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BIM-based LCA method to analyze envelope alternatives of single-family houses: case study in Uruguay

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Abstract

Currently, Uruguay is developing several measures to reduce the environmental impact of human activities and CO_2 emissions. In 2015 more than 90% of electricity was produced by renewable sources. Despite this fact, the construction, transport and building sectors are still responsible for more than 60% of CO_2 emissions. Reducing building environmental impacts is becoming an increasing challenge. Life Cycle Assessment (LCA) is recognized as a method that can help to reduce environmental impacts of the building sector. It can be used as an early stage decision-making tool to assess environmental impacts design choices. The present paper developed a method based on LCA which integrates Building Information Modeling (BIM) to assess building envelope alternatives. The method is validated by the application in a single-family house - the most popular typology - in Uruguay, considering three envelope alternatives, including frequent and non-frequent materials. Results focused on comparing the embodied impacts, transport, and operational energy consumptions of each scenario. The results evidence that the developed method can help during the building design process, especially to define dimension and thickness of materials.

Key words: Environmental Impact Assessment; Life Cycle Assessment; Building Information Modeling; Single-family house; Uruguay.

Abbreviations: AEC, Architecture Engineering and Construction; ANV, Agencia Nacional de Vivienda; BIM, Building Information Modelling; CC, Climate Change; EN, European Standard; EPD, Environmental Product Declaration; FWE, Freshwater aquatic Ecotoxicity; GWP, Global Warming Potential; ISO, International Organization for Standardization; HT, Human Toxicity; HVAC, Heating, Ventilating and Air Conditioning; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; ODP, Ozone Depletion Potential.

Introduction

The growing interest in reducing the environmental impact of human activities is evidenced by the environmental global agreements of 2015 and 2016 (United Nations Conference 2016; United Nations Conference and United Nations 2015). The responsibility of the building sector for that fact is proved by the intensive use of mineral resources, energy and waste generation (Cuéllar-Franca and Azapagic 2012). Thus, there is an urgency to mitigate undesirable problems arising from our lifestyle (Cabeza et al. 2014). Several recent measures (MVOTMA and SNRCC 2015; SNRCC 2010; United Nations Conference and United Nations 2015) conducted to reduce environmental impacts of the building sector are developed at global and local scales.

In Latin America, Uruguay is one of the countries whose progress in the reduction of environmental impacts and renewable energy production has been significant. Thus, local authorities recently announced that more than 90% of electricity consumed in 2015 belonged to 100% renewable sources (DNE-MIEM 2015). Despite this fact, there is still some way to go before the minimization of environmental impacts from the transport and residential sectors, responsible for more than 60% of CO_2 total emissions from this developing nation (MVOTMA and SNRCC 2015). Moreover, the residential, services and commercial sectors are responsible for 28% of national energy consumption (MIEM 2015). Furthermore, the Uruguayan residential sector is mainly based on single-family typologies, where over 76.57 % of the population lives in single-family houses (INE 2017). The challenge of reducing the building environmental impacts, especially in popular buildings typologies, is recognized by local authorities (MIEM 2015).

Life Cycle Assessment (LCA) is recognized as a method to quantify environmental impacts (ISO 2006a). The growing use of this method to assess single-family houses is demonstrated by the increasing number of recent publications (Agya Utama et al. 2012; Cuéllar-Franca and Azapagic 2012; Fouquet et al. 2015; Gervasio et al. 2014; Hanandeh 2015; Houlihan Wiberg et al. 2014; Iddon and Firth 2013; Lewandowska et al. 2013; Monteiro and Freire 2012; Mosteiro-Romero et al. 2014; Motuziene et al. 2016; Oyarzo and Peuportier 2014; Peuportier et al. 2013), including developed and developing nation cases of Europe, America, and Asia. The benefit of using the LCA method to assess environmental impacts of different construction alternatives in developing nations has been demonstrated in Agya Utama et al. (2012) and Hanandeh (2015). Agya Utama et al. (2012), for example, focus the LCA method application on comparing embodied environmental impacts of residential houses located in Indonesia. Hanandeh (2015), uses the LCA method to compare popular single-family house construction alternatives. Furthermore, several studies underline the advantages of the method to calculate the environmental impacts during the whole building life cycle from early stages of design (Gervasio et al. 2014). However, the application of LCA to buildings is still recognized as a complex and time-consuming process (Basbagill et al. 2013). Research gaps in the way of improving and reducing efforts in the LCA application of single-family houses have been identified (Soust-Verdaguer et al. 2016).

