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MOHAMMAD NAJJAR

OPTIMIZING THE SUSTAINABLE DECISION-MAKING PROCESS TOWARDS IMPROVING ENERGY PERFORMANCE OVER THE ENTIRE LIFE CYCLE OF BUILDINGS

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OTIMIZANDO O PROCESSO DE DECISÃO SUSTENTÁVEL PARA MELHORAR O DESEMPENHO ENERGÉTICO AO LONGO DO CICLO DE VIDA DOS EDIFÍCIOS

Tese de Doutorado apresentada ao Programa de Engenharia Ambiental, Escola Politécnica & Escola de Química, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutorado em Engenharia Ambiental.

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PhD Candidate: Mohammad Najjar

Supervisor: Prof. Assed Naked Haddad, D.Sc.

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1. Modelagem de informações de construção
2. Avaliação do ciclo de vida
3. Construção sustentável
4. Consumo de energia
5. Desempenho energético sustentável em edifícios
6. Impactos ambientais
7. Processo de tomada de decisão sustentável.

OPTIMIZING THE SUSTAINABLE DECISION-MAKING PROCESS TOWARDS

IMPROVING ENERGY PERFORMANCE OVER THE ENTIRE LIFE CYCLE OF BUILDING

Mohammad Najjar

Orientador: **Assed Naked Haddad**, D.Sc.

Aprovada pela Banca:

Prof. ALI AKBARNEZHAD (PhD, University of Sydney, Australia)

Prof. DIETER THOMAS BOER (PhD, University Rovira i Virgili, Spain)

Prof. CARLOS ALBERTO PEREIRA SOARES (D.Sc, UFF, Brazil)

Profa. ANA CAROLINA BADALOTTI PASSUELLO (PhD, UFRGS, Brazil)

Prof. MARCELO GOMES MIGUEZ (D.Sc, UFRJ, Brazil)

Prof. LEANDRO TORRES DI GREGORIO (D.Sc, UFRJ, Brazil)

Rio de Janeiro

2019

Dedico essa tese ao povo brasileiro que apesar de mais simples, ele é um grande exemplo de generosidade e hospitalidade

I dedicate this thesis to the Brazilian people who, although simple, they are a great example of generosity and hospitality

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بسم الله الرحمن الرحيم ((وما أوتيتم من العلم إلا قليلا)) صدق الله العظيم

((Só vos tem sido concedida uma ínfima parte do saber))

الحمد لله الذي بفضله تدوم النعم

بسم الله الرحمن الرحيم ((وقضى ربك ألا تعبدوا إلا إياه وبالوالدين إحسانا)) صدق الله العظيم

((E teu Senhor decretou que não adoreis senão a Ele; e decretou benevolência para com os pais))

آيات الشكر والحب والتقدير والامتنان لوالدي الحاج خالد ولوالدتي الحاجة سميرة

بدعواتكما ورضاكما ودعمكما استطعت الوصول إلى ما أنا عليه الآن ... أسأل المولى عز وجل أن يمدكما بالصحة والقوة وراحة البال فأنتما سندي وقوتي وعزوتي التي أحتاج أينما رحلت

بسم الله الرحمن الرحيم ((ومن آياته أن خلق لكم من أنفسكم أزواجا لتسكنوا إليها وجعل بينكم مودة ورحمة)) صدق الله العظيم

((E, dentre Seus sinais, está que Ele criou para vós, mulheres, de vós mesmos, para vos tranquilizardes junto delas, e fez entre vós afeição e misericórdia))

باقة ورد ملؤها المحبة ... عنوانها الجمال ... عطرها فواح إلى الأبد ... لعائلتي الجميلة المحاطة بظل وارف من الصديقة

والحبيبة ورفيقة هذا المشوار هند ... و هدايا الله عز وجل *Maria Lionela ... Khaled ... Nancy...*

الحب موصول لمن لا يعوضهم الزمن ... أخوتي

و أهل زوجتي

لمحبتكم ودعمكم كان هذا العمل

RESUMO

Najjar, Mohammad. Otimizando O Processo De Decisão Sustentável Para Melhorar O Desempenho Energético Ao Todo Do Ciclo De Vida Dos Edifícios**.** Tese (Doutorado) – Programa de Engenharia Ambiental, Escola Politécnica e Escola de Química, Universidade Federal do Rio de Janeiro. Rio de Janeiro, 2019.

