Finally, when the life span of a concrete structure is reached, it's time for the demolition/renovation phase [Figure 27]. When structures made of concrete are demolished or renovated, depending on various inputs (rules, necessities, opportunities, costs, etc.) waste generated can be trucked to landfills for disposal or treated on recycling processes. These recycling process normally consist on collect the concrete aggregate from the demolition sites and then put through a crushing machine. After crushing, the aggregates are exposed to different other methods including hand-picking and water flotation. Latter, the material obtained from the recycling process can be used, for example, as fine aggregate in concrete production or pavement materials (Dosho [34]).

5.2.2. Guideline for the application of LCA on concrete structures.

As it has already been proclaimed, LCA technique is a very strong environmental tool, with multiple feasible applications, which mainly can assess environmental burdens and impacts of any product along its complete life cycle. Nonetheless, from the previously performed SWOT analysis, it has been observed that to the date Life Cycle Assessments are not exempted of weakness on both its methodology and practice, so a great potential for improvement lies within it. As an example of these weaknesses, it is offered a case study that gave different results when changing the LCA practitioner:

> *"A case study of a multi-storey building in southern Sweden was presented in 2000 by Borjesson and Gustavsson [14]. Two design options were considered, one wooden-framed and the other concrete-framed, and assessed from a life cycle point of view studying the embodied energy, greenhouse gas emissions and forest land use. A revision of this same studied was later performed in 2002 by Lezen and Treolar [87], with regard to the embodied energy of the two design options proposed, but employing an Australian environment framework and a tiered hybrid LCA. <u>It was shown that the wooden frame design option calculations were underestimated by a factor of 2</u>."*

Therefore, when practicing a Life Cycle Assessment over a product or service, if the results obtained want to be realistic and trustful, some considerations have to be taken into account. To prevent such situations for new LCA practitioners coming from the construction industry, a guideline will be shown ahead for the practice of LCA on concrete structures according to the methodology established by the ISO 14040 (process method).

5.2.2.1. LCA study on concrete structures: goal and scope definition.

If a close look is taken into engineering or building projects, a concrete structure can be consider as a product itself (as indicated by Erlandsson and Borg [38]) integrated in a bigger product (the project). Therefore, environmental performance of concrete structures can be studied by the application of Life Cycle Assessments. First of all, a well-established description of the building case studied is necessary, including aspects such as: the functional unit (whole building or one system), geographical location of the building, system boundaries clearly set (whole life cycle of one phase of it) and determination of environmental impact categories to be studied (Khasreen et al [78]). Some further indications are shown ahead, when considering the goal and scope of a Life Cycle Assessment of a concrete structure:

- Establishing a correct functional unit is a must to allow latter comparison between structural alternatives. So, to prevent from bad selection or definition, it is highly recommended to use the whole structure as a unique functional unit (Marinkovic et al [98]).
- As durability and recyclability is concrete's greatest attribute, when performing a life cycle assessment of a concrete structure the complete life cycle should be considered. On the contrary, if a limited life cycle of the structure is established, concrete appears to be at a disadvantage when compared to other structure materials. This situation is due to concrete's relatively high initial embodied energy and environmental impact through the manufacture of cement and the mining of aggregate (Palmer [118]).
- When it comes to establishing a project's life span, it would be good to use normalized criteria. As an example, ISO has published the principle for the service life planning of buildings in ISO TC 59/SC 14 "Design Life" (ISO 15686 series) (Haapio and Viitaniemi [59]).
- When performing an LCA, practitioner's assumptions must be minimal as this is one source for latter unreliability and impediment of studies comparison (Lippke et al [91]).
- When considering the life cycle of a product carbon stored in products should be considered. Carbon stored is functionally equivalent to a negative carbon emission produced in the manufacture of those products.
- LCA of concrete structures do not usually account for carbonation of concrete during the primary or secondary life. The findings show that, although carbonation during primary life is relatively small, significant carbonation occurs during secondary life when the demolished concrete, broken into waste fragments and recycled, has a higher exposed surface area available to react with CO_2. If carbonation is ignored, emissions can be over-estimated by 13-48% depending on the type of cement-binder and the application of RCA during secondary life (Collins [27]).
- Repair and maintenance activities of concrete structures must be considered during all the use period of the building, the so-called "management" phase, as they do consume much energy and resources, and produce a heavy environmental burden and large quantities of waste (Arskog et al [7]).
- Wastes generated during the construction of concrete structures must be included on the study. As well as the rates for recycling and reutilization of materials, once arrived their end-of-life stage (Gian Andrea [50]).
- The transportation distances considered for materials in the construction phase are different from the one from the disposal-demolition phase (Gian Andrea [50]).

Although these last were some points to have into consideration during the establishing of the goal and scope of a LCA study, ahead will be listed a more schematic way for performing this first step of an a LCA on concrete structures:

1. Name the author or team responsible for the LCA study, as well as mention the way for contacting with them.

2. Expose a previous description of the case study, fixing aspects such as: background, motivation, object and objective of the study, etc.
3. In some LCA studies there are more than one party interested on its performance. It is recommend, when they are present, to establish this third parties.
4. Define the functional unit that, as it has already been said, it is recommended to include the whole structure.
5. The structure's life cycle considered at the study must clearly establish, as well as the limitations and assumptions included.
6. Sources of data used in later performance of LCI phase has to be named even, if its considered, organizations and some further information relating to its accessibility (for letting rear reviewing of the study).
7. Establish the tools and measures used within the study to assure data quality included on the study (statistical studies, reliability of sources, etc.).
8. Data gaps solution and assumptions introduced at the study are highly recommended to be clearly and thoroughly explained.
9. Sensitive analysis is the way to identify mistakes from bad assumptions and data utilization. So, it is recommended to expose the way for performing this sensitive analysis.
10. Expected limitations on the LCA study, established either by the authors or because of scarcity of resources, are to be exposed on this presentation of the study

Summarising, when performing the goal and scope of an LCA analysis, the objective to keep in mind by the practitioner is to establish all the initial restrictions, conditions and peculiarities expected to be confronted. If this is correctly done, future comparison and accessibility for other practitioners will be completely assured.

5.2.2.2. LCA on concrete structures: Inventory analysis.

As it has been indicated in some studies, to achieve an accurate and precise LCA of products or services, a higher level of completeness and reliability in LCI is needed (Khasreen et al [78]). If this completeness and reliability in LCI wants to be reached, a normalized procedure has to be established for the assessment. An example for an LCI procedure is offered ahead:

1. **Develop a flow diagram of the process being evaluated.** The diagram of the process should be as detailed as possible to get a high level of accuracy. The more detailed the diagram is, the more accurate the results will be (Khasreen et al [78]). Some examples of how to operate a flow diagram for a concrete structure are included ahead. These examples are shown for different regional locations (as Spain, USA and Italy) and for different phases of a construction structure. It is important to indicate that system boundaries will be subject of variations, such as: construction techniques, assumptions of the practitioner, location and project constraints, etc.

During this flow diagram, an exhaustive calculation process of materials used at the construction for the structure is performed. It is highly recommended for the practitioner to assess all materials, as some of them although being used in small quantities, have high embodied energy and large environmental impacts.

Ahead some examples of flow diagrams are offered, one for concrete production and on site-placement (Brocklesby and Davison [16]), another for on-site construction processes of a concrete slab (Guggemos and Horvarth [54]) and finally another diagram for a reinforced concrete construction.

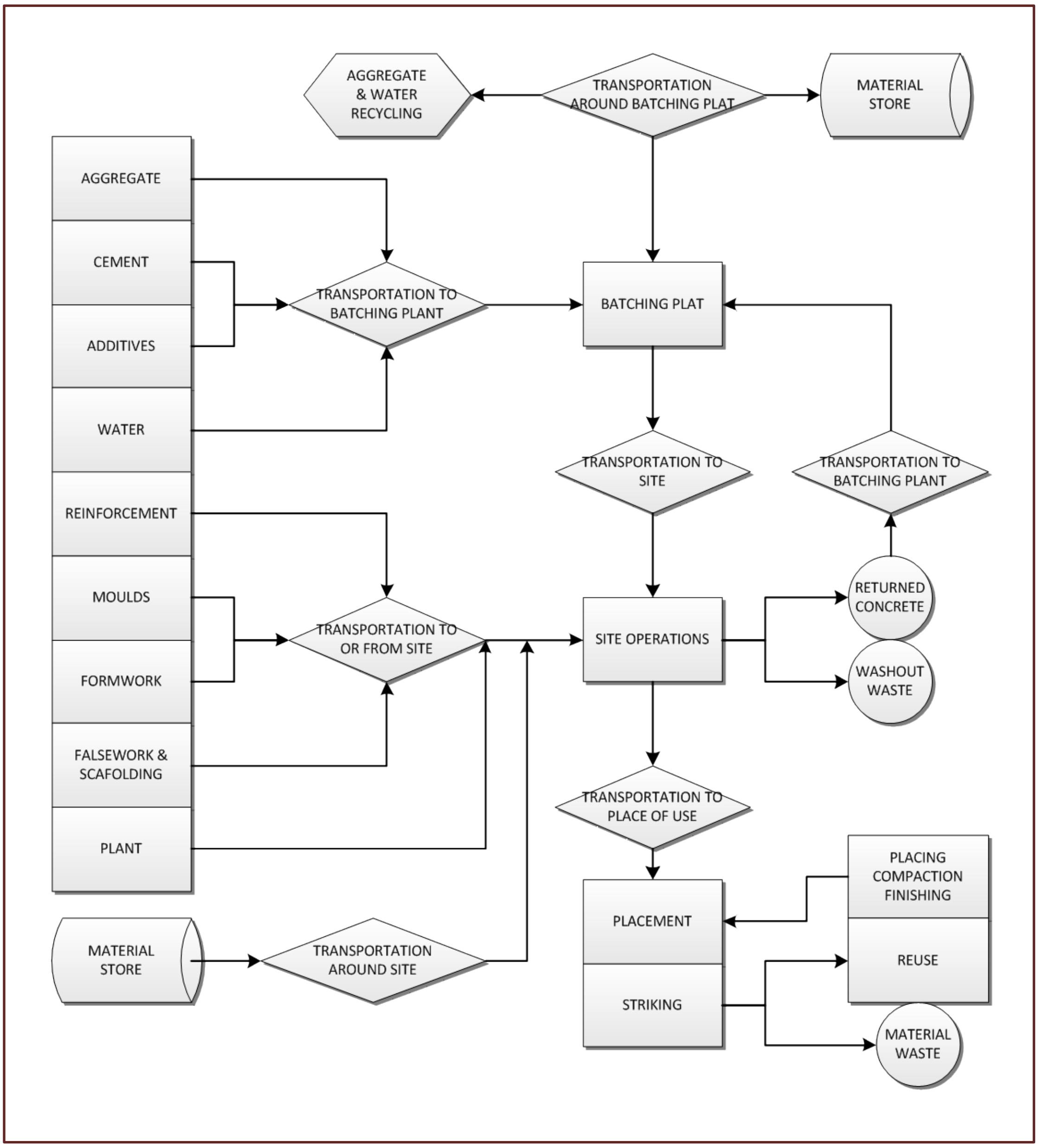


Figure 28: *Example of flow diagram for concrete production. (Source: reproduced from Brocklesby and Davison [18])*

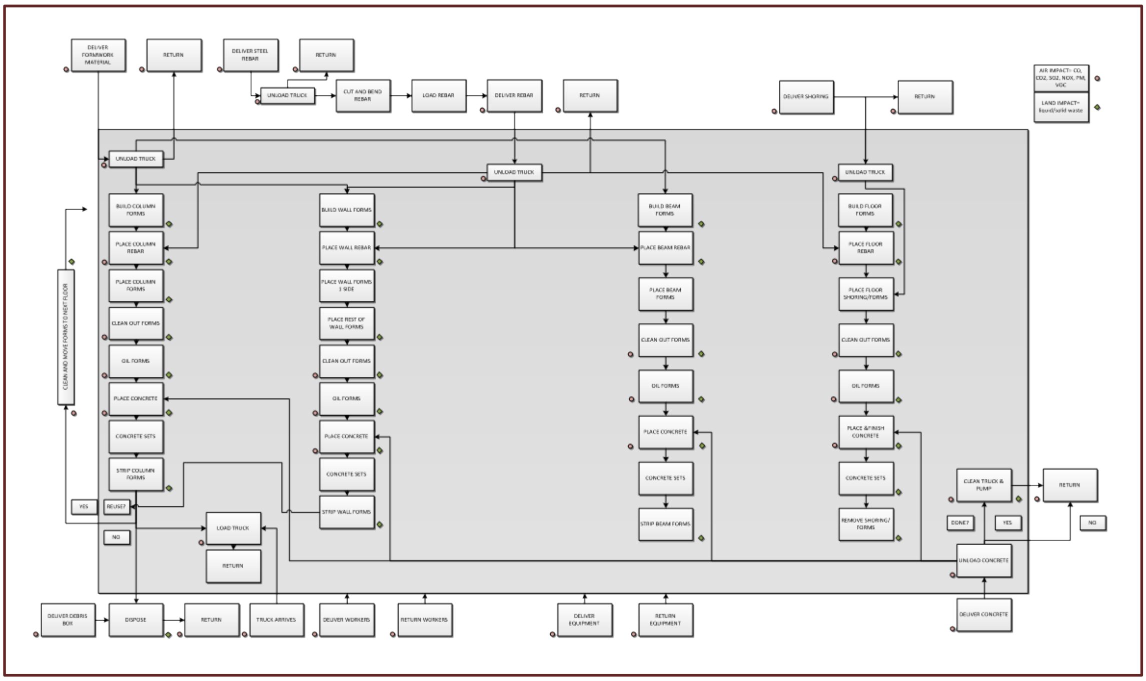


***Figure 29**: Example of flow diagram for a reinforced-concrete construction. (Source: reproduced from Guggemos and Horvath [54])*

