Applied Energy 250 (2019) 1366–1382

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings

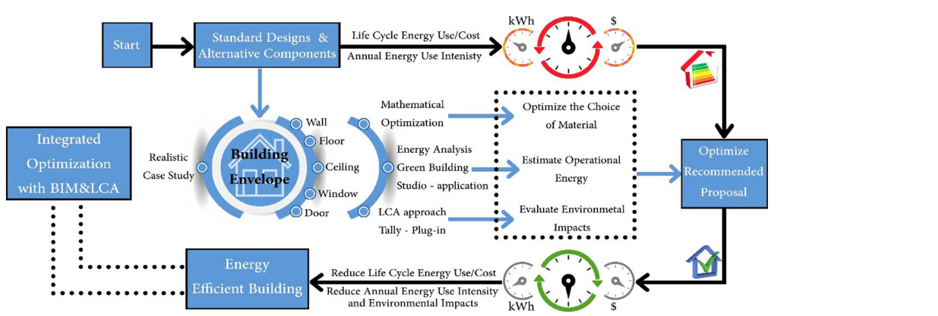
Mohammad Najjar[a], Karoline Figueiredo[a], Ahmed W.A. Hammad[b], Assed Haddad[a,*]

[a] Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
[b] University of New South Wales, Sydney, Australia

HIGHLIGHTS

- Operational energy is targeted to generate energy efficient buildings.
- A mathematical optimization model is examined to achieve the BIM-LCA integration.
- Integrated optimisation-BIM-LCA leads to sustainable residential building decisions.
- Impacts of annual energy use intensity can be reduced by about 45%.
- Environmental impacts such as global warming can be reduced by more than 30%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Building information modeling
Life cycle assessment
Energy consumption
Sustainable construction
Environmental impacts

ABSTRACT

Energy consumption in buildings is a very important issue, where the operational demand is considered to be one of the highest amongst all other sectors of an economy. Moving towards energy efficient buildings is a key factor to achieve sustainability. A novel framework for integrating mathematical optimization, Building Information Modeling, and Life Cycle Assessment to enhance the operating energy efficiency of the resulting building designs adopted, along with reducing the difficulties associated with the construction of the building, in terms of cost of construction, is developed. The framework accommodates various parameters, via integrating mathematical optimization programming, Building Information Modeling, and Life Cycle Assessment to improve the building performance, identify alternative sustainable designs, and empower the decision-making process and sustainability in the construction sector. Through the developed optimization model, the examination of various alternatives for building components that make up the envelope of a residential building is undertaken. Insights gained from the results show that all components of building envelopes influence the energy consumption in buildings, particularly, exterior walls and windows. Impacts in terms of annual energy use intensity can be reduced by about 45%, life cycle energy use and cost can be enhanced by more than 50%, and environmental impacts such as acidification and global warming potential can be reduced by more than 30%, due to use of the proposed framework. This work indicates that sustainable building decisions can be achieved by optimizing the material selection and assessment of environmental impact via Building Information Modeling and life cycle assessment.

* Corresponding author.
E-mail addresses: mnajjar@poli.ufrj.br (M. Najjar), karolinefigueiredo@poli.ufrj.br (K. Figueiredo), a.hammad@unsw.edu.au (A.W.A. Hammad), assed@poli.ufrj.br (A. Haddad).

https://doi.org/10.1016/j.apenergy.2019.05.101
Received 21 January 2019; Received in revised form 24 April 2019; Accepted 7 May 2019
Available online 16 May 2019

Nomenclature

Indices

c	component
m	material
tr	transmission (heat transfer)
ve	ventilation (heat transfer)
gn	gains
ls	loss
DHW	domestic hot water

Sets

C	set of components in the building
M	set of materials options to be used in the building

Parameters

FU_c^m	fuel unit cost per material m belonging to the component c
EU_c^m	electricity unit cost per material m belonging to the component c
$I_{m,c,\tilde{m},\tilde{c}}$	ease of instalment matrix of material m in component c and material $\tilde{m}$ in the component $\tilde{c}$
$Q_{Heat,c}^m$	quantity of heat in heating modes caused by material m to the component c
$Q_{Cool,c}^m$	quantity of heat in cooling modes caused by material m to the component c
$Q_{DHW,c}^m$	quantity of heat for domestic hot water caused by material m to the component c
$\theta_{w,0}$	temperature of inlet water
$\theta_{w,t}$	temperature of the water at the tapping point
$V_{W,c}^m$	monthly domestic hot water volume need
$\vartheta_{Heat,c}^m$	efficiency utilisation factor for heating
$\vartheta_{Cool,ls,c}^m$	efficiency utilisation factor for cooling

Variable

$$x_c^m = \begin{cases} 1, & \text{if material m is used for component c} \\ 0, & \text{otherwise} \end{cases}$$

1. Introduction

The construction industry is known for its significant consumption of high levels of energy and natural resources [1] along with its adverse impacts on the environment [2]. Energy consumption in the building sector accounts for around 40% of global CO_2 emissions and 40% of natural resources consumption [3]. The United States Energy Information Administration estimated that energy consumption in the residential sector in Brazil, between 2012 and 2040, would increase by 1.6% per year. Electricity remains the leading source of energy worldwide, with a forecasted increase from 61% in 2012 to 75% in 2040 [4]. Thus, it is essential to apply new strategies such as green building, sustainable materials usage, and integrated renewable energy systems to reduce energy consumption and enhance energy efficiency towards more energy efficient buildings.

Energy consumption in buildings results in direct and indirect impacts over the entire lifespan of the building. Increasing energy efficiency in the construction sector is becoming a priority in energy procedures and strategies [5]. Factors that influence the pattern of energy consumption in a building, include the building type, climate zone in which the building is located, level of economic development and modern technologies that explore the different properties and capabilities of construction materials [6]. The determination of building envelopes, including exterior walls, windows, and roof, along with the doors and ground floor can impact the energy consumption over the entire lifespan of a building [7]. This, in turn, would reflect on both the embodied energy and the operational energy of the building. Studies indicate that the use phase in conventional buildings represents approximately 80–90% of the life-cycle energy consumption [8], while embodied energy accounts for around 10–20% [9]. In energy efficient buildings, the aim is to reduce the dominant operational energy component [10]. The contribution of the embodied energy is however on the rise [11]. Designing energy-efficient buildings requires a multidisciplinary study over the entire life cycle phases [10], namely the prebuilding phase, building phase, and post-building phase. The building phase is often the one with the highest energy consumption period during the life cycle of buildings [8]. It encompasses all activities related to the use and maintenance of the building, such as maintaining comfortable conditions inside the building, water use and powering appliances. Hence, the proposed framework of this work only analyses the operational phase of the energy life cycle of the building to increase energy efficiency.

The operational phase of buildings deserves due attention, particularly at the early designing phase, which demands less energy [9], and highly influences the sustainability and life cycle energy and cost of buildings [12]. One method that can be utilized in order to enhance the effectiveness of energy consumption in buildings is the life cycle assessment (LCA). LCA permits the evaluation of the environmental impacts and energy consumption patterns that are associated with the building [13]. The construction components have been previously evaluated at the operational and embodied energy levels to achieve sustainability standards and reduce energy consumption in building [14]. Its use can be further extended when combined with building assessment and evaluation tools such as building information modeling (BIM) [15]. Previous attempts in the literature have integrated BIM with Building Energy Modeling at an early designing stage to increase the operating energy efficiency and empower the decision-making process in buildings [16]. The potential BIM-LCA integration in construction projects can result in an effective measure for addressing the aspects of sustainability [17]. In literature, there is significant potential for use of LCA integrated with BIM, however, past attempts have been limited to optimize the energy performance and environmental impacts in buildings via BIM-LCA integration. In addition, the decision-making process when it comes to efficient building design still lacks the use of mathematical optimization modeling [18]. Studies have attempted to optimize the structural framework for buildings, based on cost [19] and more recently environmental considerations [20], in addition to optimizing the orientation of buildings, for enhancing sustainability [21]. Yet focus on building envelope optimization for integration with BIM and LCA has not been attempted.

This paper proposes an automated framework for integrating mathematical optimization, BIM, and LCA to enhance the operating energy efficiency of the resulting building designs adopted, along with reducing the difficulties associated with the construction of the building, in terms of cost of construction. LCA is revised from a building's perspective to increase the sustainability of the building designs that are generated. A general view of the proposed framework of this study is given in Fig. 1. As can be seen, BIM is utilized as the modeling platform for the building, where, material and climate databases selection is made. Data from the BIM model is then passed on to an LCA approach that is used with two main aims: (i) increasing the operational energy efficiency; and (ii) reducing the environmental impacts of the building. The operational phase of the building is analyzed from a gate-to-gate LCA perspective, and BIM is applied to enable simulations of

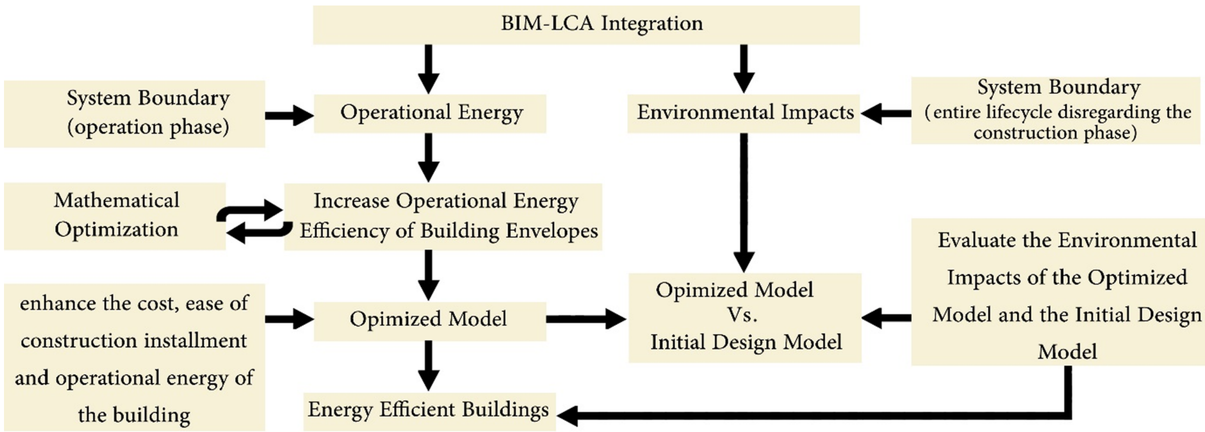


Fig. 1. A general stream of this work.

alternative construction components of envelopes towards more energy efficient buildings. A Binary Integer Programming (BIP) model is developed to optimize the choice of materials for the building envelope, both exterior and interior (i.e. external walls, ceilings, floors, doors, and windows). The optimization model is formulated as a multi-objective optimization problem, where three main objective functions are optimized, namely the monetary cost of the building, the ease of construction of the building and the operating energy of the building. The main variable that is modeled in the formulated optimization problem is the choice of material made for each component of the building, as material choice highly impacts operational energy and construction cost of the building [22]. The solution of the optimization model is contrasted with the initial solution for the building. The results are then passed on to an integrated BIM-LCA system to quantify the operational energy use and evaluate the potential environmental impacts of the building. The proposed framework to reduce the environmental impacts will focus on the entire lifespan of the building, disregarding the construction phase. This is because the focus of this study is the analysis of alternative building materials in order to reduce the environmental impacts generated, hence not focusing on the construction methods used throughout the construction phase of the building. A simulation is conducted in BIM to measure the environmental impacts in two different digital models: the optimized model found as a result of the applications of the mathematical optimization in the first part of the analysis; and the initial model (standard design), as presented in Fig. 1. The environmental impact analysis in this study is conducted to validate the optimization model and hence reveal that the most energy efficient building is also the one that generates the least environmental impacts.