Os edifícios demandam uma quantidade significativa de energia durante seus ciclos de vida, portanto, mover-se em direção a edifícios com eficiência energética é um fator-chave para alcançar a sustentabilidade. O consumo de energia em edifícios é uma questão muito importante, onde a demanda operacional é considerada uma das mais altas entre todos os outros setores de uma economia. A novidade destacada aqui é permitir que os tomadores de decisão utilizem procedimentos padrão para capacitar o processo de eficiência energética sustentável em edifícios e avaliar os impactos ambientais de materiais de construção e proteger o ambiente construído. Este estudo integra os modelos de design sustentável de forma a automatizar o processo de melhoria do desempenho energético dos edifícios, tendo em consideração a perda de energia térmica nos edifícios durante a fase de utilização, as fontes de energia renováveis acessíveis e a aplicação de materiais de construção alternativos, que estão montando o envelope do edifício. O arcabouço metodológico desenvolvido pode ser aplicado para avaliar o consumo de energia e os impactos ambientais ao longo de toda a vida útil dos edifícios (ou seja, edifícios residenciais e edifícios de escritórios) para preparar o projeto sustentável. A contribuição deste estudo está no desenvolvimento de uma abordagem diferenciada para a construção sustentável, integrando Building Information Modeling (BIM) e Life Cycle Assessment (LCA) para projetar edifícios energeticamente eficientes, e identifica as lacunas existentes em tal integração, a fim de capacitar a decisão processo de fabricação e projeto sustentável no setor da construção. Esta tese tem como objetivo alcançar os objetivos propostos no formato de periódicos e conferências apresentados na seção de apêndices, onde várias ferramentas e abordagens têm sido aplicadas e examinadas para melhorar a eficiência energética sustentável dos projetos de construção adotados, juntamente com a redução das dificuldades associadas com a construção do edifício. Várias alternativas para componentes de edifícios que compõem o envelope de edifícios são realizadas em diferentes classificações climáticas. Os insights que podem ser extraídos deste estudo incluem que todos os componentes de envoltórias influenciam o consumo de energia em edifícios, particularmente paredes externas e janelas; o impacto da área interna, aberturas exteriores e espessura do material e escolha para os componentes da envoltória do edifício em todas as classificações climáticas, auxiliando na concepção de edifícios de baixa energia. Este trabalho indica que as decisões de eficiência energética sustentável em edifícios podem ser alcançadas através da otimização da seleção de material e avaliação de impactos ambientais via integração BIM e LCA.

Palavras-chave: modelagem de informações de construção; avaliação do ciclo de vida; construção sustentável; consumo de energia; desempenho energético sustentável em edifícios; impactos ambientais; processo de tomada de decisão sustentável.

ABSTRACT

Najjar, Mohammad. Optimizing The Sustainable Decision-Making Process Towards Improving Energy Performance Over the Entire Life Cycle of Buildings. Dissertation (Doctorate) - Programa de Engenharia Ambiental, Escola Politécnica e Escola de Química, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2019.

Buildings demand a significant amount of energy during their life cycles, hence, moving towards energy efficient buildings is a key factor to achieve sustainability. 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. The novelty highlighted herein is to enable decision-makers utilizing standard procedures to empower the process of sustainable energy efficiency in buildings and evaluate the environmental impacts of building materials and protect the built environment. This study integrates the sustainable design models in a way to automate the process of improving energy performance of buildings, taking into consideration the heat energy loss in buildings during the using phase, the affordable applied sources of renewable energy, and the application of alternative construction materials that are assembling the building envelope. The developed methodological framework can be applied to evaluate the energy consumption and environmental impacts over the entire lifespan of construction projects (i.e. residential buildings and office buildings) towards preparing sustainable design. The contribution of this study is in developing a distinctive approach towards sustainable construction by integrating Building Information Modeling (BIM) and Life Cycle Assessment (LCA) for designing energy efficient buildings, and identifies the existing gaps in such integration in order to empower the decision-making process and sustainable design procedure in the construction sector. This thesis targets achieving the proposed objectives in the format of journals and conferences papers presented in the appendices section, where several tools and approaches have been applied and examined to enhance the sustainable energy efficiency of the resulting building designs adopted, along with reducing the difficulties associated with the construction of the building. Various alternatives for building components that make up the envelope of buildings are undertaken in different climate classifications. Insights that can be gleaned from this study include that all components of building envelopes influence the energy consumption in buildings, particularly, exterior walls and windows; the impact of space area, exterior openings and material thickness and choice for the envelope components of the building in all climate classifications, aiding in the design of low-energy buildings. This work indicates that sustainable energy efficiency decisions in buildings can be achieved by optimizing the material selection and assessment of environmental impacts via BIM and LCA integration.

Keywords: building information modeling; life cycle assessment; sustainable construction; energy consumption; sustainable energy performance in buildings; environmental impacts; sustainable decision-making process.

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1. CHAPTER ONE: INTRODUCTION

1.1. Motivation of the study

The construction sector consumes natural resources and energy and influences the environment. This highlights the crucial needs for finding solutions to meet the standards of sustainability in construction (Šaparauskas and Turskis 2006). Sustainable construction design plays a basic role in protecting the built environment and energy consumption during the entire lifecycle of buildings since the extracting of raw materials and manufacturing, packaging and transporting of construction materials to the site, constructing and installing, operating, until demolition and recycling (Sonnemann et al. 2003), as shown in **Figure 1**. LCA is an integrated way of treating the framework, impact assessment and data quality (Klöpffer 2006).

