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Review

Sustainability in the construction industry: A review of recent developments based on LCA

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Abstract

This review brings together research on life cycle assessment (LCA) applied within the building sector. More than ever, the construction industry is concerned with improving the social, economic and environmental indicators of sustainability. By applying LCA it is possible to optimise these aspects, from the extraction of raw materials to the final disposal of waste building materials. Firstly, this review details LCA concepts and focuses on the LCA methodology and tools employed in the built environment. Secondly, this paper outlines and discusses the differences between the LCA of building materials and components combinations versus the LCA of the full building life cycle. Finally, this work can be used by stakeholders as an important reference on LCA including up to date literature on approaches and methodologies to preserve the environment and therefore achieve sustainable development in both developed and developing countries.

The present review has tried to compile and reflect the key milestones accomplished in LCA over the last 7 years, from 2000 to 2007 within the building sector. In summary, it can be stated that the application of LCA is fundamental to sustainability and improvement in building and construction. For industrial activities, SMEs must understand the application of LCA, not only to meet consumer demands for environmentally friendly products, but also to increase the productivity and competitiveness of the green construction markets. For this reason, this review looks at LCA because of its broad international acceptance as a means to improve environmental processes and services, and also for creating goals to prevent adverse environmental impacts, consequently enhancing quality of life and allowing people to live in a healthy environment.

Keywords: Building materials; Building life cycle; Construction industry; LCA; Sustainability; Sustainable development

Contents

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1. Introduction

The term sustainable development can be described as enhancing quality of life and thus allowing people to live in a healthy environment and improve social, economic and environmental conditions for present and future generations. Since the world commission on environment and development (WCED), entitled Our Common Future (1987), sustainable development has gained much attention in all nations and a report was published which called for a strategy that united development and the environment and which also made a declaration describing sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs [1]. Sachs [2] believed that the great challenge of the 21st century would be sustainable development. Vollenbroek [3] stated that sustainable development is a balance between the available technologies, strategies of innovation and the policies of governments.

The improving social, economic and environmental indicators of sustainable development are drawing attention to the construction industry, which is a globally emerging sector, and a highly active industry in both developed and developing countries [4–6]. Socially and economically, the European Commission (2006) stated that 11.8 million operatives are directly employed in the sector and it is Europe's largest industrial employer, accounting for 7% of total employment and 28% of industrial employment in the EU-15. About 910 billion euros was invested in construction in 2003, representing 10% of the gross domestic product (GDP) and 51.2% of the Gross Fixed Capital Formation of the EU-15 [7]. By contrast environmentally, this sector is responsible for high-energy consumption, solid waste generation, global greenhouse gas emissions, external and internal pollution, environmental damage and resource depletion [8–10].

In order to overcome the increasing concern of today's resource depletion and to address environmental considerations in both developed and developing countries, life cycle assessment (LCA) can be applied to decision making in order to improve sustainability in the construction industry.

The aim of this review is to systematically examine previous LCA research on the building sector in order to analyse the current situation and to outline the key challenges concerning LCA and the construction industry. Firstly, this paper provides details of LCA and its methodology, which is based on International standard series ISO 14040. Secondly, the review systematically explores and evaluates the different ways of using LCA for building materials and component combinations (BMCC) and LCA of the whole process of the construction (WPC), for example, in urban constructions of dwellings, commercial buildings and other civil engineering projects over the last 7 years, from 2000 to 2007. Following this, we present the discussion of the perceived advantages and limitations of LCA, and finally, we look at the outlook and challenges for ongoing research in LCA and draw some conclusions.

2. Conceptual basis of life cycle assessment (LCA)

Life cycle assessment (LCA) is a methodology for evaluating the environmental load of processes and products (goods and services) during their life cycle from cradle to grave [11–16]. LCA has been used in the building sector since 1990 and is an important tool for assessing buildings [17,18].

Klöpffer [19] stated that LCA has become a widely used methodology because of its integrated way of treating topics like framework, impact assessment and data quality. The description of the LCA methodology is based on the International standards of series ISO 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the inventory, assessing the impact and finally interpreting the results [20]. This paper will now briefly explore LCA methodology.

