Life cycle assessment of residential buildings: a review of methodologies

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Abstract

Global warming is the greatest environmental challenge that humanity is phasing. Water availability and biodiversity are also important issues of concern. Efforts towards achieving a sustainable path are required in all major sectors. The construction and infrastructure sector is an important contributor to global resource depletion and environmental impact.

Life cycle assessment (LCA) is a frequently used tool to assess the potential environmental impact of a product or service throughout its life cycle. The life cycle of a product involves the extraction of raw materials, processing, production, use, and end-of-life. The environmental performance is quantified according to several impact categories such as: global warming, abiotic depletion, acidification, eutrophication, ozone layer depletion, photochemical oxidation, among others.

LCA has been applied with success in the construction and infrastructure sector, in particular for buildings of all types. Literature in LCA of buildings use a variety of methodological approaches. The objective of this literature review is to identify and compare the different methodological approaches used in LCA of residential buildings, with a particular focus on functional unit, system boundaries, environmental impact categories, and data quality. The review indicates that there are different approaches used depending on the objective of each particular study.

Keywords: LCA, sustainability, sustainable infrastructure, sustainable engineering, built environment.

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1 Introduction

The construction industry in the developing world is an important driver of socio-economic development and in turn a major consumer of energy and natural resources. In a global economy, the construction industry consumes 40% of raw materials and generates 40% to 50% of greenhouse gases and acid rain agents (Asif *et al.* [1]). The built environment plays an important role in global energy consumption; homes use energy throughout its life cycle from construction, occupancy, until the end of its useful life (Cabeza *et al.* [2]).

Concerns about the status of the local and global natural environment are increasing in the world. Global warming, ozone layer depletion, the loss of natural habitats and biodiversity are the reasons why countries have increased efforts to mitigate its effects. Particularly, Global warming, and their varied potential effects on the planet, is a result of long-term accumulation of greenhouse gases (CO_2, CH_4, N_2O, etc.) in the upper layer of the atmosphere. In recent years, an increased awareness, resulting from evidence of environmental impacts of human activity, has resulted in a broader role of sustainable development into the construction industry.

There are a variety of tools that can be used to assess environmental performance. Life Cycle Assessment (LCA) provides a comprehensive methodology to assess the environmental burden of a product or service throughout its life cycle. LCA methodological framework is standardized by ISO. The LCA methodologies have been used for the environmental assessment of products for a long time, but applications to the construction industry appeared recently at the beginning of the 21st century (Singh *et al.* [3]). It has been successfully used to assess the environmental impact and energy performance of buildings and building materials. In addition, investigations of LCA applied to the performance evaluation of structures have grown to the point of being able to find case studies along diverse countries.

The objective of this review is to identify similarities and understand the guidelines made by different researchers, taking into account the specific characteristics of each study, categorized as: type of case study, geographic location (country), functional unit selected, area of occupancy, lifespan, system boundaries, impact assessment method, and impact categories.

These similarities and differences between the studies will allow the selection and standardization of parameters to conduct a LCA study; will help defining a functional unit, system boundaries, and impact categories, which may vary according to geographical, environmental and technological conditions of each region.

2 Methods

2.1 Life Cycle Assessment, infrastructure, and residential buildings

LCA was originally developed for industrial production and processes, general considerations of life cycle application to infrastructure systems where provided in the early 1990s by Novick [4]. The first formal environmental management system was provided by the British Standards Institution (BSI) in 1992, which served as template for the development of the ISO 14000 series pertaining environmental management, in 1996. Specifically, ISO 14040 [5] series concern Life Cycle Assessment which became the standard for performing environmental impact assessment using life cycle methodology.

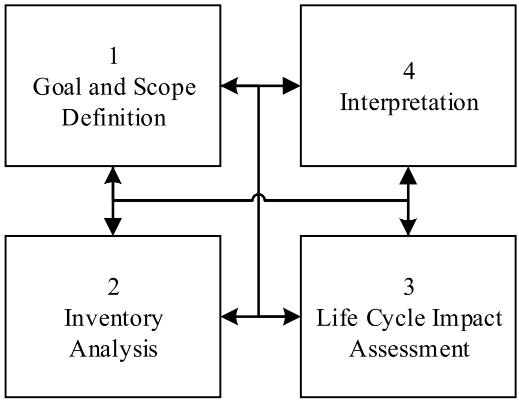

Figure 1: LCA framework based on ISO 14040.

Environmental assessment studies intended to compare different materials used for infrastructure construction date from the late 1990s. One of the first studies on its kind was made by Horvath and Hendrickson [6] conducting a life cycle inventory analysis to assist in bridge material selection comparing steel versus steel-reinforced concrete bridges. Later examples of life cycle analysis application relate to potable water pipe material selection (Dennison *et al.* [7]), environmental impacts of highways (Park *et al.* [8]) and residential buildings energy and cost improvements (Keoleian *et al.* [9]).