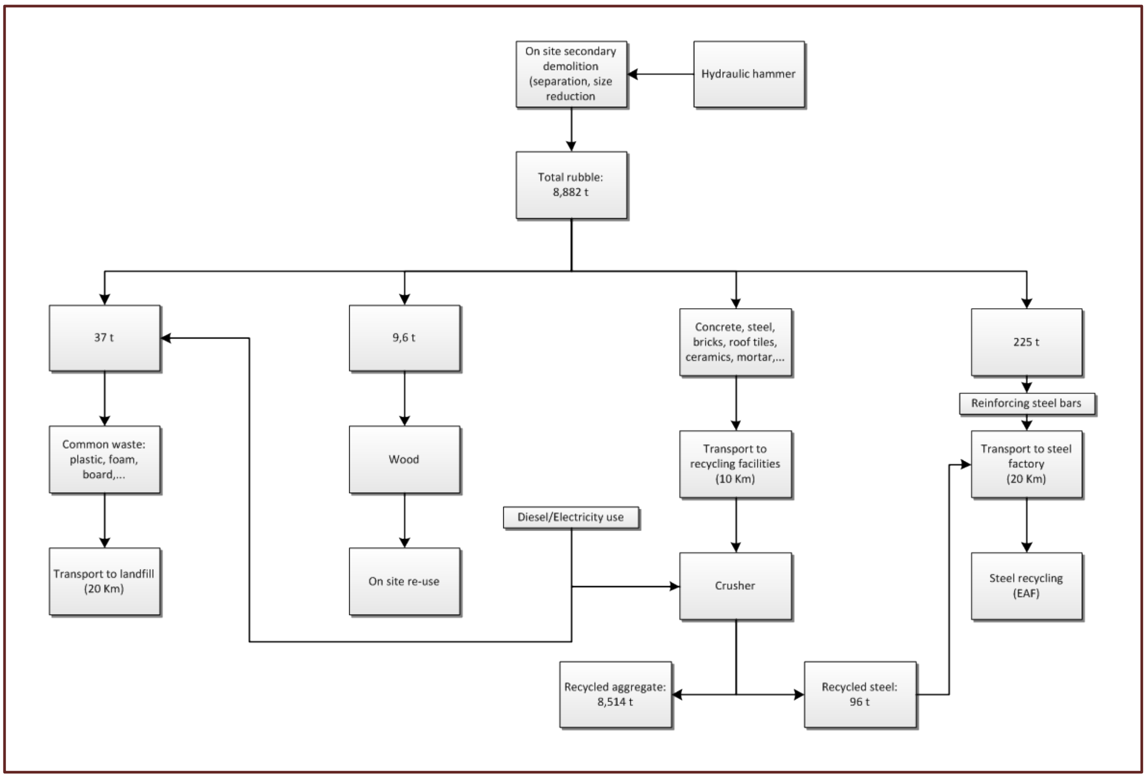


***Figure 30**: Example of flow diagram for end-of-life in reinforced-concrete construction. (Source: reproduced from Gian Andrea [50])*

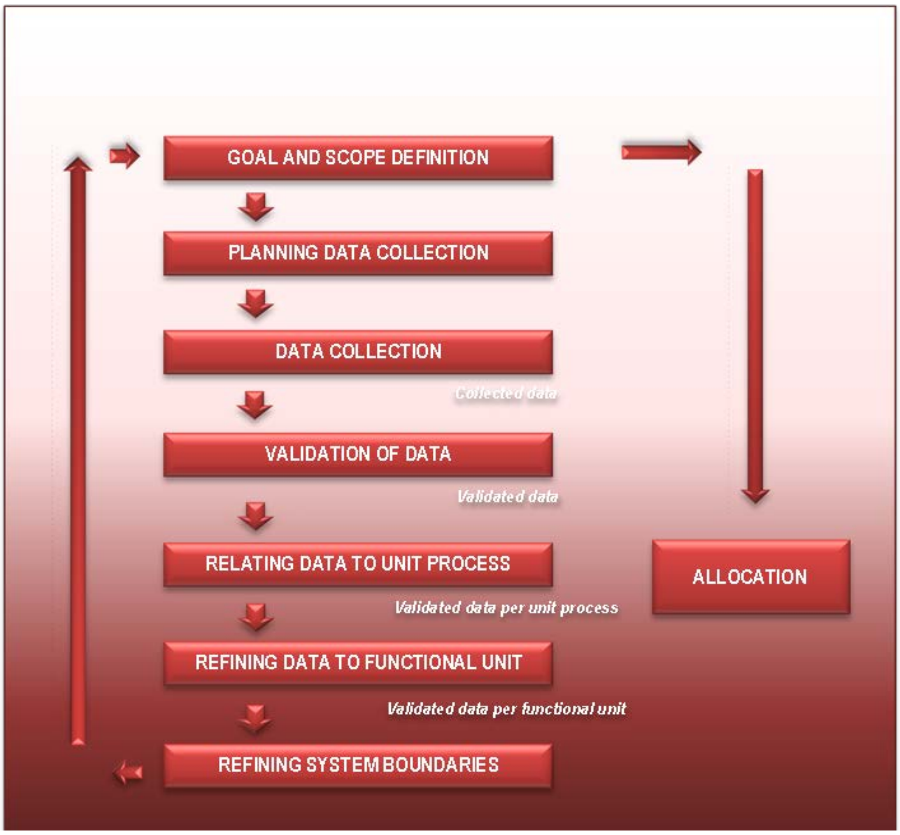


***Figure 31**: Simplified procedure for Life Cycle Inventory. (Source: reproduced from Khasreen et al [78])*

2. Develop a data collection plan. First part of the LCI is done by data recollection. When collecting data of LCI, it is advisable to establish a plan taking into account this aspects:
    - Data normally used in LCIs , according to Weidema and Wesnaes [167], are:
        - Environmental data of the own investigated processes.
        - System data on the flow of raw materials, energy and products through the investigated process.
        - Performance data related to the definition of the functional unit used to compare different product systems.
    - The source of data is a very important point to assure good LCA results. So when choosing, transparency and reliability are main conditions to accomplish.
    - As the geographical factor has the greatest effect over the results of LCA, it is important to have data according each country construction industry and traditions (Khasreen et al [78]).
    - Application of software databases from outside the country of origin should be undertaken with caution.
3. Collect and distribution of the data. Data included in the data inventory, whether collected, measured or estimated, should be described well and thoroughly referenced (Khasreen et al [78]).

Once all data is gained and validated, is time to allocation (relating data of the functional unit considered). Materials, energy, and releases are divided and allocated by LCA procedures when (Owens [116])…

- …two or more products are produced in the same operation,
- …materials are recycled,
- …or when different materials use a common waste treatment operation.

It is important to remark that the wider the system boundaries are, the less the need for allocation is, and even in some cases there is no need for allocation. This especially comes when there are no multiple products and when the system boundaries are very wide (Khasreen et al [78]).

4. **Evaluate and report the results.** The last step is to refine the system boundaries. This step includes verification of data collected using benchmarks, so the initial system boundaries may be revised. Appliance of the sensitivity analysis may result in exclusion of life-cycle stages or unit processes shown to have no significance, exclusion of inputs or outputs which are not significant to the study, or inclusion of new unit processes inputs-outputs that are shown to be significantly important (Khasreen et al [78]). Then, the results of the refining process and sensitivity analysis should be documented.

CONCEPT	UNIT	PRE-FACTORY	CEMENT FACTORY	TOTAL
RAW MATERIALS	Kg/1000 kg	18	1491	1509
WATER	Kg/1000 kg	1467	226	1693
EMBODIED ENERGY	MJ/1000 kg	1502	3296	4798
GLOBAL WARMING	Kg CO_2 eq./1000 kg	118	781	899
ACIDIFICATION	Kg SO_2 eq./1000 kg	1.1	1.3	2.4
OZONE DEPLETION	Kg CFC-11 eq./1000 kg	0.0000043	0	0.0000043
PHOTOCHEMICAL OXIDANT FORMATION	Kg C_2H_4 eq./1000 kg	0.13	0.12	0.25
EUTROPHICATION	Kg PO_4 eq./1000 kg	0.05	0.20	0.25
NON HAZARDOUS WASTE	Kg/1000 kg	665	Not relevant	665
HAZARDOUS WASTE	Kg/1000 kg	1.2	Not relevant	1.2

***Table 15**: Example of EPD for Portland cement (TYPE I). (Source: own elaboration based on **CEMBERAU**)*

CONCEPT	UNIT	AVERAGE
ENERGY RESOURCES - GER.	MJ	2053,929
ENERGY RESOURCE - RENEW.	MJ	100,234
WATER USE	l	629,455
GREENHOUSE – GWP 100	Kg CO_2 eq.	237,026
OZONE LAYER DEPLETION – ODP	Kg CFC-11 eq. g	2,00 E-06
ACIDIFICATION – AP	Kg SO_2 eq.	4,450
PHOTOCHEMICAL OXIDANT	Kg C_2H_4 eq.	0,09
EUTROPHICATION POTENTIAL	Kg PO_4 eq.	0,09
SOLID WASTE	Kg waste	41,583
HAZARDOUS SOLID WASTE	Kg waste	0,271

***Table 16**: Example of EPD for an average concrete mix. (Source: own elaboration based on **BUZZIUNICEM**)*

Previously, some examples of Environmental Product Declarations (EDPs) have been offered for cement [Table 15] and concrete products [Table 16]. The practitioner is capable of deciding when performing its study, notwithstanding firstly establishing at the goal and scope step, if collecting data from different products/processes included on the system assessed by its own or making use of available databases. As an example of this last case, we have the LCA study performed by Lopez-Mesa et al [94] that, for the comparison of two concrete slabs typologies on the Spanish environment, made used of the Eco invent database included in the LCA software SimaPro (even it can be consulted annexed at the study).

One of the main improvements to achieve for accomplishing reliability on LCA studies results passes by enabling practitioners and third parties access to data included on LCIs. Relating to this, ISO published in 2002 the ISO/TS 14048:2002 "*Environmental management--Life cycle assessment--Data documentation format*" with the objective of provide the requirements and structure for a data documentation format, to be used for transparent and unambiguous documentation and exchange of Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) data (ISO [233]). As an example for data exchange, there is the (Trusty and Deru [152]):

"EcoSpold (ecoinvent database) is used for the exchange of Life Cycle Inventory data and Life Cycle Impact Assessment methods. It is based on XML (eXtended Markup Language) and related technologies (XSL,

XSLT, Schema), and the format is fully ISO/TS 14048 compliant. Data provided in the streamlined format (EcoSpold format) can be readily converted by NERL to the full EcoSpold format, which allows sharing with the Swiss project and any other national databases that adopt the same formatting. In addition, major LCA software suppliers support the EcoSpold format, which provides an easy way to import the U.S. LCI data"

5.2.2.3. LCA on concrete structures: Impact assessment.

Impact assessment is a multi-step process that starts by selecting and defining impact categories relevant to the study, and is followed by a classification step which assigns LCI results to impact categories. Then is characterization, phase that includes energy and mass aggregation of both resources and emissions across all system operations, followed by a latter combination of emissions from different stages and locations. As characterisation takes place after inventory is made, and works from the environmental interventions it states, inventories consequently should be defined consistently (Josa et al [74]).

IMPACT CATEGORY	UNIT	CO (kg)	CO_2 (kg)	CH_4 (kg)	SO_2 (kg)	NO_X (kg)	N_2O (kg)	NH_3 (kg)	PM_{10} (kg)	NMVOC (kg)
Global Warming Potential (GWP)										
GWP20	$kgCO_2$ eq.		1.00	72.00			289.00			
GWP100	$kgCO_2$ eq.		1.00	25.00			298.00			
GWP500	$kgCO_2$ eq.		1.00	7.60			153.00			
Terrestrial Acidification Potential (TAP)										
TAP20	$kgSO_2$ eq.				1.00	0.49				
TAP100	$kgCO_2$ eq.				1.00	0.52				
TAP500	$kgCO_2$ eq.				1.00	0.71				
Photochemical Oxidant Formation	kg NMVOC	0.046	0.081	0.10		1.00				1.00
Marine Eutrophication	kg N eq.					0.128		0.112		

***Table 17**: ReCiPe characterization factors. (Source: reproduced from Boulenger [16])*

In order to offer a quick view of how to perform an LCIA phase, a characterization example making use of EDIP methodology is included ahead. After collecting all the data relate to impacts from the inventory phase, this would be multiplied by each characterization factor and summed, according to the impact category considered.

These operations can be visualized ahead for the global warming potential for 20 and 100 years (3) (4), the terrestrial acidification potential for 20 and 100 years (5) (6), as well as the photochemical oxidant formation (7):

$$GWP20\ (kg\ CO_2\ eq.) = 1.00 \times CO_2 + 72.00 \times CH_4 + 289.00 \times N_2O \quad (3)$$

$$GWP100\ (kg\ CO_2\ eq.) = 1.00 \times CO_2 + 72.00 \times CH_4 + 289.00 \times N_2O \quad (4)$$

$$TAP20\ (kg\ SO_2\ eq.) = 1.00 \times SO_2 + 0.49 \times NO_x \quad (5)$$

$$TAP100\ (kg\ SO_2\ eq.) = 1.00 \times SO_2 + 0.52 \times NO_x \quad (6)$$

$$POF\ (kg\ NMVC) = 0.046 \times CO + 0.081 \times CO_2 + 0.01 \times CH_4 + 1.00 \times NO_x + 1.00 \times NMVOC \quad (7)$$

Nevertheless and already exposed previously at this work, this is just an example as there is a wide offer of different LCIA methodologies available for practicing impact assessment step. The selection of the methodology normally responds to arbitrary criteria, which do not usually coincidence with the scope of the LCA study (for example, comparison of construction procedures alternatives). According to the study "*International Reference Life Cycle Data System (ILCD): Working documents evaluation of LCIA methods for consultation*" by the Institute for Environment and Sustainability of the Joint Research Centre (European Commission), which include an analysis (based on scientific criteria) performed for different available LCIA methodologies, it can be said that the most competent methodology corresponds with the ReCiPe method (Bolulenger [16]).

IMPACT CATEGORY	EDIP 1997	EDIP 2003	EPS 2000d	CML 2002	IMPACT 2002+	ReCiPe midpoint
Acidification	-	E	-	B	-	B
Climate Change	-	-	C	-	-	A
Eutrophication	-	B	B-C	B-C	B-C	B
Ozone Depletion	-	D	-	-	-	B
Photochemical ozone	-	-	B-C	B-C	-	B
Resource Depletion	B	B	B	C	C	B

Table 18: *LCIA methodologies rating according JCR-European Commission study. (Source: reproduced from Boulenger [16])*

Therefore, it can be said that depending on the LCIA methodology selected, the results of the study will be different as not all of them consider the same impacts and with the same characterization factors. On this sense, within the literature of LCAs applied to whole buildings, the most commonly studied LCIA impacts were global warming, acidification, eutrophication, and ozone depletion [Table 19]. Nevertheless, depending on the study, LCIA impacts considered varies much, hindering comparison between different studies (Khasreen et al [78]).

