A Proposed Methodology of Life Cycle Assessment for Hot Water Building Systems

Arthur B. Silva, Mohammad K. Najjar, Ahmed W. A. Hammad, Assed N. Haddad, and Elaine G. Vazquez

Abstract Population growth and technological development in recent decades have made human activities largely responsible for structural changes in the built environment at regional and global levels. Civil construction, as an integral part of the chain of industrial activities, is also one of the segments responsible for energy consumption and potential greenhouse gas emissions throughout its life cycle. The building materials and their systems have a direct influence on energy consumption and impact assessment, both in the pre-operational, use and end-of-life and disposal phases. In this context, Hot Water Building Systems (HWBS) are included. The variability of possibilities available with regard to the choice of energy sources, water reserve and distribution systems and the selection of materials used in these building systems allows empowering the decision-making in the designing phase. The definition of the type of installation to be used in a building is defined by technical and/or economic requirements. However, the spectrum of possibilities should consider resource consumption and generation of environmental impacts throughout the life cycle. This research proposes a novel application of an environmental management method to empower the decision-making process and encourage the selection course of HWBS. This work insights a Life Cycle Assessment (LCA) methodology to compare a specific the environmental performance of two distinct HWBS (i.e. Natural Gas Heating System and Solar Heating System) for multi-family residential developments.

Keywords Life cycle assessment methodology · Hot water building systems · Environmental performance

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1 Introduction

Population growth and technological development in recent decades have made human activities largely responsible for structural changes in the environmental landscape at regional and global levels [1, 2]. Regarding the aspects of natural resources consumption and the passive impact of human activities, the energy sector is responsible for a major part of greenhouse gas (GHG) emissions [3]. For instance, residential and commercial buildings account for around 41% of total energy consumption in the United States [4]. In these terms, building components have a direct influence on energy consumption and environmental impacts over the entire Life Cycle Assessment (LCA), basically, during the pre-operational phase (i.e. material manufacturing, transportation and construction), as well as at the end-of-life and disposal phase [5].

Buildings are major consumers of energy throughout their life cycle. Generation of energy primarily depends on conventional sources, which is the basic cause of environmental pollution [6]. The materials and their systems have a direct influence on energy consumption and impact generation, in the pre-operational phase (materials manufacturing, transportation and construction), also in the final and discarded life.

Hot Water Building Systems (HWBS) are directly related to energy consumption in residential buildings; performing the second largest energy consumer in buildings and, thus, representing an integral part of the water-energy nexus [3].

The conventional selection of a water heating system in residential buildings focuses on the financial evaluation rather than the sustainability pillars and life cycle consequences (i.e. economic x environmental pillars) [7]. At this level of the analysis, the application of LCA methodology at an early designing phase of residential buildings could empower the decision-making process and sustainability [8], as well as facilitating the selection criteria of HWBS [9], where professional and experts could evaluate the environmental performance of the installed water heating system [10, 11].

A novel application of an environmental management method is presented herein to empower the decision-making process and encourage the selection course of HWBS, taking into consideration the technical and economic aspects at an early designing phase of buildings. The aim of this work is to present a proposal for a method derived from the general LCA methodology in order to compare the environmental performance of two distinct HWBS for multi-family residential developments, through thermal heaters installed on the final roof of buildings, with supplementation of electrical supply, so that accurate information on the environmental performance of the systems can be obtained. However, the installed HWBS considered in this work are NGHS and SHS. In this work, a literature review of the LCA methodology is presented in Sect. 2. The proposed methodology to evaluate the LCA for HWBS is presented in Sect. 3. However, results are discussed in Sect. 4, while the conclusions and final recommendations are presented in the last section.