From the methodological point of view, Soust-Verdaguer et al. (2016) evidence that simplifications in the LCA application of single-family houses are needed. The EeB Guide Project (2012) defines guidelines to simplified LCA applications to buildings. Thus, several studies (Basbagill et al. 2013; Malmqvist et al. 2011; Soust-Verdaguer et al. 2016), highlight the opportunity to integrate BIM models in the LCA application, as a strategy to reduce the effort in data acquisition. Moreover, the increasing importance of the use of BIM software in the Architecture Engineering and Construction (AEC) sector is evidence by Directive European 2014/24/EU (Official Journal of the European Union 2014). In Latin America, there is also identified progress in this field. Chile, for example, has recently developed a plan to promote the use of BIM software in order to modernize the building sector (CORFO 2016). On the one hand, several studies demonstrate the advantages of BIM-based LCA applications (Ajayi et al. 2015; Al-Ghamdi and Bilec 2017; Basbagill et al. 2013; Georges et al. 2014; Gómez Pérez 2014; Houlihan Wiberg et al. 2014; Iddon and Firth 2013; Jalaei and Jrade 2014; Jrade and Jalaei 2013; Lee et al. 2015; Mesa González 2013; Navarro Osta 2014; Peng 2014; Seo et al. 2007; Shadram et al. 2016; Shafiq et al. 2015; Shin and Cho 2015; Soust-Verdaguer et al. 2017). Recent developments (Shadram et al. 2016) confirm the potentiality of BIM-based LCA framework to calculate and compare embodied impacts from the early stages of design. However, its application is limited to the existence of the EPD (Environmental Product Declaration) of different materials. Basbagill et al. (2013), also developed a semi-automated approach method to integrate BIM models to LCA. Al-Ghamdi and Bilec (2016) compared three LCA tools (*Athena Impact Estimator for Buildings, Tally and SimaPro*) commercially available to designers, starting from the BIM model of the complete building. On the other hand, several studies (Jrade and Jalaei 2013; Schlueter and Thesseling 2009; Shadram et al. 2016) underline the lack of interoperability, as well as the shortcomings of BIM software to provide enough data to LCA application (Peng 2014), such as limitations on the integration of both tools. Thus, one of the most important challenges of BIM and LCA integration is how to link different databases and automatize the design and impact calculation processes (Soust-Verdaguer et al. 2017). The present research addresses these limitations in order to reduce efforts on data acquisition and automatize their integration.

Furthermore, the use of LCA to assess different envelope alternatives in single-family houses is evidenced in Agya Utama et al. (2012). This approach, as well as several studies (Hanandeh 2015; Kolokotroni et al. 2004; Monteiro 2010; Sartori and Hestnes 2007), underlines the importance of the building facade and external walls in the environmental impact reduction of the building sector. This fact is also reinforced by Uruguayan authorities, which underlines the importance of improving the performance of the building envelope by characterizing and monitoring the existing building scenario (MIEM 2015).

Several studies (Casañas 2011; Pelufo 2011) focused on the Uruguayan context, underline the need to quantify environmental impacts of the residential sector during their life cycle, taking local characteristics into account. This fact is reinforced by the inexistence of previous tools or methods to quantify environmental impacts during the whole life cycle of buildings for this context. Moreover, the developed method can help to characterize different materials alternatives for the most popular residential typology – the single-family house.

The authors concluded that the gaps on specific literature are related to the inexistence of BIM-based LCA tools and methods, which can be used in decision-making during the envelope design of buildings as a strategy to reduce the environmental impacts of building sector. As well as, none of the earlier studies discussed in this section attempted to develop an LCA-based method use to analyze case studies located in Uruguay.

In response to current gaps, this study aims to develop a BIM-based LCA method to assess, during early stages of design, the environmental impacts of single-family houses envelope alternatives located in Uruguay. The method is conceived to help with decision making (e. g. selection of materials, selection of techniques, selection of transport distances) throughout the life cycle of the building.

Methodology

The proposed method includes a description of the data structure framework and a case study application. Thus, the method aims to optimize, simplify and adapt the LCA method to a local context by integrating and tending towards automatized BIM tools to LCA application. The method also aims to reduce efforts in data acquisition, and optimize the design process, in order to assess environmental impacts of envelope alternatives of single-family houses during design stages.

The present method is developed according to International Organization for Standardization (ISO) 14040, and ISO 14044, international references on LCA and also European Standard (EN) 15978 (2011) and EN 15804 (2014) standards, European reference on LCA to buildings. In spite of the fact that the EN 15978 (2011) standard is not geographically applicable to the case study, it is globally recognized as a single point of reference in the LCA application to buildings. Moreover, the developed method is based on previous research into LCA application, described by Baumann and Tillman (2004), and developed by García-Martínez (2010) and García-Martínez et al. (2011) to the Andalusian context of LCA application to buildings, as well as the research developed by Gómez de Cózar et al. (2017) and the Masters dissertations developed by Gómez Pérez (2014); Mesa González (2013); Ruiz Alfonsea (2016) in the MIATD (Official Master in Architectural Innovation: Technology and Design).

