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Comparative BIM-based Life Cycle Assessment of Uruguayan timber and concrete-masonry single-family houses in design stage

B. Soust-Verdaguer [a,*], C. Llatas [a], L. Moya [b]

[a] Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Spain
[b] Facultad de Arquitectura, Universidad ORT Uruguay, Uruguay

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A B S T R A C T

The use of wood and engineered wood products is today considered an opportunity for the mitigation of negative building environmental impacts, such as greenhouse gas emissions. However, the literature provides evidence that the quantification and generalization of the environmental benefits of wood during the whole building life cycle can be difficult. This paper presents a quantitative method based on Life Cycle Assessment (LCA) to compare, during their design stages, the environmental impacts produced by a timber-frame single-family house versus those of a concrete-masonry-based house built in Uruguay. The method, conceived as a decision-oriented tool, integrates Building Information Modelling (BIM) and LCA to quantify and compare the environmental impacts of one of the most common dwelling typologies in Uruguay. The results of the cradle-to-grave assessment show that the timber-frame building produced the lowest impacts in Global Warming Potential, Human Toxicity, Acidification Potential, Ozone Depletion Potential, and Freshwater Ecotoxicity, but yielded the highest impacts in Eutrophication Potential. The findings also show that the method developed herein facilitated the comparison and contrast between the pros and cons of both design options during their design stages.

1. Introduction

1.1. Context

According to the United Nations (United Nations Conference, 2015), the world faces global challenges regarding the reduction of environmental impacts produced by human activities. In this scenario, the construction and building sector plays a relevant role in reducing greenhouse gas (GHG) emissions and in achieving energy consumption objectives. The United Nations (UN) Goals related to Sustainable development for 2030 involve, among others, the so-called “Goal 11: Sustainable cities and communities” and “Goal 12: Responsible consumption and production” (UN - United Nations, 2019). Therefore, the promotion of using renewable materials, such as wood-based products for buildings (from high-rise buildings to individual houses), demands attention and contributes towards meeting those goals. Super-tall buildings with mass timber as the main structural material are being developed in a “contest manner”. The excellent load-bearing capacity allows mass timber products to be used in larger and more complex structures (Harte, 2017). Mass timber construction shows certain advantages compared to that of concrete and steel, and includes a lower environmental impact and the use of a renewable resource; these include cost savings, mostly related to on-site labour, and to the possibility of improved amenities and to a reduction in the running costs for occupiers (Kremer and Symmons, 2015). In addition, certain countries with no tradition in timber construction, for instance Argentina, are now promoting the use of this material by enforcing governmental policies stating that at least 10% of social housing must be built with timber (Cámara de Diputados de la Provincia de Entre Ríos. Argentina, 2013). In the same vein, the Uruguayan government is following similar trends. For the past three decades, the forestry sector has significantly grown, and an incipient wood-based products industry is currently under development. Even though local Uruguayan authorities recognize that the use of timber and engineered wood products for structural purposes is growing, these materials remain seldom used in the building sector (Moya and Baño, 2017).

* Corresponding author.
E-mail address: bsoust@us.es (B. Soust-Verdaguer).

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1.2. Previous studies on environmental assessment of timber buildings

The difficulties involved in the quantification of the environmental benefits of using wood in construction have been thoroughly addressed by Ramage et al. (2017) who provided a multidimensional analysis that considered the complete life cycle of a building, from the raw material (i.e., the tree) to the end-product (i.e., the building) and its end-of-life. From a global perspective, their work raises relevant questions regarding the emissions associated with global trade and transport of wooden products, and whether the use of locally sourced timber is beneficial. Achenbach et al. (2018) determined the environmental impacts of the production and construction stages for typical prefabricated timber houses in Germany. They suggested minimizing the distance between the factory and the construction site, in order to reduce the environmental impact produced by transportation. Pajchrowski et al. (2014) demonstrated the environmental benefits of including wood and wood products in the building life cycle, by comparing four detached single-family dwellings, two of which were built with masonry and the other two with wood. The study provided evidence of the need to undertake maintenance activities more frequently and of the corresponding environmental consequences of the wooden houses, compared to those of the masonry-based buildings. Wijnants et al. (2019) quantified the potential environmental impact reduction of light-weight timber-frame constructions for rooftop extensions and the effect of biogenic carbon. The study integrated various End Of Life (EOL) scenarios for the wood products and included those factors in the calculations for biogenic carbon emissions. The review of the above literature reveals that the potential benefits of using wood products in construction cannot be generalized and should therefore be analysed by integrating all stages of the life cycle, from forest management up to the end-of-life, which include processing, transport, use and maintenance, and recycling.

1.3. Previous studies on LCA application during design stages in BIM

Life Cycle Assessment (LCA) is being progressively used as a quantitative tool for the environmental assessment of timber buildings (Achenbach et al., 2018; Pajchrowski et al., 2014; Takano et al., 2015). In order to guarantee transparency and accountability of the results, the International standards ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b) establish the methodological framework of the LCA, and the standards ISO 21930:2017 (ISO, 2017), ISO 21931−1 (ISO, 2010), and ISO 21931−2 (ISO, 2019) define the respective framework of the application of LCA to buildings and civil constructions.

The benefits of applying LCA to buildings have been widely reported (Basbagill et al., 2013; Kylili et al., 2017; Malmqvist et al., 2011; Proietti et al., 2013; Zabalza Bribián et al., 2009). However, several barriers and difficulties, especially during data collection, must be overcome. For example, a base with a large amount of building data contributes towards a feasible application of LCA. In other words, the higher the availability of building data, the more feasible the application of LCA. Data is usually collected during the advanced stages of the building's life cycle when there are fewer uncertainties related to life cycle scenarios.

Due to the importance of the design process of a building, where making relevant changes could be easier than in the construction or use stages (when most of the relevant decisions have already been made), the use of LCA during the design stages of a building is gaining interest, particularly as a tool to reduce operational and embodied energy consumption (Hollberg and Ruth, 2016). Although during these stages basic information probably remains unavailable or incomplete, there is a major influence for the reduction of environmental impacts through the integration of LCA into architectural design (Hollberg et al., 2020). Tschetwertak et al. (2017) and Meex et al. (2018) suggested that the application of LCA during very early stages of design improves the life cycle performance of the building. Based on this premise, Hollberg and Ruth (2016) showed a parametric LCA approach, capable of reducing environmental impacts of buildings during early design stages. Along the same lines, Basbagill et al. (2013) developed a framework for the rapid calculation of the embodied impacts of thousands of building designs, and reinforced the ability of Building Information Modelling (BIM) to develop the environmental assessment of buildings to facilitate the decision-making during the design stages. Soust-Verdaguer et al. (2018) validated a BIM-based method for the comparison, during the design stages, of different envelope alternatives of a concrete-masonry single-family house in Uruguay.

1.4. Challenges to be addressed by the present study

Recent literature reviews (Mirabella et al., 2018; Röck et al., 2020; Soust-Verdaguer et al., 2016) based on LCA applied to buildings provide evidence that the comparison of a wooden solution versus solutions of other materials is not frequently addressed by case studies during the design stages. Possible barriers to this comparison include the lack of design-oriented methods that consider the complexity of quantifying the impacts produced during the whole building life cycle of wood alternatives. Moreover, although the potential of BIM in conducting LCA has been reported in the literature (Seyis, 2020; Soust-Verdaguer et al., 2017), it revealed that the BIM-based assessment and comparison of building alternatives made of timber versus concrete has not been fully addressed. In response to the current limitations, the authors aim to develop a BIM-based LCA focusing on the building design stage, devised as a tool to compare typical single-family houses made of timber vs. those of concrete masonry in Uruguay.