2.2 Residential buildings LCA

A number of relevant publications on LCA on residential buildings have been reported since 2000 (Table 1), these studies come from diverse geographic locations, with 8 case studies from Europe, 1 from Asia, 2 from North America, and 1 from Australia. Key study parameters of these publications can be identified; these parameters define the overall characteristics of the matter in study on each research as follows:

- Type of analysis
- Functional unit
- System boundaries
- Impact assessment methodology
- Impact categories

Following a detailed explanation of the differences found on these key parameters is provided.

Table 1: Twelve articles reviewed in which key analysis parameters are identified.

Author(s)	Year	Type of analysis	Location	Functional unit	Area	Lifespan (years)	System boundaries
Asif *et al.* [1]	2007	Materials comparison (5) for a house.	Scotland	Typical semi-detached three bedroom	$132m^2$	NA	Construction
Rossi *et al.* [10]	2012	Overall energy comparison of three distant house units.	Belgium, Portugal, Sweden	m^2 yr	$192m^2$	NA	Construction use
Cuéllar-Franca & Azapagic [17]	2012	Overall comparison of three most common building types.	UK	m^2 yr	$130m^2$, $90m^2$, $60m^2$	50	Construction use–End-of-life
Monteiro & Freire [16]	2012	Material comparison between three types of exterior walls.	Portugal	m^2 yr	$132m^2$	50	Construction use
Frijia *et al.* [11]	2012	Energy use of a typical residence.	EU	m^2 yr	$140m^2$–$325m^2$	50	Construction use
Lewandowska *et al.* [12]	2013	Energy use comparison between 4 houses.	Poland	m^2 yr	$98.04m^2$	100	Construction use–End-of-life
Asdrubali *et al.* [19]	2013	Overall comparative analysis between three typical house types.	Italy	m^2 yr	$443m^2$, $1827m^2$, $3353m^2$	50	Construction use–End-of-life
Zhang *et al.* [18]	2013	Overall analysis of one two-story residential building.	Canada	m^2	$236.15m^2$	NA	Construction use–End-of-life
Bastos *et al.* [13]	2014	Energy and GHG analysis of three typical building types.	Portugal	m^2 yr	$367m^2$, $472m^2$, $1041m^2$	75	Construction use–End-of-life
Chang *et al.* [14]	2013	Energy comparison between urban and rural residential buildings.	China	Residential building	NA	50	Construction use–End-of-life
Keoleian *et al.* [9]	2000	Overall analysis of one standard US home.	US	Single family house	$228m^2$	50	Construction use–End-of-life
Crawford [15]	2014	Energy analysis in the post-occupancy life of a house.	Australia	m^2 yr	$291.3m^2$	50	Construction use–End-of-life

3 Results

3.1 Type of analysis

Type of analysis can be defined from the main objective of each study; it is a description from the approach of the study selected by the authors. It is also directly related to a research hypothesis, a local concern, or a specific problem that need to be resolved. Types of analysis can be narrowed from the literature reviewed to three general categories: energy use comparisons, material comparative analysis, and overall analysis.

The most common type of analysis was related to energy use. Rossi *et al.* [10] developed and tested a tool for LCA of residential buildings in Europe located in Brussels (Belgium), Coimbra (Portugal) and Lulea (Sweden). The objective of their research focused on energy analysis evaluated as raw energy consumption, embodied energy and embodied carbon. Frijia *et al.* [11] explored issues related to technological changes in the operational phase and parametric models though an analyses of one-story and two-story detached homes located in Phoenix Arizona. In a similar fashion Lewandowska *et al.* [12] reported a LCA study performed to four detached single-family dwellings compared traditional and passive buildings each using wood or masonry materials, and was focused on the operation phase only. Furthermore, Bastos *et al.* [13] presented an energy and GHF analysis of three representative residential buildings within a residential area in Lisbon, Portugal. This study considered a construction phase, use phase, and retrofit phase. Chang *et al.* [14] reported a LCA analysis of buildings in China, considering urban/rural differences, quantifying energy use for both locations during each life cycle phase. Finally, Crawford [15] efforts aim the post-occupancy phase of a residential building in Australia, using a single detached unit. This study is the only one available for housing units considering system boundaries beyond use or operation.

Material comparison analysis was found on two reports, Monteiro and Freire [16] implemented a LCA model to evaluate environmental performance of six types of exterior walls using different life-cycle impact assessment methods as well, Asif *et al.* [1] research provided a LCA of a 3 bedroom semi-detached house in Scotland focused on material evaluation of wood, aluminium, glass, concrete and ceramic tiles.