Firstly, defining goal and scope involves defining purpose, audiences and system boundaries. Secondly, the life cycle inventory (LCI) involves collecting data for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to air, water and land. This phase includes calculating both the material and the energy input and output of a building system. Thirdly, the life cycle impact assessment (LCIA) phase evaluates potential environmental impacts and estimates the resources used in the modeled system. This phase consists of three mandatory elements: selection of impact categories, assignment of LCI results (classifications) and modeling category indicators (characterization). Classification of the LCI results involves assigning the emissions, wastes and resources used to the impact categories chosen, e.g. CO_2, and CH_4, CO. The converted LCI results are aggregated into an indicator result, which is the final result of the mandatory part of an LCIA. Normalization, grouping, weighting and additional LCIA data quality analysis are optional steps. In a life cycle impact assessment (LCIA), there are essentially two methods: problem-oriented methods (mid-points) and damage-oriented methods (end points) [21]. The mid-points approach involves the environmental impacts associated with climate change, acidification, eutrophication, potential photochemical ozone creation and human toxicity and the impacts can be evaluated using the CML baseline method (2001), EDIP 97& EDIP 2003 and IMPACT 2002+. The end points approach classifies flows into various environmental themes, modeling the damage each theme causes to human beings, natural environment and resources. Ecoindicator 99 and IMPACT 2002+ are methods used in the damage-oriented method.

Finally, the last stage of ISO 14040 is the interpretation. This stage identifies significant issues, evaluates findings to reach conclusions and formulate recommendations. The final report is the last element to complete the phases of LCA according to ISO 14040.

Regarding methodology, various LCA tools have been developed and made available for use in environmental assessment. These tools have been classified according to three levels. Level 3 is called "Whole building assessment framework or systems" and consists of methodologies such as BREEAM (UK), LEED (USA), SEDA (Aus); level 2 is titled "Whole building design decision or decision support tools" and uses LISA (Aus), Ecoquantum (NL), Envest (UK), ATHENA (Canada), BEE (FIN); finally level 1 is for product comparison tools and includes Gabi (GER), SimaPro (NL), TEAM (Fra) LCAiT (SE). Some databases used for environmental evaluation are: CML, DEAM TM, Ecoinvent Data, GaBi 4 Professional, IO-database for Denmark 1999, Simapro database, the Boustead Model 5.0 and US Life cycle inventory database [22–25]. It is observed that previous tools and databases vary according to users, application, data, geographical location and scope. The data represents conditions in industrialized countries. Data from developing and emerging countries, however, is still lacking [26]. For example the use of European and American database may not lead to correct decisions in developing countries. Nevertheless, Frischknecht et al. [27] studied that consistent, coherent and transparent LCA datasets for basic processes make it easier to perform LCA projects, and increase the credibility and acceptance of the LCA results. Huijbregts et al. [28] insisted on evaluating uncertainties such as parameter uncertainty, scenario uncertainty and model uncertainty to improve the application and use of LCA. Hence, LCA does not make any explicit differentiation between the emissions at diverse points of the time. For instance, Hellweg et al. [29] found that if an emission contributes today to the exhaustion of ozone in 200 years, it is treated independently from the period considered in the evaluation of the LCA.

3. Method: state of the art of LCA of building materials and component combinations (BMCC) versus LCA of the whole process of the construction (WPC)

This review of the application of LCA to the construction industry focuses on the two different ways of using LCA for the building material and component combinations (BMCC) and the Whole Process of the construction (WPC). Therefore, this review has considered LCA methodology in the determination of the Functional Unit (FU). Twenty-five case studies have been analysed, 60% of those applying LCA to BMCC and 40% applying LCA to WPC. These case studies have been taken from the last 7 years from 2000 to 2007. Furthermore, other variables for both the BMCC and WPC approaches are discussed, such as who, what, where, why and when.