2 A Literature Review of LCA Methodology

LCA is described by as a scientifically based analysis and assessment of the environmental impacts of product systems [12]. Regarding to ISO standards, this methodology was revised in 2006 and started to be condensed into ISO 14,040 and ISO 14,044 standards [13]. In Brazil, the Brazilian Association of Technical Standards, published equivalent versions initially translated in 2001 (NBR ISO 14,040, NBR ISO 14,041, NBR ISO 14,042 and NBR ISO 14,043) and later in 2009 and 2014 (NBR ISO 14,040 and NBR ISO 14,044 replacing the previous ones) in a way to support the descriptive text and definitions, as well as facilitate the understanding of the theme [14].

At the level of the energy consumption and impact assessment of products, LCA is characterized as a management methodology that help computing inputs and outputs of a production system to evaluate the environmental performance over their entire lifespan [15]. The application of LCA methodology in the construction sector focuses mainly on the characteristics of the building typology and components [16]. However, such application is facing several challenges that are giving a wide spectrum of related variables, and making it necessary and interesting to define a standardized analysis structure in order to increase its accuracy [17]. In this context, HWBS should also be assessed over their entire lifespan, so that the energy incorporated into the biogenic emissions are considered and give greater dimension to the impacts of the systems [18]. The methodology adopted for this study is related to the LCA of HWBS in multifamily residential buildings, taking into consideration comparing the different types of systems in relation to their environmental performance at an early designing step. The general scope of such application will be conducted in four phases based on the LCA methodology: Goal and Scope definition; Life Cycle Inventory analysis (LCI); Life Cycle Impact Assessment (LCIA); and Interpretation of data and results obtained by the partial and final methodological processes [19, 20].

Defining the Goal and Scope of the study means determining the intended application for the analysis and the reason for carrying out the study, the target audience to whom the results are intended to be communicated and, therefore, the means for their dissemination [19]. In these terms, the scope of the study should include the definition of the product system to be studied; the functions of this system or compared systems; the determination of the functional unit/functional equivalent; the system boundary; allocation procedures; selected impact categories and methodology for impact assessment as well as subsequent interpretation to be used; data requirements; assumption; limitations; initial requirements for data analysis; type of critical analysis, if applicable; type and format of report required for study.

The next step is to build up the LCI based on ISO 14,044, which demonstrates a definition of the inventory analysis phase that involves the cradle-to-grave character of the method; "life cycle assessment phase involving the compilation and quantification of inputs and outputs of a product system over its lifetime. life cycle". Table 1 illustrates the output results of the LCI step [21], including a list of data of the environmental impacts to be evaluated at the next step of the LCA methodology,

Table 1 Characterization of impact categories commonly demonstrated in studies

Impact Categories	Geographic Scale Global	Regional	Local
Global Warming	■		
Stratospheric ozone depletion	■		
Phoyochemical oxidant formation		■	■
Acidification		■	■
Nutrient enrichment		■	■
Ecotoxicity		■	■
Human toxicty		■	■
Working environment			■
Odour			■
Noise			■
Radiation	■	■	■
Resource consumption	■	■	■
Land use			■
Waste			■

Adapted from Stranddorf and Hoffmann [21]

which is LCIA. At this level of the analysis, LCIA aims to give an overview of the significance of the potential impacts of the examined product [22].

There are several methods to evaluate the extracted impacts from the LCI, hence, it is highly important to choose the most appropriate method for each case study [18]. LCIA can be distinguished within two levels: midpoints and endpoints [23]. At the midpoint impact assessment level, indicators are given along the environmental mechanism, while at the endpoint impact assessment level, "*Characterization considers the entire mechanism to its end point, ie. it refers to a specific damage related to the broader area of protection, which may be human health, natural environment or natural resources*" [24]. Finally, the interpretation level refers to permeate the entire analysis process, where the findings of LCI and LCIA are to be consistently combined with the defined Goal and Scope in order to draw conclusions and recommendations [19].