Phases of the method

In response to the gaps detected in previous research, the proposed method is conceived to complement and reorganize BIM software databases, in order to adapt them to the LCA application. The method aims to enhance the interoperability between BIM and LCA and also trends towards automatizing the assessment and analysis of the envelope alternatives during the building life cycle.

The proposed method matches BIM, spreadsheet, and energy simulation tool software to develop the envelope alternatives analysis. As shown in **Fig 1**, it is organized according to the following phases:

- **Layout Template (T).** It consists of the definition in the BIM software environment of the materials and pre-defined components according to local characteristics. The template contains a library, including the most relevant materials and components which users can choose to build the model. The library also contains data on the density of materials. The layout template includes tags and ID codes that are linked to supplementary data and data analysis.
- **Building Modelling (BM).** Based on the previous BIM Template (T), the user can model the buildings according to their specific geometric characteristics.
- **Layout Supplementary Data (SD).** It consists of the definition of the data on materials and components, not included in the BIM software environment. SD includes supplementary information needed to develop the LCA application to buildings, such as packaging materials, auxiliary materials, waste factors and transport (means of transport and distances). All of which are developed according to local characteristics and automatically linked to the data analysis phase. However, users can modify and edit their content if necessary. Several data, such as means of transport and distances, are manually entered by the user.

- **Data Analysis (DA).** It consists of the re-grouping, organization, and analysis of data. The life cycle scenarios are previously defined by the user. The DA phase links data about the building (data from

BIM software and SD) with environmental impact factors (from the Ecoinvent database) and energy flow calculations, to perform the environmental impact calculation. Spreadsheet software is used to perform the simple equations to obtain the impacts.

- **Layout results (R).** It is based on the communication of results strategies and their usefulness. After the calculation of environmental impacts of the building materials, the operational energy consumption of the building is included in the communication of results layout. Results are organized to obtain environmental impacts of building materials by LCA phases. However, users can also edit the layout of results and organize them as required.

Information exchange

To develop the mentioned phases, the authors propose a set of items and relations which aims to reduce efforts in LCA application, as well as to reduce the risk of mistakes, misunderstandings, and errors, with regard to exchange information along with the phases of the process. Various software are used, including BIM software (ArchiCAD© 19) and spreadsheet software (Excel© 2016). **Fig. 1** illustrates the phases of the method and the information exchange; the following items are included:

-BIM Model (M). It consists of the virtual model of the building. Based on the T template, it includes the alternatives and original cases in different files.

-BIM Components (BC). The BC are used as a starting point to organize the life cycle information on the building in the BIM software. These BC are defined as data and graphic structures which contain the main characteristics of the building materials and are used to build the virtual model of the building. For each BIM component BIM material layers and thickness are defined, similarly to building components in real buildings.

-Bill of quantities. Initial. The INITIAL bill of quantities includes the sum of the materials that compose the BIM model and it is organized according to the BIM template. This bill includes the data extracted directly from the **BIM model**. It is just composed by the names and quantities of the **BIM materials** contained in the **BIM model**.

-Bill of quantities. Final. The FINAL bill of quantities includes the SD needed to develop the LCA application, not included in the BIM model. The SD provides information such as auxiliary materials for the building process (e.g. wood for timber formworks); maintenance, repairing, refurbishment and replacement materials (e.g. paint for repainting the walls); packaging materials (e.g. palettes and sack kraft for cement). It also provides a waste production factor during construction, maintenance, repair and refurbishment stages. The distances between the suppliers and the construction site are simplified according to local characteristics. The main difference between **Initial** and **Final bill of quantities** is the amount of data that each one includes. The **Final** bill of material quantities enriches the **Initial** bill by assigning to each **BIM materials** the materials used during the maintenance, repair, refurbishment and replacement stages, their packaging materials, their **Basic materials**, and the distances from the manufacturing point to site. This SD is contained in the **BIM material sheets.**

-List of Basic Materials (LBM). The final bill of quantities was regrouped according to the material process of manufacturing. The list was organized in such a way as to be able to obtain the environmental impacts separated by material, component and LCA phases.

-Basic Process (BP). After the selection of the life cycle scenarios end of life cycle for all materials, the list of basic materials was linked to the basic process from Ecoinvent V2.0 (Frischknecht et al. 2007) database . A selection of process related to selected materials and components was included.

-Environmental Impact Calculation (EIC). Ecoinvent V2.0 (Frischknecht et al. 2007) database was used to obtain the impact factors. Results were calculated through simple mathematical operations between the impact factors and the process from the BP list.