1.5. Theoretical background of the present method

The method was developed in accordance with ISO 14040 (ISO, 2006a), ISO 14044 (ISO, 2006b), ISO 21930:2017 (ISO, 2017), and ISO 21931−2 (ISO, 2017) standards, since these are global references in the application of LCA to buildings.

Based on Soust-Verdaguer et al. (2018) and conceived as a "bridge" between BIM and LCA, the method was intended to supplement the BIM database during LCA application. Therefore, the integration of BIM methodology and LCA technique was based on the automatic/semi-automatic extraction of the Bill of Material Quantities from the BIM model, which was linked to environmental data of the building life cycle. Regarding the direction of the data flow, the approach presented herein follows *Strategy 1: Bill of quantities (BOQ) export,* one of the five strategies provided by (Wastiels and Decuypere, 2019) for the integration of LCA and BIM. *Strategy 1* was also conducted by (Panteli et al., 2018). However, *Strategy 1* reported by Wastiels and Decuypere (2019) and Panteli et al. (2018), differs from the present approach with regards to the LCA calculation. Here, an Excel spreadsheet was automatically linked by the BIM software, rather than using manual input in LCA software as considered in (Panteli et al., 2018; Wastiels and Decuypere, 2019). Through the automatic extraction of the Bill of Material Quantities from the BIM model, and the automatic link to the LCA spreadsheet, the designer is able to edit and modify materials and components of the BIM model, which enables the results to be modified automatically.

2. Methodology

The present method integrated local characteristics of the case studies in order to verify the feasibility of their application during the design stages of single-family houses, and especially to compare timber construction with other concrete-based solutions. Regarding the specific considerations for the comparison of these alternatives, the present method included the whole life cycle of buildings, and those phases especially underlined by previous studies (Pajchrowski et al., 2014; Ramage et al., 2017) as relevant for the assessment of environmental impacts of wood products, such as their transport to the site.

The experimental verification was developed using the software ArchiCAD 19 (GRAPHISOFT, 2017), (an Open BIM software) which was "automatically" linked to the BIM software, although its use remained "independent". Following the recommendations of previous studies (Gomes et al., 2019; Soust-Verdaguer et al., 2017), most of the building elements were at LOD 300 in order to develop the LCA application, which allows rapid modelling and an exhaustive definition of the layer of materials and building components. The proposed LOD allocates various materials and design alternatives during the design stages.

2.1. Background information of the case studies

Two representative single-family houses located in Uruguay, where climate conditions are temperate, were selected based on Soust-Verdaguer (2017). The selection addressed the following relevant aspects: i) the significance of determining the environmental impacts during the life cycle of typical single-family houses (Soust-Verdaguer et al., 2018); and ii) the importance of comparing the environmental performance of two different design solutions (a timber and a "conventional" solution) that include a similar area and similar technical characteristics. The timber house, called "LCU", prioritized the environmental criteria. The "conventional" (concrete-masonry) house, called "COVISA", was designed while prioritizing economic criteria beyond aesthetic and environmental issues.

2.1.1. The conventional house (COVISA)

The COVISA house (Fig. 1) is a typical three-bedroom Uruguayan house located in Sauce, a village 36 km away from Montevideo. The house, with 57 m^2 Gross Floor Area, was constructed on a single level. The load-bearing walls were made of artisanal masonry bricks, typical to this region. The external walls were finished with facing artisanal brick and internally painted with plastic paint. The lightweight roof comprised a series of steel trusses, galvanized Zinc, Polyurethane (3 cm), Air chamber (8 cm), Polystyrene (3 cm), and Cement mortar (1.5 cm) (see Table 1). The foundation was laid with small concrete piles. Single-glazed windows and wooden doors were used. Due to the characteristics of the context, the house included basic facilities including running water, sanitation, and an electricity supply. The house was built by the end user's family, in the so-called "self-construction program", encouraged by the public social-housing promoter *Agencia Nacional de Vivienda* (ANV-MVOTMA, 2017).

Fig. 1. Caption of the 3D model of the conventional house (COVISA) case study.

2.1.2. The timber house (LCU)

The timber house, called "La Casa Uruguaya" (LCU), and the winner of the international competition Solar Decathlon Latin America 2015 (Solar Decathlon Latin America, 2015), is an example of a timber construction for social housing in Uruguay (Fig. 2). The project, conceived in the context of the international competition, consisted of the design and construction of the most energy-efficient house in Cali by groups of university students and teachers. After the competition, the LCU was moved to Montevideo. The one-storey house, at first glance, is a simple "box" of 63 m^2 and three bedrooms, that was designed in accordance with sustainable criteria, and focused on qualitative aspects. This house is a typical light-frame system where the main construction material is wood. Timber piles (foundations), walls, floor, and roof structures are made of wooden studs and beams, and plywood (see Table 1). The frame cavities provide space for the internal insulation (10 cm glass wool). Extra sheets of plywood are used as interior finishes for both the walls and roof. The whole "box" is wrapped with building paper. A vertical solar protection made of wood and separated 40 cm from the "box", covers three sides, and acts as a ventilated façade, and protects the house from the sun and improves its thermal performance. At the roof level, a series of wooden trusses and plywood covered by an asphalt membrane provide the horizontal protection, while the vertical protection is provided by the "solar envelope". Double-glazed PVC-framed windows and wooden doors were used.

2.2. LCA methodological approach

The basic organisation of the method is shown in Fig. 3, and considered the workflow and stages of the building design process through four phases (Soust-Verdaguer, 2017): i) template, ii) supplementary data, iii) analysis, and iv) results.

From an operational point of view, the method combines the use of BIM software with a set of spreadsheets automatically linked to the BIM model. This enables any change made in the BIM model to be readily visualized in the graphs and tables of results and allows the simultaneous comparison of two different single-family houses.

2.3. LCA application to case studies

The LCA application comprises the following steps: (1) goal and scope of the LCA; (2) the life cycle inventory analysis; (3) the life cycle impact assessment and (4) the life cycle interpretation phase, in accordance with ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b).

2.3.1. Goal and scope definition

The study aims to assess the life-cycle environmental impact of two alternative houses: one built with a timber frame and the other with concrete masonry. The method was conceived as a "cradle to grave" LCA, including the complete life cycle of the buildings, as shown in Fig. 4. A functional unit (1 square metre of heating area) and a life span of 60[1] years were considered. Several building elements, including external and internal walls, roofs, floors,

[1] Regarding the inexistence of national reference on building's service life, a 60-year life span was assumed based on (Pelufo, 2011).

Table 1
Summary of the main characteristics of the two houses.

System		COVISA	LCU
E– Envelope			
E_W	Wall	Brick- 12 cm, Polystyrene - 3 cm, Mortar– 1.5 cm (sand, cement and bitumen), Concrete block– 12 cm, Cement mortar– 1.5 cm	Plywood (Exterior) 12 mm, Asphalted cardboard 10 mm, Glass wool 100 mm, Glass wool 100 mm, Polyethylene 200 μm, Plywood interior 12 mm
E_R	Roof	Galvanized Zinc, Polyurethane- 3 cm Air chamber 8 cm, Polystyrene - 3 cm Cement mortar– 1.5 cm	Plywood (Exterior) 12 mm Glass wool 100 mm, Glass wool 100 mm; Polyethylene 200 μm, Plywood interior 12 mm
E_WD	Windows	Aluminum	PVC, double glazing
	Doors	Aluminum/Wood	PVC, double glazing
Structure			
S_B	Beams	Steel Profile	Eucalyptus Timber
S_C	Columns	Steel Profile	Eucalyptus Timber
S_F	Foundations	Small Concrete Piles	Small timber Piles
Internal partitions			
	Wall	Concrete Blocks	Plywood (interior) 12 mm, Glass wool 100 mm, Plywood (interior) 12 mm
	Doors	Eucalyptus timber	Eucalyptus timber
Finishes			
	Wall/Roof	Mortar	Paint wood (interior)
	Wall	Paint (interior)	Paint wood (interior)
	Wall	Ceramic tile	Ceramic tile
	Roof	Paint (interior)	Paint wood (interior)
	Paving	Ceramic tile	Wood (interior)

Fig. 2. The 3D model of the timber house (LCU) case study.

structures, windows, and doors, were compared in the assessment of the potential environmental impact for the same functional unit in the two houses.