Overall analysis category, as identified in the present study, refers to broader study where a full LCA is undertaken, typically all the relevant impact categories are included and a lifespan that includes all the life-cycle phases considered. Cuéllar-Franca and Azapagic [17] analysed the environmental impacts for three of the most common types of house in the UK. Under the same analysis category Zhang *et al.* [18] reported a life cycle assessment of single-family residential buildings in Canada. This particular study considered also improvement measures. Accordingly, Keoleian *et al.* [9] published a full LCA for a single-family house, considering pre-use, use, and demolition phases. Also a comprehensive inventory of construction materials and appliances, together with a life cycle cost analysis was made.

3.2 Functional unit

Many studies define their functional unit based on area occupied during a lifespan, [10, 12, 15, 16]. For example Cuéllar-Franca and Azapagic [17], in their case study located in the UK, defined their functional unit as "construction and occupation of a house in his lifespan". Further considering that the study includes three types of buildings with 50-year lifespan and different occupation areas defined as:

- detached house 130m^2;
- semi-detached house 90m^2; and
- terraced house 60m^2.

Asdrubali *et al.* [19] in Italy, defined its functional unit in one square meter of usable / living floor area, over one year (m^2/year), defining 3 types of buildings on a lifespan of 50 years:

- a detached house 443m^2;
- a multi-dwelling building (block of flats) 1,827m^2; and
- an office building 13,602m^2.

On the other hand, Bastos *et al.* [13] in Portugal, defined the functional unit as "per square meter per year and per person per year" based that the use of area-based functional unit in larger households have lower energy needs, consequently lower emissions for the same occupation of people, but this does not necessarily result in improved environmental performance.

In contrast, use of occupancy-based functional unit, which is usually used in studies at the urban scale, can ignore the performance of the building, high occupancy could compensate for poor environmental performance, so it is highly recommended to use a functional unit depending on the objectives and scope of the study.

3.3 System boundaries

The system boundaries define which processes will be included in the study. Much of previous studies are oriented to life cycle energy assessment, where the use stage of the building predominates, so it is important to define their lifespan. While other studies using LCA methodology seek to analyse the environmental performance and not just their energy consumption, will focus on obtaining data on production of raw materials, and cover all phases from construction, use and retrofit or demolition.

Time limits are provided by the lifespan, as in the methodology of LCA and LCEA, the use stage is directly linked to lifespan, many studies have taken as reference between 50–100 years, with 50 years period most widely used [9–11, 13, 15].

Asif *et al.* [1] defined as the timeframe of their study only the construction phase, since their objective was to analyse the environmental performance of materials, with the result that concrete is the material with higher energy consumption and increased emissions.

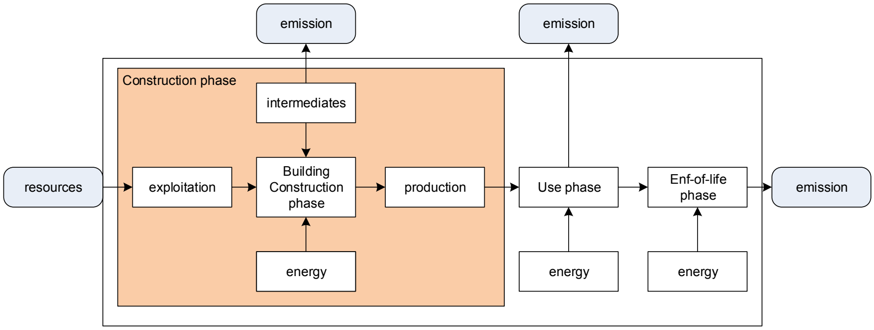

Figure 2: System boundary for residential buildings.

The processes included in LCA studies of buildings are:

Pre-construction phase: Materials production phase: Includes processes of raw material extraction, transportation to the factory, manufacturing process, recovery of recycled material.

Building construction phase: Transportation of materials from the factory to the construction site, mounting structure and possible replacement during the life of the building, the power consumption associated with equipment used in construction, the transformation from rural to urban areas, earthworks, isolated or highly dense constructions.

Use phase: These are all activities related to the use of the building, including all operating energy for heating, cooling and hot water generation, cooking, lighting and other electronic devices comprising the house.

End-of-life phase: Dismantling of the structure, demolition, transportation to the landfill or the recycling of materials.

3.4 Impact assessment methods

The impact assessment methods used in the studies reviewed have very different approaches. CED is a method that only focuses on representing primary energy needs. The other two environmental LCA methods can be differentiated as CML 2001 is problem oriented and EI'99 is damage oriented methodology. In general, results obtained from the three methods indicate that the most important lifecycle stage depends on the assumed method.