-Comparison of envelopes alternatives. The results were organized in order to easily visualize impacts of each LCA phase and material impacts of each scenario.

LCA application to case study

The LCA application complies with the ISO and EN references standards (EN 2011; ISO 2006a; b) and includes the following main phases: system boundaries definition, life cycle inventory, environmental impacts calculation, and interpretation. Moreover, the method proposes 5 stages during the BIM-based LCA application, which can be edited by the users.

Along case studies the same functional unit (the building envelope) was used to guarantee the reliability of results. This functional unit assumed to compare the envelope alternatives included the same floor, windows and doors solutions, and three different solutions for external walls and roof.

The environmental impacts categories calculated were selected according to the following criteria: the most calculated in this typology and the most representative in this zone. According to that fact, the most calculated is Global Warming Potential (GWP) based on Soust-Verdaguer et al. (2016) of single-family houses LCA application. Uruguay has a large hydrographic network, mainly composed by the Rio de la Plata's river basin, which covers 3,200,000 km² of territories belonging to Argentina, Bolivia, Brazil, Uruguay and Paraguay (MVOTMA 2013). Freshwater is a basic resource for the development of economic activities (e.g. extensive farming, agriculture) and for human consumption. Thus, Freshwater aquatic Ecotoxicity (FWE) and Human Toxicity (HT) are considered appropriate indicators in characterizing the impacts of the use of toxic substances in the fresh water resources and in human beings. Moreover, Uruguay is currently affected by the Antarctic ozone hole (Nasa 2017). Due to this proximity, the Ozone Depletion Potential (ODP) is considered a relevant indicator to be included in this study.

LCA System boundaries

The developed method is a "cradle-to-grave" LCA, that includes fabrication of building materials, construction, use, demolition and end of life phases of a single-family house. Based on the EN 15978 (EN 2011) standard for LCA phases and modules definition, **Fig. 2** represents the system boundaries of the proposed method.

According to the local context characteristics and similar studies developed in this context (Pelufo 2011), the lifespan considered for the case study is 60 years. Moreover, the selection of the most relevant LCA modules (**Fig. 2**) was based on choosing those that have a greater impact on the selection of envelope materials during the life cycle of the building. The product and construction phases included: (A1) raw of materials, (A2) transport of materials to factory, (A3) construction, (A4) transport to the construction site and the construction process (A5). The use phase (B) was restricted to operational energy (B6) and embodied impacts due to maintenance (B2), repair (B3) and replacement (B4) of building materials and components. Other operational impacts due to installations such as lighting, plug loads, HVAC (Heating, Ventilating and Air Conditioning) and water use were not included in the system boundaries. The deconstruction phase was considered as landfill to 100% of materials due to it being the most frequent end of life scenario in this context (Fichtner and LKSUR Asociados 2004).

Life Cycle Inventory

The life cycle inventory comprises the quantification of the input and output included in the system (ISO 2006a). As the aim of the method was to the reduce the efforts in data acquisition and decision-making aid during the design process, several strategies were developed. Thus, methodological aspects of the application of the LCA method, such as part of the organization of the life cycle inventory and the "basic process" definition were based on García-Martinez (García-Martínez 2010).

The Life Cycle Inventory (LCI) consisted of three stages. The first one comprised the automatic account of materials, performed by the BIM software. The second comprised the supplementary data sources contained in the **BIM material sheets** (Appendix B) and interlinked with the BIM bill of material, to ensure an automatic connection. The third comprised the re-grouping of materials into **Basic Materials** (**Table 2**) and the **Basic Process** allocation.

As one of the detected weaknesses of the integration of BIM-LCA was the insufficient data provided by BIM software to LCA application, the proposed method was centered on developing supplementary data sources based on local context materials. Hypotheses about suppliers for material data are based on previous research (Casañas 2011; Mimbacas 2012; Pelufo 2011) and also on information provided by regional manufacturers. Data on distance, means of transport and fuels were simplified taking local characteristics into account, as well as previous research on the field of study (Casañas 2011; Mimbacas 2012; Pelufo 2011). The model was developed considering the main manufacturing points (including cities and villages) for the most common building materials. **Fig. 3** shows the transport allocation model which included five distance levels: local (up to 50 km), regional (up to 250 km), extra-regional (up to 600km), continental (up to 1000 km), intercontinental (up to 15000km). Local to extra-regional level considered 16-ton lorry as the means of transport, contienntal levels considered 32-ton lorries, and intercontinental levels considered transoceanic freight ships as the means of transport. These levels were used in the **BIM material sheet** to indicate the distances covered by each **Basic material**.