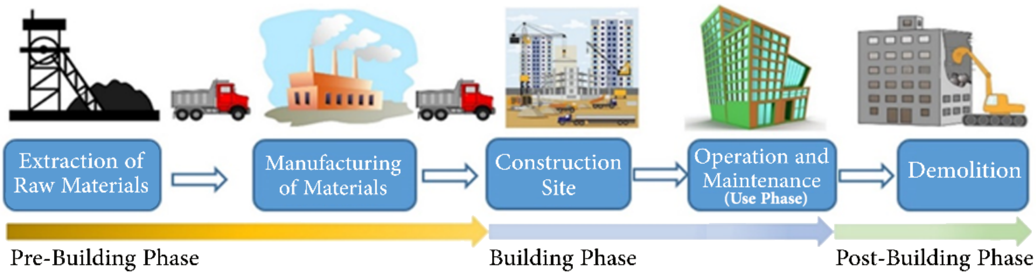

Figure 1. Life Cycle Process

The construction sector is responsible for 30% of global annual GHG emissions in developed and developing countries, and around 40% of all energy consumption. These values are expected to be doubled by the year 2030 in light of the massive growth of the construction industry and the inefficiencies of the existing building stock worldwide (UNEP 2009a). Additionally, the construction sector offers 5-10% of vacancies at the national level (UNEP 2007) and contributes up to 3.2% of the total global Gross Domestic Product (GDP) in 2012 (Aversa et al. 2013). This value is estimated to rise up to be 13.5% of the total GDP in the coming 10 years (Textura 2013). It can be clearly seen the crucial needs to consider the environmental impacts and lifecycle performance of construction projects, taking into consideration the required energy and resources throughout the total LCA of construction components.

The methodology of LCA has been widely applied in the construction sector as an important tool to assess buildings since 1990 (Fava 2006). Applying the methodology of LCA in the construction sector is considered as a crucial and distinctive working zone because of the following factors (Khasreen et al. 2009):

- The difficulty of predicting the whole life cycle of a building from cradle-to-grave in the light of the long lifetimes of buildings, often more than 50 years.
- The possible changes to the building form and function during its lifespan make uncertain opportunities to evaluate the environmental impacts.
- The critical role of proper design and material selection in reducing the environmental impacts, particularly many of the environmental impacts occur in the using phase.
- The shortage of choices of standardization for the whole building design in the light of increasing numbers of stakeholders in the construction industry and the exceptional conditions for each building with its design and specific situation.

The methodology of LCA in buildings has been divided into three main phases; each phase includes different activities, and the relevant contained energy has been classified according to the nature of each phase (Edge Environment Pty Ltd 2011; Haynes 2013; Kim et al. 1998b; Sartori and Hestnes 2007; UNEP 2007). **Figure 2** presents the relevant contained energy consumption. Studies in this field show that the right choice of building materials can save the embodied energy. Whereas, the operating energy, which is considered as the main part of the total energy used in buildings for cooling, heating, ventilation, lighting, heating water, and power, can be saved by applying an energy efficient system; providing good in-door conditions with consuming less energy (UNEP 2007). However, **Figure 2** illustrates the several variants to evaluate the LCA in buildings. Each variant depends on the exact phase of the lifecycle that is studied (Bushi et al. 2014; Haynes 2013; MBDC 2013): the cradle to gate (A), the gate to the grave (B), cradle to grave (C), and the cradle to cradle (D).

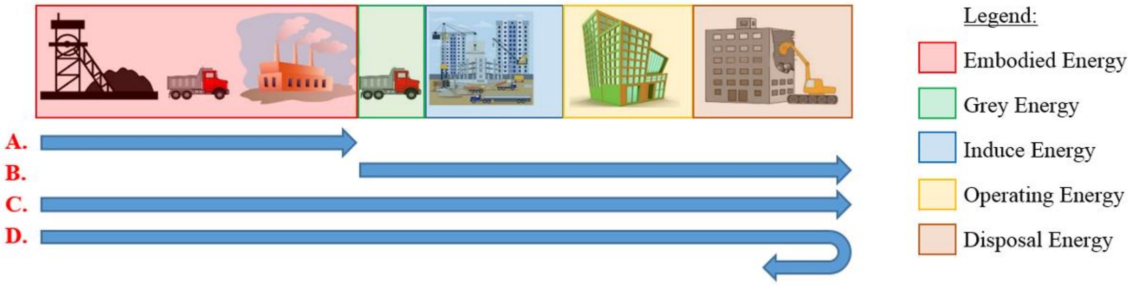

Figure 2. LCA variants and relevant contained energy

Many researchers discussed the advantages of Building Information Modeling (BIM) in providing opportunities to explore the energy consumption of construction materials at the initial designing stage (Antón and Díaz 2014a; Jrade and Jalaei 2014; Wang et al. 2011). It plays a fundamental role towards automation in construction (GhaffarianHosein et al. 2017). BIM models coordinate information to promote collaboration and stimulation among the teamwork in the construction project. The different dimensions of BIM (nD's BIM) give the capability of enabling the potential practices over the entire lifecycle phase of a construction project (GhaffarianHosein et al. 2017). BIM technology helps the project managers to schedule priorities, reduce the gap between the teamwork of the project and allocate resources and decision-making. This point was emphasized with a survey concluded in the United States including 302 BIM users involving architects, engineers, contractors and owners (Azhar 2011). The survey found that most of the specialists think that BIM technology has a positive impact on their productivity and improve project outcomes. While two-third of them realize that BIM has increased their chances of winning projects. In this context, the role of BIM appears as a building tool that simplifies the application LCA in the construction sector. BIM provides the required data to evaluate energy consumption and environmental impacts in the construction sector throughout the entire lifecycle of construction materials.