IMPACT CATEGORY	ABBREVIATION	SCALE	LCI DATA CLASSIFICATION	CHARACTERIZATION FACTOR
Global Warming	GW	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCS) Hydro chlorofluorocarbons' (HCFCS) Methyl Bromide (CH_3B_r)	Global warming potential
Acidification	A	Regional Local	Sulphur Oxides (SO_X) Nitrogen Oxides (NO_X) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)	Acidification potential
Eutrophication	E	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates and Ammonia (NH_4)	Eutrophication Potential
Ozone Depletion	OD	Global	Chlorofluorocarbons (CFCS) Hydro chlorofluorocarbons (HCFCS) Halons and Methyl Bromide (CH_3B_r)	Ozone Depletion Potential

***Table 19**: Most common Impact Categories for Whole Process Construction (WHP). (Source: reproduced from Khasreen et al [78])*

As indicated in some papers, Klopfeer [83], efforts to accomplish a unified LCIA methodology should be taken. As an example, there is the methodology BRE uses for rating processes (Kashreen et al [78]):

> *"Considering 13 or more impact categories measured in different units, makes it insufficient to just add the impact results. It is necessary to first reduce them to a common scale, and then apply weighting factors to account for their relative importance. An example can be found on the BRE methodology, as the emissions of each impact category are normalized (comparing them to those emitted by the annual average of a European citizen), therefor producing a single dimensionless number for each category. Latter, this number is multiplied by a weighting factor (referred as valuation factor in ISO 14040) obtained by consulting a 10 member-panel of experts, and the numbers produced are totalled and scaled to 100. So, the environmental impacts are scored according to their perceived importance"*

Another consideration would be relating the selection of the software tools according the best adequacy to the study performed. As it was previously exposed at point when introducing the software available for LCA performance, there are different LCIA tools and, depending on the tool selected, results will suffer variation. As an example of the importance of the tool selected, and therefore the LCIA method included in the LCA study, we have (Dubreil [35]):

"Eco-indicator 95 continues to be used, even with factual errors in the report that need to be corrected and practitioners should be aware of appropriate data. According to the author of the Eco-indicator, in 95 editions were made rather crude modelling assumptions…as in 99 versions…although it has been changed to the electronic version"

Therefore, impact assessment step within the LCA study will be directly established by the selection of the LCIA method applied. Therefore, when doing so, the practitioner of an LCA on a concrete structure will have to follow next listed pointes:

1. Describe the LCIA method selected and the motivation for its selection.
2. Impact categories considered on the study, exposing if they are mid or end-point categories.
3. Characterization factors used in the study, when included on the LCA study, allows and eases its posterior reviewing by other practitioners. Therefore, it is advisable to include these factors at this step of the assessment.
4. Characterization of impacts registered at the inventory phase is later calculated basing on the factors and classification of the LCIA methodology selected. This calculation process is recommended to be included on the study.
5. As the mandatory steps of the LCIA for a process method are included on LCIA methods, further steps (normalization, aggrupation and weighting) are to be explained before performed.

5.2.2.4. LCA on concrete structures: data quality assessment.

Data quality in LCA already was a subject treated by SETAC in a workshop (Weidema and Wesnaes [167]). The quality of inventory data is much related to source of data used. But the source, accompanied with its acquisition method and verification procedures used, plays an important role in the reliability of the LCA study performed. Another important factor is completeness of data, which is related to statistical properties, and shows how representative the sample is, and whether the sample includes sufficient amount of data or not. Three indicators (temporal, graphical and technological) to relate the correlation between the data and the data quality goals should be as well used (Khasreen et al [78]).

Assessment of the quality of data used in the analysis is very important in LCA interpretation as higher quality lends more credibility to the results, increases the robustness of the findings and gives more confidence to the LCA practitioner to draw correct conclusions and eventually make defensible decisions using the results (Junnila et al

[75]). To use a formal data quality management, that improve the data collection strategy, includes use of data quality indicators (DQIs) life the exposed ahead (Weidema and Wesnaes [167]):

- Reliability. It is related to the source, acquisition methods and verification procedures during the process for obtaining the data.
- Completeness. It is related to the statistical properties of the data: representativeness of the samples, number of data or adequate period or fluctuations.
- Temporal correlation. Represents the time correlation between the year of study and the year of the obtained data.
- Geographical correlation. This illustrates the relation of the defined area of the study and the precedence of the obtained data. As an example, impacts due to production processes on developed and underdeveloped countries offer great differences.
- Technological correlation. Is concerned with the representativeness of the enterprises, processes or materials considered in the study. In some occasions, data used may need to be older or from other locations as the assessed system require these considerations.

SCORE INDICATOR	1 LOW	2 LOW-MEDIUM	3 MEDIUM	4 MEDIUM-HIGH	5 HIGH
Reliability	Non-qualified estimate	Qualified estimate	Non-verified data partly based on assumptions	Verified data partly based on assumptions or non-verified data based on measurements	Verified data based on measurements
Completeness	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representative data from an adequate number of sites but from shorter periods	Representative data from a smaller number of sites but for adequate periods	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations
Temporal correlation	Age of data unknown or more than 15 year of difference	Less than 15 years difference	Less than 10 years difference	Less than six years difference	Less than three years of difference to year of study
Geographical correlation	Data from unknown area or area with very different production conditions	Data from area with slightly similar production conditions	Data from area with similar production conditions	Average data from larger area in which the area under study is included	Data from area under study
Technological correlation	Data on related processes or materials but different technology	Data on related processes or materials but shame technology	Data from processes and materials under study but from different technology	Data from processes and materials under study but from different enterprises	Data from enterprises, processes and materials under study

Table 20: Data quality assessment matrix. (Source: reproduced from Khasreen et al [78])

As an example of practice of the previously introduced data quality assessment, we can consider the LCA study published in 2010 by Ge [46] (see table [Table 21]). In this study, for the assessment and comparison of steel and concrete structure for a residential building in China, the author made use (as indicated within the study) of data included on the “China Environment Year Book (2002)” and the National Bureau of Statistics of China (2002)”. First, reliability of the source is considered high, as it comes from the Chinese Government but, when focusing on its completeness, the study establishes that Yearbook just considers 45 economic sectors or the 122 existing in the country, therefore reducing its quality. When looking at the temporal correlation of data used, as the study and data used do not offer a longer period than 10 year, case data is considered to be performed with up-to-date data. Geographical correlation, on the contrary is directly well considered but technological correlation is not so, as data offers obsolescence and new technologies are considered to be developed at the moment of performing the study. Therefore, in a global evaluation of the data used at the study by Ge [46] is done, it can be concluded that offer a high grade of quality and therefore, reliability of the study is ensured on this sense.

SCORE INDICATOR	1 LOW	2 LOW-MEDIUM	3 MEDIUM	4 MEDIUM-HIGH	5 HIGH
Reliability					X
Completeness				X	
Temporal correlation				X	
Geographical correlation					X
Technological correlation				X	

***Table 21**: Example of a data quality assessment matrix. (Source: own elaboration based on Khasreen et al [78])*

When considering data and methods to be used, this should be site specific, depending on the geographic and temporal area related to the object of assessment (Rice et al [131]). Energy supply assumptions can cause significant differences in the embodied energy calculations, as different countries have different energy sources (Khasreen et al [78]). The ideal would be that all the LCA studies were applied as much as possible to local practices to be able to assess the input data of the inventories according to the local method of construction. On the other hand, but also of great importance, the regular up-dating of information and methods used must be considered. Also, it has been observed on various studies that ranges, minima, maxima or distribution are rarely available in life-cycle studies, and data uncertainty analysis is not widely practiced (López-Mesa et al [94]).

5.2.2.5. LCA on concretes structures: interpretation.

When offering the results obtained from the impact assessment step and the conclusions reached from the study, these are usually supported by the introduction of graphical representations. These representations vary depending on the information practitioners want to focus attention on and, for example, they can offer: comparison between different structure materials, impacts comparison coming from different phases or parts of the construction, etc…

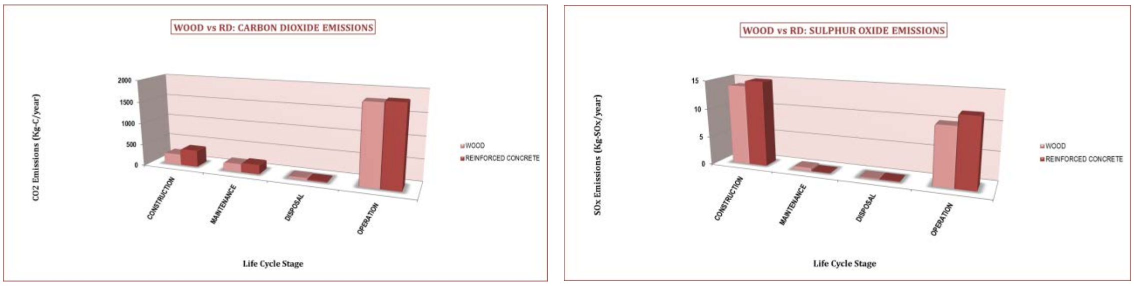


***Figure 32**: Example of an impact comparison of different materials and life cycle phases. (Source reproduced from Gerilla et al [47])*

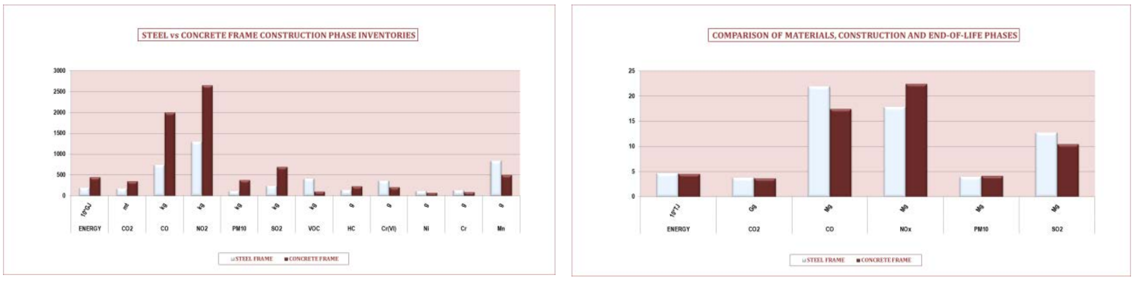


***Figure 33**: Example of impact's comparison between different materials. (Source: reproduced from Guggemos and Horvath [54])*

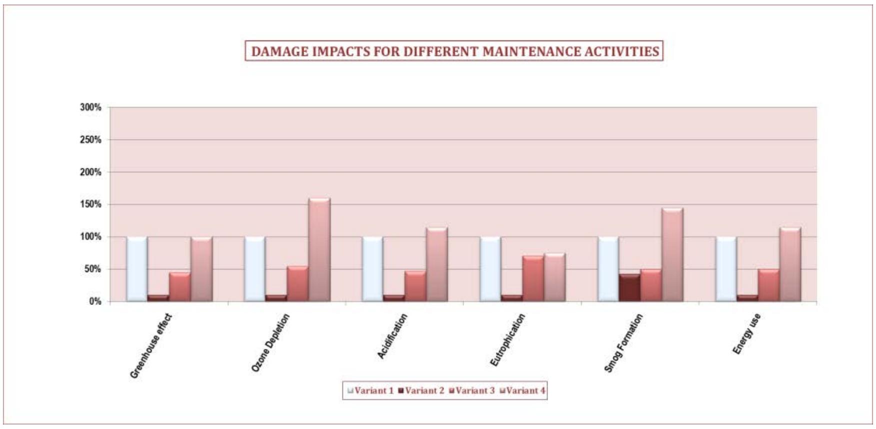


***Figure 34**: Example of impact's comparison for different alternatives. (Source: reproduced from Rosignoli et al [134])*

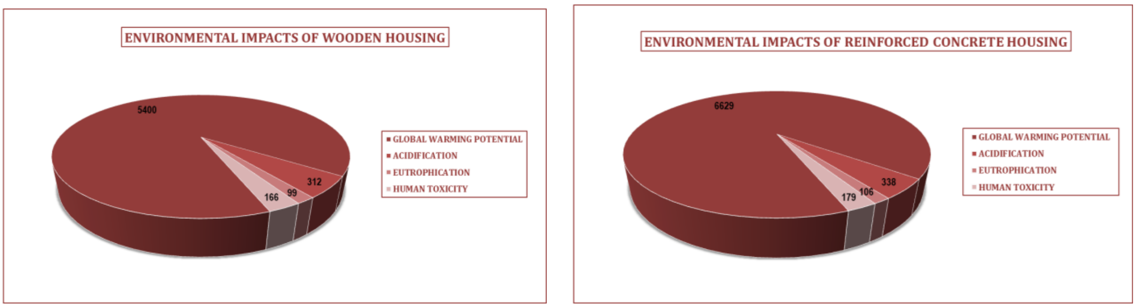


***Figure 35**: Example of impact's graphical representation of two frame materials. (Source: reproduced from Gerilla et al [47])*

Normally, this graphical information is usually and directly supplied by LCA software tools used on the practice of the study. Nevertheless, as indicated before, practitioners are the ones to expose the information on the way they consider more “convenient”. Examples of different representations can be observed on examples included before.

For the interpretation phase, to be able to compare different studies results, LCA would need a final weighting phase, step that has not yet been standardised. End-weighting has always been an issue of controversy (López-Mesa et al [94]). A good solution is to support the decisions by expressing the environmental impacts in monetary units. But the best option would be integrating LCA in a multi-criteria analysis, which can lead to selection of the best solution from the environmental point of view and based on an objective point of view. An example can be found on the study made by Sobotka and Rolak [146], which let to know the best environment friendly building selecting between different materials. Moreover, as indicated in ISO 14040, economic and social aspects/impacts are outside of LCA’s scope, nowadays just focused on the environmental impact of products or services. However, work on extension environmental life-cycle view of LCA to address economic and social aspects within sustainable development frame could bring great profits and develop a full integrated tool multiple uses.

Major goal is to develop a consistent sustainability assessment method based on LCA, LCC and social LCA. As an example of integration of LCCA and LCA models into a decision-making process is offered ahead (Gu et al [53]):

> *“A study was performed in a study to integrate both tools and use them as a decision making for a construction project. But a limitation keeps standing, as after analysing the project’s economic feasibility by LCCA and the energy and environmental impacts by LCA, decision-making methods or models (Analytic Hierarchy Process, Quality Model, Grey Theory, etc.) should be introduced so as to make the determination process be more objective, scientific and accurate”*

On his behalf, the socio-economic impact evaluation within LCA can be made by introducing social impacts of product life cycles, on health and other impact indicators. Addressing the social impacts in life cycle assessments would give the opportunity to develop and apply entirely new systems for publishing and using site-specific information in LCA (Norris [107]). Nevertheless this economic and social integration remains to be formalised, and the most important point is to find equal and consistent system boundaries for all the integrated methods (Hunkeler and Rebitzer [71], Klöppfer [83]).

5.3. LCA case study.

Previously at this work, an LCA's state-of-the-art analysis has been exposed, focusing on the tool and mainly on its concrete structures' practice, also taking special consideration to characteristics and problems existing within the methodology. Moreover, a guide for LCA application on concrete structures, based on the methodology established by ISO 14040 (ISO [227]), has been introduced to all that interested stakeholders of construction industry (designers, contractors, investors,…) aware of the necessity of improving environmental performance. Ahead, a case study will be exposed as an example for the practice of LCA on concrete structures, following the indications and tips included on the guide included at this work.