3.1. Building material and component combinations (BMCC)

Some LCA studies explicitly dedicated to BMCC have been done during the last seven years [30–36]. Those LCA studies presented are not fully comparable; there are differences in the final product and also most studies neglect cost except those works which show the application of shadow prices [37,38]. However, the most recent methodologies which incorporate information regarding environmental impacts and embodied energy in building materials are necessary for sustainable development. To achieve this, the European Commission in 2003 officially released the integrated policy product (IPP) voluntary approach [39]. This policy looks to identify products within the construction sector with the greatest potential environmental impact by focusing on the whole product life cycle and consists basically of three stages: environmental impact products (EIPRO), environmental improvement products (IMPRO) and Policy Implications. Strategies used in the implementation of the IPP are the environmental product declarations (EPD) and Ecodesign. EPD is a strategy adopted for external communication and is committed to reducing the environmental impact of a product [40]. EPDs such as those made on concrete, wood and metals such as aluminium are based on LCA and contain information associated with the acquisition of raw materials, energy use, content of materials and chemical substances, emissions into the air, land and water and waste generation [41–43]. On the other hand, Ecodesign looks at the relationship between a product and the environment. Ecodesign also summarizes techniques to reduce the environmental impact throughout different life cycle stages. Sun et al. [44] and Pujari [45] concluded that common proposals of Ecodesign include ascertaining the environmental impact of the whole production-consumption chain; considering environmental factors during the design of products, processes and activities (dematerialization), given that this is when 60–80% of their life-cycle impact is incurred. However, limited research has been published on Ecodesign in household hazardous waste derived from electrical and electronic equipment (EEE).

Statistics from the U.S. Energy information administration (2003) combined the annual energy required to operate dwelling and commercial buildings with the embodied energy of industry-produced building materials like concrete, ceramic, glass, steel etc., and revealed buildings to be the largest energy consuming and greenhouse gas emitting sector [46], Asif et al. [30] studied eight construction materials for a dwelling in Scotland. These materials were: timber, concrete, glass, aluminium, slate, ceramics tiles, plasterboard, damp course and mortar. The study concluded that the material used in the house with the highest level of embodied energy was concrete, at 61%. The other two materials, timber and ceramic tiles represented 14% and 15%, respectively of the total embodied energy. Concrete was the material responsible for 99% of the total of CO_2 of home construction. However, although there is no doubt that using timber is indispensable for reducing environmental impacts such as CO_2 [31,37], some authors stated that it is incorrect to think of wood as having a negative global warming potential, because sooner or later it will be incinerated or land filled, with the result that the CO_2 balance will be neutral or positive [47].

Alternatively, methodologies for building materials such as reused and eco-materials have been gaining the attention of academics and researchers. Erlandsson and Levin [48] studied a new methodology for reused materials. This study concluded that this strategy is better for the environment than constructing a new building, if the essential functional operation is the same. Additionally, a case study verified that the potential consequences for the environment could be reduced by nearly 70% for heating and 75% for the sewage system. However, when creating classification materials, it is essential to focus on the type of material and their environmental performance. In order to assess products' expected environmental impacts, Ross and Evans [49] performed a LCA case study for a plastic based packaging based on two strategies: re-use versus recycle. By comprehensively reviewing existing literature on building material selection, Sun et al. [50] presented a simplified method to evaluate the environmental loads associated with the material selection of a product. Materials were classified according to glass and ceramics, ferrous metal, no ferrous metal, paper, polymers and woods. Select durable and renewable materials are alternatives for grouping materials and also can promote best practices and economical techniques such as recycling, reusing and recovering materials for optimum waste disposal.

Finally, for eco-materials products, Nie and Zuo [51] studied the importance of investigating and applying building materials. This approach has lead to the development of new materials with low environmental loads during their life cycle. According to Chavan [52], smart building materials such as titanium dioxide can be used for cement and concrete products can be coated for self-cleaning effect due to their strong oxidizing properties. This technique can enable the construction industry to use nanotechnology but due to the increasing use of this field, it is important to examine the life cycle, effects and risk assessment that nanoparticles have on humans and the built environment.

3.2. Whole process of the construction (WPC)

When applied to the full building life cycle, LCA is divided up in three common scenarios: dwellings, commercial buildings and civil engineering constructions.

3.2.1. LCA for dwellings

One of the first analyses during the last seven years on the environmental impact of the dwelling as a whole was performed by Adalberth et al. [53]. The main aim of this study was to evaluate the life cycle of four dwellings located in Sweden with different construction characteristics. The selected functional unit was m^2 of usable floor area. The sensitivity analysis had three parameters: variation of electricity mix, building material data and energy use. The results showed that the factor with the greatest environmental impact was electricity mix. In addition, the paper analysed the importance of knowing which phase in the life cycle has greater environmental impact, if there are similarities between environmental impacts and energy use; or if there are differences between subsisted environmental impacts due to the selection of the construction. Considering an occupation phase of 50 years for the dwellings, this study concluded that the greatest environmental impact occurs during the use phase. Also, 70–90% of the environmental categories arise in this phase. Approximately 85% and 15% of energy consumption occurs during the occupation and manufacturing phases, respectively. SBI's LCA tool was used for the environmental impact of the building.