In CML methodology impacts these are higher for the use phase, while those of EI'99 are higher for the material production. The comparison of CML and EI'99 shows that the most important category for EI'99 are fossil fuels, while for CML is the toxicity according to Cuéllar-Franca and Azapagic [17].

4 Conclusions

Material evaluation on residential units showed that concrete, timber and ceramic tiles constitute major energy consumers among materials involved in residential building construction. Being concrete alone responsible for 65% of total embodied energy, surpassing by far the environmental impacts of other materials. On the other hand it has been found that, for total energy use in material manufacturing and construction processes, the scale effect is inverse proportional, as the area of occupancy increases, energy use decreases.

Energy evaluation on residential units evidenced that HVAC systems contribute significant CO_2 emissions. Most studies coincide on their results that confirm that most of the primary energy requirements occur during the use or operation phase of buildings ranging from 70% to 91% of total life-cycle energy consumption. Also the mix of energy generation technologies affect largely the primary energy requirement.

Full LCA studies confirmed that for all the impact categories (except Ozone layer depletion) the use phase of buildings carries the greatest burden. Ozone layer depletion is a considerable load only during the construction phase.

Finally the results evidence that location is a parameter that affects the outcome of any type of carried study. The same building, measured in its use phase, in different countries or even in different regions of the same country may have different environmental consequences. Inconsistency on the results was found when using different life-cycle impact assessment methodologies; no correlation between results could be identified.

References

[1] Asif, M., Muneer, T. & Kelley, R., Life cycle assessment: A case study of a dwelling home in Scotland. Building and Environment, 42(3), pp. 1391–1394, 2007.

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

[3] Singh, A., Berghorn, G., Joshi, S. & Syal, M., Review of Life-Cycle Assessment Applications in Building Construction. Journal of Architectural Engineering, 17(1), pp. 15–23, 2011.

[4] Novick, D., Life-Cycle Considerations in Urban Infrastructure Engineering. Journal of Management in Engineering, 6(2), pp. 186–196, 1990.

[5] International Standard Organization (ISO), ISO 14040: Environmental Management-Life Cycle Assessment-Principles and Framework, 1997.

[6] Horvath, A. & Hendrickson, C., Steel versus Steel-Reinforced Concrete Bridges: Environmental Assessment. Journal of Infrastructure Systems, 4(3), pp. 111–117, 1998.

[7] Dennison, F. J., Azapagic, A., Clift, R. & Colbourne, J. S., Life cycle assessment: Comparing strategic options for the mains infrastructure – Part I. Water science and technology, 39(10), pp. 315–319, 1999.

[8] Park, K., Hwang, Y., Seo, S. & Seo, H., Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. Journal of Construction Engineering and Management, 129(1), pp. 25–31, 2003.

[9] Keoleian, G. A., Blanchard, S. & Reppe, P., Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House. Journal of Industrial Ecology, 4(2), pp. 135–156, 2000.

[10] Rossi, B., Marique, A.-F., Glaumann, M. & Reiter, S., Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment, 51, pp. 395–401, 2012.

[11] Frijia, S., Guhathakurta, S. & Williams, E., Functional Unit, Technological Dynamics, and Scaling Properties for the Life Cycle Energy of Residences. Environmental Science and Technology, 46(3), pp. 1782–1788, 2012.

[12] Lewandowska, A., Noskowiak, A. & Pajchrowski, G., Comparative life cycle assessment of passive and traditional residential buildings' use with a special focus on energy-related aspects. Energy and Buildings, 67, pp. 635–646, 2013.

[13] Bastos, J., Batterman, S. A. & Freire, F., Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon. Energy and Buildings 69, pp. 344–353, 2014.

[14] Chang, Y., Ries, R. J. & Wang, Y., Life-cycle energy of residential buildings in China. Energy Policy, 62, pp. 656–664, 2013.

[15] Crawford, R. H., Post-occupancy life cycle energy assessment of a residential building in Australia. Architectural Science Review, 57(2), pp. 114–124, 2014.

[16] Monteiro, H. & Freire, F., Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods. Energy and Buildings 47, pp. 572–583, 2012.

[17] Cuéllar-Franca, R. M. & Azapagic, A., Environmental impacts of the UK residential sector: Life cycle assessment of houses. Building and Environment, 54, pp. 86–99, 2012.

[18] Zhang, W., Tan, S., Lei, Y. & Wang, S., Life cycle assessment of a single-family residential building in Canada: A case study. Building Simulation, 7(4), pp. 429–438, 2013.

[19] Asdrubali, F., Baldassarri, C. & Fthenakis, V., Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. Energy and Buildings, 64, pp. 73–89, 2013.