Construction and Building Materials 124 (2016) 656–666

Contents lists available at ScienceDirect

Construction and Building Materials

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

Review

Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review

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HIGHLIGHTS

- The study presents a literature review of life-cycle-assessment (LCA).
- Methods applied to the manufacturing of common and ecological concrete are reviewed.
- The green concrete LCA tools are a breakthrough in LCA studies.

ARTICLE INFO

Article history:
Received 16 May 2016
Received in revised form 22 July 2016
Accepted 25 July 2016
Available online 4 August 2016

Keywords:
Life cycle assessment
Sustainable construction
Concrete
Environmental impact

ABSTRACT

Life cycle assessment (LCA) is a methodology used to evaluate the potential environmental impact and the resources used throughout the life cycle of a product, i.e., environmental impact management is approached from the moment the raw material is extracted to the phases of production, use, disposal, and recycling. In the context of sustainable production in civil construction, products should be conceived so that at the beginning of their life cycle, they contain recycled waste as raw material and, at the end of their life cycle, they can be recycled and reused to become raw materials in other production systems. The present study is a literature review conducted to present the state-of-the-art of LCA methods applied to the manufacturing of common and ecological concrete. Concepts and tools are discussed. The need for further LCA studies on the treatment and reuse of construction waste is evident to prevent its disposal in the environment and to incorporate it in the life cycle of new concretes.

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http://dx.doi.org/10.1016/j.conbuildmat.2016.07.125

1. Introduction

The improvement of sustainable development indicators is becoming increasingly relevant for the civil construction industry because this sector is responsible for high energy consumption and environmental damage, especially with regard to the consumption of raw materials, improper waste accumulation or disposal, and greenhouse gas emissions [1,2]. The activities involved in construction processes are the main causes of the depletion of natural resources, accounting for 24% of the extraction of natural resources on a global scale, and they are also the main waste generators [3]. In addition to the depletion of natural resources, the raw material extraction that feeds into the civil construction industry causes other environmental impacts that should be carefully considered, such as landscape damage, ecosystem degradation, damage to human health, and the contamination of soil, water, and air by emissions from the production and handling of construction materials [4].

It is scientifically known that the civil construction sector is the major cause of greenhouse gas emissions, being responsible for approximately 40–50% of the world's greenhouse gas emissions [5]. Pollutant gases that cause environmental damage are released into the atmosphere throughout the entire construction process, including the transportation of materials and the energy used by machinery in the processing and manufacturing of construction materials, where the latter is responsible for approximately 86% of all emissions [6]. Additionally, the waste generated during construction or demolition constitutes a representative portion of the total waste produced in cities.

In the European Union, the life cycle of buildings, including their construction, operation, and demolition, consumes up to 50% of the total energy demand and contributes almost 50% of all CO_2 emissions released into the atmosphere [7]. In China, the cumulative environmental impacts of construction processes have increased due to the large number of construction projects underway every year, representing a serious problem with the potential to cause significant damage not only to ecosystems but also to human health and population welfare [8]. For example, to improve the air quality of Beijing during the 2008 Olympic Games, the organizing committee had to forbid construction activities before and during the Olympics to minimize construction dust and control the air quality [8].

The intersectoral relationships of civil construction practically influence all other economic sectors, providing jobs and income to a large number of skilled and unskilled workers; therefore, they can be considered an economic development factor. However, there remain discrepancies between the ideal form of sustainable economic development and the existing construction processes [9].

The term sustainable development is defined as the improvement in the quality of life that grants individuals the opportunity to live in a healthy environment with better social, economic, and environmental conditions for present and future generations [10]. One of the key sustainability challenges for the coming decades is improving the management of natural resources to reduce the current levels of anthropogenic pressure on the environment [11]. Therefore, as a proposed solution to environmental threats from the chain linked to civil construction, studies indicate the need to analyze construction materials separately, focusing on improving the use of recyclable materials, in addition to studying transportation alternatives and the adoption of construction technologies with low energy consumption [6]. Therefore, following this trend, this work addresses studies concerned with sustainability and the environment within the building construction industry, focusing on the concrete production chain.

Concrete is a key component in building construction due to its many advantages, including its low cost, mechanical properties and adequate durability, heat storage capacity, chemical inertia, and ease of being molded into different sizes and shapes [12]. However, to guarantee the future competitiveness of concrete as a construction material, it is essential to improve its sustainability, focusing on the production of sustainable raw materials and new manufacturing technologies with low environmental impact [13].

Concrete is the most commonly used construction material in infrastructures. Approximately one ton of concrete is produced every year per human being on the planet, and because of its wide global use, it is fundamental to correctly assess the environmental impacts of this material, considering the greenhouse gas emissions and the impacts on climate change it generates [14].

In the assessment of the environmental impact of concrete production processes, it is important to focus on the entire life cycle of the material, including the boundaries beyond the project. The production process as a whole, which concerns the life cycle from the extraction of material reservoirs to the final waste disposal, is important from the perspective of sustainability [15]. Attention should also be paid to environmental viability studies on the partial substitution of cement with alternative materials and their natural aggregates with recycled waste to make the material less harmful to the environmental, always careful to avoid affecting the material's technical performance [14,16]. It should be emphasized that the use of recycled waste is not associated with any environmental impact when it is included in a new production system [17–19].

It is imperative to produce a detailed diagnosis of the raw material extraction, production, distribution, use, and final disposal conditions that exist in a production process and help elaborate strategies that allow the minimization of costs and the optimization of material and energy flows in the analyzed system [18]. In this context, life cycle assessment (LCA) emerges as a methodology that is capable of providing supporting tools in projects to evaluate the environmental impact of products and processes during their entire life cycle, presenting clear results with a scientific basis. LCA has been demonstrated to be a valuable tool for the environmental viability study of the incorporation of recycled waste into the production of concrete [16,20–23].

First introduced in the early 1960s due to the concern with rationalizing the energy consumption of buildings, LCA evolved into a broader concept that integrates all environmental impacts, representing one of the main tools used in the prevention of pollution [15]. The life cycle concept is essential for sustainability, incorporating many aspects that allow the objective analysis of processes or services [24]. Hence, LCA is a methodology used in assessing environmental impacts in all life cycle phases, from the origin of the raw material to the end of its useful life and disposal, representing a global and robust methodology that is not specific to a single domain [10,18,21].

The description of the LCA methodology is based on the ISO 14.040 [25] and ISO 14.044 [26] series of international standards. It is one of the most commonly applied environmental impact assessment methods and also one of the most detailed by the recent literature compared to other environmental assessment tools [27,28]. Countries such as the United Kingdom, the Netherlands, France, Denmark, Norway, Sweden, and Finland, which are at the forefront in sustainable development studies, have concentrated their efforts in LCA studies for construction materials, integrating the environmental component with other tools such as environmental management systems [29,30].

The LCA methodology is recognized as an innovative tool that improves sustainability in the civil construction and materials industries in all life cycle phases, and to ensure the identification of a variety of environmental factors, the construction process has to be broken down systematically into small unit processes, allowing the application of the methodology [8,10,31,32].

Thus, this study consists of a literature review conducted to present the state-of-the-art of LCA methodological practices in the manufacturing of common concrete and concrete with aggregates derived from recycled waste (ecological concrete). Concepts and tools are discussed.

To meet the objectives of the investigation, the study was divided in the following manner. Section 2 discusses the LCA conceptual framework. Then, the state-of-the-art of LCA applied to the concrete industry is described in Section 3. Finally, Section 4 presents the conclusions.

2. Life cycle assessment (LCA) conceptual framework

Because of the importance of environmental issues, many companies and research centers are improving their sustainable development practices, encouraged by environmental control agencies and the mass media, which reflect the global interest in reducing environmental impacts to maintain the quality of ecosystems and ensure a better quality of life for living beings.