In a brief analysis on the evaluation of environmental impact of the building life cycle, Peuportier [47] compared three types of houses with different specifications located in France. The functional unit was 1 m^2 living area. The sensitivity analysis was based on the selection of other construction materials (wood versus concrete blocks), the type of heating energy (gas versus electricity) and the transport distance of the wood. EQUER tool was used for the environmental impact of the building. Inventories were taken from the Oekoinventare database. Previous studies in Adalberth et al. [53] and Peuportier [47] showed that the GWP and acidification impacts were highest when the main construction equipment was concrete. The dwellings that had the greatest environmental impacts were not those with the highest m^2 constructed. Hence it is necessary to choose materials with low environmental impact during the pre-construction phase. Furthermore, it can be seen that in Europe the pre-construction step has strong

Table 1
Characteristics of published LCA applied within the building sector for both BMCC and WPC

Reference	BMCC	WPC	Content, country and year.	Environmental loads analysed												
				GW	A	E	OD	HT	EL	WC	DA	W	EC	RS	AR	O
Adalberth et al. [53]		×	Life cycle of four dwellings located in Sweden (2001)	×	×	×	×	×	×							
Ardente et al. [61]	×		LCA of a solar thermal collector, Italy (2005)							×		×		×	×	
Arena and Rosa [62]		×	LCA of energy of the implementation of conservation technologies in school buildings in Mendoza, Argentina (2003)	×		×			×					×		×
Asif et al. [30]	×		LCA for eight different building materials for a dwelling located in Scotland (2005)	×												
Citherlet et al. [63]	×		LCA of a window and advanced glazing systems in Europe (2000)	×	×		×									×
Gustavsson and Sathre [31]	×		LCA Sweden case study: wood and concrete in building materials (2006)													×
Jian et al. [59]		×	LCA of urban project located in Hyogo, Japan (2003)	×					×	×		×				
Junnila [57]		×	LCA for a construction of an office: a Finland case study (2004)	×	×	×			×							×
Koroneos and Dompros [64]	×		LCA of brick production in Greek (2006)	×	×	×						×				×
Koroneos and Kottas [65]		×	LCA for energy consumption in the use phase for a house in Thessaloniki, Greece (2007)	×	×	×	×		×							×
Mroueh et al. [66]		×	A Finnish LCA case study of road construction (2001)											×	×	×
Nebel et al. [32]	×		LCA for floor covering, Germany (2006)	×	×	×	×									×
Nicoletti et al. [33]	×		LCA of flooring materials (ceramic versus marble tiles), Italy (2002)	×	×		×	×			×					×
Nyman and Simonson [54]	×		LCA of residential ventilation units over a 50 year life cycle in Finland (2005)	×	×		×				×				×	
Peuportier [47]		×	Comparison of three types of houses with different specifications located in France (2001)	×	×	×	×	×	×	×	×	×	×	×	×	
Petersen and Solberg [34]	×		LCA by comparing wood and alternative materials in Norway and Sweden (2005)		×	×	×	×								
Prek [68]	×		LCA of heating and air conditioning systems. A Case study for a single family dwelling in a residential building in Slovenia (2004)	×			×									
Ross and Evans [49]	×		An Australian LCA case study for a plastic-based packaging based on two strategies: re-use versus recycle (2003)									×		×		
Saiz et al. [35]	×		LCA for green roofs located in downtown Madrid, Spain (2006)	×	×	×	×	×		×		×				×
Scheuer et al. [58]		×	LCA to a new University building campus with a total area of 7300 m^2 in USA (2003)	×	×		×		×			×				×
Schleisner L [69]		×	LCA Case Study to produce different energy production technologies in Denmark (2000)						×							×
Seppala et al. [36]	×		LCA for Finnish metal products (2002)			×		×	×	×		×				×
Van der Lugt. et al [37]	×		LCA for using bamboo as building material versus steel, concrete and timber in Western Europe (2006)													×
Wu [38]	×		LCA: a Chinese case study for different building materials (2005)	×	×	×	×		×	×						×