The use of the generic database Ecoinvent V2.0 is justified by the inexistence of local databases on impact factors, although it is a generic database not adapted to characteristics of the context. According to similar case studies, the Ecoinvent database is the most used in LCA application of this building typology, regardless of the geographical area where it belongs (Soust-Verdaguer et al. 2016). The Ecoinvent V2.0 (Frischknecht et al. 2007) database contains a variety of processes considered within each life cycle stage, including construction materials, transport and energy. Moreover, the energy consumed for construction and deconstruction hypothesis is based on the used by Kellenberger et al. (2004) for traditional construction.

The maintenance scenario is focused on the natural degradation of materials. It assumes the re-painting of walls every 8 years, the re-painting of doors, ceramic tile cleaning every week and glass cleaning every month. In addition, waste factors during the construction phase were defined according to local characteristics and based on Peluffo (2011).

The hypothesis for the quantification of the embodied impacts of the artisanal brick was based on Casañas (2011). The study demonstrates that the highest consumption of sources in the manufacturing stage of the brick is produced during the “cooking” or heating stage. It is estimated that for every kilo of brick produced, 2.77MJ of burned wood is needed (Casañas 2011).

Operational energy calculation

The hypothesis to calculate the operational energy was based on the technical and physical characteristics of the house. Due to the design of the house being based on active concepts, heating and cooling systems are needed during summer and winter. The most common system for cooling and heating are electric heaters and split air conditioning. The calculation was focused on heating and cooling energy consumption. Domestic hot water, lighting and equipment energy consumption were not included. The envelope proprieties for external walls and roofs are defined in **Fig. 4.** For windows and doors a U-value of 2.8 $W/m^2.K$ was considered, the average according to local regulations (MVOTMA 2014). **Fig. 5** shows the electricity mix used in the operational energy calculation based on a local authority report (DNE-MIEM 2015). Based on a supplier Company UTE report a primary energy factor of 1.6 was obtained for 2015 (DNE-MIEM 2015) .

The quantification of the building energy demand was performed in DesignBuilder v4.7.0.27. (Cockcroft 2016), using Energy Plus as a thermal simulation software tool. Despite of the fact that Ecodesigner STAR, an add-on function of ArchiCAD (GRAPHISOFT 2017), allows to obtain quick results without professional knowledge on energy efficiency simulation (Jarić et al. 2013), DesignBuilder (Cockcroft 2016) (Energy Plus) allows to set a large number of building characteristics (Loh et al. 2007). Moreover, it is recognized the existence of plug-ins to export the ArchiCAD BIM model into gbXML format. However, due to the simplicity of the case study and to avoid possible errors, the building was modeled in DesignBuilder (Cockcroft 2016).

Description of case study

The selected case study is a typical single-family house built in 2010. The building is located in Sauce, a village 36 km from Montevideo, the latter´s climate being representative of more than half of local population and building stock. Moreover, the selected building is conceived as a mutual-aid housing cooperative, an innovative and singular solution for social housing buildings in this context. The house integrates a group of 72 similar houses called *COVISA cooperative*. The one-story house area is 67 square meters, and it was encouraged by the ANV (ANV-MVOTMA 2017), a public social-housing developer.

The house was built by traditional masonry, lightweight roofing, single-glazed window opening and wooden doors. The use of techniques and local materials is justified by the self-construction of the building. The use of artisanal brick production is typical in this area. This brick production, described by Casañas (2011) includes the clay extraction and transport to the manufacturing point, the preparation of the plaster, the shaping of the bricks, the drying, “cooking” (or heating) and storage. The study also demonstrates the dispersion of production points in Uruguayan territory, this means that the supply points are always local. Casañas (2011) also defines the artisanal bricks and the concrete as the most “frequent” building materials. Other materials such as aerated concrete for example, are considered “non-frequent” alternatives, although their use can improve the thermal performance of buildings.

According to the structure engineering drawings and specifications, the structure is composed of galvanized steel profile used to support the roof and small concrete columns used for reinforcing the edges. **Fig. 6** shows the interior distribution and an over-view of the house used in the data estimations. A complete technical description of the building materials and components of the envelope are included in **Fig. 4**.

Building model

The BIM model of the single-family house was drawn in ARCHICAD 19 software (GRAPHISOFT 2017), an Open BIM software. The selected LOD (Level of Development) to develop the study was 300. This LOD allows general information be obtained about the main materials and characteristics of the building during the design process. The model shown in **Fig. 7**, is organized according to the main components of the building envelope.

Building envelope alternatives

To demonstrate the usefulness of the method and its ability to compare different envelope scenarios during the design process, three envelope possibilities were considered. Two different scenarios of improvements of wall and roof performance were compared with the original scenario, and their environmental impacts during its life cycle were analyzed. The selection of the alternatives was developed according to the context characteristics.