The case study will consist on the comparison of the environmental burden generated by two different types of concrete structures, within the Spanish construction context. To accomplish this aim, data used for the inventory phase will be obtained from two different sources: data included on the ARQUÍMEDES-ACV software and the BEDEC database (both already introduced formerly at this work). First, an exposition of the two concrete structures will be performed to then initiate their assessment following the guide. Once the assessment is performed and interpretation phase is finished, some conclusions will be extracted. Finally, after the performance of the environmental assessment using LCA, some of the issues encountered during the elaboration of the case study will be offered.

5.3.1. Case study: introduction.

A comparison of two types of residential building concrete structures will serve as example for the practical application of the guide previously exposed at this work. The case study has been extracted from the automatic job introduction module (Autopem) offered by the software CYPECAD [Figure 36], tool for the design and analysis of structures (concrete, reinforced concrete, steel, etc.).

The two alternatives considered and assessed at this case study, are both reinforced concrete structures (which have been named as A and B). The structures are considered to be constructed in Valencia (Spain) and consist of: one basement, a ground floor and four floors of 500 square metres. In the calculations, the two stairway slab structures and the elevator walls will be also included as part of the structure [Figure 37].

Main difference between both alternatives are found on their slabs, as Alternative A considers a one-way spanning slab and Alternative B includes a multi-way slab by using a mass reinforced concrete slab. On this sense, construction units necessary for one or another consequently differ, as Alternative A requires of 10 construction units and Alternative B increases it to a total number of 12 [Table 22]. It is to highlight that technical or economic performance of the structure's alternatives will remain out of the assessment, and just environmental considerations will be taken into account.

***Figure 36**: Structure basic information. (Source: CYPE's Autopem module snapshot)*

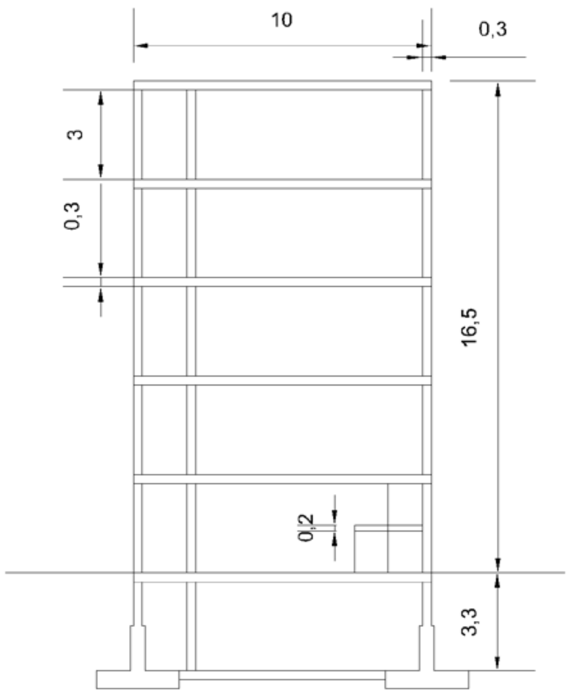


***Figure 37**: Cross section of the structure considered for the case study. (Source: own elaboration)*

CODE	UNIT	PART	CONSTRUCTION UNIT DESCRIPTION	ALTERNATIVE A (kg)	ALTERNATIVE B (kg)
CRL010	m²	Foundation	Blinding concrete surface cast-in-place (HL-150/B/20)	339.42	339.42
CCS010	m²	Foundation	Reinforced concrete basement wall cast in place (HA-25/B/20 and B-500-S)	85.20	85.20
CSZ010	m³	Foundation	Reinforced concrete pad foundations cast-in-place (HA-25/B/20 and B-500-S)	221.52	221.52
CSZ020	m²	Foundation	Modular steel frame formwork for concrete pad foundations	321.44	321.44
CAV010	m³	Foundation	Reinforced concrete foundation beam cast-in-place(HA-25/B/20 and B-500-S)	6.65	6.65
CAV020	m²	Foundation	Modular steel frame formwork for concrete foundation beam	33.26	33.26
CNE010	m³	Foundation	Reinforced concrete block for foundations cast-in-place (HA-25/B/20 and B-500-S)	3.96	3.96
EHE010	m²	Structure	Reinforced concrete stair slab cast-in-place (HA-25/B/20 and B-500-S)	44.83	44.83
EHU020	m²	Structure	Reinforced concrete one-way slab cast-in-place (HA-25/B/20 and B-500-S)	3,049.39	-
EHS010	m³	Structure	Reinforced concrete column cast-in-place (HA-25/B/20 and B-500-S)	-	73.17
EHV010	m³	Structure	Reinforced concrete beam cast-in-place (HA-25/B/20 and B-500-S)	-	90.68
EHL010	m²	Structure	Reinforced concrete slab cast-in-place (HA-25/B/20 and B-500-S)	-	3,049.38
EHN010	m³	Structure	Reinforced concrete elevator core cast-in-place (HA-25/B/20 and B-500-S)	114.07	114.07

***Table 22**: Construction unit's description for each alternative of the case study. (Source: own elaboration)*

Once the different alternatives, and its construction units, considered and compared at this case study have been introduced, an exposition of the material's quantities required by each alternative will be offered ahead. First, as the concrete is reinforced, the steel demands are established by each construction unit and alternative. As it can be observed [Table 23], Alternative B offers a higher demand of steel or, more accurately, a higher demand close to 59.62 %. When looking at the concrete demand [Table 24], same differences (although lower) happen as when measuring steel: Alternative B requires a higher demand of concrete (35.60%). Finally, for the amount of wood necessary for the form-work during concrete placement operations, the steel and concrete's trend difference for both alternative indicated previously keeps and it is observed that Alternative B demand a 8,55% more of wood than Alternative A [Table 25].

MATERIAL	CODE	RELATION	ALTERNATIVE A (kg)	ALTERNATIVE B (kg)
STEEL	CCS010	71.10 Kg/m³	6,057.72	6,057.72
	CSZ010	62.27 Kg/m³	13,793.99	13,793.99
	CAV010	82.24 Kg/m³	547.14	547.14
	CNE010	95.00 Kg/m³	376.20	376.20
	EHE010	30.00 Kg/m³	1,344.90	1,344.90
	EHU020	18.60 Kg/m³	56,718.65	-
	EHS010	3.57 Kg/m³	-	261.22
	EHV010	232.50 Kg/m³	-	21,083.10
	EHL010	27.10 Kg/m³	-	82,638.20
	EHN010	3.83 Kg/m³	436.89	436.89
		TOTAL:	79,275.49	126,539.35

Table 23*: Steel measures in each alternative of the case study. (Source: own elaboration)*

MATERIAL	CODE	RELATION	ALTERNATIVE A (m³)	ALTERNATIVE B (m³)
HL-150/B/20	CRL010	0.105 m³/m²	35.64	35.64
HA-25/B/20/IIA	CCS010	1.05 m³/m³	89.46	89.46
	CSZ010	1.10 Kg/m³	243.67	243.67
	CAV010	1.05 Kg/m³	6.96	6.96
	CNE010	1.05 Kg/m³	4.16	4.16
	EHE010	0.33 Kg/m³	14.79	14.79
	EHU020	0.17 Kg/m³	527.55	-
	EHS010	1.00 Kg/m³	-	73.17
	EHV010	1.00 Kg/m³	-	90.68
	EHL010	0.30 Kg/m³	-	914.81
	EHN010	1.05 Kg/m³	119.77	119.77
		TOTAL:	1,042.03	1,593.15

Table 24*: Concrete measures in each alternative of the case study. (Source: own elaboration)*

MATERIAL	CODE	RELATION	ALTERNATIVE A (m^2)	ALTERNATIVE B (m^2)
WOOD	EHE010	0.90 m^3/m^2	40.34	40.34
	EHU010	1.10 m^3/m^2	3,354.33	-
	EHV010	3.50 m^3/m^2	-	317.38
	EHL010	1.10 m^3/m^2	-	3,354.32
		TOTAL:	3,394.68	3,712.04

***Table 25**: Wood form-work measures in each alternative of the case study. (Source: own elaboration)*

As during construction phase of the structure different taskforce will require of both man's labour and machinery, the energy consumptions and emission related to this activities must be included as part of the system boundary latter considered. The hours of engine used for the construction phase of the structure are introduced next:

CODE	RELATION	ALTERNATIVE A (h)	ALTERNATIVE B (h)
CRL010	0.057 h/m^2	19.35	19.35
CCS010	0.312 h/m^3	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^3	1,506.40	-
EHS010	0.212 h/m^3	-	15.51
EHV010	0.193 h/m^3	-	17.50
EHL010	0.478 h/m^2	-	1,457.61
EHN010	0.349 h/m^3	39.81	39.81
	TOTAL:	1,777.43	1,761.65

***Table 26**: Construction time required by each structure unit in each alternative of the case study. (Source: own elaboration)*

5.3.2. Case study: goal and scope.

As it was established previously at this work, this if the first step of the assessment where all previous considerations to take into account in the study are exposed. As a detailed way for performing the goal and scope was exposed in the guide, this will be followed ahead. Nevertheless, as some information has already been exposed at the introduction of the case study, some points will be overpassed in order to avoid information repetition.

4. The life cycle assessment performed ahead will take as functional unit the whole structure so, on this way, problems related to wrong allocation processes will be erased from the study.
5. When considering its system boundary, the life cycle will finish at the concrete structure construction, and will decline considering operational/management and end-of-life phases.
6. For the performance of the assessment, two different databases will be used. As indicated previously, there will be data from the ARQUÍMEDES-ACV software and the offered by the BEDEC database. As limitations within this two are not avoided, some further explanation and description of limitations and assumptions will be offered ahead.
7. For the assessment of data quality, the data quality indicators system (Khasreen et al [78]) included on the guide will be used on the inventory step included ahead.
8. As indicated in point 5, life cycle considered at the assessment will reach till the construction phase of both structures. This limitation directly comes due to other life cycle phase's related data is not supplied by sources considered at the study. Therefore, to reduce the amount of assumptions on the study, the assessment scope suffered this limitation.

   Moreover, same situation happens with impacts considered in the study, as the data sources supply information related to energy consumption and CO_2 emissions to the atmosphere.
9. No sensitive analysis is considered at the study, as the scope of the case study is to offer a general view of LCA methodology practice.
10. As the case study has been performed using conventional method (established by ISO 14040) and the methodology suffers from its own limitations, therefore limitation will be expected to be translated to the results provided by the study.

As it has been considered of great importance for reliability and latter comparison of the study, a more accurate exposition of limitations and assumptions within the study is offered ahead. As the limitations and assumption have been directly related to the databases used, ahead we pass to introduce the data source more extensively.

5.3.2.1. ARQUÍMEDES-ACV: limitations and assumptions.

Data supplied by ARQUÍMEDES-ACV software just considers next life cycle phases: material production, transportation to construction site and product's installation processes. These phases are defined ahead as the different sources used for basing the calculations offered by the software:

- Product production phase. Includes the raw material extraction, its transportation to the production plant, manufacturing and packaging processes and all the internal movements required. All this information is based on the weights of all the materials needful for the construction of the designed structure. The sources consulted for reaching the values are:
    - Guía de la Edificación Sostenible. Ministerio de Fomento, Instituto para la Diversificación y Ahorro de la Energía (IDEA) y el Instituto Cerdá.
    - Informe MIES (Modelo de Investigación de Edificación Sostenible, Universidad Politécnica de Cataluña).
    - Inventory of Carbon & Energy (ICE). Universidad de Bath, UK.
    - Environmental Product Declarations (EPDs).
- Transportation. This phase includes the transportation of the product from the manufacturing plant to the construction site, including all the internal moves necessary for the distribution process. Transportation is considered to be performed using diesel engine trucks with an average load capacity and fuel consumption (according to the load and distances travelled). There are four different supply scenarios considered (local, regional, national and importation) and, depending on the product, one of them is selected. The sources consulted for reaching the values are:
    - Estudio del análisis del ciclo de vida de la madera como material alternativo del Gobierno Vasco.
    - Análisis técnico, económico y medioambiental de los potenciales sustitutos de los hidrocarburos en el mercado español de los combustibles para automoción. Tesis doctoral de Fernando Hernández Sobrino (Ingeniero Industrial de la Universidad Politécnica de Madrid) (2010).
    - Datos estadísticos aportados por agencias de transporte, en cuanto al consumo medio de gasóleo, en función de la carga a transportar y la distancia.
    - Environmental Product Declarations (EPDs).
- Product on-site placement/installation. This phase includes all the machinery, auxiliary resources and waste transportation to landfill necessary for placing and installing the supplied products to the construction site. The machinery is calculated by their fuel consumption, according to the power horse force and land topography. The auxiliary resources are calculated by the internal moves (horizontal or vertical) generated within the construction site and energy consumption due to illumination requirements. Finally, for the waste transportation to landfill, the criteria used in for transportation phase is maintained but, in this case, considering a fix travelled distance of 50 km. The sources consulted for reaching the values are:

- Estudio del análisis del ciclo de vida de la madera como material alternativo del Gobierno Vasco.
- Análisis técnico, económico y medioambiental de los potenciales sustitutos de los hidrocarburos en el mercado español de los combustibles para automoción. Tesis doctoral de Fernando Hernández Sobrino (Ingeniero Industrial de la Universidad Politécnica de Madrid) (2010).
- Environmental Product Declarations (EPDs).

On the other hand, when taking a look on the environmental impacts indicators considered, the software includes another limitation as these are reduced to the amount of energy and CO_2 emissions produced during the life cycle phases mentioned before.

5.3.2.2. BEDEC: limitations and assumptions.

The BEDEC database, as previously exposed in this work, gives information relating to energy consumptions, CO_2 emissions and wastes generated for different construction elements (mainly materials and machinery). Therefore, the database is able to provide data to all related life cycle phases of a concrete structure, but all of them based on the considerations and assumptions established by the practitioner (as the construction units have to be previously formed by aggregation of materials and machinery). Therefore, with the objective of not affecting the reliability of the study and allowing comparison with the results obtained from the ARQUÍMEDES-ACV, the data use will serve for the life cycle till the construction phase of both assessed structures (ITEC [236]). Ahead, data from the BEDEC database will be compared to that from the ARQUÍMEDES-ACV:

- Product production phase. Includes the raw material extraction, its transportation to the production plant and the general manufacturing process but internal movements required are out of the scope. As the ARQUÍMEDES-ACV, all the information is based on the weights of materials needful for the construction of the designed structure.
- Transportation. This phase is supposed to include the transportation of the product from the manufacturing plant to the construction site; nevertheless this is not included on the BEDEC database.
- Product on-site placement/installation. On the ARQUÍMEDES-ACV this phase includes all the machinery, auxiliary resources and waste transportation to landfill due to placing and installing the supplied products to the construction site. On the BEDEC database this phase impacts are just supplied by the fuel consumptions of the machinery required for each construction unit. On this sense, and as it happened for the transportation, the waste transportation to landfill is not considered and requires of the assumptions of the practitioner to be included on the study.