Abbreviations: GW, global warming potential; OD, photochemical ozone creation; WC, water consumption; DA, depletion abiotic resource; WPC, whole process construction; A, acidification; HT, human toxicity; W, waste creation; EC, ecotoxicity; BMCC, building and materials components combinations; E, eutrophication; EL, energy consumption; RS, resources consumption; O, others; AR, air emissions.

influence on energy consumption and consequently on the operation phase. For this reason the energy requirements for HVAC are much higher due to the bio-climatic conditions during the operation phase of buildings and are mainly dependent on the behaviour pattern of the citizens and directly linked to construction materials due to the fact that the buildings provide occupants with a healthy indoor environment [54]. Additionally, it can be seen that both works are similar but the sensitivity analysis were done in different scenarios and that other considerations were taken into account such as quality of life, thermal and climate performances to evaluate the entire building life cycle. There is another research done by Jian et al. [59] that analysed the LCA of urban project development through the calculation of CO_2 emissions during construction, maintenance and operation of facilities and public buildings, and their environmental impacts. Data were collected to complete a case study located in the District of Hyogo, Japan. Proposals for the mitigation and simulation of CO_2 reduction were limiting land use of suburban commercial facilities; changing non-wood dwellings to low stored wood dwelling and increasing open spaces such as parks and green areas.

Finally, more specifically, there has been one LCA case study in an indoor environment, Arjen et al. [55] studied the total amount of building materials which humans were exposed to in the use phase of a Dutch home. The emission of radon was 59%, the highest contaminant and harmful to human health; 38.7% for gamma radiating elements; 1.3%, 0.8% and 0.2% formaldehyde, toluene and others, respectively.

3.2.2. LCA for commercial constructions

There has been a fair amount of descriptive work on commercial constructions, but limited research has been published thus far on complete LCA of office buildings, although the first attempts started appearing in 2003 [56]. For example, Junnila [57] studied a construction of an office of 24 000 m^2. Almost 130 different building parts and fifty different building material groups were identified in the inventory phase. The operation phase of the building was divided into operating electricity, operation heat and other services (water use, waste water generation, courtyard care). The energy consumption calculations for the building were performed by a HVAC and electrical design using the WinEtana energy simulation program. The following environmental impacts were studied: climate change, acidification, eutrophication, summer smog and heavy metals by using the Kcl-Eco software with Ecoindicator 95. The data were taken from the Finnish LCA database for energy, LIPASTO, Eco 1999, Simapro and Boustead. The study found that the operating electricity is the most representative of environmental impacts.

Other study done by Scheuer et al. [58] applied LCA to a new university building campus with a total area of 7300 m^2. The research showed that almost 60 building materials were identified for the inventory analysis. The results showed that in the positioning of materials phase (activities required for the design, construction and renovation of a building) the total embodied primary energy was 51×106 MJ over the building life cycle. The operation phase showed 97.7% of the primary energy; the energy required for decommissioning, demolition and transport was 0.2%. The following categories of environmental impacts were studied in the operational phase: global warming (93.4%), nutrification potential (89.5%), acidification (89.5%), ozone depletion potentials (82.9%) and solid waste generation (61.9%). This study also concluded that the operation phase had higher environmental impacts compared with other life cycle phases for the building. Data were taken from Simapro, Franklin associates, DEAM™, and the Swiss Agency for the Environment, Forests and Landscape.

3.2.3. LCA for civil engineering constructions

LCA have been used in other civil engineering projects. For example, regarding highway constructions, Birgisdottir et al. [60] compared two scenarios with natural versus different types of materials. The method of the LCA was evaluated in ROAD-RES tool, which can be used for LCA in the road construction and waste disposal. Environmental impacts like global warming, acidification and ecotoxicity were analysed. Mroueh et al [66] has carried out a similar study of these impacts. It can be observed in both investigations that the application of LCA pursue strategies to minimize the environmental loads, resource consumption and applied strategies such as recycling and reusing of building materials.

The following Table 1 summarizes the characteristics of some published LCA case studies for both BMCC and WPC with their respective environmental loads.

4. Evaluation of the scenarios analysis

There are practical differences between both scenarios: LCA of building materials and components combinations (BMCC) and LCA of the full building life cycle (WPC).