1.2. Research background:

Sustainable development appeared as an environmentalism movement since the 1960s when the concerns about the environmental effects of economic growth increased. Such impacts have been presented in various publications and conferences (Paul Ehlrich [1968], Ecological Aspects of International Development Conference in Washington, D.C. [1968], UNESCO Biosphere Conference [1972], WCED [1987], and the UN Conference on Environment and Development UNCED [1992]). The Bruntland Commision, which is formally known as World Commission on Environment and Development (WCED), 1987, outlined a series of "strategic imperatives" that included conserving the base of the resource, meeting the essential needs, merging the environment and economics in decision making, reviving the current and future growth, reorienting technology and managing risk, and ensuring a sustainable level of population. Generally, the Bruntland report presented three basic components for sustainable development: environmental protection, economic growth, and social equity. Shortly after the UNCED, the Earth Council, held in RJ, was developed as a nongovernmental organization (NGO) to coordinate efforts in order to achieve sustainable development goals. This conference outlined three major documents: convention on Biological Diversity, Framework Convention on Climate Change, and Agenda 21. The importance of Agenda 21 is that it sets forth specific policy recommendations for sustainable development, identifying 27 guide principles in order to integrate three principles into all public policy: economic growth, environmental protection, and social equity (Osman Attmann 2010).

Sustainable construction depends mainly on the size of the country in addition to relevant economic, social and cultural levels. Various attempts have been participated to analyze and evaluate the different sustainable construction issues. Many methods and systems are being included worldwide; Evaluation System of Environmental Efficiency (BREEAM) in UK, Evaluation System of Sustainable Building (LEED) in USA and Canada, Evaluation System of the Environmental Performance of the Buildings (CASBEE) in Japan, Building Environmental Performance Assessment Criteria (BEPAC) in Canada, Pearl Community Rating System (ESTIDAMA) in UAE. Increasing global awareness of the importance of protecting the environment, and developing methods have appeared in order to address the impacts of products along with their life cycle. Such methods have been applied in many countries to promote the life cycle thinking such as the European Union communicated the concept of integrated product policy (IPP). Between the 1960s and early 1990s, studies that assessed the life cycle of the products were concluded under different names such as the resource and environmental profile analysis, ecobalance, integral environmental analysis, and environmental profiles. In the 1990s, the Society for Environmental Toxicology and Chemistry (SETAC) hosted workshops and published several guidelines in order to develop a standardized method of LCA (UNEP 2012). There are many standardized initiatives in the field of LCA methodology, despite the fact that the International Standards Organization (ISO) published the most important recognized standards as the following (Khasreen et al. 2009):

• ISO 14040, in 1997, Principles and framework.

• ISO 14041, in 1998, Goal definition and inventory analysis.

• ISO 14042, in 2002, Life-cycle impact assessment.

• ISO 14043, in 2000, Life-cycle interpretation.

According to ISO 14040 series, the process of LCA consists of four basic steps (UNEP 2012), (Bayer et al. 2010); Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations. LCI is the main level of LCA analysis. The data at this level contains information about material and energy consumption in addition to emissions. Elementary flows (inputs and outputs) for each unit process for a product system are already contained in the database. The next step to LCI is Life Cycle Impact Assessment (LCIA), where the quantities of materials, energy consumption, and resulting emissions are being processed (Equivalents, normalizations, and weighting) in order to make simpler understanding results for the next step in LCA; Interpretations. However, the LCIA methods used to transform the results of LCI depend on the impact category itself. Furthermore, worldwide agencies such as the Environmental Protection agency, Occupational Safety and Health Administration, and National Institute of Health have established a list of Impact Categories based on nationally recognized standards (UNEP 2012), (Bayer et al. 2010); Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Fossil Fuel Depletion, Smog Formation Potential, Ozone Depletion Potential, Water Use, etc.

A rapidly growing number of environmental LCA studies have been published since the release of the 14040 series. The international community has accepted the technical framework that is provided by the ISO 14040 series for carrying out the Environmental LCA, in addition to the Social Life Cycle (S-LCA) and Life Cycle Costing (LCC). Moreover, the Life Cycle Initiative of the United Nations Environment Program

(UNEP) and SETAC was focusing on the environmental LCA basing on ISO 14040 series, just before adopting towards sustainable development. However, the next step has been in the direction of the Life Cycle Sustainability Assessment (LCSA). This concept discusses the evaluation of environmental, social and economic impacts and the decision-making process in order to produce more sustainable products during the course of the life cycle (UNEP 2012).

LCSA = (environmental) LCA + LCC + S-LCA

BIM facilitates the energy efficiency in designs within the energy consumption assessment throughout the entire lifecycle assessment of buildings (Häkkinen and Kiviniemi 2008). According to many researchers (Abdulla and Jrade 2012; Antón and Díaz 2014b; a; Jrade and Jalaei 2014; Kylili et al. 2015), one of the suggested solutions to assess environmental impacts in the construction sector is to incorporate BIM tools and LCA methodology. This integration could be achieved by combining the decision-making process with the sustainable design procedure. Soust-Verdaguer et al (Soust-Verdaguer et al. 2017) reviewed several case studies integrated BIM and LCA in the construction sector and found that this integration simplifies quick and effective results during the early stages of design. However, the decision-making process aims to raise the awareness of architects, designers, and builders to combat environmental problems. It involves many factors such as the selection of materials, building orientation, use of passive systems, and ventilation (Canarslan 2007). Moreover, it is important to highlight that around 60% of the time is being lost insufficiently in the early stages of designing construction projects. This comes back to the urgent need of entering the same information up to seven times during one single project (Antón and Díaz 2014a).