In accord with ISO 21930:2017 (ISO, 2017), the life cycle was organized into four stages (product, construction process, use, and end of life), and was composed of various information modules (Fig. 4). In this study, the system boundary included those LC modules that contain the available data regarding the impacts and environmental aspects of the buildings: (A1) raw material supply, (A2) transport of materials to the factory, (A3) manufacturing, (A4) transport to the construction site, (A5) construction process, (B2) maintenance, (B3) repair, (B4) replacement of building materials and components, (B6) operational energy in use, (C1) deconstruction, (C2) transport to final disposal, and (C4) final disposal. Note that, in spite of the fact that B7 module (operational water use) was considered mandatory by the EeB guide project (EeB Guide Project, 2012) and by (Meex et al., 2018), it was not included in the current assessment. This is due to the module's strong dependency on user behaviour, therefore lying beyond the architect's influence. Additional information related to the assumed boundary conditions is provided by (Soust-Verdaguer, 2017).

2.3.2. Life cycle inventory

The Life Cycle Inventory (LCI), created for the quantification of input and output flows, was organized into three stages: (1) obtaining the initial bill of material quantities (automatic quantities taken from the BIM model); (2) attaining the final bill of material quantities (enriched by data such as transport and distance from the factory to construction site, materials used during replacement, repair stages, auxiliary materials, packaging materials, and waste production during construction and use phases); and (3) summarizing the basic process.

The Initial Bill of Material Quantities (IBoMQ) was directly obtained from the BIM software as suggested by Houlihan Wiberg et al. (2014) and exported to a spreadsheet file. The list was composed of materials and building elements that were included in the BIM model. Regarding the inexistence of any national classification system and naming code for the consideration of the completeness of the LCI, an ad-hoc classification system is proposed. The proposed classification integrates three levels of categorization for the building decomposition: major groups of building elements (Envelope, Structure, Finishes, and Partitions), elements (e.g., walls, floors, beams, and columns), and materials and components (e.g., concrete, glass, and aluminium) (see Table 2). Facilities and other building systems were not included in the model since the present method aims to compare the most relevant systems for the physical definition of the building shape during design stages.

The final bill of material quantities (FBoMQ) was the IBoMQ enriched by the *Library of Building Materials and Components*, that is, with auxiliary and maintenance materials, materials used during replacement, repair works, transport, packaging materials, and waste production during construction and use (maintenance, repair, replacement) phases. The *Library of Building Materials and Components* was created by integrating ratios and estimations to include those non-modelled elements that form part of the calculation of the LCA.

2.3.2.1. Transportation to construction site. Scenarios for modelling distances, means of transport, and fuel, were based on (Soust-Verdaguer et al., 2018). Transportation from the factory to the construction site was performed by a model that considers the main manufacturing points in the Uruguayan context (including cities and villages) of the most common building materials, and classifies this transportation according to five distance levels: local, regional, extra-regional, continental, and intercontinental. The model allowed easy modification of the origin of the material and the impacts can automatically be changed (see Table 3).

2.3.2.2. Use stage. The scenarios for construction and use stages were based on previous studies (Casañas, 2011; Mimbacas, 2012; Pelufo, 2011), and are also provided by regional manufacturers. Table 4 shows the replacement factors used for the service life calculation of the main elements and materials.

The proposed scenario for the use stage for the COVISA and LCU houses covered maintenance, and replacement, in accordance with the service life proposed in Table 4. For the COVISA house, these tasks cover: repainting of walls, washing of exterior walls (brick), washing of floors and tiles, washing of windowpanes, repainting of interior doors, replacement of windowpanes, and replacement of ceramic tile floor. For the LCU house, these tasks cover: repainting of walls, washing of floors, washing of windowpanes, repainting of interior doors, and replacement of windowpanes.

2.3.2.3. End-of-Life (EOL) stage. The EOL assumptions were based on the current waste treatment in Uruguay, as defined by Fichtner and LKSUR Asociados (2004). It is assumed that all C&DW (Construction and Demolition Waste) is fully landfilled.

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2.4. Environmental impact calculation

This stage included the integration of the results from the summary of the basic processes, the unit process factors, and the calculation of the energy flow, as well as the selection of the environmental impact categories.

2.4.1. Selection and calculation of environmental impact categories

The environmental impact categories were selected based on those most commonly calculated in the case study typologies (Global Warming Potential (GWP) (Soust-Verdaguer et al., 2016)), and the most representative in Uruguay considering previous studies in this field (Soust-Verdaguer, 2017): Acidification Potential (AP), Eutrophication Potential (EP), Freshwater aquatic Ecotoxicity (FWE), Human Toxicity (HT), and Ozone Depletion Potential (ODP). The impact assessment was developed using the CML 2001 method (Guinée et al., 2001).

Regarding the inexistence of local or regional databases of construction materials and products, as well as specific EPDs of national or regional products used in the case studies, the environmental impacts were calculated using the environmental database Ecoinvent V2.0 (Frischknecht et al., 2007), which is the most commonly used database in LCA application for the building typology addressed in this study, regardless of the geographical region of the case studies (Soust-Verdaguer et al., 2016). Given that one of the aims of the method is to take into account local characteristics of materials and construction processes, several materials were verified in order to adapt manufacture impacts to the local context. An example is the brick, which is manufactured using an artisan technique (Casañas, 2011). In this case, the most relevant energy consumption is produced during firing in a wood-burning oven, where the estimated energy consumption is 2.77 MJ per kilo of material (Casañas, 2011). Thus, the manufacturing process of bricks was assumed in the Ecoinvent database V2.0 (Frischknecht et al., 2007) as “logs, hardwood, burned in furnace 100 KW”.

The resulting environmental impacts were obtained by multiplying the Bill of Material Quantities (extracted from the BIM model), organized according to the “basic materials list”, and the environmental impact factors obtained from the Ecoinvent database V2.0 (Frischknecht et al., 2007).

2.4.2. Energy flow calculation

The operational energy calculation was performed in DesignBuilder (Cockcroft, 2016), following the parameters and BEPS (Building Energy Performance Simulation) considerations specified in (Soust-Verdaguer, 2017). The environmental impact calculation was adapted to the regional energy mix (DNE-MIEM, 2015),[2] and considers the following hypothesis for the COVISA house: hydropower 61%, wind 15%, biomass 17%, solar 0.4%, and fossil fuel 6.6%. In the case of the LCU, 100% of photovoltaic energy production is assumed. The estimated energy demand was 57 kWh/m^2/yr and 134 kWh/m^2/yr for electricity use and heating and cooling systems powered by electricity in the whole building. The results from the DesignBuilder (Cockcroft, 2016) were manually inserted in the spreadsheet.

The calculation of the energy (electricity and fuel) consumption for machinery and works during construction, use and end of life stages was based on (García-Martínez, 2010; Kellenberger et al., 2007), and is obtained from estimations of the total volume of building materials.