In this paper, the proposed mathematical optimization model, including the objective functions, constraints, and solution approach are described first. The method of integrating the optimization of BIM with LCA is discussed later, followed by presenting a flowchart of decision support analysis. A realistic case study that validates the methodological framework of this work is examined. Finally, the paper is concluded with remarks of the main findings, recommendations, and limitations.

2. Materials and methods

The novelty of this work is to enhance the effectiveness of the selection of energy efficient building envelopes that also generate less environmental impacts based on integrating mathematical optimization models, BIM and LCA. This gives the opportunity to estimate the energy consumption of construction projects, evaluate the environmental impacts of building components, and therefore empower the decision-making process in the construction sector. In this section, an in-depth explanation of the mathematical optimization model, decision support analysis and the methodology of linking the framework components are presented.

2.1. Decision support system

A flowchart of the decision support analysis involving the optimization-BIM-LCA integration at an early stage of the design phase of a construction project is presented in Fig. 2. The optimization model is developed to ensure the determination of the objective functions that address operational energy and ease of installment consideration. Moreover, a Binary Integer Programming Model is developed to generate an optimum solution. Then, the LCA-BIM integration is utilized to build up the 3D modeling, building modification, simulation, and impact analysis in order to achieve the objectives of this work by increasing energy efficiency and reduce environmental impacts of building materials.

2.2. Mathematical optimization model

An optimization model is formulated, where the main decision variable is the choice of material for various components involved in the building. The optimization model is formulated in order to increase the operating energy efficiency of building envelopes and enhance the constructability of the building as presented in Fig. 1. Three objective functions are formulated, which renders the problem a multi-objective optimization one. Once the model is formulated, an approach that integrates BIM with LCA is adopted.

2.2.1. Objective functions

The first objective function, Eq. (1) minimizes the cost of fuel and electricity expended in the operation of the building. It is formulated as follows:

$$\sum_{m}\sum_{c} FU_c^m \times x_c^m + EU_c^m \times x_c^m \tag{1}$$

The first term, $FU_c^m \times x_c^m$ computes the fuel cost associated with material m selected for the component c of the building, while the second terms, $EU_c^m \times x_c^m$, computes the total electricity cost associated with material m selected for the component c of the building.

The second objective function, Eq. (2) maximizes the constructability of the building, by looking at the time and skill required to install a particular component in the building, and is given as:

$$\sum_{\substack{c,\tilde{c} \\ c\neq\tilde{c}}}\sum_{\substack{m,\tilde{m} \\ m\neq\tilde{m}}} I_{m,c,\tilde{m},\tilde{c}} \times x_c^m \times x_{\tilde{c}}^{\tilde{m}} \tag{2}$$

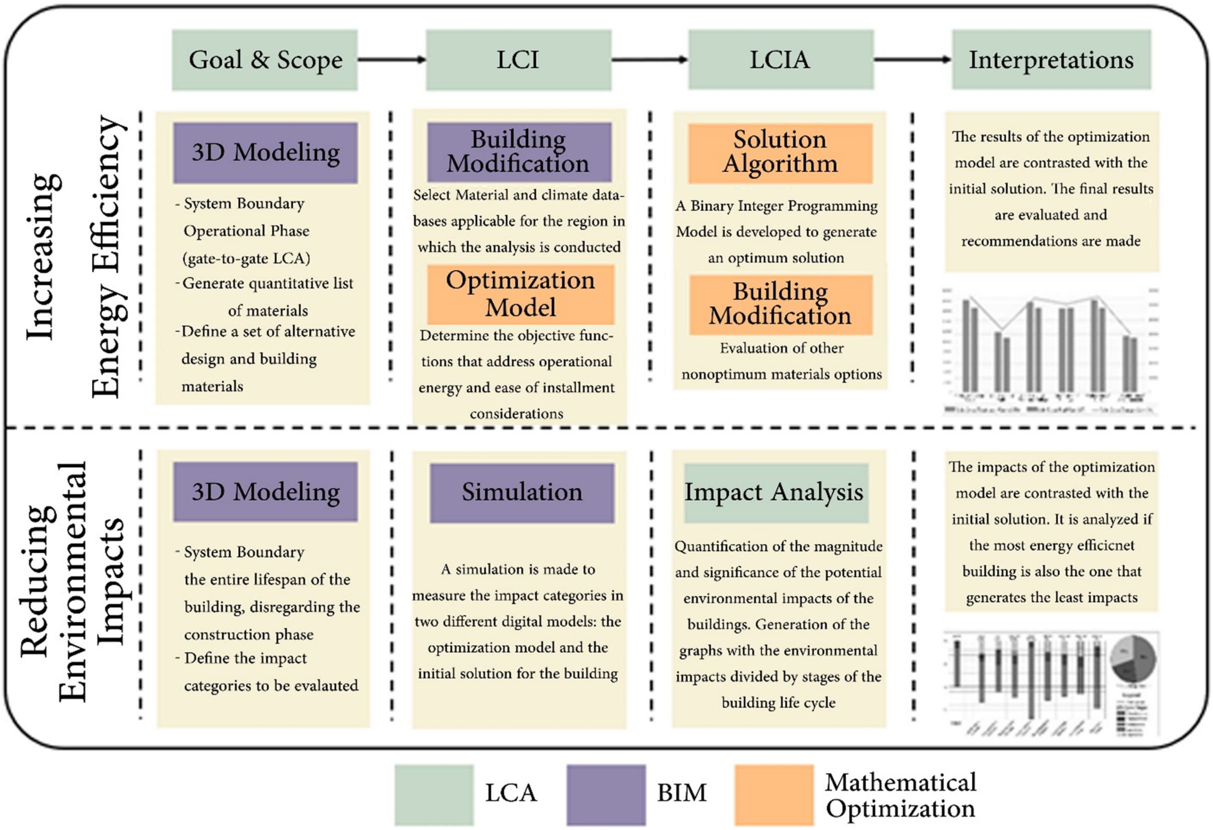


Fig. 2. Flowchart of decision support analysis.

In particular, the interaction between two components linked together in the building, namely c and $\widetilde{c}$ is assessed, in terms of the easiness of installing the components together via the ease of installment matrix, $I_{m,c,\widetilde{m},\widetilde{c}}$. The matrix is a rating provided by construction personnel working on site to determine how easy it is to install two components together, c and $\widetilde{c}$, where material m and material $\widetilde{m}$ is adopted for each respectively. To determine the value of this matrix for each of the possible combinations of the building components, weights are assigned for each of the following factors: (i) material cost, (ii) qualification of construction workers needed to install the components, (iii) the extent of training required for construction technicians, and (iv) how available the material is on the market.

The third objective function, Eq. (3), minimizes the operational energy of the building, and is given as:

$$\sum_m \sum_c Q^m_{Heat,c} x_c^m + Q^m_{Cool,c} x_c^m + Q^m_{DHW,c} x_c^m \tag{3}$$

The first term, $Q^m_{Heat,c} x_c^m$ computes the total energy expended on heating the building, as influenced by the choice of material m for component c. The second term $Q^m_{Cool,c} x_c^m$ computes the total energy associated with cooling the building, as influenced by the choice of material m for component c, and finally the third component of Eq. (3), $Q^m_{DHW,c} x_c^m$, computes the total operating energy associated with domestic water provision due to the utilization of material m for the component c.

2.2.2. Constraints

A number of constraints are formulated in order to delineate the feasible region of the optimization problem considered. The first of the constraints, Eq. (4), ensures that a single material is chosen of each building component in the building. It is formulated as:

$$\sum_{m \in M} x_c^m = 1, \quad \forall\, c \in C \tag{4}$$

The second formulated constraint, Eq. (5), excludes certain selections of materials that can be impossible due to building restrictions; the use of these constraints relies on the set *Exclusion_List*, which maps the non-permitted combination of materials and building components for a project. It is formulated as:

$$x_c^m = 0, \quad \forall\, (c, m) \in Exclusion\_List \tag{5}$$

The third formulated constraint, Eq. (6), represents the condition where two building components cannot be directly linked together in the structure (e.g. roof and foundations); these constraints are required to ensure the continuity in the structure via the selection of materials made to all components of the building. It is formulated as:

$$x_c^m \times x_{\widetilde{c}}^{\widetilde{m}} = 0, \quad \forall\, [(c, m), (\widetilde{c}, \widetilde{m})] \in Forbidden\_Instalment \tag{6}$$

The fourth formulated constraint type, Eqs. (7)–(9), computes the energy demand of the building based in heating, cooling and water requirements respectively [23]. They are formulated as follows:

$$Q^m_{Heat,c} = (Q^m_{Heat,tr,c} + Q^m_{Heat,ve,c}) - \vartheta^m_{Heat,c} \times Q^m_{Heat,gn,c} \tag{7}$$

$$Q^m_{Cool,c} = Q^m_{Cool,gn,c} - \vartheta^m_{Cool,ls,c} \times (Q^m_{Cool,tr,c} + Q^m_{Cool,ve,c}) \tag{8}$$

$$Q^m_{DHW,c} = 4.182 \times V^m_{W,c} \times (\theta_{w,t} - \theta_{w,0}) \tag{9}$$

In particular, Eq. (7) calculates the continuous heating generated monthly, while Eq. (8) considers the continuous cooling generated monthly. Eq. (9) refers to the energy needs for domestic hot water production, which is influenced by the type of building, its floor area and the temperature difference between the inlet water and the one desired at the tapping point.

The final set of constraints, Eq. (10), define the domain of the integer variable, as follows:

$$x_c^m \in \{0, 1\}, \quad \forall\, m \in M, \forall\, c \in C \tag{10}$$

2.2.3. Solution approach

To determine the Pareto optimal solutions for the multi-objective optimization problem Eqs. (1)–(10), the ε-constraint method is adopted. This method reformulates the given set of objective functions so that one is optimized whilst the rest are executed as constraints [24]. The trade-off matrix representing the best values for each objective function is obtained. This requires the application of lexicographic optimization [25]. After obtaining the trade-off table, the right-hand side of the functions converted into constraints can be varied between its corresponding nadir values and optimum values, allowing for the non-dominated solutions on the Pareto frontier to be yielded. For more information on the solution method utilized, the reader is referred to [24].

2.3. BIM-LCA integration

BIM-LCA integration is a vital process that could achieve the sustainability standards in the construction project and protect the built environment [26]. On the first hand, BIM tools give the opportunity to collaborate and integrate the work between the different stakeholders throughout the entire lifespan of buildings [17], in order to provide several design alternatives within various parameters at an early stage of designing construction projects [27]. On the second hand, LCA methodology helps to evaluate the environmental impacts and estimate the energy performance in the construction sector [28]. Such an integration procedure empowers the decision-making process towards very low energy buildings and protects the built environment [29]. This work applies the methodological framework of LCA based on ISO 14040 and 14044 guidelines [30]: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

The initial step in LCA is the Goal and Scope, as shown in Fig. 2. In this step, it is necessary to determine the functional equivalent, system boundary, the scope of the work and the set of building materials. As this study is divided into two different analyses, these assumptions must be made separately in each one of them. In the first part of the study, the goal is to increase the energy efficiency of the building, focusing on the operational phase. This decision is made due to the potential of the operational phase to consume up to 90% of all building energy [8]. Therefore, the system boundary of this analysis is the operational phase of the building, making it a gate-to-gate LCA. At this level of the analysis, the functional equivalent takes into consideration the technical and functional requirements of the building and forms a basis for comparisons of the results of the assessment [31]. In the second part of the study, the goal is to reduce the environmental impacts of the building, focusing on the analysis of alternative building materials, hence not focusing on the construction methods used throughout the construction phase of the building. For this reason, the system boundary accounts for the entire lifespan of the building, disregarding the construction phase.