The nD model is an extension of the BIM that incorporates all the required design information at each stage of the LCA of a building facility. It is a parallel utilization that enables stakeholders experiencing the building by visualizing the environment and integrating the existing and non-existing modeling approaches into a new way in order to deal with the different dimensions of a project from a predictive perspective (Succar 2009). nD BIM is commonly defined in further dimensions as shown in **Figure 3**: 3D modeling, 4D (Time), 5D (Cost), 6D Operation, 7D Sustainability, and 8D Safety (Eastman et al. 2011).

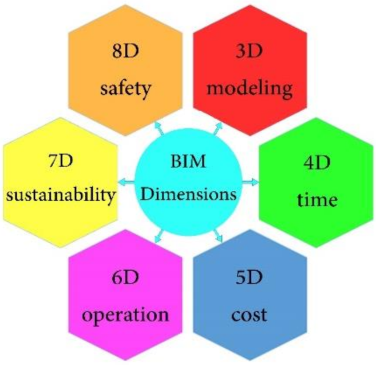

Figure 3. The various dimensions of BIM

The 4D dimension is a planning process that binds the set of data in the 3D modeling with project programming and scheduling data (Eastman et al. 2011). It accelerates the simulation analysis of construction activities (Bomfim et al. 2016; Jupp 2017; Kacprzyk and Kepa 2014; Smith 2014). This gives the opportunity for the participants of a construction project to effectively visualize, analyze, and communicate the various aspects of construction progress over the entire lifespan of buildings, as shown in **Figure 4**. The 5D dimension integrates the 4D dimension with the cost data such as quantities and prices (Eastman et al. 2011). It facilitates the accuracy of both quantity and cost estimation (Bomfim et al. 2016; Lu et al. 2016; Smith 2014, 2016; Xu 2017). This gives the opportunity for cost consultants to improve the value of construction projects, as shown in **Figure 4**. The 6D dimension extends the BIM for facilities management (Eastman et al. 2011), which is considered as an integrated approach to maintain, improve, and adapt buildings (Barrett and Baldry 2003). This dimension represents the as-built model that is used during the operational phase of construction projects (Smith 2014). This gives the opportunity to provide an integrated description of a building during its using phase, as shown in **Figure 4**. The 7D dimension incorporates the components of sustainability to the BIM models (Eastman et al. 2011). It enables designers to compare different alternatives designs for the projects and validates the decision-making process in the construction sector. The depth of this dimension differs based on the flexibility of 4D and 5D, as shown in **Figure 4**. The 8D dimension incorporates the different aspects of safety in construction projects at the designing and construction phases (Eastman et al. 2011), as shown in **Figure 4**. To sum up, it can be notified that BIM dimensions allow the construction participants to predict the performance of buildings at early design stages. This gives the opportunity to optimize, simulate, and visualize the building design and, therefore, deliver high quality construction documentations (Eastman et al. 2011; GhaffarianHosein et al. 2017). However, **Figure 4** illustrates the actual performance of BIM dimensions over the life cycle phases of construction projects.

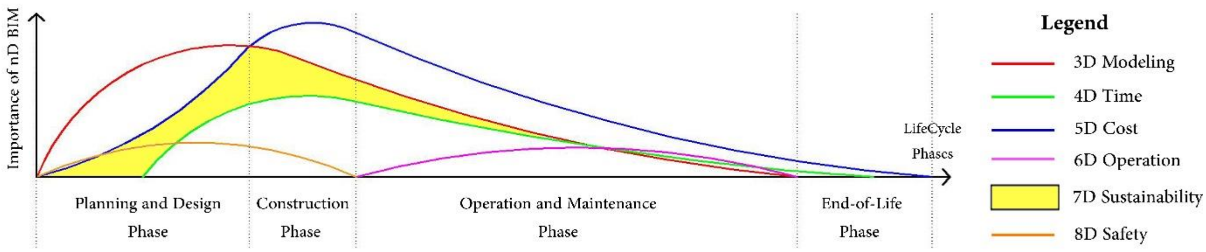

Figure 4. Performance of BIM dimensions over the life cycle phases of buildings

1.3. Statement of the problem

Sustainable Construction is a process that keeps a balanced relation between the different demands of people and the affordable possibilities in a way to raise the quality of life for residents (CIB and UNEP-IETC 2002). Several factors may prevent the efficiency and sustainability of the construction project. First, the difficulty in making any form of standardization in the construction project as a reason for both; the wide variety of stakeholders involved and the specific features of each project. Second, the lack of trust and open communication among the stakeholders; it is considered as the main reason to waste resources. This comes back to the fact that the cooperation among the stakeholders is very difficult at this level of the analysis. Third, in the case of tender, the process focuses on the price instead of quality (Antón and Díaz 2014a). There are numerous barriers to achieve the sustainability standards in construction (CIB and UNEP-IETC 2002): Lack of capacity of the construction sector, uncertain economic environment, poverty and low urban investment, lack of accurate data, lack of interest in the issue of sustainability, technological inertia, and lack of integrated research. Furthermore, measuring the energy consumption and GHG emissions in the construction industry is an essential step in order to evaluate the environmental impacts. This comes back to the different activities in the construction process that are resulting in more environmental impacts such as noise, pollution, dust, and hazardous contamination through toxic waste. (Antón and Díaz 2014a).