3. Results

3.1. Global impacts per m^2/year

The results are organized in order to visualize the environmental impacts caused by case studies during the complete life cycle of the building. Table 5 shows the environmental impacts for the GWP, AP, EP, FWE, HT, and ODP categories. The total impacts per m^2 per year provide evidence of the variability depending on the impact category considered. The LCU house obtained the lowest values especially for GWP and also for AP, FWE, HT, and ODP impact categories. The COVISA house obtained the lowest values for EP. Thus, the most favourable option was the LCU. By comparing the case studies, the results confirm that the COVISA house produced the greatest environmental impacts. This can be due to the use of concrete, cement, steel, and paint, and the worst energy performance. Another reason could be the design strategy. Among the case studies, the COVISA house is the less compact and it used the highest quantity of material per square metre of heating area.

In order to analyse the results in greater depth, and help designers to identify possible optimization measures, the results were also presented while considering the LCA phases and their relative weight (Figs. 5 and 6), and the incidence of each material (Figs. 7 and 8), and transport to site (Fig. 9). These graphs enable the identification of those LCA phases in which the detected impacts were the highest or the lowest, and of which LCA phases are the leading and lowest contributors of materials and products.

3.2. Environmental impacts by LCA phase

Figs. 5 and 6 show that the highest impacts were found in the *Use stage* (B2, B3, B4, B6), for most of the impact categories. The incidence of operational energy in use and the impact of the

[2] The 2015 energy mix report follows similar trends to those in the latest reported energy mix (2018) (DNE-MIEM, 2018).

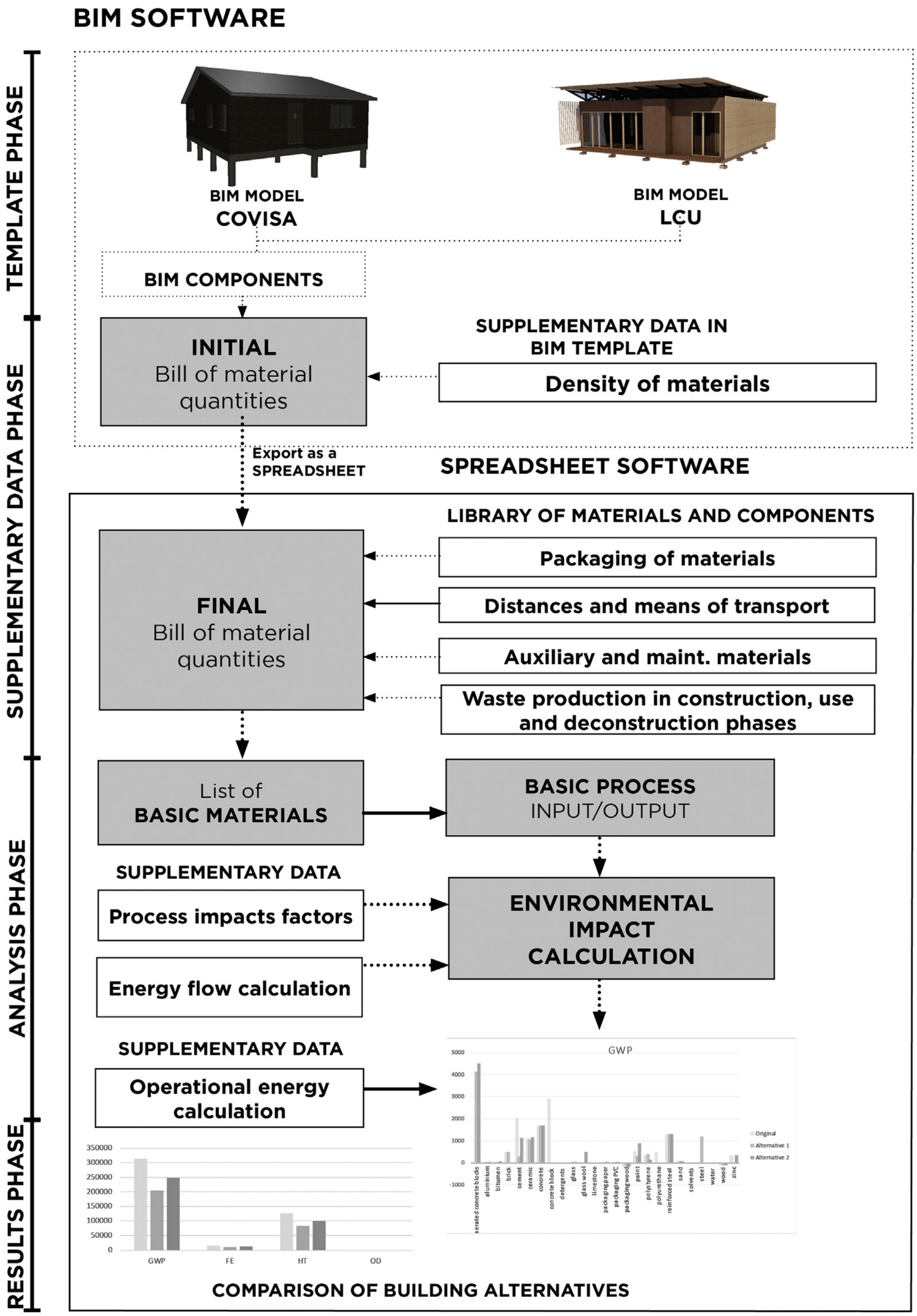

Fig. 3. Schema of the developed method.

i) Template: This phase focuses mainly on the definition of the materials and components that form the building model and was organized by using tags and codes to reference the rest of the information provided.
ii) Supplementary data: This phase aims to provide supplementary materials, components, and environmental data. The phase integrates assumptions and design scenarios that can help designers to estimate non-modelled elements and materials included in the LCA calculation. The strategy integrates predefined elements and ratios into BIM materials and components which were previously defined in the template. A similar strategy was also performed by (Röck et al., 2019).
iii) Analysis: The phase consists of re-organizing data and integrating environmental impact factors with the aim of computing the total impacts.
iv) Results: This phase consists of organizing the results in order to provide useful information for decision-making. The results were shown for the purpose of comparing the design alternatives.

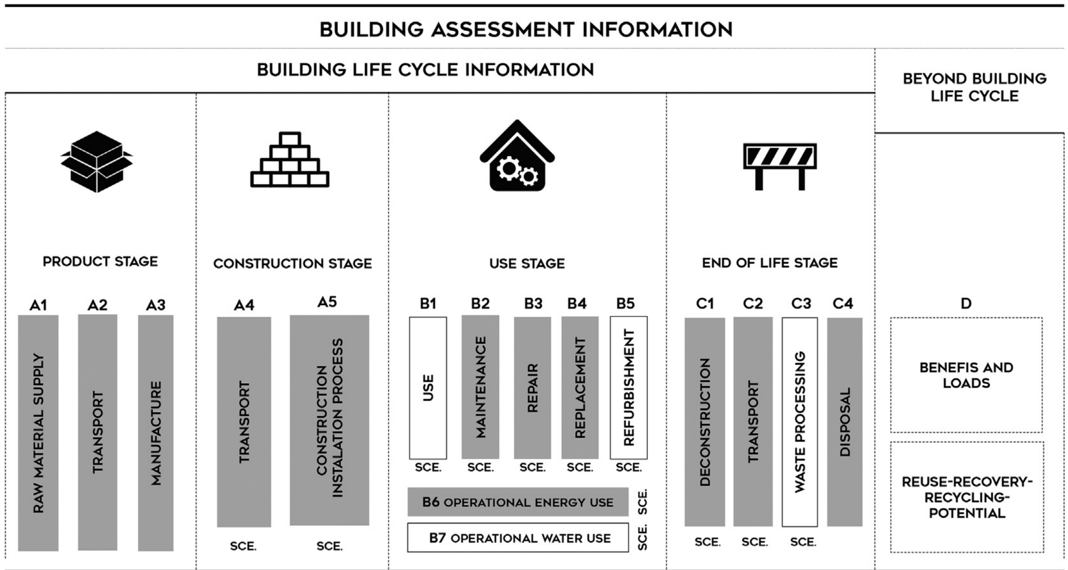

Fig. 4. Schema of modules of information included (shaded), based on ISO 21930:2017 (ISO, 2017).