The 3-D model of the building is developed based on the BIM methodology. A set of alternative design and building materials is defined in order to be used in the database. First, the whole analysis is made to increase the energy efficiency of the building. Based on material and climate databases applicable to the region in which the analysis is conducted, building modifications are proposed. The mathematical optimization model generates an optimum solution, and this result is then contrasted with the initial solution of the building.

Based on the results of the first part of the study, two different BIM models are used in the second part of the analysis, with the aim to reduce the environmental impacts of the building: the model based on the initial solution, and the optimum building based on the energy analysis. Defining the impact categories to be evaluated, a simulation is made to measure the impacts in these two models. In these terms, LCIA provides an evaluation of the significance of impacts within the elementary flows. The last step of the methodological framework of this study is to analyze, evaluate and compare the collected results from LCI and LCIA steps, classify sources and propose recommendations in order to achieve the objectives of this work. Finally, it is important to highlight the interconnected relationship between energy and the impact analyses. The results of both steps should be taken into account and, consequently, it will facilitate the best proposal that serves the objectives of the construction project.

2.4. Linking framework components

BIM models can implement several modifications and simulations; in this work, BIM is utilized to examine the building envelope in order to achieve the sustainability standards of construction projects. It uses the construction of a multi-story residential building in Brazil as a case study to analyze the validity and usability of BIM-LCA integration in estimating the energy performance and evaluating the environmental impacts in the construction sector. Accordingly, the chosen case study for this work is the plan of a typical multi-story residential building. The building components of the models are structured and dimensioned according to the regulation of the Brazilian Standard ABNT NBR 12721:2007 presented and developed as an actual building design in Minas Gerais SINDUSCON MG publication [32]. The methodology of this research, which is presented in Fig. 3, clarifies that the first step is to design the model of the building typology using a BIM software in order to define the parameters and quantify the construction materials of the building.

The scope of this research is to reduce the consumption of operating energy and protect the built environment. Thus, it investigates the operating energy needs and consumption for the building, considering the building envelope and the designed construction materials. Recently, the building energy simulations and tools such as BLAST, Energy Plus, QUEST, TRACE, DOE2, Ecotect, and Integrated Environmental Solution have been developed and applied widely in the construction industry [33]. In this work, Tally application is used, considered as an intelligent energy setting that evaluates the environmental impacts of building materials and optimizes in the entire lifespan of buildings [34]. Autodesk Green Building Studio is also used as an intelligent energy setting that facilitates the performance of building simulations and optimizes energy efficiency in buildings [35]. It uses DOE2 as a proven and validated simulation engine to provide results related to energy use, water use, and carbon emissions [36]. The results at this level of the analysis are evaluated under ANSI/ASHRAE Standard 140 [37]. The results help to assemble the Life Cycle Energy Assessment at the operation phase of buildings[38]. A reliable database of local weather data for both site studies and energy analysis for construction projects is used, taking into account a 30-year life of building use (operation phase) within 6.1% discount rate for costs, using the annual energy cost and consumption information that are estimated as an average utility rates for a country or territory [39]. Besides, it considers several parameters that are essential to be filled-in precisely to get realistic results, which are associated with building type, location, thermal properties, project phase, building envelope, analysis mode, conceptual of construction, building operating schedule, HVAC system (Heating, Ventilation, and Air Conditioning), and outdoor air information. In this discipline, the focus is on the operation phase of construction projects, while the thermal properties consider the thermal zoning for energy analysis.

Moreover, the study modifies alternative options for construction materials that are assembling the building envelope of the building based on the local materials in the construction market in Brazil [32]. The measures suggested for this work include mainly an increase in insulation thickness of walls, floors and ceilings, and the installation of energy efficient doors and windows. The idea is to achieve more efficient and high-performance building envelope. In this term, alternative options of construction materials are applied individually to the

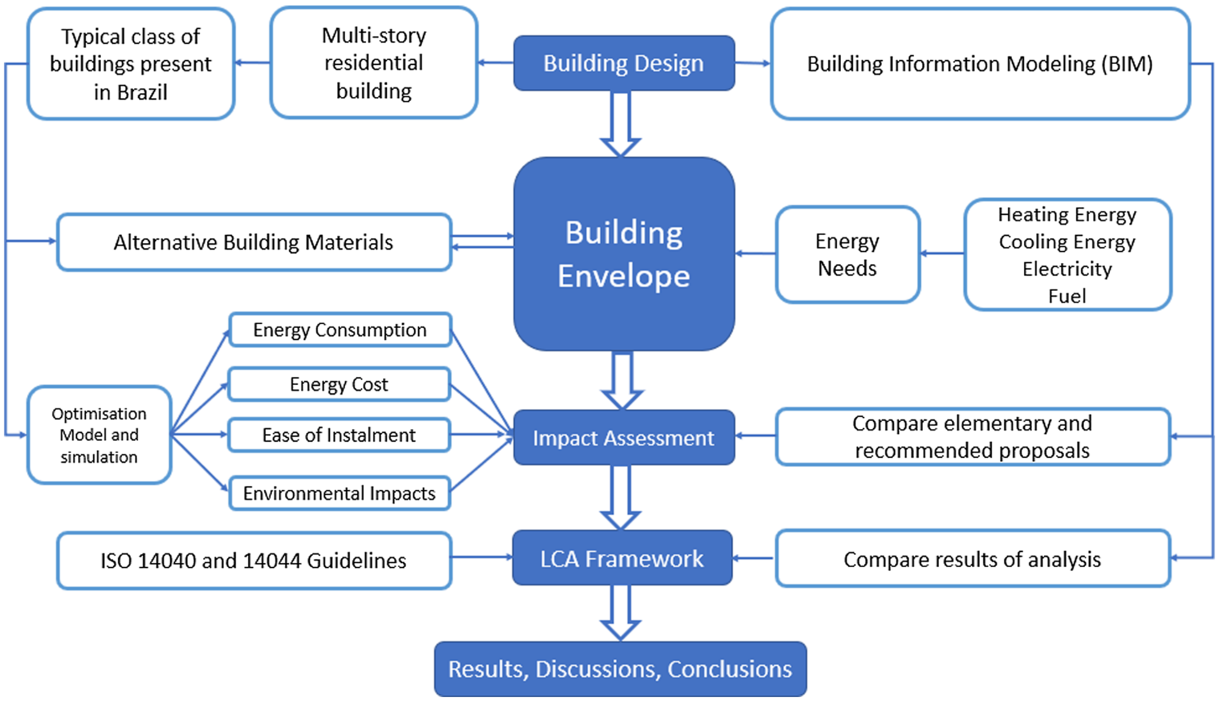


Fig. 3. The methodology of this work.

standard design proposal as a way to conduct a conceptual energy consumption analysis for this building typology.

The next step is to calculate the impact assessment and conduct interpretation [30] in order to recommend a set of construction materials that are forming the envelope of the assessed building. This research compares the LCA of the applied case study based on the standard design on the one hand, with the recommended proposal, based on a database that combines material attributes, assembly details, and architectural specifications with environmental impact data, as shown in Fig. 3. This step compares the environmental impacts of construction materials in these two models of the building. The system boundary at this level of the study considers the entire lifecycle stages of the building, excluding the construction stage. The inventory of data at this step is constructed based on the number of construction materials and the application of Tally plug-in that is powered by the GaBi database [40]. Tally links the LCA dataset of building materials, based on the GaBi 6 using GaBi database, with the elements of BIM in a way to evaluate the environmental impacts of construction materials [41]. This plug-in delivers operative feedback at the designing phase of the total LCA of construction projects [42].

3. Case study: Validating the methodological framework

In this section, the proposed optimization model is examined on a realistic case example in the city of Rio de Janeiro, Brazil. A residential building is used, comprising of 36 units, distributed over 10 levels (ground floor, 8 floors, and a roof), with a total floor area of 1558 m^2. Each apartment consists of two bedrooms, a living room, kitchen, bathroom, and service area, as seen in Fig. 4.

Autodesk Green Building Studio application in Autodesk Revit software is used to define the climate data of the case study using the virtual weather stations "*Green Building Studio Weather Stations*", which includes about 1.6 million virtual weather stations [43]. Additionally, this application is used to estimate the annual operating energy consumption of the case study building, where the graphs of energy consumption and environmental impacts are generated via DOE 2.2 simulation engine [39]. CPLEX, a highly efficient integer programming linear solving, is deployed as the optimality solver, with an optimality tolerance of 1% [44]. The time take for the optimization model to converge into an optimal solution lies between 10 and 2463 s.

The first building components utilized were based on the regulation of the Brazilian Standard ABNT NBR 12721:2007, presented in Minas

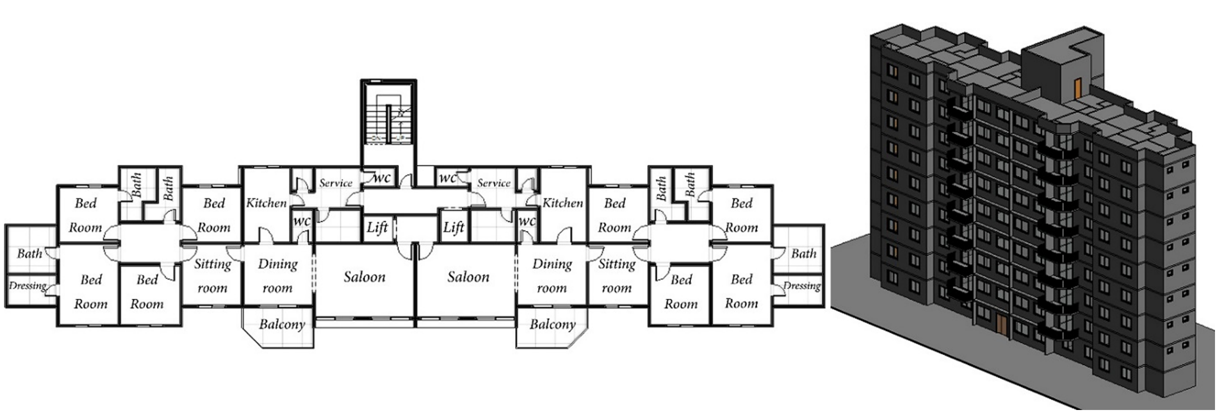
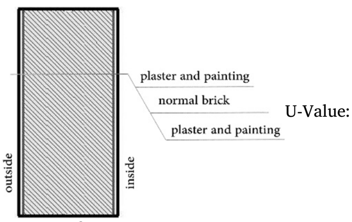
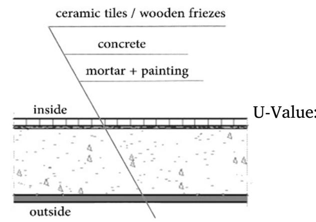
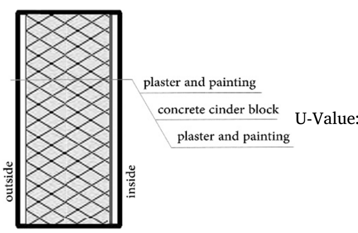
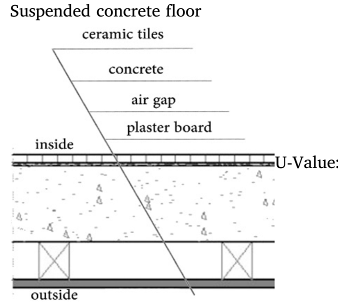
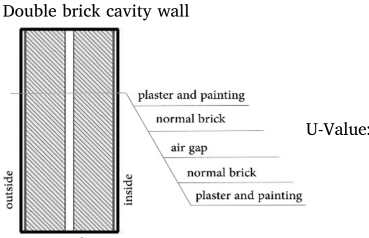
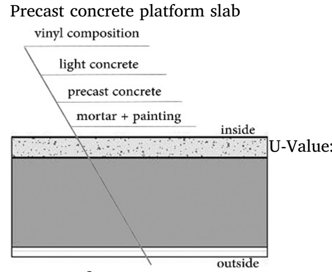
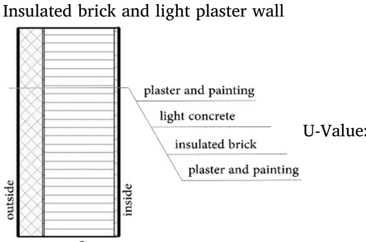
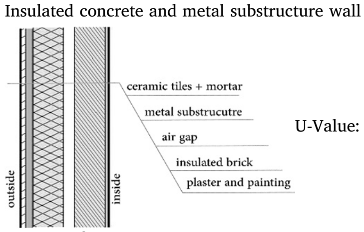


Fig. 4. 2D and 3D plan of the multi-story residential building used as a case study.