Sustainability success depends mainly on the combination of three interactive pillars: environment, economy, and society (Finkbeiner et al. 2010). The construction sector is one of the most influential sectors to these pillars (Olawumi et al. 2018a), offering millions of job opportunities (UNEP 2014). The environmental impacts of construction projects account for around 40% of the global material and energy consumption (Kwok Wai Wong and Zhou 2015; Lassio et al. 2016; Lasvaux 2010; Schlueter and Thesseling 2009). The social impacts of buildings are still underestimated; this comes back to the lack of identifying the direct and indirect involvement of many stakeholders such as workers, the local community, and the society (Dong and Ng 2016). The economic impacts are developed originally from a strict financial cost accounting perspective that has gained importance recently (UNEP/SETAC Life Cycle initiative 2012). In construction, consideration is given to make a better understanding of the four typical economic components to cover the costs of building over its entire lifespan. These are initial costs (i.e. construction cost), operation and maintenance costs, replacement costs, and end-of-life costs (Marzouk et al. 2018).

Environmental Life Cycle Assessment (LCA) is a widely recognized method that has been adopted to analyze the environmental impacts of products (UNEP/SETAC Life Cycle initiative 2012), while Life Cycle Costing (LCC) has been developed to assess the economic viability of a scheme. The environmental performance of products has gained an increasing awareness to the development of several environmental life cycle assessment (LCA) methodologies and life cycle costing (LCC) models (Swarr et al. 2011), while the social life cycle assessment (S-LCA) attracts less attention as a reason for the lack of methods that evaluate the social performance (Hellweg and Canals 2014). S-LCA is an instrument that requires further development (Martínez-Blanco et al. 2014). Life Cycle Sustainability Assessment (LCSA) is a methodology that estimates the three aspects of sustainability (Finkbeiner et al. 2010; UNEP/SETAC Life Cycle initiative 2012; Valdivia et al. 2013). It is a comprehensive approach that combines the three life cycle pillars; LCA, LCC, and S-LCA (UNEP/SETAC Life Cycle initiative 2012). In construction, sustainable development should match the requirements of users (i.e. economic, ecological and quality) along with their personal comfort needs (Ahmad and Thaheem 2017).

Despite that LCA is the best tool to evaluate the environmental impacts, there are numerous challenges facing this process that depends on the available and completed data (LCI). For instance, the affordable data is considered as the main challenge to apply the LCA methodology to a building: The main challenge is Data Collection. This is an exhausting issue particularly in cases of insufficient and deficiencies. This pursues the experts to collect data from other sources, such as the manufacturers of the product, in order to complete the LCI database and use the LCA methodology. However, aggregated LCA of building assemblies see that further development in BEES and Eco-Calculator will help LCA experts to construct the LCA of building with less consideration to the manual data collection. Another challenge is Data Quality, which is highly important to collect reliable and consistent data in order to complete the LCI database. Dependable data needs to be validated by a third party, such as the industry trade associations, rather than being collected from a single manufacturer. Otherwise, the comparison between products would be unfair and lead to wrong results.

Building information modeling (BIM) is being regarded as an innovative designing technology that delivers extensive values to construction projects over the entire life cycle stages (Olawumi et al. 2018a). BIM tools allow the elaboration of reliable data storage and avoid data uncertainty, give an opportunity to gather the data of the three pillars of sustainability in the same dimensional model, and facilitate the estimation of the necessary data to carry out different types of analyzes such as studies involving the energy consumption of construction materials (Abanda and Byers 2016; Antón and Díaz 2014a; Jrade and Jalaei 2014). In addition to this, BIM tools could empower the decision-making process in construction projects (Peng 2015; Shafiq et al. 2015), which could enhance the sustainable building features at an early stage of design (Azhar et al. 2011).

BIM generates intelligent 3D models supported with associated figures and precise geometry, which facilitate the forward design steps, rendering, fabrication quantity, and surveys and can be easily shared through the online system between project team members (Dowhower 2010). However, estimating the environmental impacts in construction projects is one of the basic challenges that are facing researchers in this field of study. According to many researchers, one of the suggested solutions is to incorporate the two methods; BIM and LCA, in the construction project in order to automate the sustainable construction and integrate the decision-making process. Also, it aims to support sustainable design and face new challenges in the construction field (Antón and Díaz 2014a). This integration has turned urgent in the light of avoiding the gaps that are located in the process of LCA; as a reason for its dependence on the quality and availability of the data. This means that in case of insufficient, not up-to-date or below standard data, It will lead to more assumption and inaccurate information and increase the risk of mistakes and misunderstanding (Antón and Díaz 2014b). The process of decision-making aims to raise the awareness of the architects, designers, and builders to combat environmental problems. The basic part of this process is the selection of building materials with the purpose of protecting the environment (Canarslan 2007).

There are two aspects to consider the implementation of BIM tools: first, the use of software to analyze building modeling; second, the use of BIM dimensions such as cost, schedule, safety, and sustainability as a source of information for the various stakeholders (Olawumi et al. 2018a). Therefore, integrating BIM and sustainability implies leveraging on BIM tools and plugins to facilitate sustainability assessment in buildings (Olawumi et al. 2018b). One can perceive a gap lies in the inadequate methodological details that are covering BIM and sustainability integration. This part of the study needs to be systematically defined and addressed in a more comprehensive way to empower the decision-making process in the construction sector and protect the built environment.