For the development of the data included on the database, different collaborations where established with organizations such as "Institut Català d'Energia" (ICAEN) or the "Centre tecnològic de la Construcció" (imat). In order to supply data gaps, other databases were consulted (mainly Ecoinvent 1.3) and EPDs as environmental information supplied from manufacturers was included. Furthermore, in order to contrast or test the validity of the data included in BEDEC, a review was performed by consulting databases such as: Inventory of Carbon and Energy (ICE), Construction Industry Research and Information Association (CIRIA), Institute of Environmental Sciences (CML) or Instituto de Diversificación y Ahorro Energético (IDAE).

Therefore, according to all previously exposed information, assumptions will have to be introduced in the study in order to supply gap of transportation activities and aggregation of construction elements in each construction unit. These assumptions are exposed and grouped at next table:

CODE	MATERIALS	TRANSPORTATION	ON-SITE CONSTRUCTION	WASTE TRANSPORTATION	OTHER
CRL010	Blinding concrete (HL-150/B/20)	Concrete mixer truck ($6m^3$ capacity)	Concrete mixer truck ($6m^3$ capacity)	Load truck (7 tonnes capacity)	25 Km (for supplying materials and products) 50 Km (waste transportation to landfill or disposal) 60 km/h (average speed for concrete mixer) 80 km/h(average speed for crane truck)
CCS010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD)	Crane truck (5 tonnes capacity) Concrete mixer truck ($6m^3$ capacity)	Steel formwork panel (150 uses) Concrete mixer truck ($6m^3$ capacity) Concrete vibrator	Load truck (7 tonnes capacity)	
CSZ010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD)	Crane truck (5 tonnes capacity) Concrete mixer truck ($6m^3$ capacity)	Concrete mixer truck ($6m^3$ capacity) Concrete vibrator	Load truck (7 tonnes capacity)	
CSZ020	Steel rods (B500SD) Galvanized steel wire	Crane truck (5 tonnes capacity)	Steel formwork panel (150 uses) Electric welding equipment	Load truck (7 tonnes capacity)	
CAV010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD)	Crane truck (5 tonnes capacity) Concrete mixer truck ($6m^3$ capacity)	Concrete mixer truck ($6m^3$ capacity) Concrete vibrator	Load truck (7 tonnes capacity)	
CAV020	Steel rods (B500SD) Galvanized steel wire	Crane truck (5 tonnes capacity)	Steel formwork panel (150 uses) Electric welding equipment	Load truck (7 tonnes capacity)	
CNE010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD)	Crane truck (5 tonnes capacity) Concrete mixer truck ($6m^3$ capacity)	Steel formwork panel (150 uses) Concrete mixer truck ($6m^3$ capacity) Concrete vibrator Electric welding equip.	Load truck (7 tonnes capacity)	

CODE	MATERIALS	TRANSPORTATION	ON-SITE CONSTRUCTION	WASTE TRANSPORTATION	OTHER
EHE010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD) Wood formwork panel (2 uses)	Crane truck (5 tonnes capacity) Concrete mixer truck (6m³ capacity)	Concrete mixer truck (6m³ capacity) Concrete vibrator Electric welding equipment	Load truck (7 tonnes capacity)	
EHU020	One-way slab (concrete semi-beams with cement moulds) Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD) Wood formwork panel (2 uses)	Crane truck (5 tonnes capacity) Concrete mixer truck (6m³ capacity)	Steel formwork panel (150 uses) Concrete mixer truck (6m³ capacity) Concrete vibrator Electric welding equipment	Load truck (7 tonnes capacity)	
EHS010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD)	Crane truck (5 tonnes capacity) Concrete mixer truck (6m³ capacity)	Steel formwork panel (150 uses) Concrete mixer truck (6m³ capacity) Concrete vibrator Electric welding equipment	Load truck (7 tonnes capacity)	
EHV010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD) Wood formwork panel (2 uses)	Crane truck (5 tonnes capacity) Concrete mixer truck (6m³ capacity)	Concrete mixer truck (6m³ capacity) Concrete vibrator Electric welding equipment	Load truck (7 tonnes capacity)	
EHL010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD) Wood formwork panel (2 uses)	Crane truck (5 tonnes capacity) Concrete mixer truck (6m³ capacity)	Concrete mixer truck (6m³ capacity) Concrete vibrator Electric welding equipment	Load truck (7 tonnes capacity)	
EHN010	Structural concrete (HA-25/B/20/IIa) Steel rods (B500SD)	Crane truck (5 tonnes capacity) Concrete mixer truck (6m³ capacity)	Concrete mixer truck (6m³ capacity) Concrete vibrator Electric welding equipment	Load truck (7 tonnes capacity)	

***Table 27**: Construction unit's composition according to BEDEC database construction elements. (Source: own elaboration)*

5.3.3. Case study: Impact inventory.

After establishing all the initial considerations of the LCA study at the goal and scope, next step of the methodology is to establish the system boundary. The graphical representation of the system boundary proposed ahead for the case study includes both alternatives considered, as take into consideration a general view of the limited life cycle considered at the study. As it can be observed, there are the inputs (energy and materials) to the system and the outputs (CO2 emissions and wastes generated). For the life cycle, it is considered from the raw material extraction to the waste transportation to disposal facilities, passing by the on-site installation or placing of the three main materials considered at the study: concrete, steel (reinforcement) and wood (form-work).

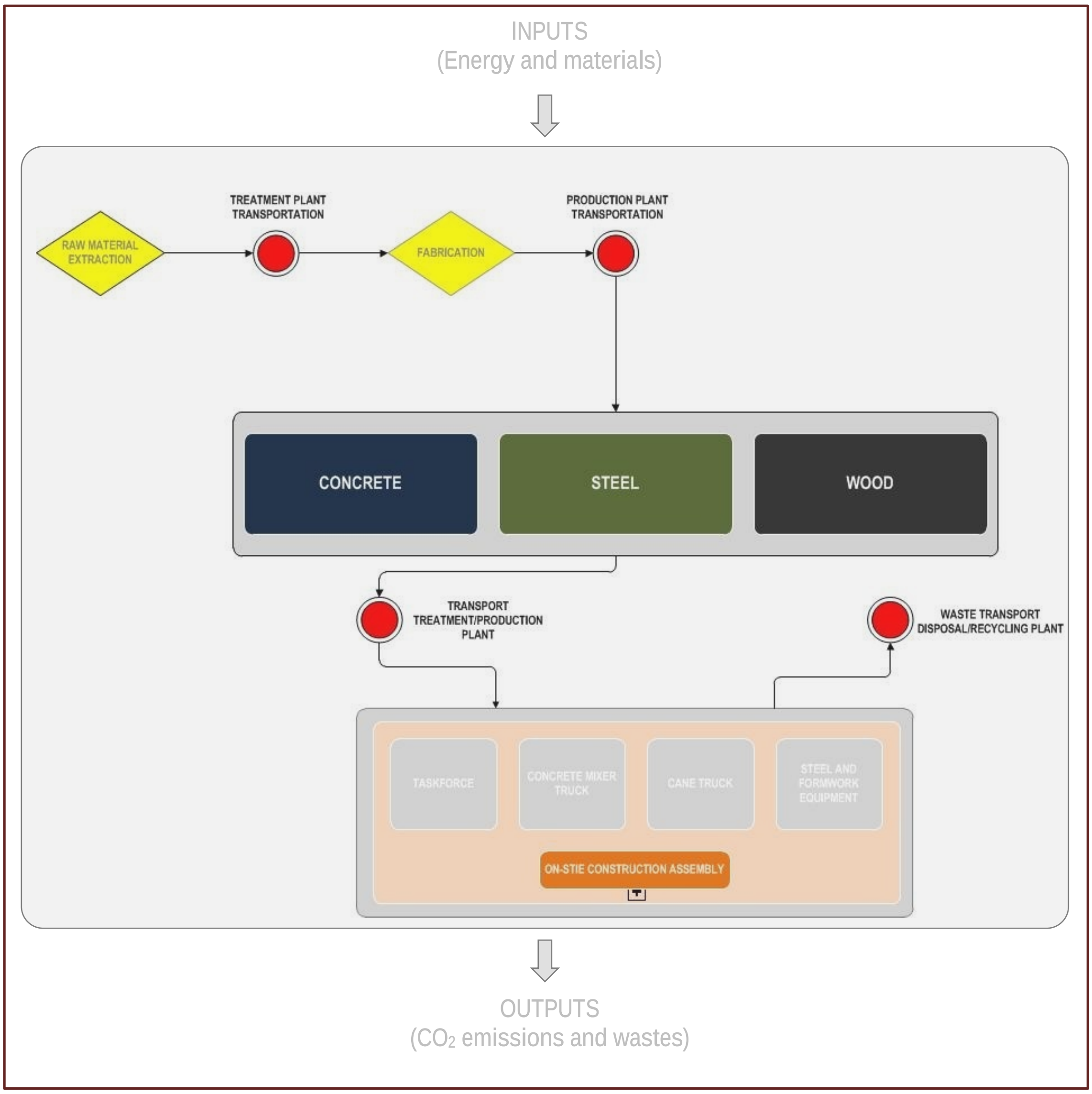


***Figure 38**: System boundary considered for the assessment of both structure alternatives. (Source: own elaboration)*

Once the system boundary is established, it is time for assigning to each construction unit their related impacts (which in this case corresponds to energy consumption and CO_2 emissions). In order to reduce the calculation process performed during the study, and allowing future review or reproduction at the same time, data extracted from each database and used on the assessment will be annexed at the end of this work ([Table 36] and [Table 37]) and just the results reached will be exposed ahead (from table [Table 28] to [Table 31]).

CONSTRUCTION UNIT	ALTERNATIVE A			ALTERNATIVE B		
	MANUFACTURING	CONSTRUCTION		MANUFACTURING	CONSTRUCTION	
	A1-A2A-A3	A4	A5	A1-A2A-A3	A4	A5
CRL010	85.248,73	1.455,77	42,77	85.248,73	1.455,77	42,77
CCS010	448.257,82	5.726,46	141,01	448.257,82	5.726,46	141,01
CSZ010	1.065.673,64	14.607,85	299,05	1.065.673,64	14.607,85	299,05
CSZ020	13.452,26	31,18	33,11	13.452,26	31,18	33,11
CAV010	35.859,67	469,96	8,60	35.859,67	469,96	8,60
CAV020	1.391,93	3,23	3,29	1.391,93	3,23	3,29
CNE010	23.822,57	297,68	6,25	23.822,57	297,68	6,25
EHE010	83.127,51	1.057,54	34,92	83.127,51	1.057,54	34,92
EHU020	4.072.063,92	62.966,85	4.070,94	-	-	-
EHS010	-	-	-	220.588,77	3.123,06	129,36
EHV010	-	-	-	957.755,46	10.838,96	170,83
EHL010	-	-	-	5.093.159,86	65.342,11	1.655,81
EHN010	331.569,78	5.077,60	174,87	331.569,78	5.077,60	174,87

***Table 28**: Energy consumption (MJ) for each alternative according to ARQUÍMEDES-ACV. (Source: own elaboration)*

CONSTRUCTION UNIT	ALTERNATIVE A			ALTERNATIVE B		
	MANUFACTURING	CONSTRUCTION		MANUFACTURING	CONSTRUCTION	
	A1-A2A-A3	A4	A5	A1-A2A-A3	A4	A5
CRL010	8.013,37	107,60	3,73	8.013,37	107,60	3,73
CCS010	38.856,40	423,78	11,25	38.856,40	423,78	11,25
CSZ010	93.413,90	1.081,01	24,37	93.413,90	1.081,01	24,37
CSZ020	1.071,04	2,25	3,54	1.071,04	2,25	3,54
CAV010	3.102,71	34,78	0,68	3.102,71	34,78	0,68
CAV020	110,82	0,23	0,37	110,82	0,23	0,37
CNE010	2.045,05	22,03	0,49	2.045,05	22,03	0,49
EHE010	7.111,34	78,27	3,23	7.111,34	78,27	3,23
EHU020	355.961,39	4.659,47	335,43	-	-	-
EHS010	-	-	-	20.097,29	231,13	10,39
EHV010	-	-	-	79.590,95	802,12	13,60
EHL010	-	-	-	437.805,59	4.836,32	155,52
EHN010	30.536,54	375,75	14,26	30.536,54	375,75	14,26

***Table 29**: CO2 emissions (kg) for each alternative according to ARQUÍMEDES-ACV. (Source: own elaboration)*

CONSTRUCTION UNIT	ALTERNATIVE A			ALTERNATIVE B		
	MANUFACTURING	CONSTRUCTION		MANUFACTURING	CONSTRUCTION	
	A1-A2A-A3	A4	A5	A1-A2A-A3	A4	A5
CRL010	32.317,18	2.349,83	14.699,50	32.317,18	2.349,83	14.699,50
CCS010	354.510,00	6.497,59	10.735,52	354.510,00	6.497,59	10.735,52
CSZ010	870.909,92	17.430,51	25.332,55	870.909,92	17.430,51	25.332,55
CSZ020	2.357,92	4,77	9.525,04	2.357,92	4,77	9.525,04
CAV010	30.276,11	514,71	153,47	30.276,11	514,71	153,47
CAV020	1.233,46	3,45	1,94	1.233,46	3,45	1,94
CNE010	19.789,49	311,36	173,75	19.789,49	311,36	173,75
EHE010	72.710,62	1.570,28	6.439,35	72.710,62	1.570,28	6.439,35
EHU020	6.394.963,68	222.847,68	345.419,59	-	-	-
EHS010	-	-	-	125.686,27	4.984,99	3.579,75
EHV010	-	-	-	901.446,39	9.633,09	4.025,97
EHL010	-	-	-	4.551.702,80	147.024,20	333.901,51
EHN010	206.055,53	7.940,36	9.174,56	206.055,53	7.940,36	9.174,56

***Table 30**: Energy consumption (MJ) for each alternative according to BEDEC database. (Source: own elaboration)*

CONSTRUCTION UNIT	ALTERNATIVE A			ALTERNATIVE B		
	MANUFACTURING	CONSTRUCTION		MANUFACTURING	CONSTRUCTION	
	A1-A2A-A3	A4	A5	A1-A2A-A3	A4	A5
CRL010	8.977,13	652,74	4.083,26	8.977,13	652,74	4.083,26
CCS010	98.461,59	1.804,91	2.982,10	98.461,59	1.804,91	2.982,10
CSZ010	241.888,90	4.841,88	7.036,88	241.888,90	4.841,88	7.036,88
CSZ020	654,93	1,32	2.645,84	654,93	1,32	2.645,84
CAV010	8.408,82	142,98	42,63	8.408,82	142,98	42,63
CAV020	342,56	0,96	0,54	342,56	0,96	0,54
CNE010	5.496,25	86,49	48,26	5.496,25	86,49	48,26
EHE010	20.194,39	436,20	1.788,72	20.194,39	436,20	1.788,72
EHU020	1.776.254,73	61.903,05	95.950,57	-	-	-
EHS010	-	-	-	34.912,31	1.384,74	990,45
EHV010	-	-	-	250.354,80	2.675,90	1.118,33
EHL010	-	-	-	1.264.176,89	40.840,66	92.751,08
EHN010	57.236,74	2.205,69	2.548,49	57.236,74	2.205,69	2.548,49

***Table 31**: CO2 emissions (kg) for each alternative according to BEDEC database. (Source: own elaboration)*

As it can be observed, results have been divided for each construction unit required for the execution of each alternative structure. Moreover, for each one of them, the energy and CO_2 emissions have been divided by the different life cycle phases considered in the study: product's manufacturing (A1-A2-A3), transportation (A4) and on-site construction or installation of the products (A5).