Table 1
Standard design and alternative materials for the building components in the case study.

	Exterior walls	Floors	Windows	Doors
Standard Design	Ceramic masonry block 9 cm × 19 cm × 19 cm  2.48 W/m^2 K	Concrete floor with mixed of Wooden friezes and ceramic tiles  2.64 W/m^2 K	Sliding window 1.20 m × 1.20 m Aluminum frame, brass color, with glass 4 mm U-Value: 3.58 W/m^2 K	Waxed solid wood U-Value: 3.00 W/m^2 K
Material Alternative 1	Concrete block wall  2.22 W/m^2 K	Suspended concrete floor  2.37 W/m^2 K	Sliding Birchwood window 1.20 m × 1.20 m U-Value: 3.67 W/m^2 K	Wood with stainless steel U-Value: 3.12 W/m^2 K
Material Alternative 2	Double brick cavity wall  1.50 W/m^2 K	Precast concrete platform slab  1.98 W/m^2 K	Double casement aluminum window 1.20 m × 1.20 m U-Value: 2.02 W/m^2 K	Wood and EPS door U-Value: 3.27 W/m^2 K
Material Alternative 3	Insulated brick and light plaster wall  1.20 W/m^2 K	X	Sliding Pinewood window 1.20 m × 1.20 m U-Value: 1.78 W/m^2 K	PVC with glazing beads door U-Value: 2.20 W/m^2 K
Material Alternative 4	Insulated concrete and metal substructure wall  1.88 W/m^2 K	X	Standard window 1.00 m × 1.20 m (narrow size) U-Value: 3.58 W/m^2 K	Steel galvanized with insulation glazed U-Value: 2.40 W/m^2 K

Gerais SINDUSCON MG publication [32]. The details on these building components are presented in Table 1, referred to as Standard Design. A list of possible alternative materials that are established in line with what is available on the Brazilian market is presented in the same table. These alternatives are tested and compared in the case study via simulation. Energy simulation is built according to the Brazilian Labelling Schemes for Commercial, Public and Services Buildings (RTQ-R), which were developed through the National Program of Energy Efficiency in Buildings [45]. RTQ-R supports the practical application of energy conservation measures in residential buildings in Brazil to meet the ASHRAE Standard 140 [46]. RTQ-R label proposes 26 °C as a residential comfort summer temperature, natural ventilation as a ventilation system; and no air change rate. This label encourages bioclimatic strategies; hence, there are no requirements for primary energy demand, and heating or cooling demand/load [47]. However, the U-value of the applied building components is collected from Autodesk Revit software, as presented in Table 1.

Table 2
Energy use and cost based on a modification of exterior walls.

Material	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (kWh)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (kWh/m^2)	Annual Energy Use Intensity (kWh/m^2)	Ease of Instalment
Building component: exterior walls							
Insulated brick and light plaster wall	1.434.517	415.693.89	86.176	76	22.22	98.22	2.50
Insulated concrete and metal substructure wall	2.315.013	549.153.61	136.722	177	38.33	215.33	2.50
Concrete block wall	2.277.514	573.475.56	135.148	173	40.55	213.55	4.25
Double brick cavity wall	1.104.470	283.049.44	69.651	85	21.39	106.39	4.00

3.1. Estimating the annual operating energy consumption and cost based on the standard design

The evaluation of the building used as a case study is based on the calculation of the consumption and the cost of the life cycle energy, along with the annual energy use intensity, divided into electricity use intensity (EUI) and fuel use intensity (FUI). In these terms, Autodesk Green Building Studio application estimates the life cycle of energy use/cost over a 30-year building life period, in which all energy inputs are accounted for over the proposed length of the operational phase of a building. The annual energy use intensity (i.e. annual electricity use intensity and annual fuel use intensity) refers to the amount of energy consumed per square meter per year. The performance of energy in the building is estimated via DOE 2.2 simulation [39]. A value of 0.12 $/kWh for electricity consumption and 0.01 $/MJ (equals to 0.036 $/kWh) for fuel consumption is estimated in order to assess the life-cycle energy cost. At this level of the analysis, the majority of energy demand in buildings is associated with the use phase for heating and cooling systems, lighting fixtures, and electrical appliances [48]. It is important to note that the operational energy of the majority of the residential buildings in Brazil is dedicated for cooling [47].

The output results of the functional equivalent of the building typology, considering the building as a single unit and based on the standard design of materials, show that: (i) the annual fuel use intensity is estimated to be 41,67 (kWh/m^2); (ii) the annual electricity use intensity is estimated to be 175 (kWh/m^2); (iii) the annual energy use intensity is estimated to be 216,67 (kWh/m^2); (iv) the life cycle electricity use is estimated to be 2,534,630 (kWh); (v) the life cycle fuel use is estimated to be 611633,33 (kWh); and vi) the life cycle energy cost is estimated to be 149,893 ($). These results are compared, individually, with the output results of the functional equivalent of the building typology based on the recommended proposals of materials in Section 3.3.

3.2. Estimating the annual operating energy consumption based on the modified building materials via optimization

The optimization model developed in Section 3 is now applied to the case study building displayed above in Fig. 4, in order to enhance the energy efficiency of the design. Alternative options of construction materials that form the building envelope are presented in a database, based on the local materials that are available in the construction market in Brazil. This is displayed in Table 1. The selection of materials is made to achieve more efficient and high-performance components. The idea is to examine each alternative construction material individually within the standard designs in order to assess the possible changes in the conceptual energy performance analysis for each building, considering the cost of construction materials in the local market in Brazil. This clarifies the application of some alternative options of building components on one or more case study buildings, and vice versa.

The results of the optimization model will then be contrasted with the initial solution presented in Section 3.1., based on the standard design. In the case study examined, the preference relationship is given such that first priority is towards minimizing the cost of operating the building, followed by maximizing the ease of instalment, and then finally minimizing the operational energy of the building.

3.2.1. Optimum exterior walls

Alternative options of construction materials, as seen in Table 1, such as concrete block wall, double brick cavity wall, insulated concrete and metal substructure wall, and insulated brick and light plaster wall are evaluated and contrasted.

Insulated brick and light plaster wall proved to be the optimum of exterior walls. The optimum material selected replaces the standard design of building materials that are forming the components of exterior walls in the case study.

3.2.2. Evaluation of other non-optimum material options for exterior walls

Alternative options of construction materials are evaluated and contrasted with the optimum selection made, based on FUI, EUI, operating energy and ease of installment. Results of the life cycle of energy use and cost are presented in Table 2.

Comparing the collected results in Table 2 with the standard design element of the exterior walls, presented in Table 1, facilitates the selection process of the best building components that better fit the exterior walls towards more energy efficient buildings, as presented in Fig. 5. The presented results show that the life cycle energy use of the standard wall component is the worst among the other alternatives while using the double brick cavity wall will enhance the life cycle electricity use by around 56% and the life cycle fuel use by around 53%. However, the annual energy use intensity and ease of installment of the insulated brick and light plaster wall results in better operational energy savings, leading to more energy efficient buildings.

3.2.3. Optimum floors and ceilings

Two types of floor and ceiling components: suspended concrete floor and precast concrete platform slab, are replacing the construction materials that are forming the components of floors and ceilings in the building, as seen in Table 1. The suspended concrete floor consists of ceramic tiles and structural concrete for floors, and plasterboard with an air gap for ceilings, while precast concrete platform slab consists of vinyl composition and precast structural concrete for floors and mortar and painting for ceilings.

Precast concrete platform slab proved to be the optimum of floors and ceilings. The optimum material selected replaces the standard design of building materials that are forming the components of floors and ceilings in the case study.

3.2.4. Evaluation of other non-optimum material option for floors and ceilings

An alternative option of construction materials is evaluated and contrasted with the optimum selection made, based on FUI, EUI, operating energy and ease of installment. The total life cycle of energy use and cost in such type of analysis is presented in Table 3.

Comparing the collected results in Table 3 with the standard design element of the floors and ceilings, presented in Table 1, facilitates the selection process of the best building components that better fit this part of the building envelope towards more energy efficient buildings, as presented in Fig. 6. The presented results show that the life cycle energy use of the standard floor and ceiling component is the worst among the other alternatives, while the precast concrete platform slab could be the most energy efficient component of the ceiling and floors in such types of buildings that could result in a better operational energy savings, leading to more energy efficient buildings.

3.2.5. Optimum windows

Alternative options of windows such as sliding birchwood window, double casement aluminum window, sliding pinewood window, and the same windows in standard design with narrower sizes, as seen in Table 1, are replacing the construction materials that are structuring the components of windows in the building. This examines the impacts on the consumption of energy in buildings as a reason for the wide range of alternative materials with different thermal parameters and dimensions. For example, the application of sliding pine wood window is proposed to be protected by the vinyl exterior, stainless steel finishing, and low-emissivity glass.

Sliding pinewood window proved to be the optimum of windows. The optimum material selected replaces the standard design of building materials that are forming the components of windows in the case study.

3.2.6. Evaluation of other non-optimum material options for windows

Alternative options of construction materials are evaluated and contrasted with the optimum selection made, based on FUI, EUI, operating energy and ease of installment. The total life cycle of energy use and cost in such type of analysis is presented in Table 4.

Comparing the collected results in Table 4 with the standard design element of the windows, presented in Table 1, facilitates the selection process of the best building components that better fit this part of the building envelope towards more energy efficient buildings, as presented in Fig. 7. The presented results show that the life cycle energy use of sliding birchwood window (1.20 m × 1.20 m) is the worst among the other alternatives, while the life cycle energy use of sliding pinewood window (1.20 m × 1.20 m) could be the most energy efficient window component in such types of buildings that could result in a better

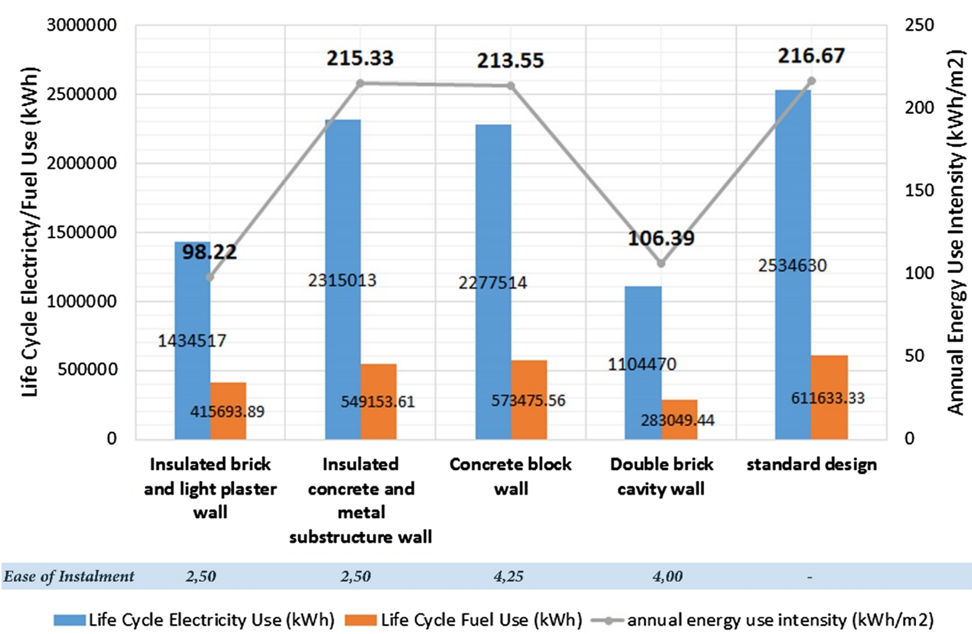


Fig. 5. Comparison of the exterior wall components applied in the case study.