1.4. Research objectives

The consumption of energy in buildings results in direct and indirect impacts over the entire lifespan of the building hence the priority is to increase the energy efficiency in the construction (Larriva et al. 2014). Some factors play an important role in determining the pattern of the energy used in buildings, such as the building type, the climate zone, and the level of economic development in the area (UNEP 2007). Introducing and stimulating the usage of LCA in the construction sector requires integration with BIM tools (Anand and Amor 2017). Such tools provide users with the ability to explore the different alternatives to improve energy efficiency in buildings. It offers the opportunity to save time that is consumed by designers, engineers, and architects to re-enter all the building geometry and necessary information to complete the energy analysis (Jrade and Jalaei 2014). The collected results at this level of the analysis include statistics related to the energy use and breakdowns of consumption and loads (Autodesk Sustainable Design Resources 2011).

The determination of building envelopes (i.e. exterior walls, openings, roofs, and floors) can influence the energy consumption over the entire lifespan of a building (Petrasiunas 2016). Such determination could highly affect the embodied energy and the operational energy of the building, however, in energy efficient buildings, the aim is to reduce the dominant operational energy component (Yüksek and Karadayi 2017). BIM tools facilitate the evaluation of the impact of natural daylight in buildings at the earliest stages of the design by assessing the potential impact of daylight performance metrics. BIM tools harmonize the information about building materials and facilitate the calculation of their environmental impacts using LCA plug-ins (Anand and Amor 2017). LCA has been developed as an integral tool in the decision-making process due to the ability to assess the three pillars of sustainability over the entire lifespan of products (Menoufi 2011). The use of LCA in the construction sector finds applications, which become instrumental in the direction of more sustainable buildings (Domingos et al. 2015), in evaluating building design and construction processes (Singh et al. 2011).

To achieve the novelty of this study, it proposes several sub-objectives to be achieved. These sub-objectives are being organized as a sequence as follows:

1st Sub-objective: Develop a decision support system to estimate the energy efficiency in buildings and evaluate the environmental impacts of building materials in order to help designers and architects in their building design and selection of construction materials based on sustainability principles.

2nd Sub-objective: Develop an integrated and systematic methodological framework that reviews LCA from a building perspective and examines the integration process with BIM tools for designing energy efficient buildings in order to empower the decision-making process and sustainable design procedure in the construction sector.

3rd Sub-objective: Examine the validity of BIM-LCA integration within the available database in order to improve the energy efficiency in buildings, particularly the operational energy which represents the main agent of the life-cycle energy consumption.

4th Sub-objective: Identify the existing gaps in the integration process between BIM and LCA and improve the functionality of such integration using various tools and approaches in order to suggest constructive recommendations.

5th Sub-objective: Develop a systematic methodological framework that integrates the sustainable design models in a way to automate the process of improving energy performance of buildings, taking into consideration the heat energy loss in buildings during the using phase, the affordable sources of renewable energy, and the application of alternative construction materials that are assembling the building envelope.

6th Sub-objective: Validate the proposed frameworks on realistic case studies, taking into consideration the requirements of sustainable design.

1.5. Research Hypotheses:

This research aims to improve the energy efficiency in buildings via integrating LCA methodology with BIM models, taking into consideration the typical and modern construction materials that are assembling the building envelops of buildings, renewable energy sources, and the available technologies and software that could affect the environmental impacts and energy performance in the construction sector. This gives the opportunity to compare different construction materials in order to evaluate the environmental impacts and energy consumption in buildings. Two hypotheses have been developed to achieve the aims and objectives of this work, mainly in the residential and office buildings.

The first hypotheses (1) of this research proposes that the use of local and current construction materials in buildings are resulting in high impact on the environment and leading to more energy consumption. This proposal aims to integrate the LCA of building materials with the BIM models in order to improve energy efficiency in buildings, evaluate the environmental impacts of construction materials, and protect the built environment, as presented in **Appendix 1**, **Appendix 2**, **Appendix 3**, **Appendix 4**, **Appendix 5**, and **Appendix 6**.

The second hypotheses (2) of this research proposes that the use of sustainable construction components and renewable energy sources in buildings will increase the operational energy efficiency in buildings. This proposal aims to estimate the energy consumption, as presented in **Appendix 7** (including **Appendix 7A** and **Appendix 7B**), and assess energy loss in buildings during the using phase, particularly the heat energy loss, as presented in **Appendix 8**, and investigate the technologies that are accommodating a wide range of needs in the field of energy consumption such as Building Integrated Photovoltaic (BIPV) systems, as presented in **Appendix 9**.

However, **Appendix 10** is conducted as a literature review study that reviews the sustainable energy life cycle assessment in buildings, as will be presented down in Subsection 2.2.

1.6. Performance analysis of the study

This Sub-section illustrates the development analysis of this work towards achieving the proposed sub-objectives presented in the previous Sub-section. **Figure 5** presents that the exploration of this work is in proposing contributed frameworks that applies the BIM tools and the LCA methodology to perform the energy simulation in buildings and evaluate the environmental impacts of construction materials in order to achieve the novelty of this work by enabling decision-makers utilizing standard procedures to empower the process of sustainable energy efficiency in buildings and evaluate the environmental impacts of building materials and protect the built environment. In these terms, several tools are applied such as BIM software (i.e. Autodesk Revit); Energy plug-in (i.e. Autodesk Green Building Studio); LCA plug-in (i.e. Tally); and LCA software (i.e. Open LCA), as well as applying the parametric analysis and mathematical optimization methods.