The guidelines for sustainable production serve not only to reinforce laws and standards but also to commit to the environment; thus, new production processes are not focused exclusively on the search for high irresponsible productivity and unconditional profit but instead start to follow the global trend of using renewable resources and optimize the use of non-renewable resources, evaluating the level of raw material exploitation to ensure the conservation of these resources for future generations.

To support industries in the improvement of environmental management, the tool called LCA was developed; in LCA, the life cycle is the sequence of transformations of raw materials and energy, including the extraction of raw materials, manufacturing, distribution, use, materials recovery, recycling, and reuse, with the purpose of studying in this cycle how society can optimize the use of resources, meeting human needs without losing the quality attributes [33]. Section 2.1 presents a brief historical review of the emergence of the LCA methodology to report the industrial origin of this tool.

2.1. Historical review of the emergence of the LCA methodology

The outset of LCA occurred between the 1960s and the 1980s, when the large industrial organizations at the time decided to inventory the energy consumption involved in the manufacturing of their products to improve the use of natural resources and seek better energy alternatives during the first oil crisis.

In the 1960s, focusing on political debates on recycling, Coca-Cola hired the Midwest Research Institute (MRI) to evaluate the different types of packaging that contained the company's products to verify which type would cause the lowest environmental impact with regard to environmental emissions and the best performance in relation to the use of natural resources, a study that was known as resource and environmental profile analysis (REPA).

During the following years, environmental assessments gained popularity, focusing many studies on different production processes; thus, in 1974, the methodology known at the time as REPA, considered the precursor of today's LCA, was improved by the MRI.

Years later, the diversity of studies and results presented by the application of LCA clarified the need for having a standard method and establishing strict criteria to guide the performance of studies before they are made public. Hence, the Society for Environmental Toxicology and Chemistry (SETAC), the first institution to start working on the systematization and standardization of LCA terms and criteria, was created.

In 1993, the ISO formed Technical Committee TC-207 to produce standards concerning environmental management and its tools, and in 1997 and 2006, series ISO 14.040 [25] and series ISO 14.044 were produced, respectively; together, these series currently include the main and most important standards for LCA, which are applicable to various industrial, extractive, agroindustrial, commercial, service and governmental activities. Focused on the concrete industry, in 2012, Technical Committee TC-71, responsible for establishing guidelines and parameters for concrete technical standards, produced ISO 13.315-1, which provides a framework and basic rules on environmental management related to concrete. In 2014, Technical Committee TC-71 produced ISO 13.315-2, which provides principles and requirements related to determining system boundaries and acquiring inventory data for conducting LCAs. Table 1 presents the standards of series ISO 14.040 [25], ISO 14.044 [26] and ISO 13.315 [34,35] in increasing chronological order.

Section 2.2 presents the LCA tool, emphasizing its application phases.

2.2. The life cycle assessment (LCA) method

LCA is a methodology for evaluating, qualitatively and quantitatively, the potential environmental impacts of and the resources used throughout the life cycle of a product, i.e., environmental impact management is approached from the time of raw material extraction to the phases of production, use, disposal, and recycling, which requires specific data on the production process [14,16,39–41]. LCA is a methodology for the analytical analysis of the interactions between human activities and the environment from the management perspective, and it also allows focusing on and evaluating the critical points of and the margins for the improvement of a product life cycle [42–46].

The description of the LCA methodology is based on the requirements of the international standard of the ISO 14.040 [25] and ISO 14.044 [26] series and consists of 4 distinct analysis phases (Fig. 1): goal and scope definition, life cycle inventory (LCI) creation and analysis, life cycle impact assessment (LCIA), and interpretation of results [14,16,33,46–49].

2.2.1. Goal and scope definition

The first phase of the LCA methodology is the goal and scope definition, which focuses on providing a specific limit for the environmental impact considerations, considering the infinite number of parameters that could be analyzed in a production chain [8,33].

The goal of an LCA study should state the intended application, the purpose of the study, and the target public, i.e., to whom the study results will be communicated, to clarify what data and units should be considered [14,16,46]. In the scope definition, the function and functional unit (liter, m^2, m^3, etc.), the system boundaries, the data quality requirements, the comparison between systems, and the considerations concerning the critical analyses should be considered and clearly described [14,16,46].

According to ISO standard 14.041 [36], the definition of the goal and scope should specify the definition of the functional unit, the process of the product studied, the system boundaries, the input and output allocation procedures, the types of impact evaluated, the data quality requirements with the time period of collection and the geographical area covered, and, finally, the source of the data collected.

2.2.2. Life cycle inventory (LCI) creation and analysis

The life cycle inventory (LCI) creation and analysis involves the compilation and quantification of the inputs and outputs and

Table 1
Standards of series ISO 14.040 [25], ISO 14.044 [26] and ISO 13.315 [34,35]. Adapted from series ISO 14.040 [25], ISO 14.044 [26] and ISO 13.315 [34,35].

Standard	Year published	Title of standard	Description of standard
ISO 14.040 [25]	1997	LIFE CYCLE ASSESSMENT – Principles and framework	Establishes the basic principles and requirements for the performance and publication of LCA study results
ISO 14.041 [36]	1998	LIFE CYCLE ASSESSMENT – Goal and scope definition and inventory analysis	Details the requirements for the definition of the goal and scope of an LCA study
ISO 14.042 [37]	2000	LIFE CYCLE ASSESSMENT – Life cycle impact assessment	Presents the general principles for the performance of the impact assessment, the selection of impact categories, and describes the classification and characterization steps
ISO 14.043 [38]	2000	LIFE CYCLE ASSESSMENT – Life cycle interpretation	Presents the requirements and recommendations for the interpretation of the results of an inventory analysis or impact assessment
ISO 14.044 [26]	2006	LIFE CYCLE ASSESSMENT – Requirements and guidelines	Specifies requirements and provides a guide for life cycle assessment, including examples
ISO 13.315-1 [34]	2012	ENVIRONMENTAL MANAGEMENT FOR CONCRETE AND CONCRETE STRUCTURES – Part 1: General principles	Provides a framework and basic rules on environmental management related to concrete and concrete structures. Includes the assessment of the environmental impacts and methods of implementing environmental improvement based on the assessment
ISO 13.315-2 [35]	2014	ENVIRONMENTAL MANAGEMENT FOR CONCRETE AND CONCRETE STRUCTURES – Part 2: System boundary and inventory data	Provides a general framework, principles, and requirements related to the determination of system boundaries and the acquisition of inventory data necessary for conducting an LCA of concrete, precast concrete, and concrete structures

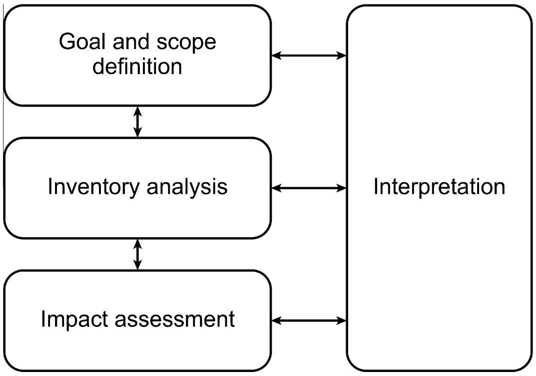

Fig. 1. LCA phases. Source: Adapted from ISO 14.040 [25].

includes the collection and analysis of data with regard to the production system; these data are also the input for the life cycle impact assessment, comprising an extensive database, and this phase is the phase that requires the most time [14,16,33,46].

The LCI should contain data on all the inputs and outputs of each individual process in the system studied, including the flows of pollutants, materials, and resources at their different phases (raw material acquisition, transportation of inputs, product manufacturing, product transportation, and the use, disposal, recycling, and reuse phases), adopting a standard unit (e.g., m^3) of material (Fig. 2) [50–53].