Table 2
Hierarchical decomposition of BIM materials and components included in the Initial Bill of Material Quantities (IBoMQ).

Initial Bill of Material Quantities. COVISA				Initial Bill of Material Quantities. LCU			
Code	Name	Unit	Quantity	Code	Name	Unit	Quantity
E	ENVEOPE			E	ENVELOPE		
E_W	Envelope_Walls			E_W	Envelope_Walls		
E_W_M1	Envelope_Walls_Bitumen	kg	151,81	E_W_M1	Envelope_Walls_Bitumen	kg	264,18
E_W_M2	Envelope_Walls_Brick	kg	36243,234	E_W_M2	Envelope_Walls_Glass wool	kg	1254,69
E_W_M3	Envelope_Walls_Concrete Blocks	kg	14724,50	E_W_M3	Envelope_Walls_Plywood_Exterior	m3	2,6778
E_W_M4	Envelope_Walls Polystyrene	kg	71,53	E_W_M4	Envelope_Walls_Polyethylene	m3	0,0287
E_W_M5	Envelope_Walls_Mortar	kg	2400,12	E_W_M5	Envelope_Walls_Plywood_Interior	m3	2,4177
E_WD	Envelope_Windows			E_WD	Envelope_Windows		
E_WD_M1	Envelope_Windows_ Aluminium	kg	56,48	E_WD_M1	Envelope_Windows_Polyvinyl chloride	kg	49,693056
E_WD_M2	Envelope_Windows_ Glass	kg	78,1344	E_WD_M2	Envelope_Windows_Aluminium	kg	16,3296
				E_WD_M3	Envelope_Windows_ Glass	kg	102,2232
E_F	Envelope_Floors				Envelope_Floors		
E_F_M1	Envelope_Floor_Ceramic tile	kg	1119,60	E_F_M1	Envelope_Floor_Wood	m3	0,3506
E_F_M2	Envelope_Floor_Mortar Ceramics	kg	2015,28				
E_F_M3	Envelope_Floor_Concrete	m3	11,72				
E_F	Envelope_Roof			E_F	Envelope_Roof		
E_R_M1	Envelope_Roof _Zinc	m2	73,82	E_R_M2	Envelope_Walls_Plywood_exterior	m3	–
E_R_M2	Envelope_Roof_Polystyrene	kg	44,29	E_R_M2	Partitions_Plywood_interior	m3	–
E_R_M3	Envelope_Roof_Polyurethane	kg	88,58				
F	FINISHES			F	FINISHES		
F_M1	Finishes_Mortar	kg	5233,86	F_M1	Finishes_Paint_Wood_Exterior	kg	573,45
F_W_M1	Finishes_Walls_ Ceramic_tile_bath	kg	1446	F_M1	Finishes_Paint_Wood_Interior	kg	294,45
F_W_M2	Finishes_Walls_Paint	kg	246	F_R_M1	Finishes_Paint_Wood_Roof	kg	70,65
F_R_M1	Finishes_Roof_ Paint	kg	11,10				
P	INTERNAL PARTITIONS			P	INTERNAL PARTITIONS		
P_M1	Partitions_Concrete blocks	kg	11368,28	P_M1	Partitions_Plywood_interior	m3	2,4177
P_M2	Partitions_Doors_wood	m3	0,58	P_M1	Partitions_Doors_Wood	m3	0,510783
S	STRUCTURE			S	STRUCTURE		
S_C_M1	Structure_Columns_Concrete	m3	0,10	S_F_M2	Structure_Steel_floor	m3	0,0282
S_S_M1	Structure_Slabs_Concrete	m3	4143	S_B_M2	Structure_Beam_Floor_Wood	m3	4,8762
S_S_M2	Structure_Slabs_Steel	kg	483,60	S_B_M2	Structure_Beam_Roof_Wood	m3	1,0574
S_F_M1	Structure_Foundations_Concrete	m3	0,81	S_C_M1	Structure_Columns_Wood	m3	5,0046

materials, particularly maintenance, repair, and replacement, are clearly shown in this stage, and are indirectly outlined in the product stage due to their influence in the maintenance and service life scenario. Results can also confirm that, on comparing the two houses, the timber house LCU produced higher impacts in the B2, B3, and B4 modules compared to those generated by COVISA. For most of the impact categories (GWP, AP, FWE, ODP, HT), the impact produced during the use stage (B2—B4) is higher than that in the product stage (A1-A3): this fact can be attributed to the more frequent maintenance and replacement work, since it includes hazardous substances (e.g., paints) that are needed more by the LCU rather than by the COVISA. Our findings also confirm the low incidence of the EOL stages (C1, C2, C4), and of the construction and transport-to-site (A4) stage, in the total impacts.

The GWP results confirm the low incidence of wooden materials in the product stages (A1, A2, A3) for the LCU, although during the

Table 3
Model to assign the transportation distances.

Level		Distance	Transport
1	Local	up to 50 km	Lorry, 16 ton
2	Regional	up to 250 km	Lorry, 16 ton
3	Extra-regional	up to 600 km	Lorry, 16 ton
4	Continental	up to 1000 km	Lorry, 28 ton
5	Intercontinental	up to 15000 km	Ship, Transoceanic freight

Table 4
Scenarios for maintenance and service life of materials and building elements of case studies. (Source: based on (Pelufo, 2011; Soust-Verdaguer, 2017; Tavares, 2006)).

Material	Years	Factor
Steel structure (Roof)	100	1.0
Timber stakes	73	1.0
Insulated panels	69	1.0
Brick wall, mortar	100	1.0
Plaster (exterior)	60	1.0
Wood floor	50	1.2
Ceramic tile (floor)	30	2.0
Paint exterior	8	7.5
Paint interior	8	7.5
Wood Panel	45	1.33
Waterproofing	10	6.0
Paint (Roof)	11	5.45
Mortar (Finishes)	60	1.0
Concrete floor	100	1.0
Glass	30	2

use stage (B2, B3, B4) the impacts were higher than those of the concrete-masonry house (COVISA). The results also provide evidence of the relevance of operational energy in use (55%), which shows the highest values for COVISA. The AP results show the great influence of operational energy in use (39% LCU, 70% COVISA) in the total impacts, especially in the COVISA house. The major difference observed between houses can be attributed to the difference in the energy mix and the differences in the operational energy in use. The EP results show the highest values for the LCU, particularly for the influence of the product stage (A1-A3) and the use stage (B2—B4, B6) (82%).

With respect to FWE, the use stage (B2—B4, B6) in the LCU dominates, and accounts for approximately 47% and 33% of the B2—B4 modules and B6 module, respectively. However, COVISA obtains the highest values in the product stage (A1-A3) (36%). For the HT, the highest impacts are found in the operational energy consumption module, the product stage, and the use stage, respectively. In spite of the fact that the LCU house obtains the highest values in the operational energy consumption module (B6)

Table 5
Total impacts per m^2/year.