Table 3
Energy use and cost based on a modification of floors and ceilings.

Building component: floors and ceilings							
Material	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (kWh)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (kWh/m^2)	Annual Energy Use Intensity (kWh/m^2)	Ease of Instalment
Suspended concrete floor	2.517.384	611.633.33	148.953	180	41.67	221.67	4.50
Precast concrete platform slab	2.480.264	611.633.33	146.931	170	41.67	211.67	2.50

operational energy savings, leading to more energy efficient buildings.

3.2.7. Optimum doors

Different options for doors such as wood with stainless steel, PVC with glazing beads door, steel galvanized with insulation glazed, and wood and EPS door, as seen in Table 1, are replacing the standard components of doors in the case study. The wide range of alternative options of materials with different thermal parameters would affect the consumption of energy in buildings. Moreover, the application of EPS (expanded polystyrene insulation materials) in doors would provide more energy efficient and soundproofing in buildings [49].

PVC with glazing beads door proved to be the optimum of doors. The optimum material selected replaces the standard design of building materials that are forming the components of doors in the case study.

3.2.8. Evaluation of other non-optimum material options for doors

Alternative options of construction materials are evaluated and contrasted with the optimum selection made, based on FUI, EUI, operating energy and ease of installment. The total life cycle of energy use and cost in such type of analysis is presented in Table 5.

Comparing the collected results in Table 5 with the standard design element of the doors, as presented in Table 1, facilitates the selection process of the best building components that better fit this part of the building envelope towards more energy efficient buildings, as presented in Fig. 8. The presented results show that the life cycle energy use of wood with stainless steel door component is the worst among the other alternatives, while the life cycle energy use of PVC with glazing beads doors could be the most energy efficient door component in such types of buildings that could result in a better operational energy savings, leading to more energy efficient buildings.

3.3. Estimating the operating energy based on the recommended proposal

Based on the previous step, this work conducted a conceptual energy analysis for the building, taking into consideration the recommended construction materials of the final proposal. The energy use and cost are evaluated via simulation, and the results show that: (i) the annual fuel use intensity is estimated to be 23,05 (kWh/m^2); (ii) the annual electricity use intensity is estimated to be 96 (kWh/m^2); (iii) the annual energy use intensity is estimated to be 119,05 (kWh/m^2); (iv) the life cycle electricity use is estimated to be 1,099,673 (kWh); (v) the life cycle fuel use is estimated to be 283049,44 (kWh); and (vi) the life cycle energy cost is estimated to be 62,494 ($). This work facilitates the comparison process between the estimated operating energy of the functional equivalent of the building typology based on the standard design on the one hand and the recommended proposal on the other hand, as presented in Table 6. This Table shows that the recommended proposal can be a vital option to improve the energy efficiency of the functional equivalent of the case study. For example, it is expected to achieve a reduction of around 45% for the annual fuel use intensity and the annual electricity use intensity in such types of buildings. Furthermore, the recommended proposal can achieve a noticeable improvement in the life cycle energy use/cost compared to the standard design.

3.4. Evaluating the environmental impacts of the standard design and recommended proposals of the case study via LCA

At this level, attention is given to the list of impact categories for the case study, considering both the standard design and recommended proposals to evaluate the environmental impacts of building

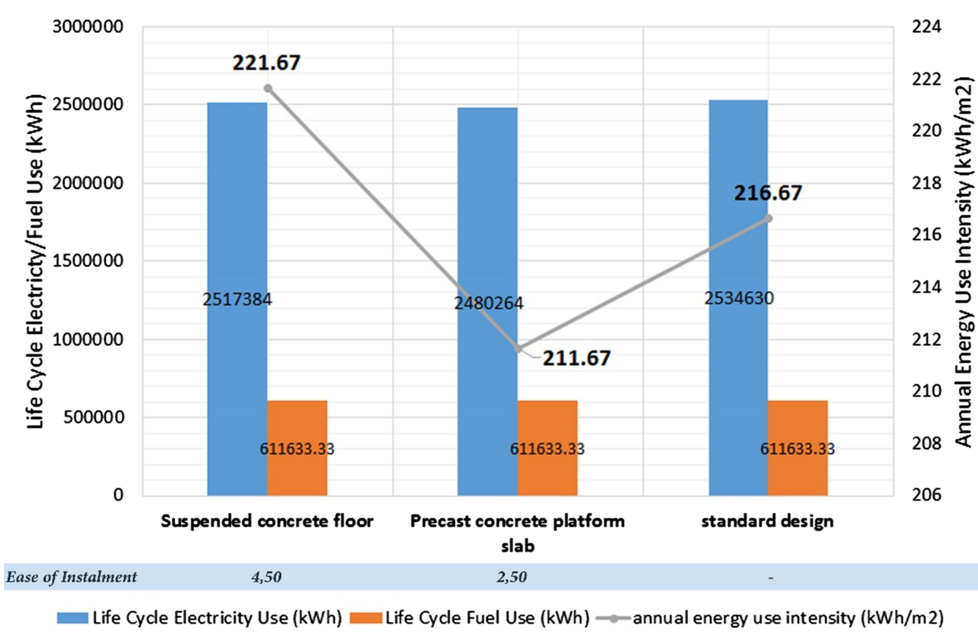


Fig. 6. Comparison of the floor and ceiling components applied in the case study.

Table 4
Energy use and cost based on a modification of windows.

Building Component: Windows

Material	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (kWh)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (kWh/m^2)	Annual Energy Use Intensity (kWh/m^2)	Ease of Instalment
Sliding Birchwood window 1.20 × 1.20 m.	2.579.977	611.633.33	152.363	177	41.67	218.67	2.25
Double casement aluminum window 1.20 × 1.20 m	2.178.083	611.633.33	130.468	149	41.67	190.67	3.50
Sliding Pinewood window 1.20 × 1.20 m	2.137.651	611.633.33	128.265	145	41.67	186.67	2.25
Standard window 1.00 × 1.20 m. (narrow size)	2.381.870	611.633.33	141.570	163	41.67	204.67	4.25

components. This analysis targets to measure the variables of impacts and evaluates the different outcomes achieved based on different building components in the building.

The functional equivalent that defines the evaluated product or system at the building level considers the entire building as a single product [31]. A Cradle-to-Grave system boundary is used, including the entire lifespan of construction materials, disregarding the construction phase, as previously presented in Fig. 1, because the focus of this study is the analysis of building materials, not focusing on the construction methods used throughout the construction phase. Therefore, the analysis includes material extraction and manufacturing, transportation, use, and end-of-life phases, and the materials and energy used across all life cycle stages. Setting up a complete analysis in Tally requires using the results of operational energy use [41], which was previously estimated for the standard design and the recommended proposal. However, LCA modeling in Tally is conducted based on GaBi life cycle databases, using the Environmental Product Declarations data [50]. Building a reliable analysis in Tally requires considering the annual energy use (electricity and fuel) at the operational phase of the standard design and recommended proposal, individually, as presented previously in Table 6. This work considers that roads are the main transportation mode for all construction phases in Brazil using vehicles with capacities of 16 and 32 metric tons. Hence, a set of average distances for transportation in Brazil is assumed to conduct the environmental impact analysis. For example, an average distance of 10 km to transport materials to the construction site, 12 km to landfill wastes, and 55 km for recycling purposes, is assumed [40]. At this step of the analysis, the operational phase is considered to combine both use and maintenance periods of buildings. The input of data at the manufacturing and end-of-life phases are dependent on the used materials. At this level of the analysis, a summary of input data of construction materials applied in the case study of this work, standard design and recommended proposal, are illustrated in the Appendix A, where the inventory materials with their corresponding databases are presented.

After calculating the quantities of construction materials, a simulation was made to measure the impact categories such as acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, primary energy demand, non-renewable energy, and renewable energy. The list of environmental impact categories used follows the characterization of TRACI 2.1, a widely disseminated midpoint method [51]. The evaluation of the environmental impacts of the case study building based on standard design is illustrated in Fig. 9, which shows the quantification of the potential environmental impacts of the building, divided by stages of the building life cycle. The results presented are already classified and characterized, that is, the substances were multiplied by a factor which reflects their relative contribution to the environmental impact in each category. For example, acidification potential is expressed using the reference unit, kg SO_2 equivalent.

The evaluation of the environmental impacts of the case study building based on the recommended proposal is presented in Fig. 10, which shows the quantification of the potential environmental impacts of the building, divided by stages of the building life cycle. Results show that environmental impacts can be greatly reduced, as well as the operating energy.

The acidification potential decreased from 13,042 kg SO_2 equivalent in the standard design model to 8724 kg SO_2 equivalent in the building based on the recommended proposal, which corresponds to a decrease of 33.11%. Besides, the global warming potential was from 4,537,449 kg CO_2 equivalent to 2,934,501 kg CO_2 equivalent, which corresponds to a decrease of 35.33%. The same applies to the other impact categories analyzed. It is noteworthy that there was a great reduction in the quantification of impacts, even if the total mass of the building has increased in the recommended proposal.

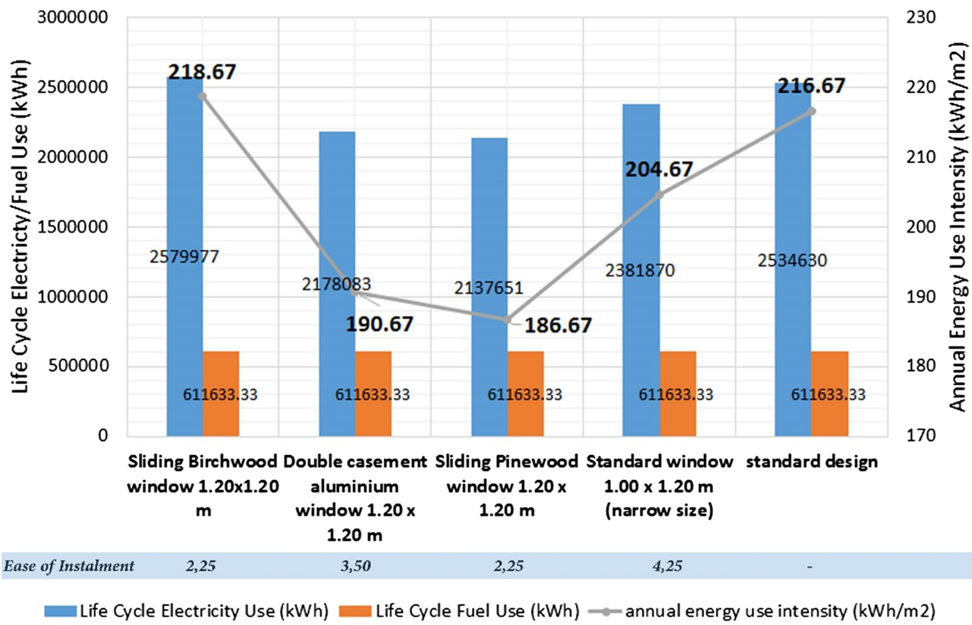


Fig. 7. Comparison of the window components applied in the case study.

Table 5
Energy use and cost based on the modification of doors.