The original envelope for an external wall consisted of "frequent" materials such as bricks and concrete blocks with a thermal isolation layer (Polystyrene). Alternative 1 included both "non-frequent" materials and "frequent" materials such as aerated concrete blocks and bricks, and alternative 2 included only aerated concrete blocks (a "non-frequent" solution). Furthermore, the original envelope for the roof consisted of lightweight materials such as galvanized zinc, an air chamber and thermal isolation (Polyurethane and Polyethylene) installed by separate layers. Alternative 1 contained sandwich panels composed of galvanized steel and thermal isolation (Polystyrene), and alternative 2 included galvanized zinc and thermal isolation (Glass wool and Polyethylene) installed by separate layers.

The thermal performance and materials descriptions are shown in **Fig. 4**. The performance of the original envelope complies with **Level 1** (max U-value 1.6 W/m$^{2\cdot}$.K for walls and max U-value 1.0 W/m^{2}.K for roofs) of the standards of social housing performance (MVOTMA 2011) developed by local authorities. For cases built from March 2011, there is established an improved scenario (called **Level 2**), described in the regulation for social housing promotion (MVOTMA 2014). It defines a maximum U-value of 0.85 W/m^{2}.K for dwellings (roofs and walls). The envelope alternatives 1 and 2 comply with this standard and include several "non-frequent" materials such as aerated concrete, an extra-regional manufacturing product. Thus, the selected envelope alternatives compare regional "frequent" components with low thermal performance with extra-regional "non-frequent" components with improved thermal performance. The relevance of environmental impacts due to transport and operative energy consumption of different envelope alternatives are analyzed in the results.

Results

The characterization of the life cycle inventory was carried out using the CML2 baseline 2000 methodology and based on García-Martínez (García-Martínez 2010). Results obtained compare the energy consumption of the alternatives and the environmental impacts of building materials considering the LCA phases.

Table 2 demonstrates that the results are within the expected range. The improved scenarios have reduced the energy consumption of the house almost 20%. Alternative 1 has improved the energy consumption of the house by 22% and Alternative 2 has improved the energy consumption of the original scenario by 19%.

The **Table 3** is organized in order to identify the environmental impacts of the considered alternatives during the LCA phases, according to EN 15978 standard (EN 2011).

According to **Table 3**, during the manufacturing phase (including A1-A2-A3 modules) Alternative 1 has the highest impacts in the four impact categories considered. **Fig. 8** to **11** confirm that it is mainly due to the use of steel and aerated concrete block. The transport from cradle to site and operational energy consumption are analyzed in **Fig. 12** and **13**. During the use phase (including B2/B3/B4/B5 modules) Alternative 2 produces the highest impacts due to the use of painting surfaces in the façade. For the disposal phase, results confirm that in the original scenario, the use of paintings, polyurethane, polystyrene and bitumen mainly affect the FWE and GWP. However, the ODP and the HT are mainly affected by the use of bricks, paint, sand and concrete blocks. Otherwise, for Alternatives 1 and 2, the use of paintings, polystyrene and aerated concrete blocks mainly affect the FWE and GWP. Moreover, ODP and HT are affected by the use of paintings, aerated concrete blocks and sand.

Fig. 8 to 11 compare the environmental impacts including A1, A2, A3 and A4 LCA modules, of the considered materials. According to the GWP the impacts of non-frequent materials such as aerated concrete blocks, are higher than the frequent materials such as concrete blocks. However, it also shows that the use of cement was higher in Alternative 1.

Fig. 9 and 10 demonstrate that steel has the highest impacts, this means that the roof solution for Alternative 1 is the worst option for human health and the conservation of freshwater.

Results for Ozone Depletion shows (**Fig. 10**) that the use of aerated blocks can be harmful and it also demonstrates that the use of painted surfaces can raise this indicator.

Fig. 12 demonstrates that Alternative 2 produces the lowest impacts in GWP, FWE, HT, and ODP. This is mostly due to the use of extra-regional, regional and local materials. It should be noted that transport impacts related to local, regional and extra regional levels are assumed as lorry 16-ton transport, results evidence that these have proportionately the greatest impact. As shown in **Fig. 12** the results of the case study are also coherent with the energy consumption expectation.

Discussion

The results indicate that the embodied impacts of materials, operational energy consumption and transport are not clear-cut. In terms of operational impacts, Alternative 1 is the most efficient, despite producing the highest environmental impacts in transport and embodied energy of construction materials. Results also demonstrate that materials have to be analyzed according to different categories and a multi-criteria point of view (Agya Utama et al. 2012).

Considering the skewness of the results shown in **Fig. 13**, the authors established a ratio to compare the embodied impacts and the operational energy consumption of the envelope alternatives. **Table 4** demonstrates that the original scenario presents the lowest embodied impacts for GWP, HT and ODP, despite the fact that the sum of embodied impacts and operational energy indicates Alternative 1 is still the best alternative.