The LCI documents the energy, material, and emission flows to represent the relationship between the unit processes and their environmental impacts. However, the product life cycle is composed of hundreds and thousands of unit processes, and the collection of these data would take too much time and resources, making some studies impracticable. Therefore, a more pragmatic alternative is the use of life cycle inventory databases that store the inventory data of different production processes specific to a country of origin [20,54,55].

Table 2 provides information on the developer, country of origin, and the main data source of 5 databases used internationally.

The databases contribute to optimizing the time of application of an LCA and comprise several databases containing different environmental information on the production of consumer goods, which is important for the treatment and collection of data; otherwise the studies would become slow and inaccurate and could be outdated before the treatment of data [56]. When there is a need for information that is not part of any database, an estimation

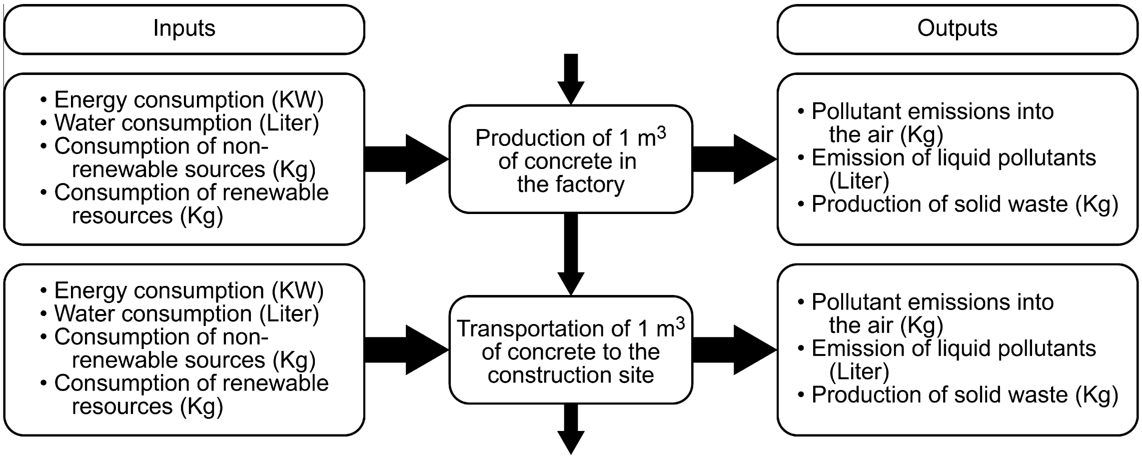

Fig. 2. Life cycle inventory inputs and outputs. Source: Prepared by the authors.

Table 2
General view of 5 databases used internationally. Source: Adapted by Takano et al. [20].

Database	Developer	Country of origin	Main data source
GaBi	PE International	Germany	Industrial data/Data from the literature/Other databases
Ecoinvent	Swiss Centre for Life Cycle Inventories	Switzerland	Industrial data/Data from the literature
IBO	Austrian Institute for Healthy and Ecological Building	Austria	Industrial data/Data from the literature/Other databases
CFP	Japan Association for Industry	Japan	Statistical data/Data from the literature
Synergia	Finnish Environment Institute	Finland	Industrial data/Data from the literature

may be made, provided that this estimation is based on existing data [57].

Given the importance and relevance of databases for the LCI, there is an evident and global need for their development to subsidize LCA studies, requiring the collaboration of research institutions for the creation of databases, the government for defining public policies, and companies for providing data on the production processes.

2.2.3. Life cycle impact assessment (LCIA)

The goal of the life cycle impact assessment (LCIA) phase is to understand and assess the environmental impacts based on the inventory analysis, that is, the scope of and reasons to conduct the study, and this phase may be considered the most important and critical phase of the study because the standards of the ISO 14.040 series [25] do not establish a fixed evaluation criterion, which leads to discrepancies from one study to another [14,16,33,46].

In this phase, the data are grouped into specific impact categories according to an impact assessment method that can be divided into single-category or multi-category methods, where the multi-category methods are the most commonly used and can be problem-oriented (midpoint) or damage-oriented (endpoint), always with the same goal of classifying, characterizing, standardizing, and valuing the potential impacts on ecosystems, human health, and the depletion of natural resources [49,58].

In the midpoint approach, all of the materials from the LCI are properly combined into impact categories according to a common characteristic of the cause-effect relationship, and the potential impact indicators are listed, although the final consequences with regard to the environmental trajectory of the listed emissions are not represented [59,60]. This classification generally takes advantage of a greater scientific consensus, and issues such as climate change, the destruction of the ozone layer, human toxicity, acidification, the depletion of abiotic resources, and eutrophication are discussed [61,62].

In turn, the endpoint approach addresses the damages as results of climate change, which is connected to the midpoint impact categories and describes a model that characterizes the severity of the environmental damages caused by the LCI [59,61,62].

Because the endpoint methods are damage-oriented, they are generally considered more comprehensible for decision makers. However, the methods are highly subjective, which is the opposite of the midpoint methods, which are less subjective but also less relevant as decision-making support [61,62]. Fig. 3 represents the interpretation times of the midpoint and endpoint approaches.

The LCIA methods are integrated in the databases and implemented in LCA computational tools. Different methodologies are used; thus, there is no single model for this step [63]. According to the LCIA Manual “Analysis of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment (LCA)” [64], the main LCIA methodologies are listed in Table 3, including the developers, country of origin, and approach.

2.2.4. Interpretation of results

The interpretation of results is the phase that combines the observations of the inventory analysis and the impact assessment, in a manner consistent with the defined goal and scope to reach conclusions, clarify limitations that could be an obstacle to the initial goals, identify the main life cycle phases that contribute to the environmental impacts, and provide final recommendations [14,16,33,46]. The interpretation phase is extremely important because it is the key to making the impact assessment results comparable and comprehensible.

2.3. LCA computational tools

Due to the large amount of data required for the performance of an LCA study, it is fundamental to use software that makes the study more efficient, considering that these software packages are integrated with inventory databases and impact analysis methodologies [3,65]. Currently, there are many LCA software tools that make possible studies with different levels of detail (Table 4) [16,66,67].

The LCA software packages have LCA databases and methods integrated into their system, reducing the time required for the collection of inventory data and for performing the impact assessment, generating tables and graphs that help with the interpretation of results [65,67].

All software programs are designed to help the user during the LCA inventory phase, and therefore they should be user-friendly, have data processing capacity, and produce fast and accurate results, considering that each software package has advantages and disadvantages with regard to price or functionality.

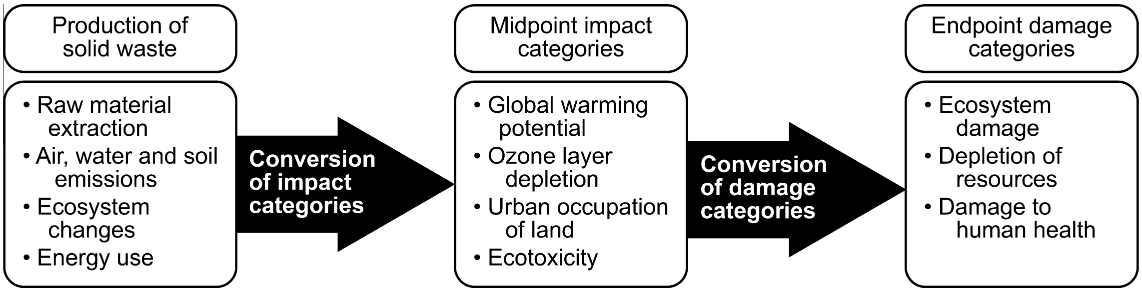

Fig. 3. Midpoint and endpoint approaches. Source: Adapted from Blankendaal et al. [4].