Building Component: Doors							
Material	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (kWh)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (kWh/m^2)	Annual Energy Use Intensity (kWh/m^2)	Ease of Instalment
Wood with stainless steel	2.675.378	683.636.94	152.363	183	41.67	224.67	3.00
Wood and EPS door	2.570.780	611.633.33	151.862	178	41.67	219.67	2.75
PVC with glazing beads door	2.516.484	611.633.33	148.904	169	41.67	210.67	3.50
Steel galvanized with insulation glazed	2.517.238	611.633.33	148.945	170	41.67	211.67	3.00

4. Discussion

The building used as a case study was simulated using a BIM software, and the consumption of operating energy was estimated considering the modifications of different options of construction materials. These modifications included the main components that are forming the building envelopes such as walls, floors and ceilings, windows and doors. Alternative options of construction materials are

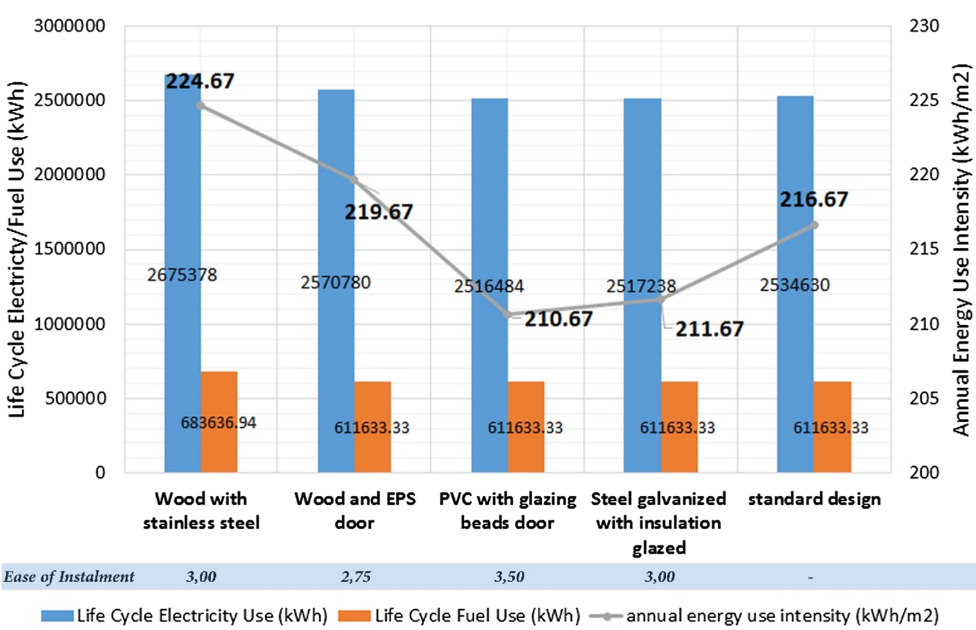


Fig. 8. Comparison of the door components applied in the case study.

Table 6
The estimated operational energy of the functional equivalent based on the standard design and the recommended proposal.

Type of analysis	Standard Design	Recommended Proposal
Annual fuel use intensity (kWh/m^2)	41.67	23.05
Annual electricity use intensity (kWh/m^2)	175	96
Annual energy use intensity (kWh/m^2)	216.67	119.05
Life cycle electricity use (kWh)	2,534,630	1,099,673
Life cycle fuel use (kWh)	611633.33	283049.44
Life cycle energy cost ($)	149,893	62,494

applied to the standard design, individually, and a mathematical optimization model is being used to identify components that are affecting the energy efficiency of building envelopes. Then this work compared the acquired results within the standard designs to recommend the most efficient components that would reduce the consumption of operating energy in the building. Finally, the environmental impacts generated by the list of materials defined as the optimal solution were calculated. These results were contrasted with the impacts generated by the initial solution of the building.

This work illustrates that BIM models allow using various construction materials within different performance parameters at the early stages of designing buildings in order to empower the decision-making process in the construction sector. It shows that the LCA methodology aims to evaluate the environmental impacts of the applied construction materials over the entire lifespan of the construction project. This work presents a clarified framework of optimization-BIM-LCA integration in order to analyze construction projects from a sustainable perspective, using a mathematical algorithm to help in finding the optimum solution for the building. It built up a new proposal for the

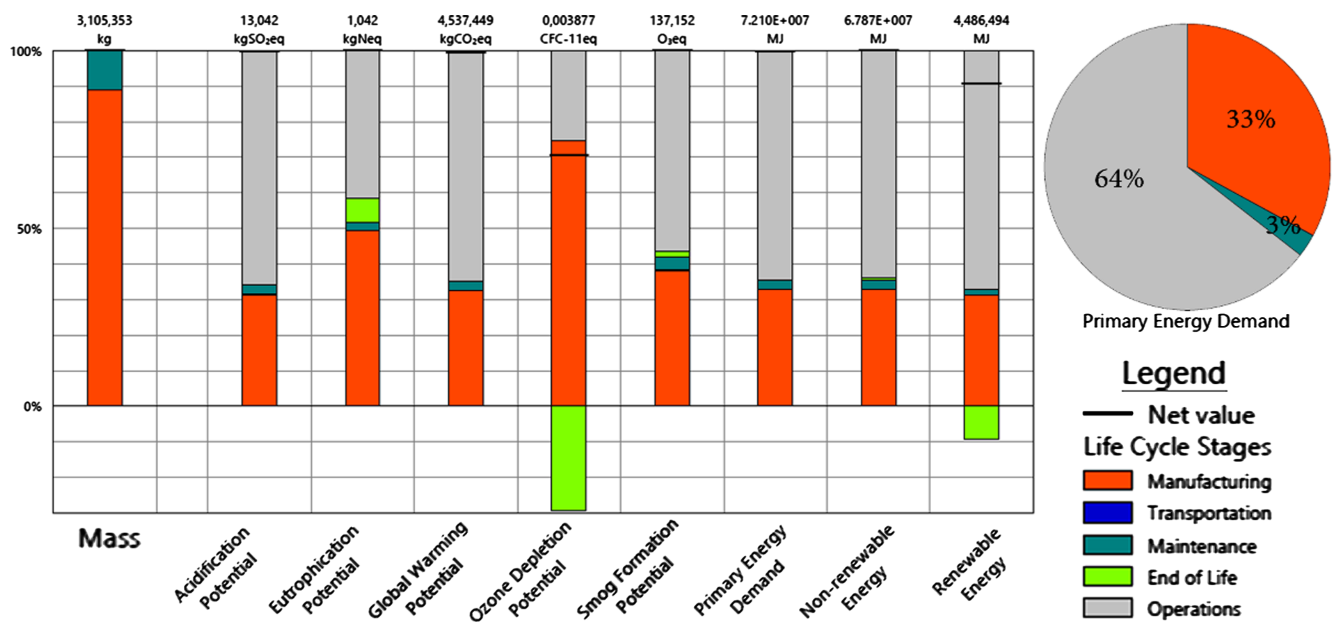


Fig. 9. Environmental impacts of the building based on a standard design.

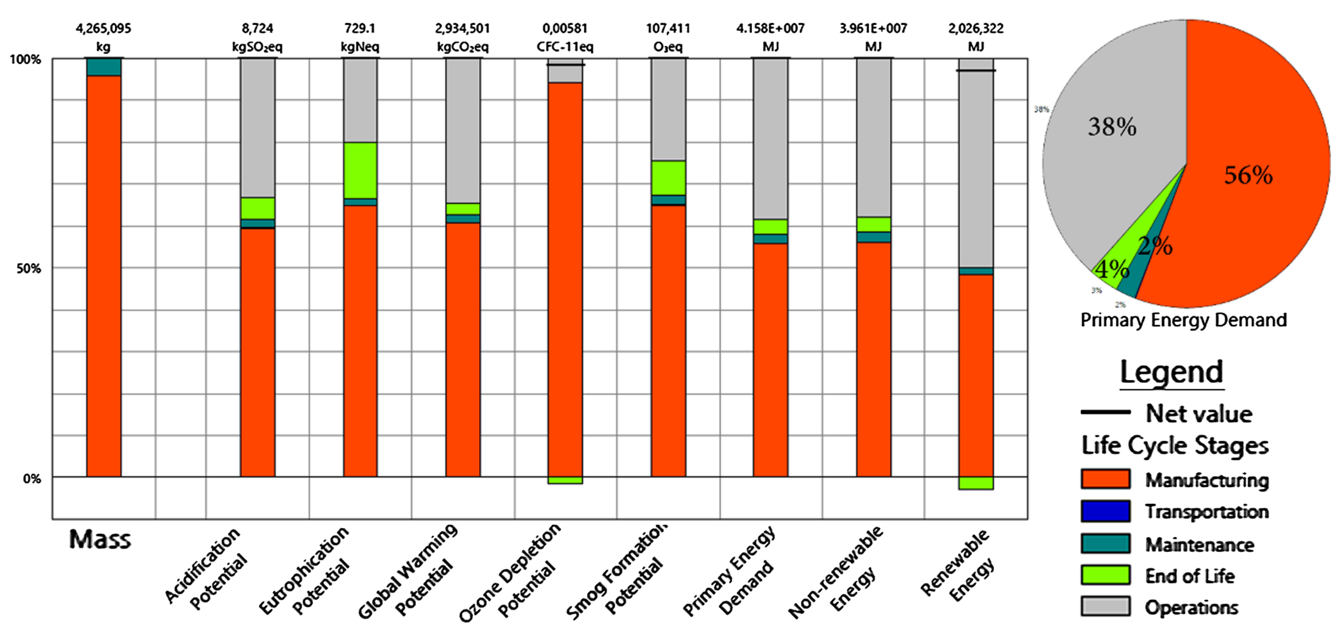


Fig. 10. Environmental impacts of the building based on a recommended proposal.

Table 7
Annual energy use intensity in standard and optimum designs.

Building Components			Results	
			Annual EUI	Annual FUI
Standard design			175	41.67
Change made to the Standard Design by modifying the materials of one building component at a time	Walls	*Optimum design*	76	22.22
	Floors and Ceilings	*Optimum design*	170	41.67
	Windows	*Optimum design*	145	41.67
	Doors	*Optimum design*	169	41.67
Recommended design using all optimum materials together			96	23.05

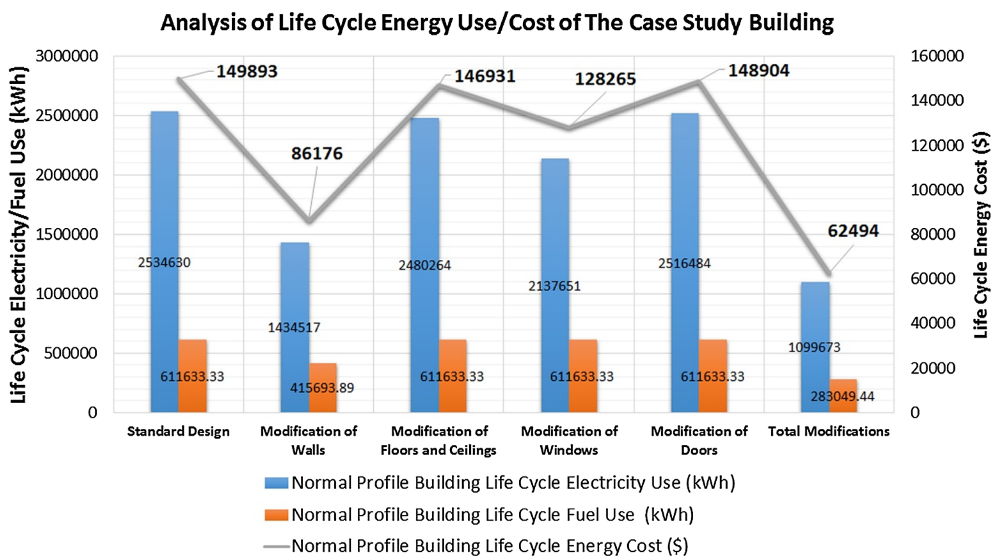


Fig. 11. Analysis of lifecycle energy use/cost in the case study.

building and compared the potential reduction in energy consumption and environmental impacts.