First, from the reviewed scientific literature it was found that LCA of the full building life cycle as a process is not static; it varies from building to building since each has its own function and different characteristics of engineering [67,70]. For example, construction techniques, architectural style and different conditions such as household size, climate and cultural consumption behaviour vary from country to country. Furthermore, a variation in each design can affect the environment during all life cycle stages of a building. Second, the notation that has been chosen for this review was based on the functional unit. The functional unit for the building material and component combinations was focused on a final product, while for whole building the FU was analysed, taking into account a dwelling, building or m^2 usable floor area. Third, LCA for both scenarios is very industry specific. For instance, construction and building projects have complex processes and many assumptions have to be made, while in building materials and products, processes are based on a single product. Paulsen and Borg [71] stated that characteristic of buildings and building products is their significantly longer life compared to most other building materials and industrial products, and the involvement of many different factors during their life cycle. Furthermore, Gregory and Yost [72] concluded that the direct application of LCA in the construction sector is not a simple or straightforward process. It is expensive and cannot be applied without assumptions or additional modifications. Fourth, most LCA initiatives were focused on evaluating environmental impacts. For example, LCA for the whole building have been evaluated, considering aspects such as cultural consumption behaviours and patterns during the use phase. Promoting better insulation alternatives, replacing materials with less environmental burdens and supporting the application of technologies in renewable energies were the main alternatives evaluated in this scenario. LCA for BMCC have been applied to compare products, promote new products and contribute to better environmental decisions and policies and to improve environmental considerations of products. Fifth, most LCA of WPC data have been taken from architects, engineers, drawings, engineering specifications, suppliers and interviews, while the LCA for BMCC are based in industrial processes. Fig. 1 indicates the life cycle of both scenarios. The phases involved in the building life cycle include raw materials, construction, use and maintenance and finish with final disposal or demolition (cradle to grave). Building materials involve processes such as production, use and final disposal.

5. Discussion of perceived advantages and limitations of LCA

The present review, though not claiming to be exhaustive, demonstrates the progressive evolution of LCA in the building sector during the last seven years. It illustrated how approaches for both BMCC and WPC have been evaluated on scientific evidence. It has been shown that the use of LCA for evaluating building material and LCA for the whole process of the construction and edification is not novel, nor is the use of cost and data sensitivity analysis. However, most analyses of LCA focused on the evaluation and use of sustainability indicators. The results showed that LCA of BMCC and WPC definitely represent an innovative methodology which improves sustainability in the construction sector throughout all stages of the building life cycle. It is also observed that more than 90%–95% of the LCA case studies were focused on evaluating environmental impacts and assisting the decision-making within the building sector. The choice of impact categories was made between loads that are commonly analysed. More environmental burdens identified were global warming potential (GWP), acidification and energy consumption. Nevertheless, other environmental impacts were evaluated such as: inefficient land use, water shortage, air pollution, traffic congestion, deterioration of ecological systems, high consumption of energy, and waste management [73,74]. However the Green Building Challenge Stockholm [75] and Borg [76] declared that aspects like global warming potential (GWP), land use, acidification, eutrophication, stratospheric ozone depletion, abiotic resources and human toxicity are impacts more identified within the building sector. The main influence of climate change were emissions of greenhouse gases. Regarding the selection of the impact categories, Houghton et al. [77] classified the most relevant greenhouse emissions as being carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs).

It has been also seen that global warming potential was the greatest environmental challenge facing the built environment due to the significant period of occupancy occur for the service life caused by the heating, ventilating and air conditioning (HVAC) [78–80].

More generally the review has demonstrated that most LCA studies focus on energy consumption. In response to steadily increasing concern over energy consumption, Kotaji et al. [81] stated that energy consumed during preconstruction accounted from 10% to 20%; during the occupation phase, Adalberth [82] and Bisset [83] stated that energy household activities are estimated between 40% and 50% and for the dismantling phase, Kotaji et al. [81] concluded that energy use is less than 1% through treatment of their final disposition. A detailed study has been found taking into account household energy consumption. For example, Hertwich [26] compared the annual energy consumption per-capita and CO_2 emissions. The results