	GWP (kgCO2/m2/yr)	AP (kg SO2 eq./m2/yr)	EP (kg (PO4)3eq/m2)	FWE (points/m2)	HT (points/m2)	ODP (kgCO2/m2)
COVISA	4,31	0,0252	0,0039	1,16	1,7	0,0000004
LCU	−1,64	0,0252	0,0045	0,24	0,81	0,0000003

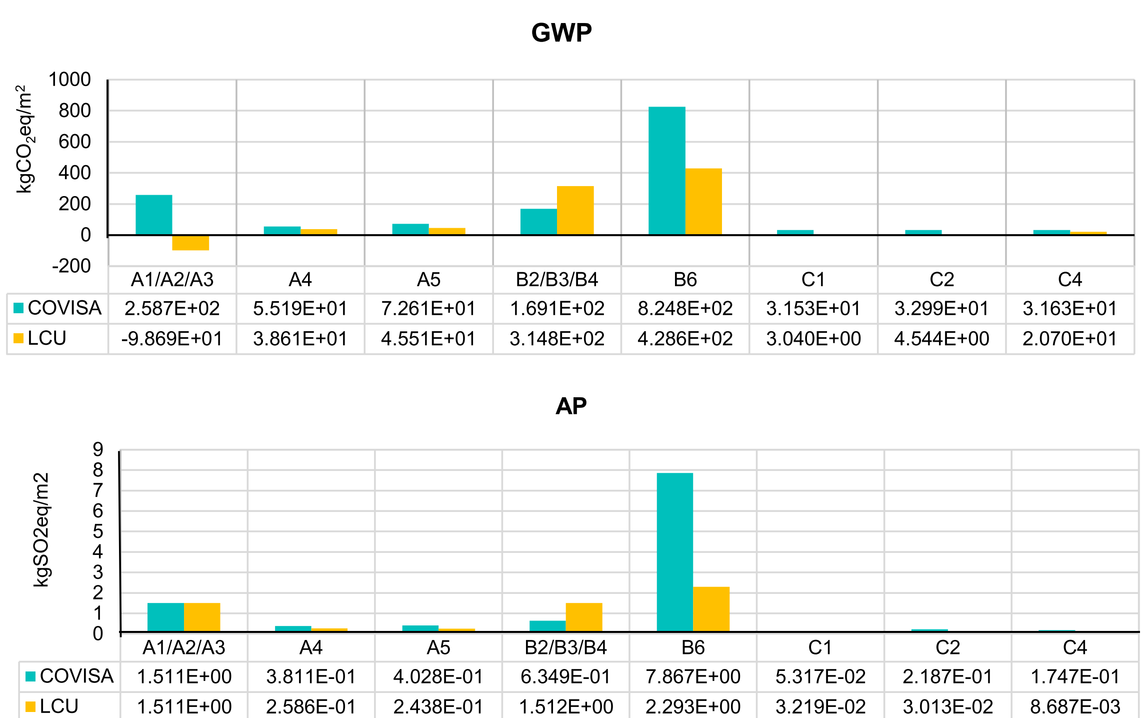

Fig. 5. GWP and AP impacts by LCA modules of information, expressed in $kgCO_2eq/m^2$ (GWP) and $kgSO_2eq/m^2$ (AP).

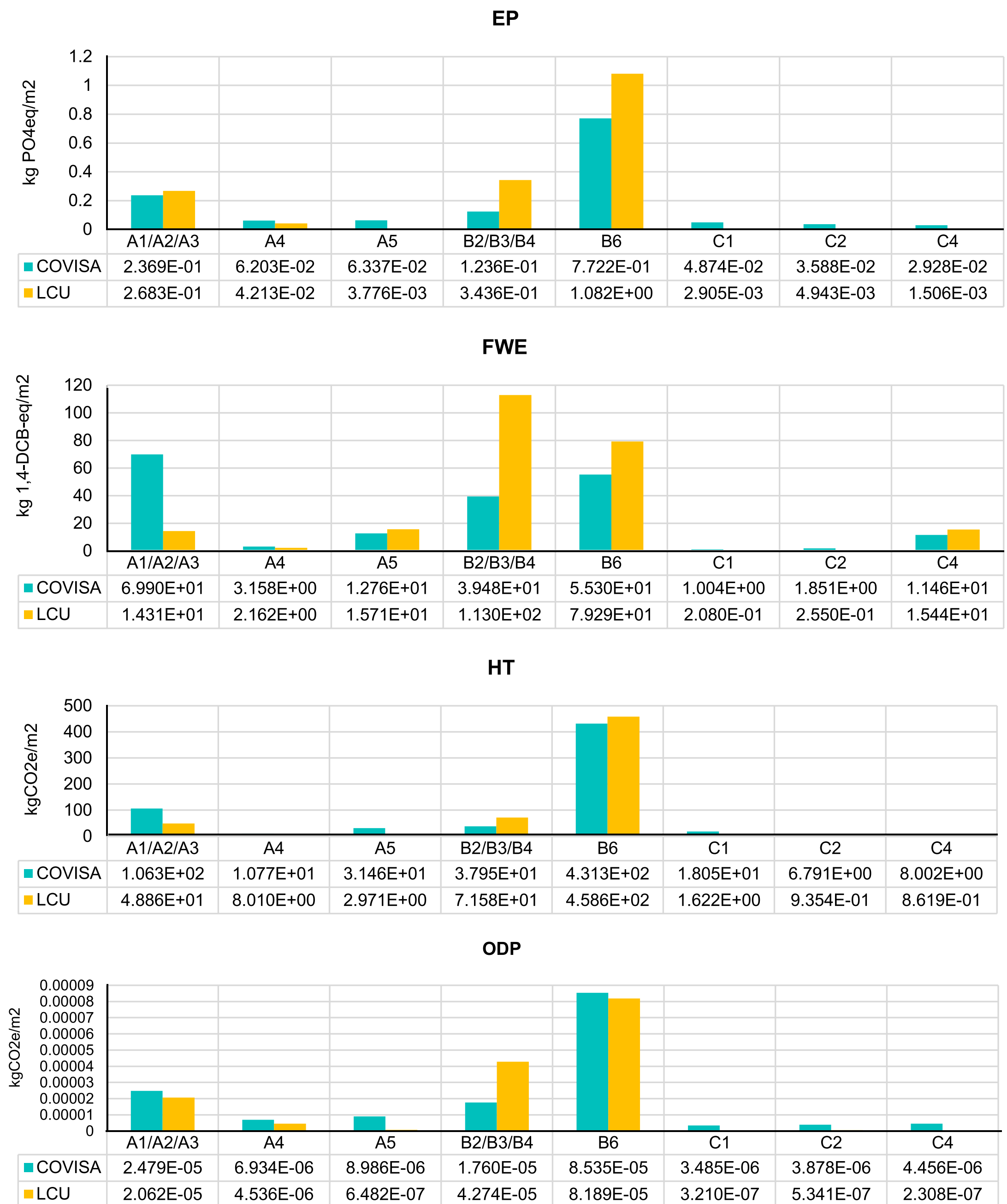

Fig. 6. EP, FWE, HT, and ODP impacts by LCA modules of information, expressed in kg PO4-eq/m^2 (EP), kg 1,4-DCB-eq/m^2 (FWE), kg 1,4-DCB-eq/m^2 (HT) and kg CFC-11-eq/m^2 (ODP).

and use modules (B2–B4), respectively, the total impacts are higher than COVISA impacts, due to the great difference between them in product stage impacts (101,914 points). The ODP results show that the highest impacts are focused on the operational energy consumption module, the rest of the use stage modules, and the product stage. In this impact category, the total values are also higher for the COVISA house than for the LCU house.

3.3. Embodied impacts by material

Figs. 7 and 8 depict the impacts produced by the layers of material, as organized in the BIM model, and as devised to help the designer to identify the materials that produce the highest and lowest impacts, and to subsequently define design strategies to reduce said impacts (e.g., thickness or height reduction).

Results for the GWP show the great contributions of reinforced steel, cement-based materials (concrete block, cement, concrete), glass wool and painted wood, and the benefits of using wood-based materials (wood structure, plywood). For AP, the highest values were obtained in plywood (exterior and interior), painted wood, reinforced steel, zinc, wood (structure), glass wool and cement-based materials (concrete block, cement, concrete). Regarding the results obtained in Fig. 5, the embodied impacts (A1-A4) were closer for both houses. For the EP impact category, the great contributors are similar to those of AP.