However, one of the basic limitations of this work is the difficulty in estimating the energy efficiency of building envelopes separately from other building aspects such as the function of the building and essential services. This work conducted a comparison of the annual energy use intensity, divided into electricity use intensity (EUI per kWh/m^2) and fuel use intensity (FUI per kWh/m^2), for the all variants within the respective performance of building components, based on the case study applied in this work, as shown in Table 7. This table helps drawing a better understanding of the annual energy use intensity of the building components applied in this work.

Consequently, the analysis of the life cycle of the operating energy consumption and cost in the building based on the recommended building components of the final proposal is shown in Fig. 11. This illustrates that applying the optimum building components could achieve a significant improvement in the energy efficiency of the building envelope compared to the standard building design, as summarized in the following points:

(i) Applying the optimum component for exterior walls only enhances the life cycle electricity use by around 43%, the life cycle fuel use by around 32%, and the life cycle energy cost by around 42%.
(ii) Applying the optimum component for floors and ceiling only has a slight impact on improving the life cycle electricity use and the life cycle energy cost by around 2%, individually, while it has no impact on the life cycle fuel use of the standard design building.
(iii) Applying the optimum component for windows only enhances the life cycle of electricity use by around 16%, and the life cycle energy cost by around 14%. Such individual assumption has a neglected impact on the life cycle fuel use of the standard design building.
(iv) Applying the optimum component for doors only has a slight impact on improving the life cycle electricity use and the life cycle energy cost by around 1% and 0.5%, respectively, while it has no impact on the life cycle fuel use of the standard design building.
(v) Applying all the optimum components for the whole building envelope enhances the life cycle electricity use by around 57%, the life cycle fuel use by around 54%, and the life cycle energy cost by around 58%.

Insights of the results show that all components of building envelopes are affecting the consumption of energy in buildings, however, exterior walls and windows are the most accountable for these values. Hence, it is highly important to recognize the construction materials that are forming such components as a prior step to invest in such type of buildings in Brazil. In other words, great efforts should be dedicated to increasing the energy efficiency of construction materials throughout the entire life cycle stages, particularly at the operation stage.

Finally, according to the analysis of the environmental impact for both standard design and recommended proposal, the results show that the recommended building proposal in this work can considerably reduce the environmental impacts based on the impact categories analyzed; reduces the environmental impacts by almost one-third, particularly the global warming impact and acidification potential impact, and consequently protect the built environment.

5. Conclusion

Buildings consume a significant amount of energy during their operating life phase. This work presented an energy analysis framework for optimizing the design of building envelopes, in such a way that the operating energy consumption is reduced. The framework is based on integrating a mathematical optimization model for the optimum selection of materials for various building components, together with Building Information Modeling and Life Cycle Assessment in order to analyze the operational energy requirement, cost of adopted designs, ease of construction of building projects, as well as the environmental impacts generated. It stimulates the concept of sustainable construction in the operating life cycle phase of buildings, and empowers the decision-making process involved, leading to the ability to examine alternative options of building components that are forming the building envelopes. Utilization of the framework enables the reduction of the operational energy in the building, as well as optimizing the energy cost and ease of installment. Life Cycle Assessment was utilized in order to evaluate the building performance and analyze the potential impacts generated throughout the building's life cycle, disregarding the construction phase, while BIM tools were adopted to intelligently link the 3D building model with all aspects of project life-cycle management information related to time, cost and sustainability in the building, that is required for computing the overall operating energy.

The framework is examined on a multi-story residential building in Brazil, in order to reduce its energy consumption, minimize its environmental impacts and promote the decision-making process in the sustainable material selection that leads to minimizing the operational energy, and installment complexities in buildings. The novelty of this work is that it presents the important integration of mathematical optimization, with Building Information Modeling and Life Cycle Assessment in order to increase the operating energy efficiency of building envelopes and to evaluate the environmental impacts of construction materials. This work followed the Life Cycle Assessment methodology based on ISO 14,040 and 14,044 guidelines to assess the importance of impacts and elementary flows, compare solutions, and propose recommendations.

This study focused only on the use phase of buildings to optimize the operational energy consumption since it represents the majority of the life-cycle energy consumption [8], while it considered the entire life cycle of buildings, disregarding the construction phase, to evaluate the environmental impacts of construction materials. In the case study, it was possible to achieve a reduction of about 45% for the annual fuel use intensity and the annual electricity use intensity in such types of buildings. Insights gained from the results show that all construction components influence the operating energy efficiency of building envelopes. Exterior walls and windows are the two main agents of energy efficiency in buildings. For example, applying the optimum component for exterior walls and windows could highly improve the life cycle electricity use, the life cycle fuel use, and the life cycle energy cost in buildings. In these terms, the case study example shows that applying all the optimum components for the whole building envelope could enhance the life cycle energy use/cost in buildings for more than 50%, whereas the environmental impacts could be reduced by almost one-third. The developed methodology can be used to achieve even greater reductions in energy consumption since the proposed framework allows the analysis of a wide range of alternative materials and different kinds of building components.

Results presented in this work reveal that utilizing an integrated optimization of Building Information Modeling models with Life Cycle Assessment methodology is an optimal procedure to estimate the energy use and cost in the construction sector and evaluate the environmental impacts of construction materials. The methodology proposed for this work can be applied to any type of buildings in order to identify which components of the building generate the greatest consumption of operational energy and lead to the highest level of environmental impacts. Even though this study aimed to produce energy efficient buildings by examining the operating life cycle phase of buildings, the proposed framework can be easily expanded to cover all stages of a building's life cycle. The limitations of this work can be stated as follows. First, it is difficult to estimate the energy efficiency of building envelopes separately from other building aspects such as the function of the building and essential services. As a result, future work will look at the impacts that such linked decisions can have on the total energy expended. Second, the geographical sources in the database used are limited to some specific regions. Future research can focus on exploring other regions to generalize the results of this study. Third, the system boundary of the case study to analyze the environmental impacts disregarded the construction phase of the building, focusing on the materials analysis. As a result, a recommendation for future work would be to consider the entire lifespan of the building in order to point out reliable results. Another recommendation could be to investigate a wider range of construction components that are assembling the building envelope of construction projects, taking into consideration an adapted climate data and geographical sources to cover more regions worldwide.

Acknowledgments

This study was financed in part by the Coordination for the Improvement of Higher Education Personnel (CAPES) - Finance Code 001, and CNPq (Brazilian National Council for Scientific and Technological Development).

Appendix A

Inventory	Entry source	Manufacturing scope	End of life scope
Fiberglass board acoustic ceiling tile, 5/8″ thick	US: Fiberglass Duct Board NAIMA (2007)	Cradle to gate of panel only, excludes suspended grid system and installation hardware	100% landfilled (inert waste)
Aluminum sheet, formed and cut	NA: Primary Aluminum Ingot AA (2011); EU-27: Aluminum sheet PE (2012); GLO: Steel sheet stamping and bending (5% loss) PE (2012); US: Electricity grid mix PE (2010); US: Lubricants at refinery PE (2010); GLO: Compressed air 7 bar (medium power consumption) PE (2010); EU-27: Aluminum clean scrap remelting & casting (2010) EAA (2011)	Cradle to gate	95% recovered (includes recycling, scrap preparation, and avoided burden credit) 5% landfilled (inert material)
Anodized aluminum sheet, formed and cut	DE: Anodization of aluminum (EN15804 A1-A3) PE (2012); NA: Primary Aluminum Ingot AA (2011); EU-27: Aluminum sheet PE (2012); GLO: Steel sheet stamping and bending (5% loss); PE (2012) US: Electricity grid mix PE (2010); US: Lubricants at refinery PE (2010); GLO: Compressed air 7 bar (medium power consumption) PE (2010); EU-27: Aluminum clean scrap remelting & casting (2010); EAA (2011)	Cradle to gate	95% recovered (includes recycling, scrap preparation, and avoided burden credit) 5% landfilled (inert material)

2000 kg/m^3 fired brick	DE: Stoneware tiles, unglazed (EN15804 A1-A3) PE (2012)	Cradle to gate excludes mortar anchors, ties, and metal accessories outside of scope (< 1% mass)	50% recycled into coarse aggregate (includes grinding energy and avoided burden credit) 50% landfilled (inert material)
Ceramic tile, glazed	DE: Stoneware tiles, glazed (EN15804 A1-A3) PE (2012)	Cradle to gate	50% recycled into coarse aggregate (includes grinding energy and avoided burden credit) 50% landfilled (inert material)
Wood framing	RNA: Softwood lumber CORRIM (2011)	Cradle to gate	14.5% recovered (credited as avoided burden) 22% incinerated with energy recovery 63.5% landfilled (untreated wood waste)
Fiberglass mat gypsum sheathing board	DE: Gypsum plaster-board (Moisture resistant) (EN15804 A1-A3) PE (2012); US: Fiberglass Duct Board NAIMA (2007)	Cradle to gate	100% fiberglass landfilled Gypsum: 54% recycled into gypsum stone (includes grinding and avoided burden credit) 46% landfilled (inert waste)
Glazing, monolithic sheet, tempered	DE: Window glass simple (EN15804 A1-A3) PE (2012) US: Electricity grid mix PE (2010) US: Thermal energy from natural gas PE (2010)	Cradle to gate	100% to landfill (inert waste)
Lightweight concrete (58% cement, 42% water, < 1% admixtures)	US: Portland cement, at plant USLCI/PE (2009) US: Tap water from groundwater PE (2012) US: Diethanolamine (DEA) PE (2012) US: Tensides (alcohol ethoxy sulfate (AES)) PE (2012) DE: Butyldiglycol PE (2012)	Cradle to gate excludes mixing and pouring impacts	50% recycled into coarse aggregate (includes grinding energy and avoided burden credit) 50% landfilled (inert material)
Lime mortar (20–65% sand, 40–70% limestone, 5–15% hydrated lime, 7–15% cement)	DE: Light plaster (lime-cement) PE (2012)	Cradle to gate	50% recycled into coarse aggregate (includes grinding energy and avoided burden credit) 50% landfilled (inert material)
Paint, exterior acrylic latex, 4.5% organic solvents	DE: Application paint emulsion (building, exterior, white) PE (2012)	Cradle to gate, including emissions during application	100% to landfill (plastic waste)
Wall covering, plastic and resin, EPD - InPro	EPD (US), InPro (2013)	Cradle to gate, including packaging and installation	Includes disposal and any relevant recycling processes and resulting credits
Steel, reinforcing rod	GLO: Steel rebar worldsteel (2007)	Cradle to gate	70% recovered (product has 69.8% scrap input while the remainder is processed and credited as avoided burden) 30% landfilled (inert material)
Portland cement stucco, applied directly to concrete	US: Silica sand (Excavation and processing) PE (2012) US: Portland cement, at plant USLCI/PE (2009) US: Lime (CaO) calcination PE (2012)	Cradle to gate	100% to landfill (inert waste)
Acoustic ceiling system, fabric faced fiberglass	NA: Steel hot dip galvanized worldsteel (2007) US: Metal roll forming (MCA) (2010) US: Electricity grid mix PE (2010) US: Thermal energy from natural gas PE (2010) GLO: Value of scrap worldsteel (2007)	Cradle to gate	98% recovered (product has 10.3.% scrap input while the remainder is processed and credited as avoided burden) 2% landfilled (inert material)
Mortar Type N (moderate strength mortar for use in masonry walls and flooring)	DE: Masonry mortar (MG II a) PE (2012)	Cradle to gate	50% recycled into coarse aggregate (includes grinding energy and avoided burden credit) 50% landfilled (inert material)
Wall covering, textile	US: Nylon (PA 6.6) - fabric PE (2012)	Cradle to gate, excludes adhesives, backings, or any additional coatings	100% landfilled (plastic waste)
Fiberglass board acoustic ceiling tile, 5/8″ thick	US: Fiberglass Duct Board NAIMA (2007)	Cradle to gate of panel only, excludes suspended grid system and installation hardware	100% landfilled (inert waste)
Fluid applied synthetic polymer air barrier	US: Styrene-butadiene rubber (SBR) PE (2012); US: Silica sand (flour) PE (2012)	Cradle to gate for materials only, neglects manufacturing requirements	70% landfilled (plastic waste)
Glazing, double, insulated (air-filled), 1/4″ float glass clear, inclusive of sealant, and spacers	DE: Double glazing unit PE (2012), modified to exclude coating and argon	Cradle to gate	100% to landfill (inert waste)
Structural concrete, generic, 5000 psi	US: Portland cement, at plant USLCI/PE (2009) US: Tap water from groundwater PE (2012) EU-27: Gravel 2/32 PE (2012) US: Silica sand (Excavation and processing) PE (2012)	Cradle to gate, excluding mixing and pouring impacts	50% recycled into coarse aggregate (includes grinding energy and avoided burden credit) 50% landfilled (inert material)

References

[1] De Lassio J, França J, Santo KE, Haddad A. Case study: LCA methodology applied to materials management in a Brazilian residential construction site. J Eng 2016;2016. https://doi.org/10.1155/2016/8513293.