Moreover, results evidence that the use of several “frequent” materials causes less embodied impacts than “non-frequent” materials. According to **Fig. 8** the “frequent” wall solution (Original scenario) composed by bricks, concrete blocks, mortar, bitumen and polystyrene produces less GWP embodied impacts than the “non-frequent” solution (Alternative 1) composed by aerated concrete blocks, bricks and mortar. **Fig. 9** and **10** also demonstrate that lightweight roof solutions (Original and Alternative 2) composed by zinc and thermal isolation (glass wool or polyurethane) produces less FWE and HT embodied impacts than the sandwich panel solution (Alternative 1).

The results of the case study not contradict the assumption that the improved scenarios cause fewer impacts than the original one. **Fig. 13** confirms that Alternatives 1 and 2 produce the lowest GWP, considering the embodied impacts, transport and operational energy consumption. The use of renewal energy sources has reduced operational energy consumption impacts in all the scenarios. Results also evidence that the greatest impacts for operational energy phase are produced by the non-renewable energy source – electricity from oil–, even though it represents 6.6% of the national electricity mix. Removing the energy from oil, the GWP of operational energy consumption can be reduced by more than 400%.

To reduce environmental impacts on transport from cradle-to-site, results evidence the need to modify the means of transport in local, regional and extra-regional levels. Despite the fact that Alternative 2 includes extra-regional materials, the impacts of transport cradle-to-site have been less than the original scenario.

Conclusions

The present paper demonstrates that the proposed method can be used to assess envelope alternatives for single-family houses located in Uruguay where the use of "non-frequent" materials for the construction of the single-family house has grown over the last decades. In certain cases, that type of materials is not locally manufactured. Thus, the developed method allows the comparison of different materials considering transport, manufacturing, maintenance and operative impacts. The method also permitted the identification of waste from packaging materials and auxiliary materials used in the construction process.

From the methodological point of view, the developed method provided a way to solve the problems of the shortcomings of BIM software to provide enough data for LCA application, by including supplementary databases and a transport allocation model. Moreover, several strategies to simplify the LCA application have been developed, such as to reducing the efforts on data acquisition from generic databases (e.g. Ecoinvent V2.0). The use of secondary data is justified by the uncertainties during the design process and by the inexistence of databases and data about process such as construction, transports, use, maintenance, replacements, repair, refurbishments and end-of-life adapted to regional characteristics. Thus, it is recommended for future developments, the development and use of a local database on environmental impacts considering local process in this type of method. To reduce the number of environmental impact categories, the study focused on the most globally used (GWP) and locally relevant impact categories (ODP, HT, FWE) for this building typology.

From the results point of view, among the four environmental impact categories considered in the study Alternative 1, (the most energy efficient scenario) was the best scenario in GWP and ODP. The study demonstrates the importance of including different environmental criteria in the design process of envelope alternatives.

It should be noted that the proposed method is developed as an external framework which can interact with BIM software output and semi-automatically apply the LCA method to a building. This fact allows the method to be used in any BIM software, if the input data structure is respected. The method is developed for architects and engineers to select materials, dimension thickness, modify the building geometry and select the cradle-to-site distances of materials, for three alternatives. It allows easy comparison of environmental impacts of different materials, as well as coherent results that can aid in making-decision during design stages. A limited number of BIM materials and building envelope alternatives is remarked. Future development should include more BIM materials in the BIM template, more processes, and different LCA scenarios for end of life stages.

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Figure captions list

Fig. 1. Scheme of the developed method.

Fig. 2. Table 1. EN 15978 standard LCA modules included in the method.

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Fig. 10. Comparison of HT of embodied impacts of envelope alternatives.

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Fig. 12. Comparison of transport cradle-to-site.

Fig. 13. Comparison of the different scenarios considering the environment impacts GWP, FWE, HT and ODP for Operational Energy Consumption (B6), Embodied Impacts, (including A1-A2-A3 and transport from cradle-to-site (A4)).

Tables

Table 1. Summary of the "Basic materials" bill of quantities.