Table 3
Main LCIA methodologies. Source: Adapted from the *ILCD Handbook* [64].

Methodology	Developer	Country of origin	Approach
CML 2002	CML	Netherlands	Endpoint
Eco-indicator 99	Pré Consultants	Netherlands	Endpoint
EDIP97 – EDIP2003	DTU	Denmark	Midpoint
EPS 2000	IVL	Sweden	Endpoint
Impact 2002+	EPFL	Switzerland	Midpoint/ Endpoint
LIME	AIST	Japan	Midpoint/ Endpoint
LUCAS	CIRAIG	Canada	Midpoint
ReCiPe	RUN + PRé + CML + RIVM	Netherlands	Midpoint/ Endpoint
Swiss Ecoscarcity 07	E2 + SEU-services	Switzerland	Midpoint
TRACI	US EPA	United States	Midpoint
MEEuP	VhK	Netherlands	Midpoint

Table 4
Examples of LCA software. Source: Adapted from Bribián et al. [3] and Islam et al. [67].

LCA Software	Website of developer	Country of origin
Boustead	www.boustead-consulting.co.uk	United Kingdom
Eco-it	www.pre.nl	Netherlands
Ecopro	www.sinum.com	Netherlands
Ecoscan	www.ind.tno.nl	Netherlands
KCL Eco	www.kcl.fi/eco	Finland
Gabi	www.gabi-software.com	Germany
LCAit	www.ekologik.cit.chalmers.se	Sweden
Miet	www.leidenuniv.nl/cml/ssp/software	Netherlands
Pems	www.piranet.com/pack/lca_software.htm	United States
SimaPro	www.pre-sustainability.com	Netherlands
Team	www.ecobilan.com	France
Wisard	www.pwcglobal.com	France
Umberto	www.umberto.de	Germany
LCA PIX	www.kmlmtd.com	United States

3. The state-of-the-art of the life cycle assessment applied to the concrete manufacturing industry

3.1. Review of the definitions and concepts in the study of concretes

Concrete is applied to a great variety of structures, from large embankments to sophisticated buildings; and in comparison to other metallic, ceramic, and polymeric construction materials, concrete is less expensive and exhibits adequate resistance and durability [4]. Its annual consumption is approximately 6.5 billion tons, making it the second most commonly consumed material by humans after water.

Based on compressive strength criteria after 28 days, concrete can be classified into the following categories: low-strength concrete with compressive strength below 20 MPa, medium-strength concrete with compressive strength between 20 and 40 MPa, and high-strength concrete with compressive strength above 40 MPa [68].

Concrete is a mixture of different amounts of Portland cement, coarse aggregates, fine aggregates, water, additives, and mineral admixtures, and when it is hydrated with water, the cement forms a resistant paste that bonds to the aggregate fragments, forming a monolithic block [4,69]. The concrete dosage known as a "mixture" is the set of procedures and decisions that allow the establishment of relative proportions or amounts of the materials that constitute the concrete [68].

The most important part of concrete is the cement, which acts as a bonding material [4]. In general terms, cement is any material with adhesive and cohesive properties, able to bond mineral fragments, forming a compact body [70]. The Portland cement manufactured today consists of clinker, a sinterized and pelletized material that results from the calcination at approximately 1450 °C of a mixture of limestone, clay, and eventual chemical correctors of siliceous, aluminous, or ferrous nature [4,68,70].

Another important factor in the preparation of concrete is the care taken with the quality and quantity of water used because water is responsible for the activation of the chemical reaction that transforms cement into an agglomerating paste. If the quantity is too small, then the reaction does not completely occur, and if it is greater than the ideal, then the resistance decreases due to the pores that will appear when the excess water evaporates [68–70]. Cement hydration consists of the transformation of more soluble anhydrous compounds into less soluble hydrated compounds [68–70]. Therefore, the chemical elements, along with the water, are rearranged into new crystal systems, conferring rigidity to the mixture, which is the main rheological property expected in the product [68–70]. In this hydration process, the calcium sulfate present in the cement composition acts as a bond retardant, preventing the immediate hardening of the paste caused by the reaction of C3A with water [68–70].

Aggregates are granular materials with no defined shape or volume, generally inert, with dimensions and properties suitable for use in construction [68–70]. Considering that the aggregates are interlinked in a monolithic body by the cement paste, they confer extremely advantageous technical characteristics to concrete, which is provided with better dimensional stability and greater durability in relation to pure cement paste [68–70]. The term coarse aggregate is used to describe aggregates larger than 4.8 mm, and the term fine aggregate is used to describe particles smaller than 4.8 mm [68–70]. The production of aggregates can be classified as natural or artificial. Natural aggregates, generally the most commonly used, are derived from sand, gravel, and grit. Artificial aggregates are generally derived from residues and solid waste from industrial activities [71]. In areas with a scarcity of sand, gravel, or grit, different types of recycled construction waste that do not react with quicklime may be used as aggregate material, including recycled concrete if it is grinded and reaches the average size of aggregates [4,72].

For specific concrete-use situations, it is necessary to use additives, which are substances added intentionally during the mixing process, in amounts not larger than 5% of the cement mass to enhance or improve certain characteristics, also helping its preparation and use, modifying the mixture properties at its fresh or hardened state [68–70].

The term mineral admixture refers to any material apart from water, aggregates, and cement that is used as a component in the concrete mixture immediately before or during mixing as a partial substitute for the cement or natural aggregates due to their similar properties [73,74]. To substitute for parts of the cement, the most commonly used mineral admixtures can be classified as cementing and pozzolans and include ground granulated blast furnace slag, fly ash, metakaolin, rice husk ash, and other materials being studied [75,76]. To partially substitute for the aggregates, natural fillers such as limestone, quartz powder, and rock residues can be used [77].

In the context of this study, mineral admixtures are fundamentally important for the sustainability and improvement of the life cycle of concrete because as partial substitutes for Portland cement and aggregates, these materials provide considerable energy and cost reductions, in addition to not being disposed in the environment, which would generate more environmental problems [68–70,73,74].

Fig. 4 presents the life cycle of concrete with the phases that constitute its production chain. First, the original materials composing

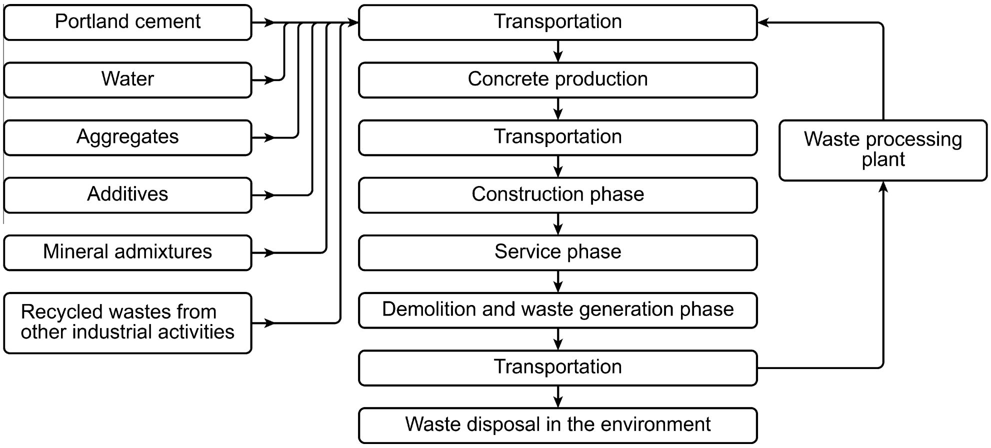

Fig. 4. Life cycle of concrete.

the mixture (cement, water, aggregates, additives, and admixtures) are transported to a concrete production plant (production phase) where they are mixed and once again transported in concrete mixer trucks to construction sites (construction phase). After the concrete is molded and undergoes the curing process, it starts to be used (service phase). Years later, when the material has undergone fatigue by the action of time or is not useful anymore, it can be demolished (demolition phase), generating a large amount of waste. The waste generated is then disposed of; however, it has great recycling potential and can be processed and returned to the beginning of the life cycle of a new concrete or mortar.