Regarding the FWE impact category, Fig. 6 confirms that

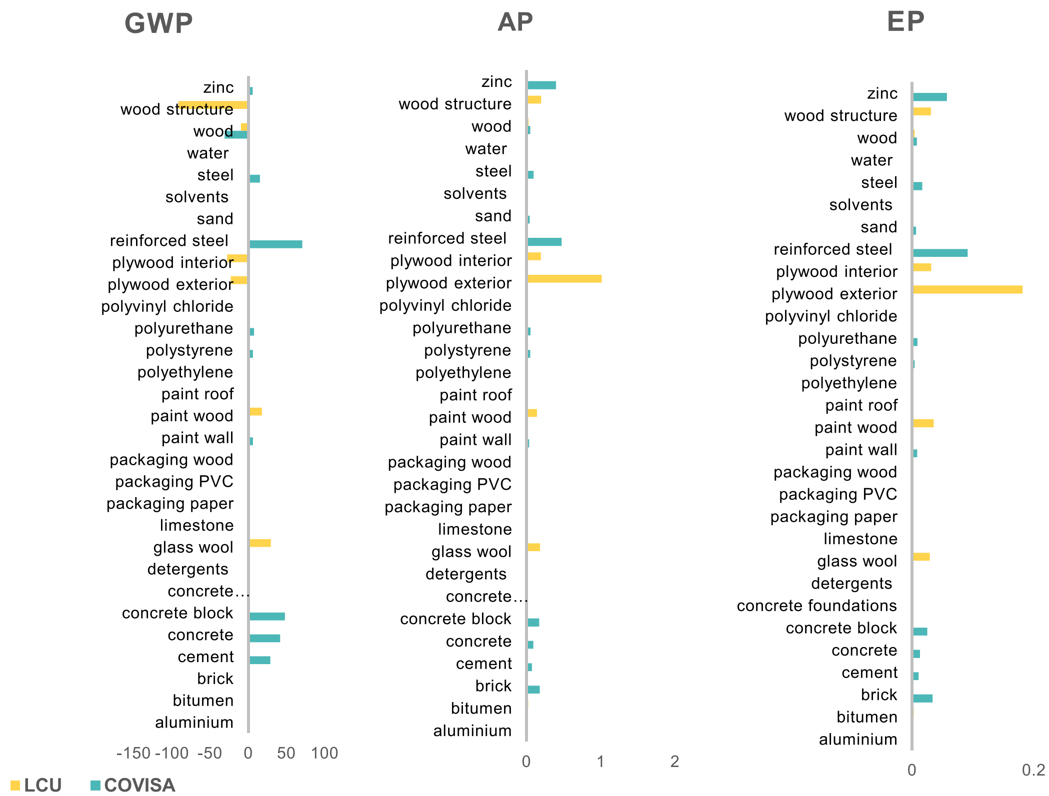

Fig. 7. Embodied impacts (A1-A2-A3-A4) for GWP (kg CO_2. eq.), AP (kg SO2 eq.) and EP (kg (PO4)3eq.

embodied impacts (A1-A4) in the COVISA house had the greatest relative weight among total impacts (36%). This fact can probably be explained by the use of reinforced steel and steel, and their negative consequences in this category. The HT results show the influence of: wood (plywood, timber, and other wood-based products), (LCU); metals (zinc, reinforced steel, and steel), (COVISA); concrete (concrete blocks, cement), (COVISA); glass wool, and bricks in the embodied impacts. Similar trends were obtained for the ODP impact category. In general terms, Figs. 5 and 6 show that the LCU house obtained higher values than the COVISA house in all the impact categories (GWP, AP, EP, FWE, HT, ODP) for the use stage (B2–B4). Results for embodied impacts of building materials (Figs. 7 and 8) provide evidence that this could probably be due to the intense use of paint in wood maintenance (B2).

3.4. Comparison of transport to site impacts

Results of the case studies show low relevance of the transport-to-site impacts in relation to total impacts (Figs. 5, 6 and 9). In spite of the fact that several studies (Achenbach et al., 2018; Ramage et al., 2017) underline the relevance of transport impacts to consider the environmental benefits of wood constructions, graphs compare separately incidence of transport to site (A4). As shown in Fig. 9, the LCU produces lower impacts during A4 module compared to COVISA, probably due to the volume and weight of materials required per square metre of heating area of the house, during the construction process. In order to analyse the compactness of the buildings, a ratio of the volume of materials per square metre of heating area was calculated. For LCU and COVISA the ratios were 0.68 m^3/m^2 and 1.125 m^3/m^2, respectively, indicating that COVISA consumed almost twice the material volume of the LCU. Therefore, a more compact architectural design implies lower environmental impacts. Further reasons for increasing the transport-to-site impacts include the type of means of transport and the fuel of the transport: in this case, a 16-ton diesel-fuelled lorry is used. A strategy to reduce the environmental impacts of transport could involve the selection of low-impact vehicles, such as trains.

4. Discussion

The application of the method to the case studies demonstrates that it can be employed for the estimation, in the design stages, of the highest impacts produced during the life cycle of the building. In the case studies, the highest impacts were produced during the operational energy consumption module (B6), and during maintenance, repair and replacement (B2, B3, and B4). Moreover, the information provided can help towards defining the improvement scenarios. Regarding the case studies context, the consideration of measures for the reduction of the operational energy consumption could include, for instance, improvement of the envelope performance. For the reduction of the impacts caused by the maintenance, repair, and replacement modules, two alternatives could be considered. First, those materials or substances, such as solvents and paints, could be substituted with other eco-friendly materials. Second, there could be a reduction of the amount of materials and products that require frequent replacement or reparation, by substituting them with other products that produce lower impacts or need less frequent replacement.

The present study also demonstrate that the application of the method could help designers regarding the complexity of the assessment of wood alternatives for construction, since it enables the identification of the distribution of the life cycle impacts while considering the LCA modules of information (Fig. 4), and the use of materials (either directly in the product stage, or indirectly in the use stage).