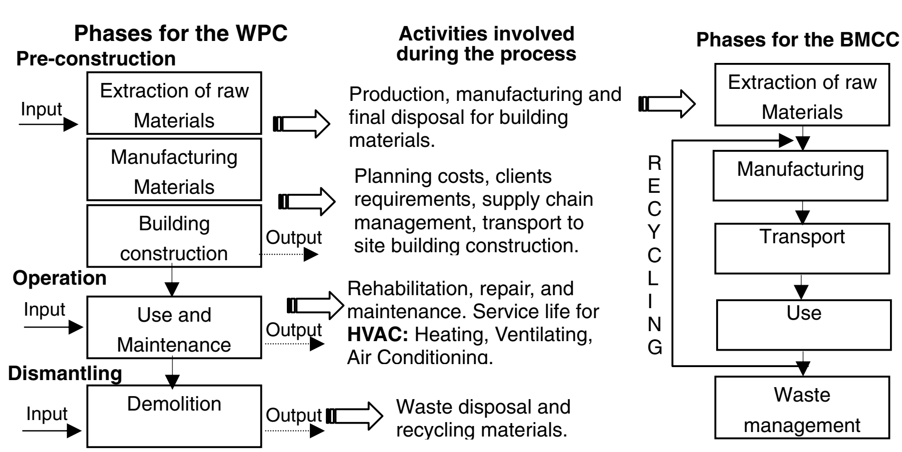

Fig. 1. Schematic representation of the building life cycle.

showed that the United States is the maximum CO_2 emitter per capita as well as energy consumer. But due to high levels of industrial and economic investment in China, it is unquestionable that this Asian giant will exceed the USA's CO_2 emissions in the coming years. Runming et al. [84] observes that China's building sector currently accounts for 23% of China's total energy use and this is projected to increase to one-third by 2010. Therefore, there is no doubt that reducing the environmental impact of the building sector is important to achieve sustainable development. For example, a proper construction can achieve sustainable development by using fewer natural materials, materials with low environmental impacts, green materials and applying renewable energies to reduce environmental loads and energy and water consumption [85], thereby promoting the principles of sustainable construction [86]. Based on these reflections, there are currently two examples worldwide that could be considered best practices and that fulfilled the requirements and applications integrating the principles of materials and energy as well as the reduced cost required to operate buildings: the European project passive house [87] and the American Off-Grid Zero Emission Buildings [88].

6. SMEs: methodologies applied within the construction industry and perspectives in developing countries

Over the years, it has been observed that there are various methodologies applied within the construction industry in pursuit of continuous improvement for sustainability indicators [89–91]. Despite the application of methodologies as eco-efficiency, cleaner production, extended polluter responsibility, industrial ecology, Eco-label and Environmental Management Systems, there are still a lot of adverse environmental loads emitted by small and medium enterprises (SMEs) and research is required to evaluate the environmental burdens emitted into the atmosphere by SMEs, both globally and locally [92].

Nevertheless, there are pros and cons associated with SMEs. Social and economically, SMEs are a strong base for the economy of any country. For instance, 99.8% and 90% of all companies are SMEs in the UK and Europe, respectively [93]. The European Commission 2006 [94] stated that SMEs in the industrial sector could fluctuate according to macroeconomic indicators like the GDP due to their high indices of investment and contribution to the growth in employment. Some sustainability indicators, for example the Spanish Central Directory of Companies (DIRCE) [95] showed that SMEs 12.79% exert their activity in the construction sector, while the National Statistics Institute (INE) showed that the number of houses built had increased from 302 000 units in 1995 to 750 000 in 2006. In Colombia, the Administrative Department of National Statistics (DANE) [96] stated that the building sector participates in 5.2% of the GDP and SMEs in 2004 contributed to a 96.4% of the industrial activities and that 63% of employment is generated for SMEs. The DANE in 2003 confirmed that 70 000 dwellings for social interest and other 125 000 dwellings for not social interest were built and it is also projected that in 2019, 80% of Colombians will live in urban centers. By contrast, environmentally, Hillary [97] suggested that the industrial sector of SMEs contributes up to 70% of industrial pollution and there is a need to increase the modernization of industrial process in developing countries and promote best practices engineering [98–100].