LCA applied to concrete production has led to many studies with the purpose of increasing the sustainability of the material, considering its socioeconomic importance worldwide. Many points in the life cycle of concrete illustrated in Fig. 4 are currently being studied to make the material more sustainable, and these are discussed in Section 3.2. Studies on concrete mixtures focus on the creation of alternatives to substitute for a large amount of Portland cement and natural aggregates with mineral admixtures and recycled waste from other industries (an increasing amount of admixtures and less clinker), always cautiously so the material quality is maintained, ensuring the longest possible useful life in the service phase. In the logistics part of the process, studies are analyzing the types of transportation, the distances, and the geographical locations of plants to find the best possible interaction. At the end of the life cycle, the wastes generated are being analyzed to maximize their use and once again become inputs in the production of more concrete and another industrial production chain.

3.2. LCA in the concrete manufacturing industry

LCA has been used in the construction sector since 1990 and is an important tool for the environmental impact assessment of materials and for the environmental performance assessment of buildings [48,78–80]. The methodology has become widely used due to its integrated way of treating topics such as the environmental framework, impact assessment, and the quality of data [81].

In the construction industry, LCA studies can be performed at 3 different system boundary levels. The first level includes the cradle-to-gate approach, which considers the impacts of raw material extraction and material production until the exit of the product from the factory. The second level includes the cradle-to-grave approach, which considers the impacts of raw material extraction, material production, the exit of the final product from the factory, and the use, demolition, and waste phases. The third level, focusing more on sustainability, includes the cradle-to-cradle approach, which considers the impacts of raw material extraction, material production, the exit of the final product from the factory, and the phases of use, demolition, waste, recycling, and extensive reuse of the waste [14].

In a sustainable production context in civil construction, products should be conceived so that at the beginning of their life cycle, they absorb recycled waste as raw material, and at the end of their life cycle, they can be recycled and reused to become raw materials for another production system. Concrete is an example of this concept; its design and mixture can be adjusted to absorb waste at the beginning of the life cycle, and after its useful life, at the end of the life cycle, its remains can be used as raw material in the production of cement and aggregates in the production of new concretes [14].

To better understand the scientific advancements in the attempt to decrease the environmental impacts of the concrete life cycle, 12 studies were identified that describe the general characteristics of the applications of the LCA methodology in the environmental assessment of common and ecological concretes (Table 5).

Concrete is the main product manufactured and sold around the world, and therefore, its by-products represent a large volume of industrial production, which justifies the study performed by Habert et al. [11], which discusses the need for having a specific LCIA method for the production of concrete with more reliable indicators of the regional depletion of natural resources, representing the first study to identify this need. The study aimed to propose a reliable and clear indicator capable of evaluating the current state of local depletion of natural resources in different regions because the indicators commonly used to assess the consumption of resources in the LCIA are not completely adapted to the specific sector of the concrete industry. To solve this problem, a new method for calculating this consumption of resources was proposed, using a specific assessment of the stock of resources for the reality of concrete production. The new proposal allowed the identification of different impacts on the resources used in the production of concrete; however, this new proposal was not found in other studies nor was it integrated in specific LCIA methodologies used internationally.

Another alternative to solving resource depletion problems is observed in Chen et al. [82], who evaluated the use of waste such as blast furnace slag and fly ash as inputs in the production of concrete, replacing part of the Portland cement and making it possible to economize non-renewable inputs, saving such inputs and avoiding their depletion.

In the concrete industry, the concern with non-renewable resource depletion is notorious, and therefore, alternatives for

Table 5
LCA studies applied to the production of concrete. Source: Prepared by the authors.

References	Country	Publication year	LCA application
Celik et al. (2015)	United States	2015	Two concrete mixtures were compared to measure pollutant emission using the "GreenConcrete LCA" tool developed specifically to perform LCA in concretes.
Dong et al. (2015)	China	2015	Investigation of the substitution of LCI data from international databases with local data in studies on concretes manufactured in Hong Kong.
Laurent et al. (2014a)	Denmark	2014	Critical review of 222 LCA published studies on solid waste management systems, discussing lessons learned and perspectives.
Laurent et al. (2014b)	Denmark	2014	Critical review of 222 LCA published studies on solid waste management systems, discussing methodological guidelines for best practices.
Ingrao et al. (2014a)	Italy	2014	LCA application in the environmental assessment of input and output flows of pollutant emissions related to the production of concrete, using basalt aggregates.
Gursel and Horvath (2014)	United States	2014	Analysis of the strong points and weak points of the LCIs of concrete, offering an investigation routine to improve the quality of future LCIs in the concrete production processes, meeting the needs of large LCA users.
Blankendaal et al. (2014)	Netherlands	2014	Application of LCA to evaluate alternatives for the reduction of environmental impact in the production of concrete and asphalt.
Valipour et al. (2014)	Iran	2013	Application of LCA to evaluate the global warming potential of concrete containing zeolite compared to conventional concrete.
Van den Heede and De Belie (2012)	Belgium	2012	Literature review of LCA applied to the production of common and ecological concretes.
Marinković et al. (2010)	Serbia	2010	Application of LCA to compare the environmental impacts of concretes produced with natural and recycled aggregates.
Chen et al. (2010)	France	2010	Application of LCA to evaluate the use of recycled waste as by-product of concrete production.
Habert et al. (2010)	France	2010	Proposal of a reliable indicator of local resource depletion for the production of concrete.

the use of aggregates originating from concrete recycling are also being studied. One example is Marinkovic et al. [16], for whom one of the objectives was to compare the LCA of concretes produced with natural aggregates (NAC) and concretes produced with recycled aggregates from construction and demolition waste (RAC); remarkable discoveries were made.

In Marinkovic et al. [16], the part of the life cycle of concrete analyzed includes the production and transportation of aggregates and cement, the concrete production in the factory, and the transportation of concrete to the construction site. The construction phase, the service phase, and the demolition phase are not considered in the study because both concretes were designed to meet similar functional requirements, and therefore, it was considered that these phases do not influence the study results. The LCA results indicate that the total environmental impacts, in terms of energy use, global warming, eutrophication, acidification, and the creation of photochemical oxidants, depend mainly on the distances and the types of transportation used in the process, emphasizing that the environmental viability of using recycled aggregates is only obtained when recycling plants are located near concrete plants, although there are significant gains in the categories of waste decrease and the minimization of natural resource depletion.

A large variety of environmental impacts studies applied to comparisons of ecological concretes with traditional concretes have been conducted; thus, Van Den and De Belie [14] performed a literature review on the factors that influence LCA for these concretes, considering 3 main points that require more attention: (I) in the goal and scope definition, the selection of a functional unit is viewed as one of the factors of greatest influence, and therefore, it is necessary to select a unit where all physical and chemical characteristics are equal in magnitude; (II) in the creation and inventory analysis phase, the quality of the data has a strong influence on the quality of the LCA results, and therefore, the preference will be for data collected first-hand and better adapted to the region of the study, ensuring accuracy and representativeness; and (III) in the impact assessment, the LCIA method should analyze more than climate change and should be problem-oriented.

The great concern with greenhouse gas emissions generated by the cement industry is the subject of Valipour et al. [12], who compare the LCA of conventional concrete with that of concretes manufactured with zeolite, partially substituting for cement to reach lower greenhouse gas emissions. This study compares a conventional concrete to 3 concretes produced with the substitution of 10%, 20%, and 30% of cement by zeolite. With the LCA, it was possible to identify a reduction in the global warming potential of 60.3%, 69.7%, and 64.3%, respectively.