3 Proposed LCA Methodology for HWBS

The objective of this work is to Present a methodological work flowchart for the comparative application of LCA for HWBS in multi-family residential buildings, as a way to obtain data for analysis regarding the environmental impacts of such systems, taking into consideration the energy consumption during of the operation phase of HWBS and its impact on the living standards, combined with the LCA database of the of the applied materials. The developed method herein is developed based on nine main phases, which guide the elaboration and evaluation of the projects and their respective analysis and are the organization of the general phases of methodological application of the LCA recommended by ISO Standards. At this level of the analysis, the interpretation phase is divided into four distinct stages; Interpretation (A), Interpretation (B), Interpretation (C) and Interpretation (D). Each stage has been oriented and modified to verify the output results collected from the previous steps (LCI and LCIA), as well as evaluating their quality, coherence and importance to the study. Figure 1 describes in detail the steps contained in phases I, II, III, and IV of the study, which are Goal and Scope Definition (A), Interpretation (A), Goal and Scope Definition (B), and Interpretation (B), respectively.

The starting point of the analysis, as presented in Fig. 1 is to determine the environmental profile of a certain HWBS. Phase I, Goal and Scope Definition (A), means to conduct general definitions, function, and functional unit. At this level of the analysis, Item (I.1), presented in Fig. 1, means determining the general purpose of the analysis to be performed. Such an objective must be clear and consistent with the reality of the place of application so that it can be valid and have real importance in the context in which it will be applied. The results of the analysis of the performance of the HWBS during the operation phase can be used to make a decision about the use of a particular type of system still in the design phase, with the general objective being traced, for example, as the definition of the type of system, system to be used for the distribution of water in a specific building type, or if a copper or PVC pipe is defined in the project, given the observed impacts.

Item (I.2), presented in Fig. 1, means determining the target audience. In the case of the building installation project, the target audience can be defined as the end user, who will actually use the system and wants to know which one is most advantageous in this respect, or the builder who will do the work and needs the best cost- benefit, or it may be the own design team that needs the determination of the system that consumes the least environmental resources or generates the least impact in order to have a sustainable building profile that seeks environmental certification. Next, item (I.3) determines the scope of the analysis. At this point, a phase of refinement of objectives is to be included, defining the stages of application, scope, work team involved and other important aspects to the elaboration. Moreover, the evaluated function in the employed method can be traced in item (I.4). The main functions of cold water, hot water and piped gas systems can be analyzed, considering that the functions are closely linked to the uses of systems. The functional unit of the study, presented in item (I.5) in Fig. 1, deals with the quantification of the determined function or product performance characteristic. In these terms, the functional unit must, in the case of building systems, be worked as a performance unit and not a mass or metric unit.

Phase II, Interpretation (A), refers to identify stakeholders, focusing on a more managerial profile of the process. Construction projects involves many stakeholders (i.e. facility owners and users, project managers, project team members, facility managers, designers and architects, allotment companies, shareholders of