As it was exposed on the guide, an analysis of data quality is necessary in order to increase LCA results' reliability. On this way, a methodology based on subjective data quality indicators or DQI's was introduced on the guide (Khasreen et al [78]). Therefore, an analysis of data introduced on this case study will be performed for both data sources considered: ARQUÍMEDES-ACV and BEDEC.

SCORE INDICATOR	1 LOW	2 LOW-MEDIUM	3 MEDIUM	4 MEDIUM-HIGH	5 HIGH
Reliability				X	
Completeness		X			
Temporal correlation				X	
Geographical correlation					X
Technological correlation				X	

***Table 32**: Data quality assessment matrix for ARQUÍMDES-ACV. (Source: own elaboration)*

SCORE INDICATOR	1 LOW	2 LOW-MEDIUM	3 MEDIUM	4 MEDIUM-HIGH	5 HIGH
Reliability				X	
Completeness		X			
Temporal correlation				X	
Geographical correlation				X	
Technological correlation				X	

***Table 33**: Data quality assessment matrix for BEDEC. (Source: own elaboration)*

After the analysis, it is concluded that both databases offer almost the same quality. This is due to that both use very similar sources, such as the "Inventory of Carbon & Energy" (ICE) and the sustainable building guide published by "Instituto para la Diversificación y Ahorro de la Energía" (IDAE). Nevertheless, it is to point that Arquímedes-ACV incorporates a bigger number or Spanish data sources, therefore its geographical correlation is considered to be better than that offered by BEDEC.

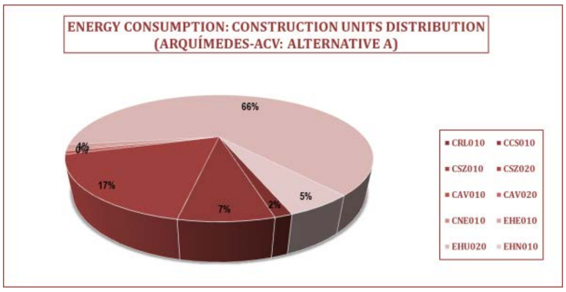
5.3.4. Case study: interpretation.

Once energy consumption and CO_2 emissions were calculated, according to data from the two databases considered in the study, a graphical analysis of the results obtained was performed. This analysis, with the results and impressions that were reached, will be exposed ahead.

First comparison was made on each construction unit environmental contribution to the whole energy consumption and CO_2 emissions to the atmosphere. When compared, both for ARQUÍMEDES-ACV and BEDEC data sources, the most relevant construction unit contribution was made by the EHU020 and EHL010, for alternative A and B respectively. This situation can be explained by the percentage present in each alternative and for the reinforcement needs of both construction units. But, although the general results obtained were the same, it can be observed that representativeness of EHU020 on Alternative A passes from 66%, considering data from ARQUÍMEDES-ACV, to an 80% when using the BEDEC database. On the same way, although with a lower difference, for the construction unit EHL010 on Alternative B it passes from 61%, considering data from ARQUÍMEDES-ACV, to 65% when using the BEDEC database. This observed behaviour is the same for both energy consumptions and CO2 emissions calculated, as it is displayed at the table ahead:

	ENERGY CONSUMPTION (MJ)		CO_2 EMISSIONS (kg)	
	ARQUÍMEDES-ACV	BEDEC	ARQUÍMEDES-ACV	BEDEC
ALTERNATIVE A	EHU020 (66%)	EHU020 (80%)	EHU020 (66%)	EHU020 (80%)
ALTERNATIVE B	EHL010 (61%)	EHL010 (65%)	EHL010 (61%)	EHL010 (65%)

***Table 34**: Summarise of construction units' behaviour between data sources. (Source: own elaboration)*



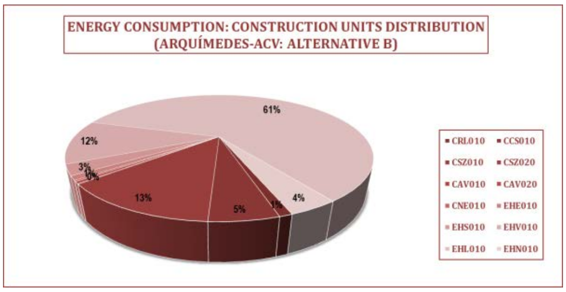


***Chart 31**: Distribution of energy consumption by each construction unit for alternatives A and B (ARQUÍMEDES-ACV). (Source: own elaboration)*

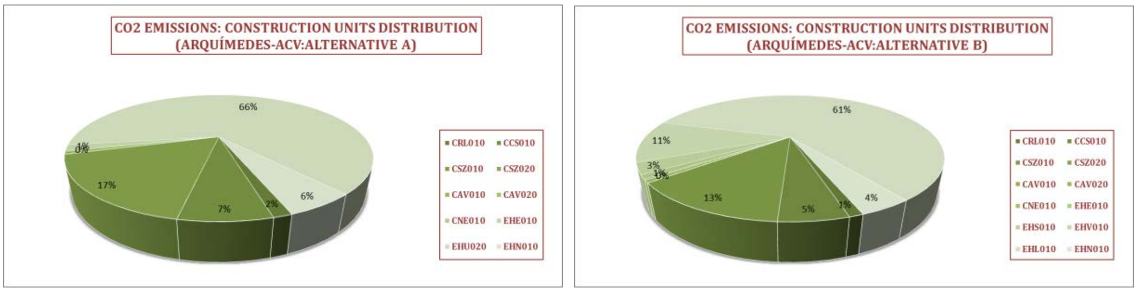


***Chart 32**: Distribution of CO2 emissions by each construction unit for alternatives A and B (ARQUÍMEDES-ACV). (Source: own elaboration)*

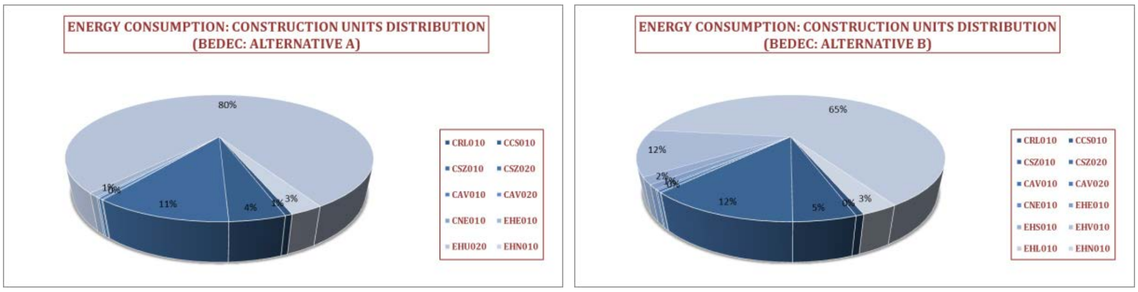


***Chart 33**: Distribution of energy consumption by each construction unit for alternatives A and B (BEDEC). (Source: own elaboration)*

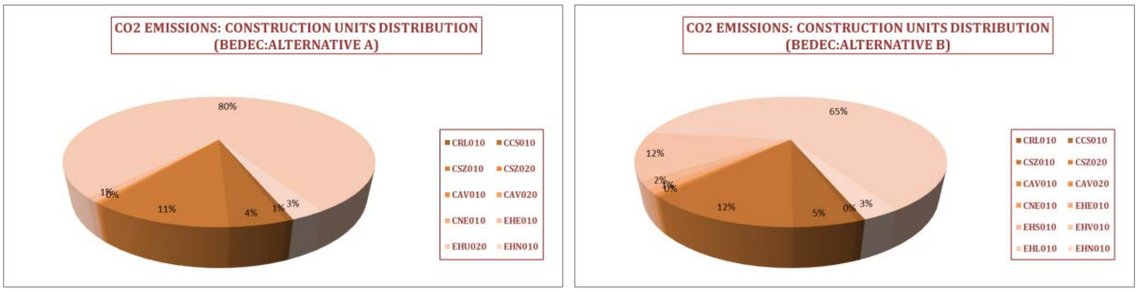


***Chart 34**: Distribution of CO2 emissions by each construction unit for alternatives A and B (BEDEC). (Source: own elaboration)*

Then a comparison of the energy consumptions and CO_2 emissions produced within each life cycle phase was performed. This analysis allowed reaching the conclusion that for the construction of the reinforced concrete structure, independently of the alternative selected or the database used, the environmental burden of materials and products supplied are the items which most increase the burden of the structure. On the other hand, when looking and comparing alternatives A and B from the results obtained when using data of ARQUÍMEDES-ACV and BEDEC, it is observed that results behave the other way round. This means with data provided by ARQUÍMEDES-ACV, Alternative A offers lower energy consumptions and CO_2 emission than alternative B [Chart 35], but when looking at BEDEC this changes the other way round, and alternative A offers worse result than B.

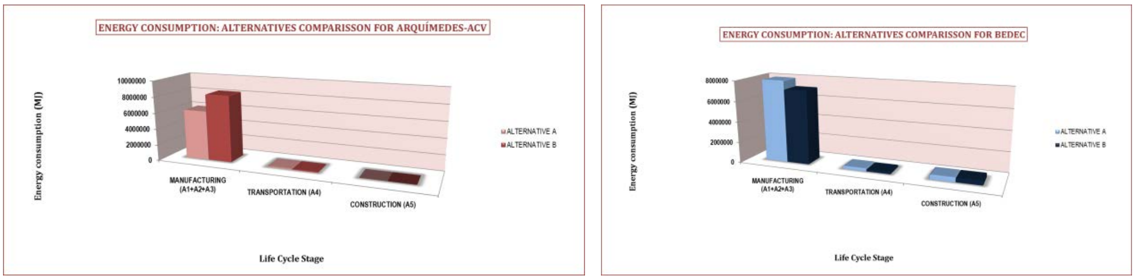


***Chart 35**: Distribution of energy consumption by each phase of the life cycle for alternatives A and B. (Source: own elaboration)*

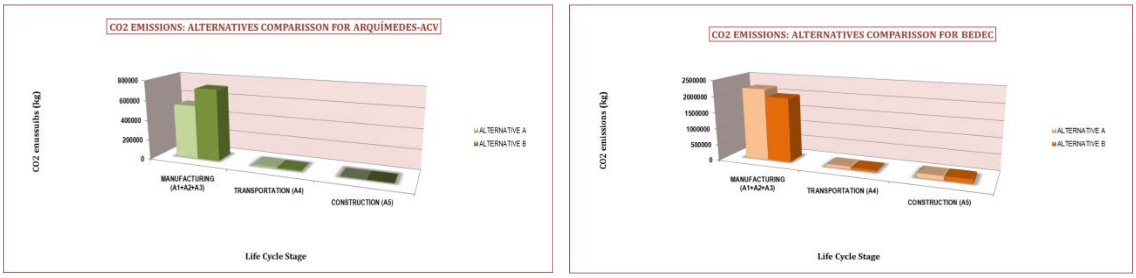


***Chart 36**: Distribution of CO2 emissions by each phase of the life cycle for alternatives A and B. (Source: own elaboration)*

Finally, in order to analyse more accurately differences observed within each data source considered on the study, a comparison of the life cycle results was performed. The analysis allowed observing that BEDEC database increases the results of Alternative A and decreases that of Alternative B, therefore giving a completely different result than that given by ARQUÍMEDES-ACV. Therefore, selection of Alternative A or Alternative B is no clearly established by the analysis performed, as the results have come to be completely contrary on both impacts considered: energy consumption and CO_2 emissions.

	ENERGY CONSUMPTION (MJ)		CO_2 EMISSIONS (kg)	
	ARQUÍMEDES-ACV	BEDEC	ARQUÍMEDES-ACV	BEDEC
ALTERNATIVE A	6,256,976.75	8,666,249.73	547,405.06	2,407,119.55
ALTERNATIVE B	8,470,639.26	7,785,003.72	729,991.67	2,162,216.37

***Table 35**: Summarise of alternatives behaviour between data sources. (Source: own elaboration)*

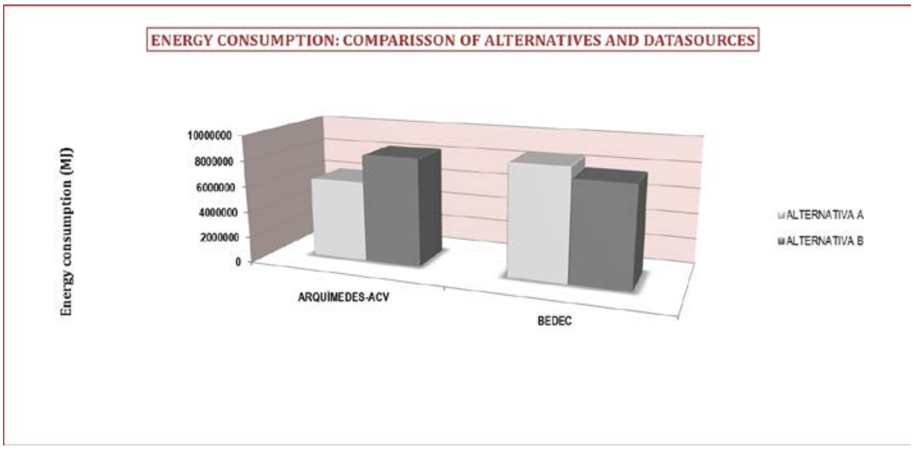


Chart 37: *Comparison of alternatives and data sources results on energy consumption. (Source: own elaboration)*

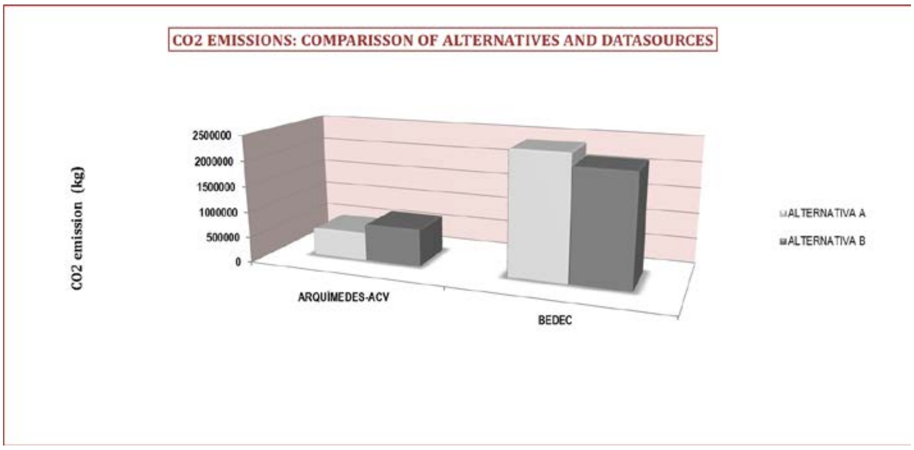


Chart 38: *Comparison of alternatives and data sources results on CO_2 emissions. (Source: own elaboration)*

Notwithstanding, it was observed that when analysing the data quality of both data sources, this gave close results in all the indicators considered. Therefore it is concluded that variation on the results are directly due to assumptions introduced by the practitioner when forming the different construction units with the construction elements supplied by BEDEC [Table 27]. Moreover, this was already pointed out previously at this work when offering the difference pointed out by the study of Lezen and Treolar [87], which assessed the same building that the study by Borjesson and Gustavsson [14] for a of a multi-storey building in southern Sweden (wooden structure resulted to be underestimated by a factor 2). So, in order to improve deficiencies and problems within the tool, more researching on the specific field of construction units is required. On this way, if construction processes are clearly enough established, as their related impacts, more accurate and reliable results will be offered to decision-makers on the construction industry (designers, investors, contractors...).