[2] Žigart M, Kovačič Lukman R, Premrov M, Žegarac Leskovar V. Environmental impact assessment of building envelope components for low-rise buildings. Energy 2018;163:501–12. https://doi.org/10.1016/j.energy.2018.08.149.

[3] Kwok Wai Wong J, Zhou J. Enhancing environmental sustainability over building life cycles through green BIM: A review. Autom Constr 2015;57:156–65. https://doi.org/10.1016/j.autcon.2015.06.003.

[4] U.S. Energy Information Administration, International Energy Outlook 2016; 2016.

[5] de Larriva RA, Rodríguez GC, López JMC, Raugei M, Palmer PFi. A decision-making LCA for energy refurbishment of buildings: Conditions of comfort. Energy Build 2014;70:333–42.

[6] UNEP. Buildings and Climate Change; Status, Challenges and Opportunities; 2007.

[7] Petrasiunas R. Renovation of residential building according to Finnish and Lithuanian national building codes. MAMK Univesity Appled Sci 2016.

[8] Khasreen MM, Banfill PFG, Menzies GF. Life-cycle assessment and the environmental impact of buildings: a review. J Sustain 2009:674–701. https://doi.org/10.3390/su1030674.

[9] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: An overview. Energy Build 2010;42:1592–600. https://doi.org/10.1016/j.enbuild.2010.05.007.

[10] Yüksek I, Karadayi TT. Building life cycle energy-efficient building design in the context of building life cycle. In: IntechOpen; 2017. https://doi.org/10.5772/66670.

[11] Rahman Azari. Life Cycle Energy Consumption of Buildings; Embodied + Operational. In: Sustainable Construction Technologies: Life-Cycle Assessment; 2019. p. 123–44. https://doi.org/10.1016/B978-0-12-811749-1.00004-3.

[12] Bragança L, Vieira SM, Andrade JB. Early stage design decisions: the way to achieve

sustainable buildings at lower costs. Sci World J 2014;2014.
[13] Soust-Verdaguer B, Llatas C, García-Martínez A. Critical review of bim-based LCA method to buildings. Energy Build 2017;136:110–20.
[14] Hay R, Ostertag CP. Life cycle assessment (LCA) of double-skin façade (DSF) system with fiber-reinforced concrete for sustainable and energy-efficient buildings in the tropics. Build Environ 2018;142:327–41. https://doi.org/10.1016/j.buildenv.2018.06.024.
[15] Sahar Mirzaie. The EN 15804 Building Product LCA Standard: More Challenges than Benefits, PRé. https://www.pre-sustainability.com/the-en-15804-building-product-lca-standard-more-challenges-than-benefits; 2016 [accessed 04.04.19].
[16] Gao H, Koch C, Wu Y. Building information modelling based building energy modelling: a review. Appl Energy 2019;238:320–43. https://doi.org/10.1016/j.apenergy.2019.01.032.
[17] Antón LÁ, Díaz J. Integration of LCA and BIM for sustainable construction, world academy of science, engineering and technology. Int J Soc, Educ, Econ Manage Eng 2014;8:1356–60.
[18] Chen X, Yang H. A multi-stage optimization of passively designed high-rise residential buildings in multiple building operation scenarios. Appl Energy 2017;206:541–57. https://doi.org/10.1016/j.apenergy.2017.08.204.
[19] Liu M, Wen YK, Burns SA. Life cycle cost oriented seismic design optimization of steel moment frame structures with risk-taking preference. Eng Struct 2004;26:1407–21. https://doi.org/10.1016/j.engstruct.2004.05.015.
[20] Cuce E, Cuce PM, Wood CJ, Riffat SB. Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings. Energy Build 2014;77:28–39. https://doi.org/10.1016/j.enbuild.2014.03.034.
[21] Jalal SJ, Bani RK. Energy for Sustainable Development Orientation modeling of high-rise buildings for optimizing exposure / transfer of insolation, case study of Sulaimani, Iraq. Energy Sustain Dev 2017;41:157–64. https://doi.org/10.1016/j.esd.2017.09.003.
[22] Kontogiorgos P, Chrysanthopoulos N, Papavassilopoulos GP. A mixed-integer programming model for assessing energy-saving investments in domestic buildings under uncertainty. Energies 2018;11. https://doi.org/10.3390/en11040989.
[23] Santos P, Martins R, Gervásio H, Simões Da Silva L. Assessment of building operational energy at early stages of design – A monthly quasi-steady-state approach. Energy Build 2014;79:58–73. https://doi.org/10.1016/j.enbuild.2014.02.084.
[24] Mavrotas G. Effective implementation of the ε-constraint method in Multi-Objective Mathematical Programming problems. Appl Math Comput 2009;213:455–65. https://doi.org/10.1016/j.amc.2009.03.037.
[25] Zykina AV. A lexicographic optimization algorithm. Autom Remote Control 2004;65:363–8. https://doi.org/10.1023/B:AURC.0000019366.84601.8e.
[26] Eleftheriadis S, Mumovic D, Greening P. Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. Renew Sustain Energy Rev 2017;67:811–25.
[27] Autodesk. Building Information Modeling for Sustainable Design; 2003.
[28] Basbagill JP, Flager F, Lepech M. Measuring the impact of dynamic life cycle performance feedback on conceptual building design. J Clean Prod 2017;164:726–35.
[29] Shadram F, Johansson TD, Lu W, Schade J, Olofsson T. An integrated BIM-based framework for minimizing embodied energy during building design. Energy Build 2016;128:592–604. https://doi.org/10.1016/j.enbuild.2016.07.007.
[30] UNEP/SETAC Life Cycle initiative, Towards a Life Cycle Sustainability Assessment; 2012.
[31] BSI Standards Publication. BSI Standards Publication Sustainability of construction works — Assessment of buildings. Part 2: Framework for the assessment of environmental performance; 2012.
[32] SINDUSCON-MG. Custo unitário básico (CUB/m2): Principais aspectos, Estado de Minas Gerais; 2007.
[33] Jalaei F, Jrade A. An automated BIM model to conceptually design, analyze, simulate, and assess sustainable building projects. J Constr Eng 2014;2014. https://doi.org/10.1155/2014/672896 Research.
[34] Tally, Meet Tally. http://choosetally.com/overview/; 2016 [accessed 24.04.19].
[35] Autodesk. Welcome to Green Building Studio. https://gbs.autodesk.com/GBS/; 2013 [accessed 24.04.19].
[36] Autodesk. Features to Help Make Your Project Profitable, Autodesk Green Building Studio. https://gbs.autodesk.com/GBS/; 2013 [accessed 24.04.19].
[37] Autodesk. Green Building Studio Validation. https://googleweblight.com/?lite_url=https://knowledge.autodesk.com/search-result/caas/CloudHelp/cloudhelp/ENU/BPA-GBSWebService/files/GUID-EF68E7D5-C0A5-4805-BFE5-7C74C57B712E-htm.html&lc=pt-BR&s=1&m=654&host=www.google.com.br&ts=1506512870&sig=ANTY_L3qf; 2014 [accessed 24.04.19].
[38] Eleftheriadis S, Mumovic D, Greening P. Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. Coventry University's Repository Original 2016. https://doi.org/10.1016/j.rser.2016.09.028.
[39] Autodesk. Getting started with autodesk green building studio, Autodesk® EcotectTM Analysis; 2011. p.17.
[40] Najjar M, Figueiredo K, Palumbo M, Haddad A. Integration of BIM and LCA: evaluating the environmental impacts of building materials at an early stage of designing a typical office building. J Build Eng 2017;14:115–26. https://doi.org/10.1016/j.jobe.2017.10.005.
[41] Yang W, Li QY, Yang L, Ren J, Yang XQ. Analyzing the life cycle environmental impacts in the Chinese building design process. In: Caspeele R, Taerwe L, Frangopol DM, editors. Proceedings of the Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018). Ghent, Belgium: CRC Press; 2018.
[42] Autodesk. Flying High with Revit and Tally: Lifecycle Assessment for the Atlanta Falcons Stadium. https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/auonline/content/au/global/en/au-online/classes-on-demand/class-catalog/classes/year-2014/revit-for-architects/ab6581/jcr-content.html; 2017 [accessed 24.04.19].
[43] Autodesk. Weather Data Sources and Methodology, Autodesk Knowledge Network.. https://knowledge.autodesk.com/search-result/caas/CloudHelp/cloudhelp/ENU/BPA-Help/files/GUID-DDF449B0-058E-465C-AFF4-7E45917B08EF-htm.html; 2014 [accessed 24.04.19].
[44] IBM. CPLEX Optimizer. https://www.ibm.com/analytics/cplex-optimizer; n.d. [accessed 24.04.19].
[45] Instituto Nacional de Metrologia Normalizaçao e Qualidade Industrial. Regulamento Técnico da Qualidade Para o Nível de Eficiência Energética Edificações Residenciais (RTQ-R), Rio de Janeiro, Brazil; 2012.
[46] Scalco VA, Fossati M, De Souza Versage R, Sorgato MJ, Lamberts R, Morishita C. Innovations in the Brazilian regulations for energy efficiency of residential buildings. Archit Sci Rev 2012;55:71–81. https://doi.org/10.1080/00038628.2011.641731.
[47] Tubelo R, Rodrigues L, Gillott M. A comparative study of the brazilian energy labelling system and the Passivhaus standard for housing. Buildings 2014;4:207–21. https://doi.org/10.3390/buildings4020207.
[48] Lechner N. Heating, cooling, lighting: sustainable design methods for architects. John Wiley & Sons; 2014. https://books.google.com.br/books?hl=pt-BR&lr=&id=WjetCwAAQBAJ&oi=fnd&pg=PR11&dq=Heating,+Cooling,+Lighting+Sustainable+Design+Methods+for+Architects+4th&ots=YNKgETPI88&sig=6LA9wCMFfTyJm6opj9g6hpCHjFQ#v=onepage&q=Heating%2C Cooling%2C Lighting Sustainable [accessed 24.04.19].
[49] Fernando PLN, Jayasinghe MTR, Jayasinghe C. Structural feasibility of Expanded Polystyrene (EPS) based lightweight concrete sandwich wall panels. Constr Build Mater 2017;139:45–51.
[50] Tally, Meet Tally. http://choosetally.com/methods/; 2016 [accessed 24.04.19].
[51] Bare J, Young D, Hopton M. Tool for the reduction and assessment of chemical and other environmental impacts (TRACI); 2012.