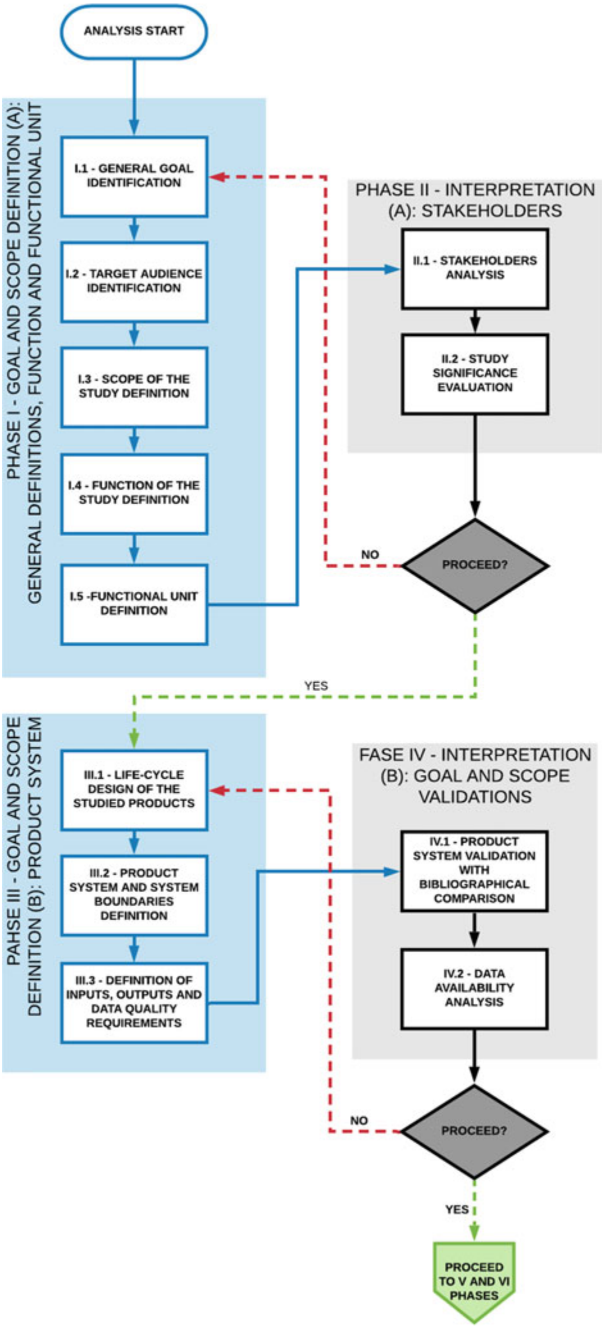

Fig. 1 Detailed flowchart of the proposed methodology of this work—Phases I to IV

the company that develops the enterprise, the public administration, construction workers, subcontractors and outsourced service providers, competitors, banks, insurance companies, representatives of the surrounding community, the general public, and others) [25].

Phase III, Goal and Scope Definition (B) begins by defining the product system, inputs and outputs, which determines the life cycle design of the studied facility systems, as well as the system boundaries. At this level of the analysis, it is necessary to trace the processes and phases involved in the life cycle of the hydraulic installations from the production of the component materials to the final disposal of the system after the operation phase. Conducting the life cycle design of the studied products leads to item (III.2), where the product system and system boundary are to be determined. Item (III.3), presented in Fig. 1, necessitates defining the inputs and outputs of the product system and data requirements. In this work, the most important issue when building up the inventory of database is the quality, relevance, accuracy completeness, and representativeness of the data due to technological and profile changes of the products used to HWBS, taking into account the type and location of installation, consistency and reproducibility of the products.

Phase IV, Interpretation (B), refers to validate the product system. For this, a comparison should be made between the determined life cycle and product system for analysis with other similar related studies and make adjustments that the professional deems necessary to make the system as objective as possible with respect to the results. This factor is extremely important to the legitimacy of the study, since the geographical location and the local social and environmental profile have a direct influence on the quantification and qualification of the impacts of a product system represented by a building installation.

The second sequence of the detailed flowchart of the proposed methodology if this work is illustrated in Fig. 2a, represented by Preliminary System Design Development (Phase V), Inventory Analysis (Phase VI), and Interpretation (C) (Phase VII).

Phases V and VI should begin concurrently or sequentially, as the first step in the inventory phase is to define and organize data sources to enable collection, organized according to requirements. In order to obtain these, it is oriented to use an internationally consolidated database, since the exact obtaining of the production processes involved denotes time and resources. However, such a process may lead to variability of results with respect to the actual life cycle of the examined system and compromise the reliability and requirements of the data. Data collection at this level of the analysis may involve the need for bibliographic and market research that fosters the assembly of product system processes and guides the volume of materials consumed for them.

Phase V consists of the preliminary design of building systems for analysis objects for the primary purpose of obtaining the data necessary to foster life cycle inventory analysis, as presented in Fig. 2a. Hence, four main sequential activities related to good engineering practices are to be defined, as follows:

(a) An architectural assessment of the needs and demands of the building should be carried out.