The results of this study also confirm the feasibility of

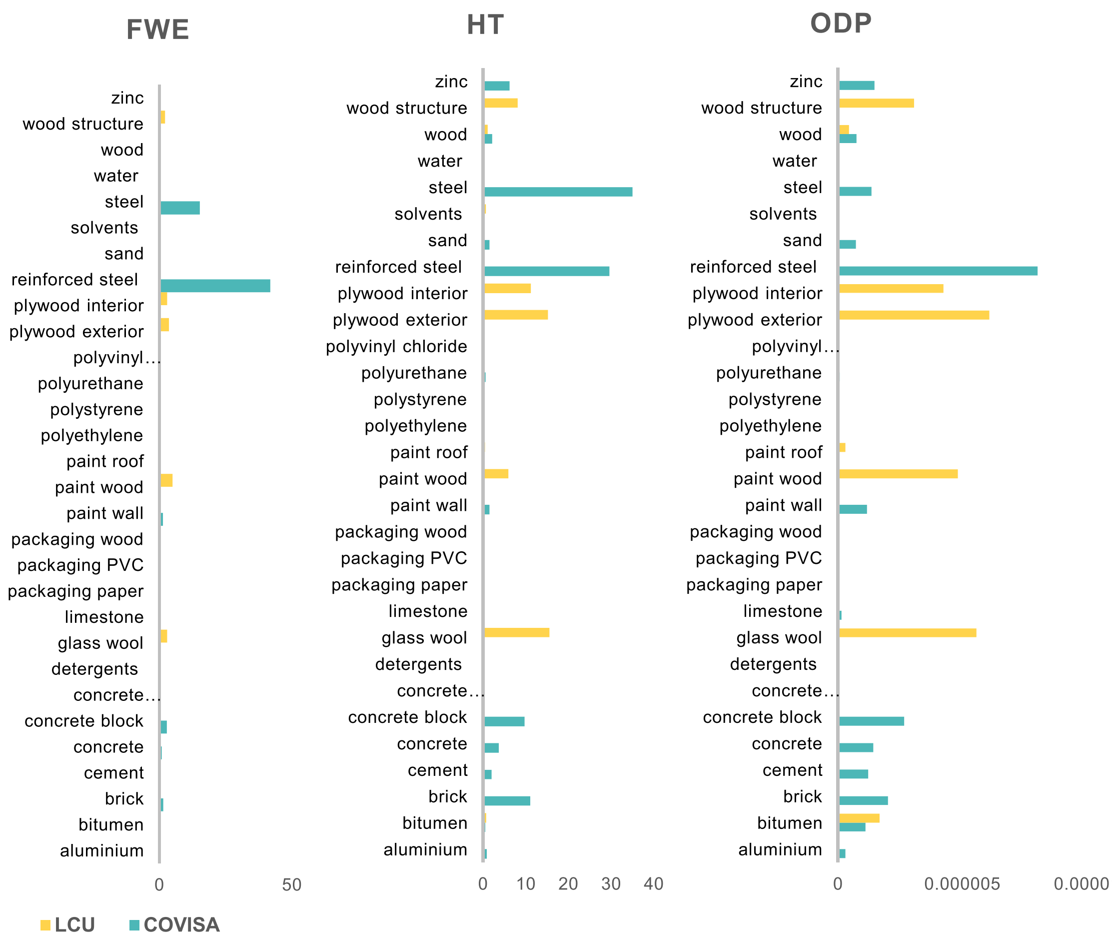

Fig. 8. Embodied impacts (A1-A2-A3-A4) for FWE (kg 1.4-DCB-eq/m^2), HT (kg 1.4-DCB-eq/m^2), and ODP (kg CFC 11 eq).

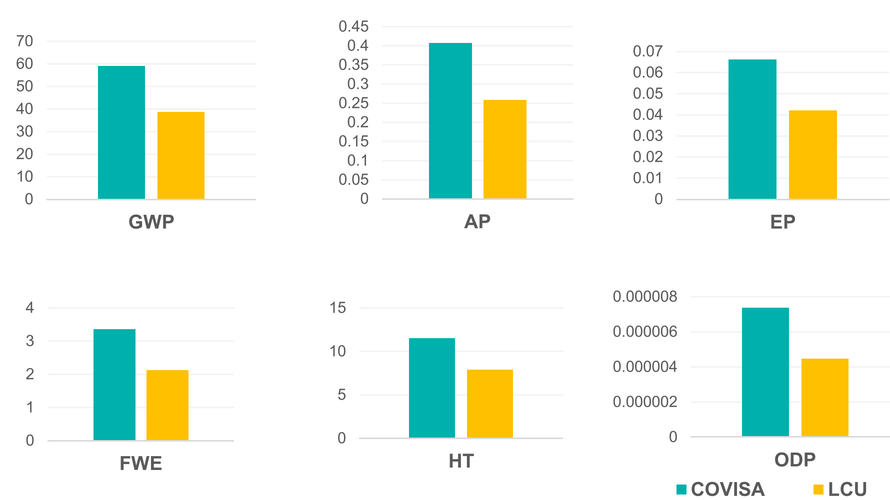

Fig. 9. Comparison of transport to site impacts (A4) for GWP (kg CO_2. eq.), AP (kg SO2 eq.) and EP (kg (PO4)3eq, FWE (kg 1.4-DCB-eq/m^2), HT (kg 1.4-DCB-eq/m^2) and ODP (kg CFC 11 eq).

conducting a BIM-based LCA by integrating estimations for all the life cycle stages of the building (including product, transport, construction, maintenance, repair, replacement, operational energy in use, and end of life stage), in order to improve the assessment and comparison of wood and conventional alternatives for buildings. However, several limitations and possible aspects to improve the method have been identified.

4.1. Challenges and limitations

In this section, several limitations and aspects to be addressed by future developments are outlined.

- *Data acquisition and data reliability.* The experimental application of the method provides evidence of the inexistence of local and regionally adapted databases, adapted to the Latin-American context, as other studies have already shown (Oyarzo and Peuportier, 2014). There is also a lack of data related to the standardization of both the use stage scenarios and of the reference service life of the building elements and materials adapted to this context.

- *Biogenic and fossil carbon emissions and C&DW valorization scenarios:* The proposed method does not include a separate report for the account of biogenic and fossil carbon emissions considering current standards (such as ISO 21930, 2017) and carbon neutrality principle. The possibility of integrating different EOL stages for wood and wood products may well modify the impact results, as certain studies have already shown (Takano et al., 2015; Wijnants et al., 2019). Moreover, the possible integration of C&DW as possible scenarios for the assessment of the potentialities of the recyclability of products, especially wooden products, can also help to integrate circular economy strategies into the design process.
- *Benchmarks, reference, and target values.* Regarding the usability of results and their contributions to guide designers (architects and engineers) during the design stages of buildings, the present study was limited to the comparison of only two alternatives by analysing the applicability of a method. Future work should involve the definition of regional and local benchmarks and target values, with the aim of helping the designer during the decision-making stage, in accordance with the relevance reported by (Hollberg et al., 2019). This strategy, in turn, could help architects and engineers to envision and calibrate the potential benefits of using timber as structural material during design stages.
- *Environmental assessment design-oriented tools and methods.* Despite the major effort performed towards the development of tools and methods for the calculation of the environmental impacts produced by buildings during their life cycle, the potentialities of BIM for the improvement of the environmental performance of buildings have yet to be fully exploited. This is probably due to the lack of environmental awareness in the building sector, and to the scarcity of tools and methods that can easily integrate reliable environmental parameters during the design stages of buildings.

5. Conclusions

The BIM-based LCA method developed in this study helps to supplement the required data during the design stages of buildings and simplifies the comparison of timber-based versus concrete-masonry houses. The method enables building materials and element dimensions to be edited in the BIM software, and automatically shows the environmental impacts of those modifications. The study improved the development of assumptions, datasets, data structure, and simplified models. In particular, the type of data structure is enriched by the parametrization of ratios at BIM material, element, and building levels, and by the integration of a transport module. In order to quantify the environmental benefits of building with timber compared to other construction technologies, the method contrasts the embodied, operational, and transport-to-site impacts versus relevant impacts that have been previously detected in the use stages. The proposed approach permits designers to identify the highest and the lowest material contributors to environmental impacts during the complete life cycle of a building, thereby enabling the designer to modify (thickness and distributions) and replace materials that produce the greatest impacts. It also allows the identification and organization of the distribution of environmental impacts over the life cycle of the building in accordance with current LCA regulations. The case study application proves the relevance of certain LCA stages over others, whereby the product stage and the use stage constitute the most significant stages for the assessment of the impact categories.

The present study demonstrates that during the design process, the use of quantitative environmental assessment methods can contribute towards the identification of the environmental impacts produced during the life cycle of the single-family houses in the context under consideration. Moreover, the environmental benefits of using wood in comparison with other building materials are demonstrated by the best indicators found in the majority of the impact categories analysed (GWP, AP, FWE, HT, and ODP). It is also proved that the lowest volume of materials per square metre indicates the best environmental performance during the life cycle of the building. Furthermore, increasing the level of compactness of the building can also help reduce environmental impacts.

The proposed method is envisioned as a guidance tool for decision-making on both urban and neighbourhood scales, which enables the easy comparison of the impacts produced by various designs and materials of a common house typology.

CRediT authorship contribution statement

B. Soust-Verdaguer: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing. **C. Llatas:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing. **L. Moya:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing.

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