BASIC materials	Units	Original	Alternative 1	Alternative 2
aerated concrete blocks	kg	0	6789.058	6960.639
aluminium	kg	23.350	23.350	23.350
bitumen	kg	72.167	0	0
brick	MJ	32345.847	32345.847	0
cement	kg	2218.720	3181.088	1218.212
ceramic	kg	1265.374	1417.247	1265.374
concrete	m3	12.594	12.254	13.0819
concrete block	kg	9872.057	0	0
detergents	kg	0	0	0
glass	kg	48.687	48.687	48.687
glass wool	kg	0	0	363.014
limestone	kg	485.733	346.636	596.789
packaging paper	kg	0.275	0.308	0.275
packaging PVC	kg	19.263	14.827	24.215
packaging wood	m3	0.239	0.223	0.045
paint	kg	242.147	245.481	372.119
polystyrene	kg	102.140	167.950	68.334
polyurethane	kg	104.442	0	0
reinforced steel	kg	893.038	868.951	927.623
sand	kg	13162.933	10162.751	6911.012
solvents	kg	0.006	0.006	0.006
steel	kg	0	659.350	0
water	kg	4745.094	4542.524	3260.584
wood	kg	0.138	0.138	0.138
zinc	m2	91.431	0	91.431

Table 2. Operational energy consumption

Building envelope	Walls U-value (W/m^{2}.K)	Roof U-value (W/m^{2}.K)	Energy consumption	
			Heating (kWh/yr.)	Cooling (kWh/yr.)
Original	1.089	0.807	5333.06	363.58
Alternative 1	0.626	0.435	4119.69	355.89
Alternative 2	0.692	0.386	4255.04	385.08

Table 3. Environmental impacts organized by category and LCA modules.

Parameters	LCA phase	Global Warming Potential	Freshwater aquatic Ecotoxicity	Human Toxicity	Ozone Depletion Potential
ORIGINAL	A1/A2/A3	8.006x10^{3}	1.142x10^{3}	2.110x10^{3}	6.644x10^{-4}
	A4	4.814x10^{3}	2.705x10^{2}	9.891x10^{2}	5.732x10^{-4}
	A5	6.691x10^{2}	1.621x10^{1}	1.483x10^{2}	5.739x10^{-5}
	B2/B3/B4/B5	6.096x10^{3}	1.179x10^{3}	1.536x10^{3}	9.652x10^{-4}
	B6	4.555x10^{4}	3.054x10^{3}	2.382x10^{4}	4.714x10^{-3}
	C1	4.910x10^{2}	3.359x10^{1}	2.620x10^{2}	5.185x10^{-5}
	C2	1.121x10^{3}	6.294x10^{1}	2.308x10^{2}	1.318x10^{-4}
	C4	2.134x10^{3}	6.428x10^{2}	3.800x10^{2}	2.133x10^{-4}
ALTERNATIVE 1	A1/A2/A3	1.046E+0^{4}	2.157E+0^{3}	4.169E+0^{3}	7.616E-0^{-4}
	A4	5.517E+0^{3}	3.101E+0^{2}	2.152E+0^{3}	6.557E-0^{-4}
	A5	7.438E+0^{2}	4.233E+0^{1}	2.017E+0^{2}	7.589E-0^{-5}
	B2/B3/B4/B5	5.800E+0^{3}	1.180E+0^{3}	1.532E+0^{3}	9.724E-0^{-4}
	B6	3.780E+0^{4}	2.534E+0^{3}	1.977E+0^{4}	3.911E-0^{-3}
	C1	5.356E+0^{2}	3.665E+0^{1}	2.858E+0^{2}	5.656E-0^{-5}
	C2	1.029E+0^{3}	5.773E+0^{1}	2.117E+0^{2}	1.209E-0^{-4}
	C4	2.847E+0^{3}	5.410E+0^{2}	7.982E+0^{2}	2.944E-0^{-4}
ALTERNATIVE 2	A1/A2/A3	9.640x10^{3}	1.246x10^{3}	2.081x10^{3}	9.251x10^{-4}
	A4	4.746x10^{3}	2.659x10^{2}	9.844x10^{2}	5.650x10^{-4}
	A5	6.478x10^{2}	4.758x10^{1}	1.592x10^{2}	6.197x10^{-5}
	B2/B3/B4/B5	3.934x10^{4}	2.638x10^{3}	2.057x10^{4}	4.071x10^{-3}
	B6	3.934x10^{4}	2.638x10^{3}	2.057x10^{4}	4.071x10^{-3}

	C1	4.910x10^{2}	3.359x10^{1}	2.620x10^{2}	5.185x10^{-5}
	C2	1.121x10^{3}	6.294x10^{1}	2.308x10^{2}	1.318x10^{-4}
	C4	1.564x10^{3}	6.111x10^{2}	1.837x10^{2}	1.234x10^{-4}

Table 4. Ratio embodied impacts-operational energy.

RATIO	Global Warming Potential	Freshwater aquatic Ecotoxicity	Human Toxicity	Ozone Depletion Potential
Original	0.281418534	0.46248572	0.130097145	0.262532541
Alternative 1	0.422641197	0.973624803	0.319800132	0.362349342
Alternative 2	0.365645161	0.573319592	0.148981619	0.366017055