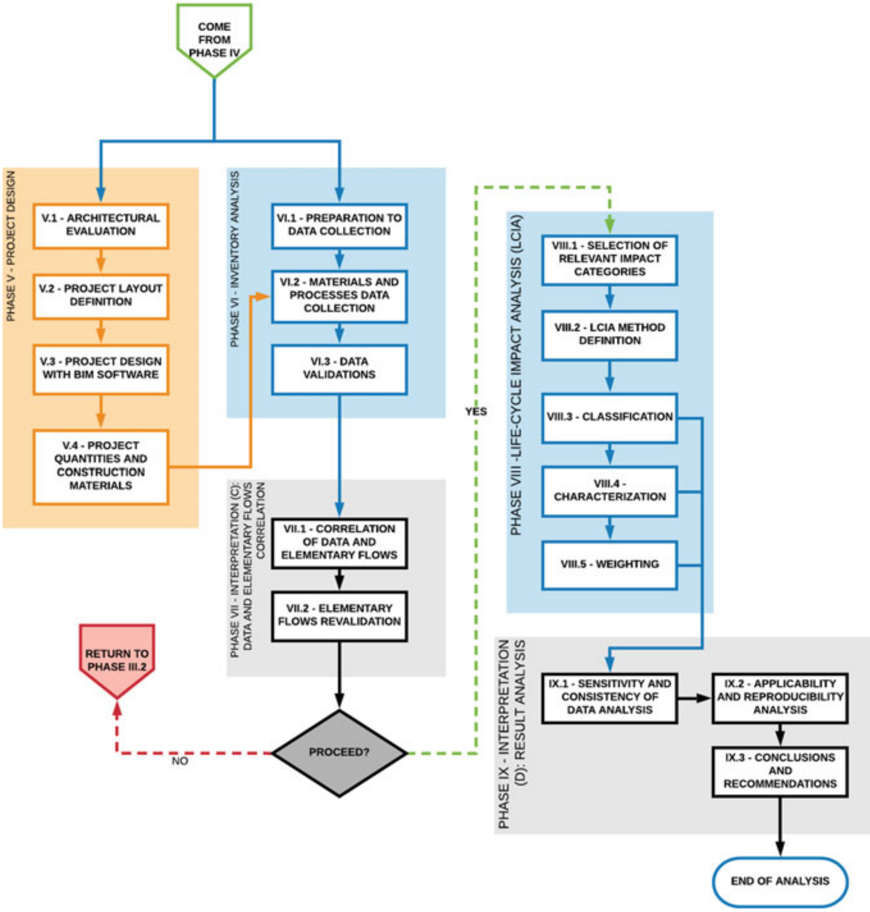

Fig. 2 Detailed flowchart of the proposed methodology of this work—Phases V to IX

(b) The project layout should be defined, taking into consideration elements such as technical reserve location, water or power inlet leasing, internal distribution pipe division, better leasing of equipment needed for system operation.

(c) The effective elaboration of the projects should be considered based on the current norms and available database. Hence, one should seek to understand the level of details that the project necessitates to meet the requirements of the LCA methodology such as the specifications of buildings components, taking into consideration that the LCA methodology involves processes such as "cradle to grave", that is, from the extraction and manufacturing phase until the end of life; "cradle to gate", that is, from the extraction until the end of manufacturing phase; "cradle to cradle", that is, from the extraction and manufacturing until the end of life and recycling to be reused again [13].

(d) The project materials and construction components should be quantified, considering the use of the products that will actually be installed to increase the reliability and completeness of the data obtained.

Phase VI, inventory analysis, is the elaboration phase of the projects that ends up with obtaining the list of materials that fosters the inventory data. The data collection requires obtaining data related to the life cycle of the components of the HWBS; a factor that is intended to be performed with the help of a database, such as Ecoinvent. This phase necessitates guiding the modeling of the product system with the aid of LCA software, such as OpenLCA. System modeling often involves the combination of basic processes and raw materials in the database to obtain the desired products [26], a factor that can create uncertainties in the process, given the insufficient knowledge obtained about the process. production or misuse of processes. At this level of the analysis, the data collection stages consider the database collections, materials and processes data collection, and culminate in the data validation. The data collected in the inventory should be evaluated against the data requirements defined at the beginning of the study in a way to determine the relevance or discard of collected data by screening the material.