Valipour et al. [12] showed that the LCA methodology was very efficient in analyzing greenhouse gas emissions and making comparisons, and the results indicated a significant reduction in the global warming index when zeolite was used. The study also indicated that the partial substitution of cement by zeolite can decrease the global warming potential; however, only LCA allowed the identification of the optimal percentage of substitution to identify the most effective mixture.

In 2014, the application of the LCA methodology became even more relevant in the concrete production sector; similar to Chen et al. [82], Blankendaal et al. [4] evaluated alternatives to reduce environmental impacts using an LCIA endpoint method named ReCiPe to compare 10 concrete mixture scenarios to identify which is best. The study concluded that the best method for decreasing the environmental impacts of concrete is by substituting part of the Portland cement with recycled or recovered mineral admixtures, and it highlighted that the use of blast furnace slag and fly ash could reduce environmental impacts in the life cycle of concrete by 39%.

In the same year, Gursel et al. [83] noted 3 important factors that need to be treated more carefully in future LCA studies on concrete: (I) the lack of a holistic assessment of environmental impacts in current LCAs because studies are focused on energy use and greenhouse gas emissions and are not analyzing other factors such as volatile organic compounds, heavy metals, and other toxic emissions from the inputs of concrete production; (II) the lack of applications of regional and technological variations in current LCA studies; and (III) the neglect of phases considered to be insignificant based on suppositions or previous studies.

Of the studies discussed here, the study that best exemplifies the LCA methodology in concrete production was performed by Ingrao et al. [46]. They performed a complete application of the methodology to conduct the environmental assessment of the input and output flows related to concrete production using basalt aggregates in Italy. The study used the Ecoinvent database, the

Impact 2002+ impact method, and the SimaPro software package, which is currently the most commonly used computational tool in LCA studies, to process the data. The study results indicate "Human Health" as the most affected damage category due to the emissions of particulate matter from the extraction of basalt.

The concern with solid waste is the focus of Laurent et al. [84,85], who highlight that the LCA tool is fundamental to improving the efficiency of solid waste management systems. Laurent et al. [84,85] performed a critical review of 222 LCA studies applied to solid waste management systems, observing the geographical distribution, the types of waste under analysis, and the quality of these studies. It was found that the studies were mainly concentrated in Europe, with little application to developing countries, and that they largely ignored the application to construction and demolition waste, which are greatly relevant in the life cycle of concrete. With regard to the quality of the studies, the results indicate that the LCA methodology is being erroneously applied in many aspects of the assessment, generating unreliable results. Some examples include the frequent neglect of defining the goal, a frequent lack of transparency and precision in the definition of the scope, the unclear delineation of system boundaries, difficulties in capturing the local influential specifications such as the representative waste compositions for the inventory, and frequent uncertainty in the analysis of results. To improve the application of the LCA methodology in solid waste management, Laurent et al. [85] provided detailed recommendations for each study phase.

Two studies from 2015 were also analyzed. Dong et al. [54] investigated the substitution of LCI data from international databases by local data in studies on concretes manufactured in Hong Kong because, currently, the majority of the internationally available databases are provided with data based on the European reality, making it difficult to perform LCA studies in other continents where the main changes in the LCA of concrete are caused by adjustments in the cement and transportation distances and types.

Finally, Celik et al. [86] present a major advancement because they applied a specific computational tool, called "GreenConcrete LCA", developed by Gursel and Horvath [87] at the University of California, for the LCA of concrete production. This tool evaluates the environmental profile of concrete mixtures, using 2 direct inputs and the supply chain. The tool also allows the application of regional variations and technological changes to the production processes; however, no information was found on the database that this tool links to or on the LCIA method used for the impact assessment. The tool is available at http://greenconcrete.berkeley.edu/. The work by Celik et al. [86] is a major breakthrough in the study of concrete because it provides a new approach to assessing alternative mineral admixtures, making it clear that in addition to analyzing the mechanical properties of the alternative material, its entire life cycle should be paid more attention to by means of an LCA study.

4. Conclusions

The present review compiles the LCA concepts and tools applied to concrete manufacturing. LCA is an innovative methodology for improving the industry's sustainability in all life cycle phases. The methodology was discussed considering all phases of the ISO 14.040 [25] and 14.044 [26] series of international standards, explaining in detail the 4 phases of its application: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation of results. Additionally, the importance of using an LCI database, an LCIA method, and a software package to improve the efficiency of the study was discussed.

To explain the scientific breakthroughs of LCA studies on concrete, 12 studies were reviewed to characterize the current scenario, leading to the following conclusions:

- There is a great need to incorporate recycled waste at the start of the concrete life cycle, in addition to a need to transform the waste generated at the end of its life cycle into inputs for another production system or even for the concrete production system.
- The need for further LCA studies on the treatment and reuse of construction waste is evident to prevent its disposal in the environment and to incorporate it in the life cycle of new concretes.
- Currently, it is possible to classify LCA studies on concrete into 3 system boundaries: cradle-to-gate, cradle-to-grave, and cradle-to-cradle. Although the most commonly used boundary is the cradle-to-gate, the tendency is to advance to the cradle-to-cradle approach.
- Studies indicate a trend toward evaluations of the use of waste such as blast furnace slag, fly ash, and other mineral admixtures (with less clinker and more mineral admixtures) for the production of concrete, substituting for part of the Portland cement because cement is the main factor responsible for the environmental impacts caused by the life cycle of concrete.
- In the LCA of the use of recycled waste as aggregates in concrete production, considerable attention should be paid to the types of transportation used in the process and the distance from the waste processing plant to ensure considerable gains in the greatest number of environmental impact categories.
- Three factors that should be considered when comparing the LCA of common concrete to that of ecological concrete are the selection of the functional unit, the inventory data, and the LCIA method.
- Three factors that should receive more attention in future studies are the lack of a holistic assessment of environmental impacts, the lack of applications that consider regional and technological variations, and the neglect of phases.
- Among the LCIA methods, LCI databases, and the LCA software developed, the predominance of European and North American countries is evident, with emphasis on Germany, the Netherlands and the United States, thus confirming that these countries are at the forefront in the development of LCA studies.
- The LCA methodology has been found to be an excellent tool for the comparison of scenarios with different concrete mixtures in the search for an optimal amount of alternative mineral admixtures, seeking the lowest environmental impact.
- The "GreenConcrete LCA" tool is a major breakthrough in LCA studies on concrete because, different from the tools available for LCA studies, it is specific and adapted to concrete manufacturing.
- The new approach to assessing the technical performance of alternative mineral admixtures is evident, showing that in addition to the analyzing the material's mechanical properties, the analysis of its life cycle is also relevant and will indicate whether it will be environmentally viable to use the mineral admixture at the complete scale of the life cycle of concrete.

Acknowledgements

The authors would like to acknowledge the support of the Research Chair in Management of Aeronautical Projects at the University of Quebec at Trois-Rivières.

References

[1] R. Feiz, J. Ammenberg, L. Baas, M. Eklund, A. Helgstrand, R. Marshall, Improving the CO_2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry, J. Cleaner Prod. 98 (2015) 272–281.

[2] M. Zimmermann, H. Althaus, A. Haas, Benchmarks for sustainable construction, Energy Build. 37 (2005) 1147–1157.

[3] I.Z. Bribían, A.V. Capilla, A.A. Usón, Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco efficiency improvement potential, Build. Environ. 46 (2010) 1133–1140.

[4] T. Blankendaal, P. Schuur, H. Voordijk, Reducing the environmental impact of concrete and asphalt: a scenario approach, J. Cleaner Prod. 66 (2014) 27–36.