5.4. LCA application issues.

While practicing the LCI assessment of this study, it has been seen that its application to concrete structures is feasible but is not free of limitations and issues. The first problem encounter was the software tool and data to be used, as there is not any specifically adapted for the application of LCAs to the construction environment. This, among other problems, are exposed and treated right ahead:

- When establishing the functional unit of the study, the wider it is the better for avoiding latter allocation problems during the life cycle inventory. So, for the assessment of concrete structures, the best solution is to select the whole structure as the functional unit.
- When considering the system boundary in a process method LCA, it is advisable to establish a simple flow diagram to understand in an easier way the system under analyses.
- It's been tested that LCA is a very high time consuming method, due to the amount of data considered and managed. The best option is to support the calculations with software tools available at the market.
- Access to construction industry related data is not an easy option, as the databases are not completely specialized and offer data for a wide range of industries and fields. On the other hand, the databases used in this study are limited (as CYPE database that do not consider data for the operational/end of life phases).
- When access to data and software tools are not feasible, it is recommendable to revise the scope of the study and adapt it to each study limitations.
- Impact data of specific or rare items (specific products, machinery, rare construction activities, demolition procedures, reuse/recycling of materials,) are not usually included in the databases. This has to be changed by the development of new and updated impact calculations.
- Data, source, location and up-date are not clearly established on the databases accessed for the study. This brings to the study a grade of uncertainty that can even finish by dismissing its results and conclusions.
- During the study, it was not possible to include operational and maintenance phases due to the lack of data related. There are, obviously, available EPD's of products but assumptions on maintenance operations had to be done.
- This same happen when end-of-life phase (demolition, recycling, etc.) of the study had to be included.
- Finally, for closing the loop of the life cycle, data related to the assumption of reutilization and recycling of construction materials once overpassed the life cycle of the structure was not accessible.

ANALYSIS OF LCA APPLICABILITY TO C.S.

6. ANALYSIS OF LCA APPLICABILITY TO CONCRETE STRUCTURES.

In this sixth (and final) chapter of the master's work, a summing-up and discussion of the work developed will be offered. There will be offered a personal critical review related to the state of the art and the results obtained after the work performed. It will be followed by the introduction of some recommendations and tips to take into account for future practitioners of LCA when an assessment of a concrete structure has to be done. Finally, the conclusions reached after the elaboration will be included, as some future research lines for the topic at hand.

6.1. Discussion and recommendations.

Sustainability concern has reached the construction industry, and its relevance is daily taking head positions when designing a construction project, choosing materials, taking into action operational activities or, even, in demolition activities. As it has been seen at the state of the art, this situation is already being applied/ included on construction projects. So, it can be said that construction projects are going greener and greener with the time.

Nevertheless, the construction industry has been scarce to the date of tools and managerial elements able to offer a systematic evaluation of their impact on the environment. With the introduction of LCA to this scheme, this situation is supposed to change, as it's an environmental assessment tool capable of identifying items with greatest potential for environmental improvement.

The methodology to practice LCA studies was normalized with the publication of the ISO standard 14040. Notwithstanding, LCA analysis within this standard (process or conventional) needs further improvement as it presents limitations and variability on their results (Khashreen et al [78]). On this purpose, an integration of economic aspects was introduced on LCA studies to obtain the Input-Output LCA method which equally presents limitations on their practice as well (Lenzen and Treolar [87]). A combination of both methods, taking advantage of their strong points, was later developed and named Hybrid LCA. Notwithstanding, during the analysis of LCA studies on concrete structures published to the date, it was seen that, even with the disadvantages contained within the method proposed by ISO standard, it is the most used by authors.

But limitations of LCA's standardized methodology are not the only issue of the tool, as its real practice introduces subjectivity to the studies. This aspect has been pointed out by some articles, as the one by Junilla et al [75], Klöpffer [84] and Russell et al [136]. Moreover, when conducting an LCA, there are wide optional tools and databases which do again introduce more diverge to each study. This altogether, drives LCA studies to very different results even when they are assessing the system depending on the practitioner and its assumptions of the same object can vary the results obtained. As pointed out by Khashreen et al [78] this situation would be resolved by establishing very clearly each assumption on the goal and scope definition step of the assessment.

As already indicated, multiple tools, software and databases are available to perform LCA studies. Some studies have focused on the analysis of this topic, as the one by Trusty and Horts [153] and Haapio and Vittaniemi [60], even establishing a classification of existing available LCA tools. Moreover, as the study by Rice et al [131] analyzed sixteen different software tools on the European market in 1997, concluding that almost every LCA software tool had the same main purpose but some of them were more complete as: SimaPro, TEAM, PEMS and Bousted model.

As LCA is directly based on data to performed its impact inventory step, and its transparency and reliability are essential due to their influence on LCA results, evaluation of data introduced on LCA studies is a must, as indicated and treated in the articles by Björklund [13] and Khashreen et al [78]. Some authors have even introduced the concept of statistical methods to minimize inaccuracy and improve reliability on data used for LCA studies, such as Owens [116]. But, on the contrary, few LCA studies published to the date have taken these recommendations into account and have not assessed properly the kindness and goodness of data introduced in their studies.

It has been observed that the LCA studies published to the date mainly have focused their attention on the impacts derived from building construction and operational phases (such as that of Addalberth [2] and Peuportier [121]). On the contrary, few studies have taken into account maintenance and end-of-life phases of buildings, except ones included in paper made by Arskog et al [7] and Ortiz et al [113] or Viera and Horvath [165]. It was also appreciated that many comparisons between different buildings were also conducted, but focusing on commercial, residential and office uses. It was not widely used for the assessment of industrial hall, as that one published by Courard et al [30], focusing on its construction and demolition and avoiding operation/maintenance phases.

About the specific practice of LCA to concrete structure, it's mainly purpose has been to compare and identify the best environmental frame materials. Concrete structures have been assessed comparing to that of: wooden frames (such as studies by Gerilla et al [47] and Gustavsson et al [57]), steel frames (Guggemos and Horvath [54]) and bamboo frames (Van der Lugt et al [161]). But their application has been focused mainly on building structures, scarce studies have been done on other types of constructions, such as concrete bridges(Bouhaya et al [15] and Horvath and Hendrickson [68]) or even concrete sidewalks (Oliver-Solá et al [111]).

When focusing attention over the method used by the authors to assess the concrete structures, it is seen that predominant is the process analysis (ISO 14040). It was appreciated that just one study applied and EIO-LCA, the one performed by Horvath and Hendrickson [68], and three applied a Hybrid LCA (Guggemos and Horvath [54], Bilec et al [12] and Gerilla et al [47]). And pointing to their scope, it was seen that their predominant life cycle were cradle-to-gate and cradle-to-grave. Small amount of studies considered into the LCA calculations the factors for reutilization and recycling of materials at the end-of-life of the structures. This normally happened due to the few information related about the topic.

According to the results obtained from the case study performed in this work following the indications established in the LCA guide to concrete structures, steel offered a greater impact when compared to concrete, as indicated by the study performed by Guggemos and Horvath [54]. Moreover, it was also appreciated that the embodied energy and emissions produced within the manufacture of materials used in the construction of the concrete structure overpassed the impacts due to its construction process (as indicated too in the study performed by Guggemos and Horvath [54]). Finally, when comparing the different construction units necessary for the case study, it was appreciated that the biggest impact corresponded to that produced by the concrete slab as it was already concluded in the study performed by Lopez-Mesa et al [94]. This situation drives to a suppose that construction of concrete structures, even using different methodologies, assumptions and databases, give results that more or less can be commonly accepted for standard concrete constructions.

Limitations when using the LCA guide proposed on this work on the case study were not possible to be avoided. As it has previously been indicated, when performing LCA on concrete structures there is a lack of data and complete knowledge about operational/maintenance and end-of-life phases. Moreover, access to software and database available on the market had relevant constraints, as they demand license payment for their use. In our case study, these limitations established the scope for the case study. Notwithstanding, when performing a LCA study on a real scenario, available project data and assumptions from the designer can prevent limitation of the LCA study's scope. This and other considerations to take into account during the practice to an LCA study of a concrete structure are offered ahead as key recommendations:

1. Number of assumptions introduced in the LCA study must be minimal as they have a direct effect on the objectiveness of the results. Nevertheless, when it's indispensable, they must be clearly exposed at the goal and scope definition step.
2. Every conditioning and limitation considered on the LCA study must be included on its goal and scope definition to let future results be compared with other LCA studies, as other practitioners or third parties reviewing.
3. When establishing the functional unit of the LCA study, it is advisable to widen its scope, due to on this manner allocation problems during LCI are diminished, or even fully avoided.
4. When establishing the system boundary, it is advisable to propose the simplest flow diagram of the processes within it, in order to ease the latter performance of the LCI.
5. Data incorporated to the assessment must come from trustful resources, such as databases or public organizations.
6. It is highly recommended to use EPD of products used on the project, and not the data of product included on databases. By this, the results obtained from the LCA study are more accurate and personalized.

7. It is recommended to perform a statistical analysis of data coming from different sources, when access to LCI databases is not possible, therefore selecting the data used on the study with a statistical basis and not allowing great deviations of results.
8. In order to ease the practice of LCA studies, it is highly recommend using LCA software available on the market. Moreover, the use of this software allows at the same time the objective of letting future comparisons and reviews of the results obtained from the LCA study.
9. When choosing the LCIA methodology of the LCA study, it is advisable to consider a methodology fitting the scope of the study, as each LCIA assume its own impacts and their importance.
10. It is advisable to perform various sensitive analyses, establishing different scenarios on the LCA studies, in order to establish the affection of assumptions caused on the results of the LCA study performed.

One relative important point of great interest has been the integration of LCA to economic tools, such as LCC (as the one performed in the study by Gu et al [53]). This also has been done by developing the so called EIO LCA and the hybrid analysis that take into account economic sector. But the great subject to work on for the future of LCA passes by the integration of social concerns during its assessments, which was treated more deeply by Hunkeler and Rebitzer [71] and Norris [107]. This is a very important issue to improve within the practice of LCA, as integration on one tool of the three components of sustainable development (environmental, economic and social) can contribute to widen its practice to all sectors of human activity.

Therefore, and going back to the applicability of LCA to concrete structures, improvement and development of specific databases and information related to all the phases of the life cycle included, must be accomplished first. Moreover, if this objective is reached, practice of LCA to assess other types of construction projects will be also feasible. But this needs of more researching, studying and effort from behalf of all stakeholders included in the construction industry.

6.2. Conclusions.

The present master's work has been performed to expose a complete view and analysis of the actual situation of Life Cycle Assessment and, more specifically, on its application on concrete structures. First, a bibliographical research on the subject was performed to obtain the data related with the topic. Then, a quantitative and qualitative assessment, this last including an S.W.O.T. analysis, was done for the scientific publications recovered from the research. Finally, after the state of the art was completely introduced, a guide for the practice of LCA to concrete structures was proposed, including a case study on a concrete structure taking into consideration the tips established at the guide.

Life Cycle Assessment practice has been seen to be increasing its importance and relevance as an environmental assessment tool. Different policies and measures coming both from public and private parties are promoting its use as, for example, the European Platform of Life Cycle Assessment or the UNEP-SETAC Life Cycle Initiative. On the construction industry, this trend is being applied on the promotion of Environmental Product Declarations for construction products, such as: cement, concrete, aggregates, asphalt, etc.

But, on the contrary, even being standardized by the ISO standard 14040, LCA's studies procedure is not free of variability and uncertainty. First, there are the different typologies of analysis (process, Input-Output and Hybrid) for the whole LCA. Second, there are the assumptions (system boundary, allocation, scope…) introduced by LCA practitioners, already pointed out by various authors such as Junilla et all [75] (among others). Third, there is quality and reliability of data introduced on the assessment, as there is no normalized or widely accepted procedure to analyze and reject inappropriate data from a study (as indicated by authors as Khasreen et al [78]). And, finally, there are the different LCIA methodologies available (EDIP, CML, Eco-indicator…) which introduce different assumptions on the assessment of the impacts studied on LCA. Therefore, LCA studies offer a positive methodology for environmental assessment of products and systems, but with some difficulties and disadvantages for their comparison due to the variability of the results obtained.

Life Cycle Assessment practice on concrete structures has already been broadly applied, as it can be checked taking a look at examples of studies performed to the date. In this sense, it has been also appreciated that LCA studies on concrete structures have the ability to indicate (all along their life cycle) which materials, phases, processes… account greater environmental impacts. Therefore, LCA is considered to be a very useful tool to improve environmental performance of concrete structures, as it allows efficiently aiming points to deal with.

And when focusing on real world use of LCA studies on construction industry, there are few studies that reflect the use of LCA as a decision-making tool during design phases, for material selection or to assess operational activities. The vast majority of studies published to the date have been applied once the construction project was finished, what offers a vision of potentialities of LCA's applicability on construction sector, but do not offer a real example of controversy encounter by the introduction of result of LCA to decision-making processes.

During the case study conducted on this work, problems related to scarcity of specific and related data to construction industry were encountered. This mentioned problems took form as access limitations to impact data of construction products EPDs, construction processes, operational/maintenance and demolition activities, as well as assumptions related to reuse and recycling rates at the end of the concrete structure life cycle. So, there is a demand on improvement of access to data if construction LCA studies want to be widely applied within the sector. This same problem would be solved by the development and operability of a wide open source database that let practitioners extract data for their assessments. This would require the integration and participation of many construction industry stakeholders, such as: politics, product manufacturers, designers or construction professionals.