Phase VII is Interpretation (C), where the correlation of data and elementary flows is ranked in the classification of the collected data according to the defined flows for the studied functional unit [27]. Thus, it is verified whether all flows considered have consistent and sufficient data for the elaboration of the LCIA, if other data are needed or if there is not enough data available for the definition of all flows. At the end of this analysis, a decision should be taken whether to continue the process or to redefine and redo the completed phases to ensure concise results. The carried inventory and the refined product system facilitate proceeding to the LCIA and final interpretations, which are detailed in the figure, Fig. 2b, which demonstrates the final phases of the proposed methodology of this work.

Phase VIII, LCIA, means selecting the relevant impact categories to the study, taking into consideration the history of application of LCA for analysis of hydraulic systems. The major impact categories, as previously presented in Table 1, can be exposed to global warming, human toxicity (carcinogenic and non-carcinogenic), shortage of fossil resources and mineral resources and waste, impacts considered directly related to the building systems of employment of the study. The next step after selecting the impact categories, the LCIA step is to be conducted according to the item (VIII.2), illustrated in Fig. 2b. Hence, it is important to consider the midpoint impact assessment, which has less data uncertainties [28], using an impact assessment method such as ReCiPe, which combines the Eco-indicator 99 and CML methods, giving them an update regarding the content, deriving characterization factors according to a midpoint approach (with 17 indicators) or endpoint (with 3 indicators) [29]. There is a fundamental relationship between midpoint indicators, direct impacts, and endpoint indicators. The structure overview of ReCiPe impact assessment method is presented in Fig. 3 [30]. Phase IX, Interpretation (D), which necessitates evaluating the completeness, sensitivity and consistency of the data.