In order to overcome these adverse environmental impacts and due to the fact that the construction sector must react quickly to changing environmental considerations, lack of knowledge, capacity and initiative to apply a life cycle method to the SMEs, LCAs are sought worldwide and this methodology is not a utopian tool to deploy in developing countries. Although financial supports, technology and technical assistance play a significant role when applying LCA throughout industrial activities in developing countries, in developed countries LCA is the cornerstone for most industrial activities [101–104]. It is, therefore important to apply the nascent LCA methodology in both developed and developing countries to allow sustainable development [105,106].

7. Outlook and challenges for ongoing research in LCA

From the reviewed literature it was proofed that there have been some LCA studies published thus far on complete LCA of the full building life cycle. For example, LCA was applied to evaluate environmental impacts and energy use of a residential home in Michigan [107]. Asif et al. [30] performed a LCA for a dwelling home in Scotland for eight construction materials. Another study by Adalberth et al. [53] has used LCA to evaluate the life cycle of four dwellings located in Sweden. Peuportier [47] compared three types of houses with different specifications located in France. While the previously referenced studies describe in various environmental considerations and energy use detail for dwellings in Europe and USA, there are no comparable studies in the literature from developing countries especially in Latin America.

Therefore, there is no doubt that applying LCA within the building sector can be very important in achieving sustainable development. Curran [108] stated that the most appropriate method for a holistic assessment is LCA, a systematic study of the life cycle (materials manufacturing, construction/ manufacturing processes, use, maintenance, renovation, and end of life treatment) and supply chain environmental effects of products, processes and services. Consequently, LCA is required to promote the best practical methodologies to evaluate, analysis and check the construction life cycle to prevent environmental impacts and assist the field of engineering techniques of buildings.

Finally, the promotion of the principles of sustainable construction in developed and developing countries is important for sustainable development, and the following questions should be considered: which materials can lead towards sustainable construction considering the criteria of sustainable development? How is it possible to get stakeholders in the building sector to apply LCA? How can SMEs improve their processes for their product life cycle? These questions will be answered in future studies in this project, which will consider the evaluation of environmental impacts during the building life cycle in Spanish and Colombian scenarios, as well as analysing whether the practical Ecodesign guidelines used in the sector in Spain and Europe, strong depending on climate conditions, can be applied in tropical areas. Social and economic indicators, the two other legs of sustainability, will also be considered because of their major specific role in developing countries. During this research, key issues will be energy, industrial development, air pollution/ atmosphere and climate change, along with the revision of behavioural patterns in the use phase. The outcome of this research will be used to develop guidelines based on LCA and Ecodesign, which will assist SMEs in developing countries to preserve the environment and contribute to the principles of sustainable construction.

8. Conclusions

The present review compiles and reflects the key milestones accomplished in Life Cycle Assessment over the last 7 years, from 2000 to 2007. It deals with topics such as the differences between LCAs of building materials and components (BMCC) versus LCAs of the whole process of constructions (WPC). LCA is recognized as an innovative methodology which improves sustainability in the construction industry throughout all stages of the building life cycle.

More attention has to be paid to SME's activities in the building sector. The aim for them should be to upgrade their processes and improve their economic and environmental viability. Socially and economically, SME's are a strong base for any country and consequently improvements in environmental behaviour have to be disseminated and applied to them.

It can be seen from the literature reviewed that there has been a large number of LCA studies which deal with a specific part of the building life cycle but few of them deal with the whole life span. Although most LCA case studies have been done in developed countries in Europe and the USA, there are no comparable studies in the literature from developing countries. Therefore, sustainability indicators in design, construction, operations and dismantling need to be developed and used in order to target environmental and energy considerations worldwide.

Among the environmental loads considered in the building sector the operation phase is the most critical in European scenarios. This is because of the higher environmental loads emitted into the atmosphere due to the high-energy requirement for HVAC, domestic hot water and lighting. The contribution made by the operation phase in buildings from tropical zones is not as significant due to lower energy consumption for HVAC. The need to properly evaluate energy requirements for HVAC depending on bioclimatic conditions and the behaviour patterns of citizens is clearly shown.

Finally, governments and environmental agencies should apply construction codes and other environmental policies to improve sustainability in the building sector. The other stakeholders also need to have a serious level of effort and commitment. For this reason, entities involved in the construction industry must be proactive in creating environmental, social and economic indicators, which bring about building sector sustainability and promote the use of sustainable construction practices in both developed and developing countries.

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