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 on LCA assessment are in course. For example, integration of LCA with LCCA (Life Cycle Cost Analysis) have already been done on different papers (Gu et al [53]), but the most difficult subject is found on integration of social concerns. If development of LCA achieves the integration of environmental, economic and social issues; then LCA practitioners will count on a tool for decision-making that meets with the triple-bottom objectives of Sustainable Development.

So, according to everything previously exposed, Life Cycle Assessment is an environmental assessment tool with wide applicability and great number of opportunities on the construction environment. Nevertheless, it requires of great efforts on improving problems related to variability and unreliability of its results. Moreover, if the integration of environmental-economic-social concerns is achieved, LCA practitioners will count on a trustful and reliable tool that will give scientific and objective base to decisions taken during the whole life cycle of construction projects.

6.3. Future lines of research.

During the time employed for making this work, different ideas for future lines of research on the topic came into mind. Nevertheless, due to the wide applicability of LCA, some of them were not too related to the topic discussed, or even to the construction industry. Therefore, some of the ideas were rejected and just the pertaining to the construction industry was finally considered. Ahead, the selected lines of future research are being exposed and explained:

1. As the applicability of LCA to concrete structure has been demonstrate, and the case study used on this work was just a theoretical approximation to reality, it would be interesting <u>to perform the guideline on real cases</u>. This would pass by first contacting private construction or design consultant companies interested, so to allow accessing the widest amount of data. Different scenarios would be proposed, and assessed then by practicing LCA studies on each of them, to finally select the most environmental-friendly design alternative.

2. Due to the difficulties encountered during the case study to access data relating operational/maintenance and end-of-life phases, it has been considered of relevance to <u>develop trustful information relating different phases of a concrete structure's life cycle</u>. This proposal would take into consideration a complete analysis of phases existing within a concrete structure and would extract the information from different companies related to this phases. Thereby, direct and real data from the activities could be analyzed and studied to supply LCA practitioners with coherent data, leaving wrong assumptions out of LCA studies.

3. Although, as it was already pointed out in this work, concrete structures are the most used construction items on the construction industry, they are also many other. If improvement of construction sustainability wants to be achieved, it is also important to assess environmental performance of other construction project, such as: roads, railways, harbors, etc. Another future line of research would be to <u>analyze the applicability of LCA to other construction projects</u>, or even widening this scope to the construction industry as a whole.

4. As it was indicated in this work, the results obtained by LCA studies can helped to introduce environmental issues to decision-making process and, therefore, to obtain a more environmental-friendly management. Standards of the ISO 14040 series for the practice of LCA are included in the ISO 14000 series for environmental management. Consequently, it would be of real interest to <u>analyze the application an integration of LCA studies on the environmental management system of a construction company</u>. As nowadays, almost every construction company counts with their own certificated system, it could be possible to introduce the result obtain both from a realistic and academic perspective.

5. When analyzing the state of the art, as it is been indicated in the discussion, the assessment of whole buildings just focused on three types of uses: residential, commercial and offices. Just one study took into consideration the assessment of an industrial hall, and in this same study the operational/maintenance phase of its life cycle was avoided. Consequently, a line of research would be the assessment of different industrial constructions, emphasizing on real cases, and analyzing their effects on the production process performed at their facilities.

6. It has been appreciated during this work that few articles gave data related to the application of LCA on construction industry. So, another line of research would be to analyze data about LCA studies performed on the construction industry all over the world. For that, a research and contact with different construction companies would be done, at the same time that a search on public databases and publications. This study would serve as the base to set future measures to introduce LCA into the construction industry more efficiently.

7. LCA environmental concerns, together with integration of economic and social issues, would result on a technique that would take into consideration the complete objective of sustainable development. Therefore, it is considered of interest to analyze and develop an integrated LCA that assessed the triple-bottom objective of sustainable development. This research would require of a widening of the state of the art performed at this work, and a latter proposal of a method that subsequently would be tested on a case study (that could be a real case study) to test the feasibility of the proposed method.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7. REFERENCES

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ADDINGS

8. ADDINGS

8.1. LCI data.

CONS. UNIT	CONSUMPTION		LIFE CYCLE PHASE					
			MANUFACTURING		CONSTRUCTION			
			A1-A2-A3		A4		A5	
			Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)
CRL010	Materials	(kg)						
	Concrete	241,50	251,16	23,61	4,29	0,32		
	Auxiliary sources						0,02	0,00
	Wastes	(kg)						
	Waste transportation	2,42					0,11	0,01
CCS010	Materials	(kg)						
	Steel	78,56	2.749,64	219,97	24,32	1,80		
	Concrete	2.415,00	2.511,60	236,09	42,89	3,17		
	Auxiliary sources						0,14	0,02
	Wastes	(kg)						
	Waste transportation	34,16					1,52	0,11
CSZ010	Materials	(kg)						
	Steel	62,27	2.179,56	174,36	21,01	1,56		
	Concrete	2.530,00	2.631,20	247,33	44,93	3,33		
	Auxiliary sources						0,14	0,02
	Wastes	(kg)						
	Waste transportation	27,36					1,22	0,09
CSZ020	Materials	Peso (kg)						
	Steel	1,14	39,90	3,19	0,08	0,01		
	Galvanized steel	0,05	1,95	0,14	0,02	0,00		
	Auxiliary sources						0,06	0,01
	Wastes	Peso (kg)						
	Waste transportation	1,05					0,05	0,00

CONS. UNIT	CONSUMPTION		LIFE CYCLE PHASE					
			MANUFACTURING		CONSTRUCTION			
			A1-A2-A3		A4		A5	
			Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)
CAV010	Materials	(kg)						
	Steel	82,24	2.878,40	230,27	27,75	2,05		
	Concrete	2.415,00	2.511,60	236,09	42,89	3,17		
	Auxiliary sources						0,08	0,01
	Wastes	(kg)						
	Waste transportation	27,26					1,21	0,09
CAV020	Materials	(kg)						
	Steel	1,14	39,90	3,19	0,08	0,01		
	Galvanized steel	0,05	1,95	0,14	0,02	0,00		
	Auxiliary sources						0,05	0,01
	Wastes	(kg)						
	Waste transportation.	1,05					0,05	0,00
CNE010	Materials	(kg)						
	Steel	100,12	3.504,20	280,34	32,28	2,39		
	Concrete	2.415,00	2.511,60	236,09	42,89	3,17		
	Auxiliary sources						0,11	0,02
	Wastes	(kg)						
	Waste transportation	33,02					1,47	0,11
EHE010	Materials	(kg)						
	Steel	30,43	1.065,18	85,21	10,14	0,75		
	Wood	3,90	11,71	0,34	0,17	0,01		
	Concrete	747,50	777,40	73,08	13,28	0,98		
	Auxiliary sources						0,20	0,03
	Wastes	(kg)						
	Waste transportation	13,00					0,58	0,04

CONS. UNIT	CONSUMPTION		LIFE CYCLE PHASE					
			MANUFACTURING		CONSTRUCTION			
			A1-A2-A3		A4		A5	
			Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)
EHU020	Materials	(kg)						
	Steel	20,54	718,73	57,50	6,84	0,51		
	Wood	0,83	2,48	0,07	0,04	0,00		
	Pre-cast concrete	113,91	117,32	11,03	5,06	0,37		
	Pre-cast concrete	36,80	73,59	7,95	1,63	0,12		
	Concrete	397,90	413,82	38,90	7,07	0,52		
	Envelopes	(kg)						
	Plastic	0,12	8,51	1,26	0,01	0,00		
	Wood	0,31	0,92	0,03	0,01	0,00		
	Auxiliary sources						0,16	0,02
	Wastes	(kg)						
	Waste transportation	26,50					1,18	0,09
EHS010	Materials	(kg)						
	Steel	17,80	622,87	49,83	1,84	0,14		
	Concrete	2.300,00	2.392,00	224,85	40,85	3,02		
	Auxiliary sources						0,15	0,02
	Wastes	(kg)						
	Waste transportation	36,45					1,62	0,12
EHV010	Materials	(kg)						
	Steel	233,03	8.156,10	652,49	78,48	5,81		
	Wood	4,76	14,29	0,42	0,21	0,02		
	Concrete	2.300,00	2.392,00	224,85	40,85	3,02		
	Auxiliary sources						0,15	0,02
	Wastes	(kg)						
	Waste transportation	38,96					1,73	0,13

CONS. UNIT	CONSUMPTION		LIFE CYCLE PHASE					
			MANUFACTURING		CONSTRUCTION			
			A1-A2-A3		A4		A5	
			Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)	Energy (MJ)	CO_2 Emissions (kg)
EHL010	Materials	(kg)						
	Steel	27,17	950,83	76,07	9,15	0,68		
	Wood	0,60	1,80	0,05	0,03	0,00		
	Concrete	690,00	717,60	67,45	12,25	0,91		
	Auxiliary sources						0,16	0,02
	Wastes	(kg)						
	Waste transportation	8,63					0,38	0,03
EHN010	Materials	(kg)						
	Steel	11,29	395,12	31,61	1,62	0,12		
	Concrete	2.415,00	2.511,60	236,09	42,89	3,17		
	Auxiliary sources						0,17	0,02
	Wastes	(kg)						
	Waste transportation	30,80					1,37	0,10

***Table 36**: LCI data obtained from ARQUÍMEDES-ACV software. (Source: own elaboration)*

CONSTRUCTION ELEMENTS	CONSUMPTION	WEIGHT (kg)	ENERGY CONSUMPTION (MJ)	CO2 EMISSIONS (Kwh)
BLINDING CONRETE	B06NLA2B (m³). Hormigón de limpieza, con una dosificación de 150 kg/m3 de cemento, consistencia blanda y tamaño máximo del árido 20 mm, HL-150/B/20			
	Components	2.510,90	906,79	251,89
	Water	97,5	0,59	0,16
	Aggregate	2.263,40	339,51	94,31
	Cement	150	566,7	157,42
	Total:	2.510,90	906,79	251,89
STRUCTRURAL CONCRETE	B065990B (m3) Hormigón HA-25/B/20/IIa de consistencia blanda, tamaño máximo del árido 20 mm, con >= 350 kg/m3 de cemento, apto para clase de exposición IIa.			
	Components	2.354,31	1.592,71	442,42
	Water	210	1,26	0,35
	Aggregate	1.794,31	269,15	74,76
	Cement	350	1.322,30	367,31
	Total:	2.354,31	1.592,71	442,42
STEEL RODS	B0B2C000 (kg). Acero en barras corrugadas B500SD de límite elástico >= 500 N/mm2.			
	Components	1	35	9,72
	Steel	1	35	9,72
	Total:	1	35	9,72
WOOD (FORM-WORK)	B0D732A0 (m2) Tablero elaborado con aglomerado de madera, de 25 mm de espesor, para 2 usos, para seguridad y salud.			
	Components	7,88	120,64	33,51
	Galzanized steel	0,38	15,64	4,34
	Wood	7,5	105	29,17
	Total:	7,88	120,64	33,51
GALVANIZED STEEL WIRE	B0A1_01 (Kg). Alambre galvanizando para atar.			
	Components	1	41,71	11,59
	acero galvanizado	1	41,71	11,59
	Total:	1	41,71	11,59
CRANE TRUCK	C150_01 – (h). Camión gruía para transporte.			
	Components	-	949,45	263,74
	gasoil	-	949,45	263,74
	Total:	-	949,45	263,74

CONSTRUCTION ELEMENTS	CONSUMPTION	WEIGHT	ENERGY CONSUMPTION	CO2 EMISSIONS
		(kg)	(MJ)	(Kwh)
CONCRETE MIXER TRUCK	C170MM00 (h). Camión hormigonera de 6 m3.			
	Components	-	949,45	263,74
	Gasoil	-	949,45	263,74
	Total:	-	949,45	263,74
STEEL FORM-WORK PANNEL	B0D810A0 (m2). Panel metálico para 150 usos.			
	Components	0,23	7,93	2,2
	Steel	0,23	7,93	2,2
	Total:	0,23	7,93	2,2
CONCRETE VIBRATOR	C200D000 (h). Vibrador de aguja.			
	Components	-	55,95	15,54
	Electric	-	55,95	15,54
	Total:	-	55,95	15,54
ELECTRIC WELDING EQUIPMENTS	C200P000 (h). Equipo y elementos auxiliares para soldadura eléctrica.			
	Components	-	139,5	38,75
	Electric	-	139,5	38,75
	Total:	-	139,5	38,75
	E2441230 (m3). Carga con medios mecánicos y transporte de residuos inertes o no peligrosos (no especiales) dentro de la obra, con camión para transporte de 7 t.			
	Components	-	37,07	10,3
	gasoil	-	37,07	10,3
	Total:	-	37,07	10,3

***Table 37**: LCI data obtained from the BEDEC database. (Source: own elaboration)*

8.2. Glossary.

1. Allocation is the partition and distribution of input/output flows of a process or product system, between the own product system assessed and one or more other product systems.

2. Embodied energy is that required by the production process of a product, including all the consumptions of the activities comprehend from the acquisition of natural resources and the energy used in making equipment or other supporting functions.

3. Environmental impact is every adverse effect caused by any human activity or by the release of a substance in the environment.

4. Environmental Product Declaration (EPD) is a quantified product's environmental performance verified by a qualified third party

5. Functional unit is the quantified reference unit of a product or service which performance is used for the assessment of that same product or service.

6. Life cycle includes all the consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

7. Life Cycle Assessment (LCA) is an environmental assessment tools use for the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a system considering its complete life cycle.

8. Life Cycle Impact Assessment (LCIA) is the phase of LCA aimed at understanding and evaluating the potential environmental impacts generated by a product system throughout its life cycle.

9. Life cycle interpretation is the phase of LCA in which inventory analysis or impact assessment results, or both, are evaluated in order to reach conclusions and recommendations.

10. Life Cycle Inventory analysis (LCI) is the phase of LCA in which inputs and outputs of a product are compiled and quantified considering their life cycle.

11. **Life span** is the average or maximum length of time an organism, material, or object can be expected to survive or last.

12. **Raw materials** are all the primary or secondary (recycled) materials that are used for the manufacturing of a product.

13. **Sensitive analysis** is a systematic procedure for estimating the effects of choices made regarding methods and data on the outcome of a LCA study.

14. **System boundary** is the set of criteria specifying which unit processes are part of a product system.

15. **Sustainability** is the optimal balance of environment, economic, and social systems over time.

16. **Sustainable Development** is the development that meets the needs of the present without compromising the ability of future generations to meet their own.

8.3. Index of contents.

8.4. Index of charts.

8.5. Index of figures.

8.6. Index of tables.