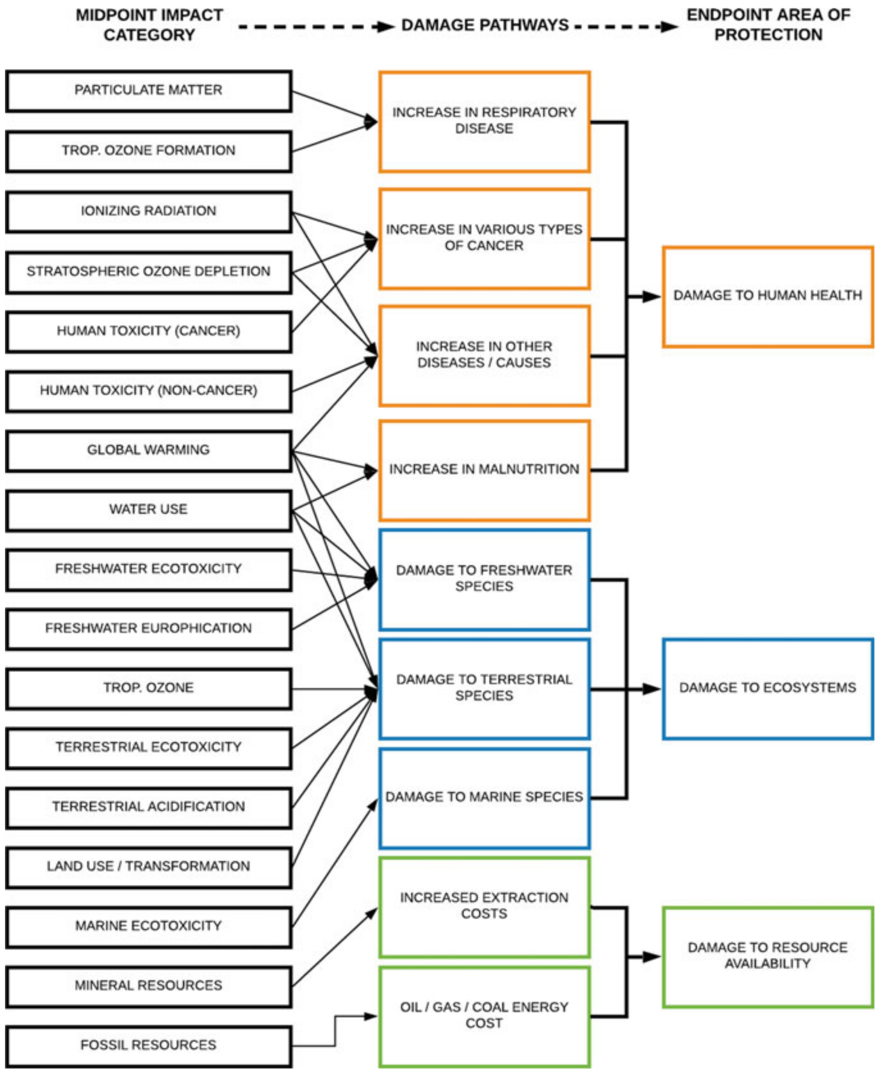

Fig. 3 Structure overview of ReCiPe impact assessment method (Adapted by RIVM [33])

4 Results and Discussion

This work insights a Life Cycle Assessment (LCA) methodology to compare a specific the environmental performance of two distinct HWBS (i.e. Natural Gas Heating System and Solar Heating System) for multi-family residential developments.

The proposed methodology presented in this work intends to facilitates analyzing the life cycle analysis of Hot Water Building Systems at early stages of building design, taking into consideration from a cradle-to-gate perspective; including primary extraction of component materials, beneficiation and production and transportation to the place of execution of the projected installation. Hence, the energy consumption incorporated to them and their biogenic emissions are considered and given larger dimensions of impact assessment.

Based on the expected results, an analysis of the impacts obtained can be performed and the study is concluded by checking the quality of the conclusive data and its reproducibility, defining improvements to the method and observed limitations, and culminating in guidelines for the methodological application.

5 Conclusions

Population growth and technological development have made human activities largely responsible for structural changes in the built environment at regional and global levels. Building materials and their systems in the construction sector have a direct influence on energy consumption and impact assessment over the entire lifespan of Hot Water Building Systems. Hence, the novelty of this work is in proposing an application of an environmental management methodology to empower the decision-making process and encourage the selection course of Hot Water Building Systems, taking into consideration the technical and economic aspects at an early designing phase of buildings. The main objective of this work is to apply the Life Cycle Assessment LCA methodology to compare the environmental performance of two distinct Hot Water Building Systems; Natural Gas Heating System and Solar Heating System, in a multi-family residential development.

The construction sector has a vast and direct influence on the environmental impacts caused by human activities in the built environment at various scales. The application of Life Cycle Assessment methodology at early stages of designing buildings could provide more information related to the environmental performance of the building materials, building systems and building installations. Such useful information could culminate in the reduction of passive impacts of construction projects over their entire lifespan. At this level of the analysis, the life cycle impacts are highly interdependent, so that one phase can influence others. For example, selecting building materials can reduce the need for space heating, but can also increase built-in energy and transportation-related impacts or change the lifespan of the building as a whole.

The proposed methodology presented herein has some limitations as to its implementation. The results of the application will provide a complex set of numerical values for environmental impact indicators and a report with all related assumptions made during the analysis, which makes the interpretation of the results by non-specialists in Life Cycle Assessment are difficult to be conducted. Particularly, if there is insufficient comparative standard, which is considered as a determining factor in the results of the analysis performed for buildings and building systems. Another limitation of this work refers to the lack of an inventory database for South

America and for local studies. The application of Life Cycle Assessment methodology depends on using existing data in global bases. Hence, it is highly important to highlight the important role of the regionality of the case studies, taking into consideration the heterogeneity of the natural, cultural and economic profiles among the localities of the region. On the other hand, the determination of a methodological standardization regarding the application of Life Cycle Assessment methodology for building systems allows more professionals to be involved in this process, and data can be obtained from the results of building applications, which can be a parameter for other studies.

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