[5] M.M. Monkizkhasreen, P.F.G. Banfill, G.F. Menzies, Life-cycle assessment and the environmental impact of buildings: a review, Sustainability 1 (2009) 674–701.

[6] H. Yan, Q. Shen, L.C.H. Fan, Y. Wang, L. Zhang, Greenhouse gas emissions in building construction: a case study of one Peking in Hong Kong, Build. Environ. 45 (2010) 949–955.

[7] A. Dimoundi, C. Tompa, Energy and environmental indicators related to construction of office buildings, Resour. Conserv. Recycl. 53 (2008) 86–95.

[8] X. Li, Y. Zhu, Z. Zhang, An LCA-based environmental impact assessment model for construction processes, Build. Environ. 45 (2010) 766–775.

[9] P.T. Lam, E.H. Chan, C.K. Chau, C.S. Poon, K.P. Chun, Environmental management system vs green specifications: how do they complement each other in the construction industry?, J Environ. Manage. 92 (2011) 788–795.

[10] O. Ortiz, C. Bonnet, J.C. Bruno, F. Castells, Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain, Build. Environ. 44 (2009) 584–594.

[11] G. Habert, Y. Bouzidi, C. Chen, A. Jullien, Development of a depletion indicator for natural resources used in concrete, Resour. Conserv. Recycl. 54 (2010) 364–376.

[12] M. Valipour, M. Yekkalar, M. Shekarchi, S. Panahi, Environmental assessment of green concrete containing natural zeolite on the global warming index in marine environments, J. Cleaner Prod. 65 (2014) 418–423.

[13] T. Proske, S. Hainer, M. Rezvani, C. Graubner, Eco-friendly concretes with reduced water and cement contents — mix design principles and laboratory tests, Cem. Concr. Res. 51 (2013) 38–46.

[14] P. Van den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations, Cem. Concr. Compos. 34 (2012) 431–442.

[15] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.P. Schmidt, S. Suh, B.P. Weidema, D.W. Pennington, Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications, Environ. Int. 30 (2004) 701–720.

[16] S. Marinković, V. Radonjanin, M. Malešev, I. Ignjatović, Comparative environmental assessment of natural and recycled aggregate concrete, Waste Manage. 30 (2010) 2255–2264.

[17] J. Cleary, The incorporation of waste prevention activities into life cycle assessments of municipal solid waste management systems: methodological issues, Int. J. Life Cycle Assess. 15 (2010) 579–589.

[18] E.C. Gentil, D. Gallo, T.H. Christensen, Environmental evaluation of municipal waste prevention, Waste Manage. 31 (2011) 2371–2379.

[19] D. Laner, H. Rechberger, Quantitative evaluation of waste prevention on the level of small and medium sized enterprises (SMEs), Waste Manage. 29 (2009) 606–613.

[20] A. Takano, S. Winter, M. Hughes, L. Linkosalmi, Comparison of life cycle assessment databases: a case study on building assessment, Build. Environ. 79 (2014) 20–30.

[21] E.C. Gentil, A. Damgaard, M. Hauschild, G. Finnveden, O. Eriksson, S. Thorneloe, P.O. Kaplan, M. Barlaz, O. Muller, Y. Matsui, R. Ii, T.H. Christensen, Models for waste life cycle assessment: review of technical assumptions, Waste Manage. 30 (2010) 2636–2648.

[22] A.E. Björklund, G. Finnveden, Life cycle assessment of a national policy proposal – the case of a Swedish waste incineration tax, Waste Manage. 27 (2007) 1046–1058.

[23] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: a review, Renewable Sustainable Energy Rev. 26 (2013) 379–388.

[24] J.K. Staniskis, V. Varzinskas, Life cycle based design and product development: application of LCA to Lithuanian industry, Eng. Manage. 54 (2010) 43–53.

[25] International Organization for Standardization (ISO), Environmental management e life cycle assessment e principles and frameworks, ISO (2006) 14.040.

[26] International Organization for Standardization (ISO), Environmental management e life cycle assessment e requirements and guidelines, ISO (2006) 14.044.

[27] C.K. Chau, T.M. Leung, W.Y. Ng, A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings, Appl. Energy 143 (2015) 395–413.

[28] M. Niero, C.H. Ingvordsen, P. Peltonen-Sainio, M. Jalli, M.F. Lyngkjær, M.Z. Hauschild, R.B. Jørgensen, Eco-efficient production of spring barley in a changed climate: a life cycle assessment including primary data from future climate scenarios, Agric. Syst. 136 (2015) 46–60.

[29] G. Finnveden, J. Johansson, P. Lind, Å. Moberg, Life cycle assessment of energy from solid waste – part 1: general methodology and results, J. Cleaner Prod. 13 (2005) 213–229.

[30] Å. Moberg, G. Finnveden, J. Johansson, P. Lind, Life cycle assessment of energy from solid waste – part 2: landfilling compared to other treatment methods, J. Cleaner Prod. 13 (2005) 231–240.

[31] I. Bribián, A. Usón, S. Scarpellini, Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (2009) 2510–2520.

[32] B. Reza, R. Sadiq, K. Hewage, Emergy-based life cycle assessment (Em-LCA) of multi-unit and single-family residential buildings in Canada, Int. J. Sustainable Built Environ. 3 (2014) 207–224.

[33] A.F. Rashid, S. Yusoff, A review of life cycle assessment method for building industry, Renewable Sustainable Energy Rev. 45 (2015) 244–248.

[34] International Organization for Standardization (ISO), Environmental management for concrete and concrete structures – part 1: general principles, ISO (2012) 13.315-1.

[35] International Organization for Standardization (ISO), Environmental management for concrete and concrete structures – part 2: system boundary and inventory data, ISO (2014) 13.315-2.

[36] International Organization for Standardization (ISO), Environmental management e life cycle assessment – objectives and scope definition and inventory analysis, ISO (2006) 14.041.

[37] International Organization for Standardization (ISO), Environmental management e life cycle assessment – life cycle impact assessment, ISO (2006) 14.042.

[38] International Organization for Standardization (ISO), Environmental management e life cycle assessment – life cycle analysis, ISO (2006) 14.043.

[39] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: a review of recent developments based on LCA, Constr. Build. Mater. 23 (2009) 28–39.

[40] D. Pandey, M. Agrawal, J.S. Pandey, Carbon footprint: current methods of estimation, Environ. Monit. Assess. 178 (2011) 135–160.

[41] L. Ozawa-Meida, P. Brockway, K. Letten, J. Davies, P. Fleming, Measuring carbon performance in a UK University through a consumption-based carbon footprint: De Montfort University case study, J. Cleaner Prod. 56 (2013) 185–198.

[42] M.K. Chauhan, S. Chaudhary, S. Kumar, Life cycle assessment of sugar industry: a review, Renewable Sustainable Energy Rev. 15 (2011) 3445–3453.

[43] B. Löfgren, A. Tillman, B. Rinde, Manufacturing actor's LCA, J. Cleaner Prod. 19 (2011) 2025–2033.

[44] B.M.K. Manda, E. Worrell, M.K. Patel, Innovative membrane filtration system for micropollutant removal from drinking water – prospective environmental LCA and its integration in business decisions, J. Cleaner Prod. 72 (2014) 153–166.

[45] R. de Larriva, G. Rodríguez, J.M. López, M. Raugei, P.F. i Palmer, A decision-making LCA for energy refurbishment of buildings: conditions of comfort, Energy Build. 70 (2014) 333–342.

[46] C. Ingrao, A. Lo Giudice, C. Mbohwa, M.T. Clasadonte, Life cycle inventory analysis of a precast reinforced concrete shed for goods storage, J. Cleaner Prod. 79 (2014) 152–167.

[47] C. Ingrao, A. Lo Giudice, C. Tricase, C. Mbohwa, R. Rana, The use of basalt aggregates in the production of concrete for the prefabrication industry: environmental impact assessment, interpretation and improvement, J. Cleaner Prod. 75 (2014) 195–204.

[48] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review, Renewable Sustainable Energy Rev. 29 (2014) 394–416.

[49] H. Monteiro, F. Freire, Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods, Energy Build. 47 (2012) 572–583.

[50] S. Suh, G. Huppes, Methods for life cycle inventory of a product, J. Cleaner Prod. 13 (2005) 687–697.

[51] J. Zhou, V.W. Chang, A.G. Fane, Environmental life cycle assessment of reverse osmosis desalination: the influence of different life cycle impact assessment methods on the characterization results, Desalination 283 (2011) 227–236.

[52] A.F. Sherwani, J.A. Usmani, Life cycle assessment of solar PV based electricity generation systems: a review, Renewable Sustainable Energy Rev. 14 (2010) 540–544.

[53] H.W. Kua, S. Kamath, An attributional and consequential life cycle assessment of substituting concrete with bricks, J. Cleaner Prod. 81 (2014) 190–200.

[54] Y.H. Dong, S.T. Ng, A.H.K. Kwan, S.K. Wu, Substituting local data for overseas life cycle inventories – a case study of concrete products in Hong Kong, J. Cleaner Prod. 87 (2015) 414–422.

[55] F. Cherubini, M. Raugei, S. Ulgiati, LCA of magnesium production: technological overview and worldwide estimation of environmental burdens, Resour. Conserv. Recycl. 52 (2008) 1093–1100.

[56] P.H. Ribeiro, Contribuição ao banco de dados brasileiro para apoio a avaliação do ciclo de vida: fertilizantes nitrogenados Tese, Doutorado em Engenharia, Universidade de São Paulo, 2009.

[57] M.S.V. Costa, O enfoque de ciclo de vida Como estratégia para a gestão sustentável: um estudo de caso sobre pneus. Dissertação, Mestrado em Engenharia de Produção, 2007.

[58] K. Van Ooteghem, L. Xu, The life-cycle assessment of a single-storey retail building in Canada, Build. Environ. 49 (2012) 212–226.

[59] O. Cavalett, M.F. Chagas, J.E.A. Seabra, A. Bonomi, Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods, Int. J. Life Cycle Assess. 18 (2013) 647–658.

[60] D.W. Pennington, J. Potting, G. Finnveden, E. Lindeijer, O. Jolliet, T. Rydberg, G. Rebitzer, Life cycle assessment part 2: current impact assessment practice, Environ. Int. 30 (2004) 721–739.

[61] J.C. Bare, T.P. Gloria, Environmental impact assessment taxonomy providing comprehensive coverage of midpoints, endpoints, damages, and areas of protection, J. Cleaner Prod. 16 (2008) 1021–1035.

[62] J.C. Bare, P. Hofstetter, D.W. Pennington, H.A.U. de Haes, Midpoints versus endpoints: the sacrifices and benefits, Int. J. Life Cycle Assess. 5 (2000) 319–326.

[63] M. Pizzol, P. Christensen, J. Schmidt, M. Thomsen, Eco-toxicological impact of "metals" on the aquatic and terrestrial ecosystem: a comparison between eight different methodologies for life cycle impact assessment (LCIA), J. Cleaner Prod. 19 (2011) 687–698.

[64] JRC European Commission 2010, ILCD handbook, analysis of existing environmental impact assessment methodologies for use in life cycle assessment (LCA). Available from: <http://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf> (accessed 18 December 2014).

[65] E. Martínez, J. Blanco, E. Jiménez, J.C. Saenz-Díez, F. Sanz, Comparative evaluation of life cycle impact assessment software tools through a wind turbine case study, Renewable Energy 74 (2015) 237–246.

[66] G.K. Ding, Sustainable construction – the role of environmental assessment tools, J. Environ. Manage. 86 (2008) 451–464.

[67] H. Islam, M. Jollands, S. Setunge, Life cycle assessment and life cycle cost implication of residential buildings—a review, Renewable Sustainable Energy Rev. 42 (2015) 129–140.

[68] P.K. Mehta, P.J.M. Monteiro, Concreto: Estrutura, Propriedades e Materiais, Editora PINI, São Paulo, 1994.

[69] L.A.F. Bauer, Materiais De Construção, Editora LTC, São Paulo, 2004.

[70] A.M. Neville, Propriedades do Concreto, second ed., Editora Pini, São Paulo, 1997.

[71] F. Gameiro, J. de Brito, D.C. da Silva, Durability performance of structural concrete containing fine aggregates from waste generated by marble quarrying industry, Eng. Struct. 59 (2014) 654–662.

[72] K. Rahal, Mechanical properties of concrete with recycled coarse aggregate, Build. Environ. 42 (2007) 407–415.

[73] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete – a breakthrough towards sustainability in construction sector: a review, Constr. Build. Mater. 68 (2014) 501–516.

[74] H.S. Müller, R. Breiner, J.S. Moffatt, M. Haist, Design and properties of sustainable concrete, Procedia Eng. 95 (2014) 290–304.

[75] M.L. Nehdi, Clay in cement-based materials: critical overview of state-of-the-art, Constr. Build. Mater. 51 (2014) 372–382.

[76] D. Cree, M. Green, A. Noumowé, Residual strength of concrete containing recycled materials after exposure to fire: a review, Constr. Build. Mater. 45 (2013) 208–223.

[77] D. Matias, J. de Brito, A. Rosa, D. Pedro, Mechanical properties of concrete produced with recycled coarse aggregates – influence of the use of superplasticizers, Constr. Build. Mater. 44 (2013) 101–109.

[78] V.M. Taborianski, R.T.A. Prado, Comparative evaluation of the contribution of residential water heating systems to the variation of greenhouse gases stock in the atmosphere, Build. Environ. 39 (2004) 645–652.

[79] J.A. Fava, Will the next 10 years be as productive in advancing life cycle approaches as the last 15 years?, Int J. Life Cycle Assess. 11 (2006) 6–8.

[80] A. Brás, V. Gomes, LCA implementation in the selection of thermal enhanced mortars for energetic rehabilitation of school buildings, Energy Build. 92 (2015) 1–9.

[81] W. Klöpffer, The role of SETAC in the development of LCA, Int. J. Life Cycle Assess. 11 (2006) 116–122.

[82] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete, Resour. Conserv. Recycl. 54 (2010) 1231–1240.

[83] A. Gursel, E. Masanet, A. Horvath, A. Stadel, Life-cycle inventory analysis of concrete production: a critical review, Cem. Concr. Compos. 51 (2014) 38–48.

[84] A. Laurent, I. Bakas, J. Clavreul, A. Bernstad, M. Niero, E. Gentil, M.Z. Hauschild, T.H. Christensen, Review of LCA studies of solid waste management systems – part I: lessons learned and perspectives, Waste Manage. 34 (2014) 573–588.

[85] A. Laurent, J. Clavreul, A. Bernstad, I. Bakas, M. Niero, E. Gentil, T.H. Christensen, M.Z. Hauschild, Review of LCA studies of solid waste management systems – part II: methodological guidance for a better practice, Waste Manage. 34 (2014) 589–606.

[86] K. Celik, C. Meral, A. Petek Gursel, P.K. Mehta, A. Horvath, P.J.M. Monteiro, Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended Portland cements containing fly ash and limestone powder, Cem. Concr. Compos. 56 (2015) 59–72.

[87] A.P. Gursel, A. Horvath, GreenConcrete LCA Tool, Universidade da Califórnia, Berkeley, 2012. <http://greenconcrete.berkeley.edu> (accessed 18 December 2014).