Figure 5 illustrates that the designed sub-objectives of this study have been addressed as follows:

- The 1st sub-objective is being addressed in Appendices 1 to 8.
- The 2nd sub-objective is being addressed in Appendices 1 to 6.
- The 3rd sub-objective is being addressed in Appendices 1 to 3.
- The 4th sub-objective is being addressed in Appendices 1 to 5.
- The 5th sub-objective is being addressed in Appendices 1 to 3, and Appendices 7 to 9.
- The 6th sub-objective is being addressed in Appendices 1 to 9.

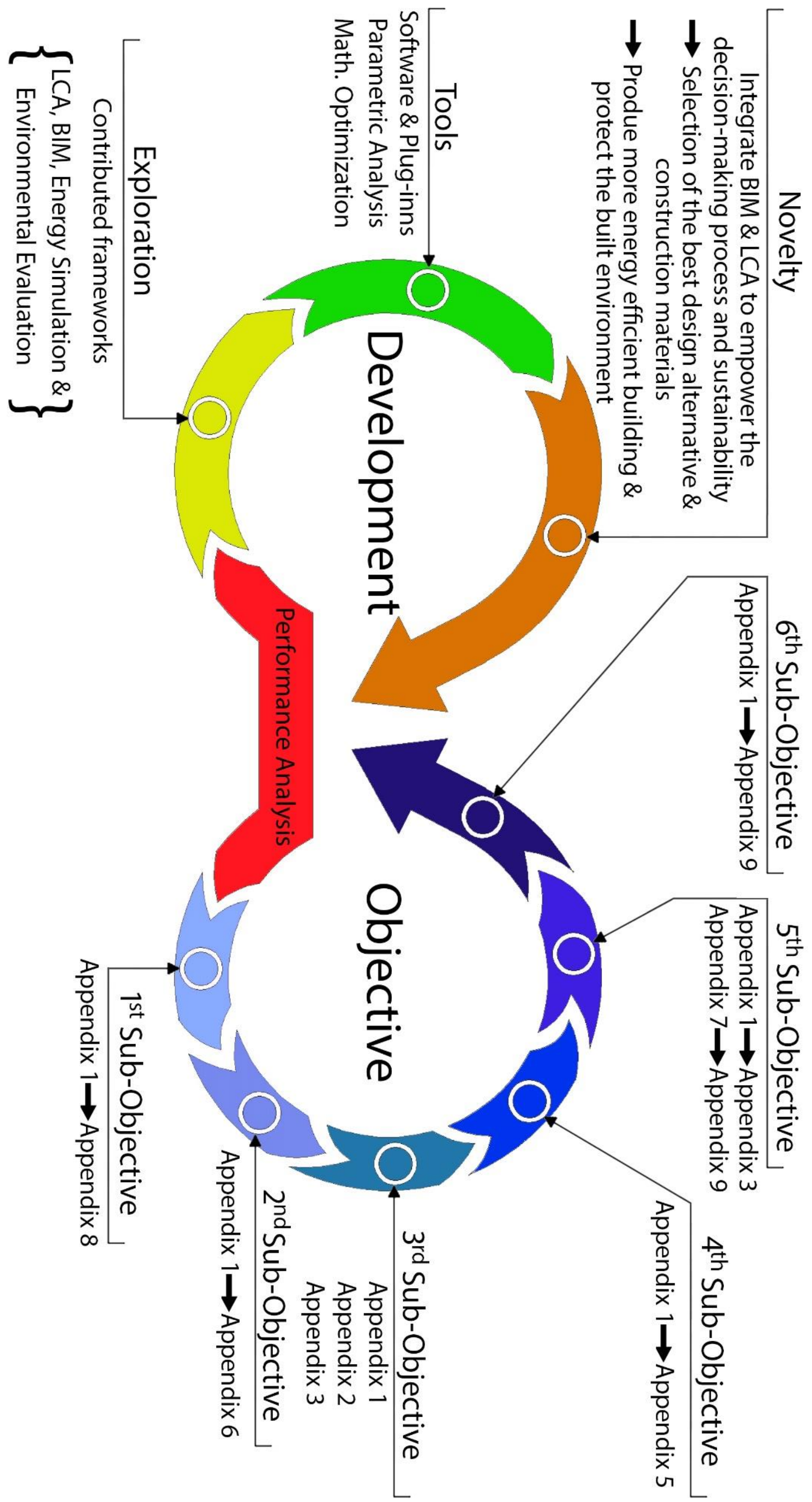

Figure 5. The performance analysis of this work

1.7. Scope and Implication of the Research:

This work plans to make direct contacts with designers, engineers, and architects to carry out inspections for the collection of data and improve the energy efficiency of construction projects via BIM and LCA integration at an early designing stage of construction projects. It examines several worldwide construction materials and optimizes the selection of these materials that are assembling the envelope of buildings such as exterior walls, openings (i.e. windows and walls), floors and ceilings. The proposed research targets to make a significant contribution to the body of knowledge in buildings. It is more on testing and applying the integration of BIM models and LCA methodologies towards sustainable energy efficiency in buildings. The implication of the research has been divided into two groups stated as Theoretical Implication and Practical Implication.

1.7.1. Theoretical Implication:

Good selection of environmentally sustainable construction materials helps the professionals in the construction sector to integrate the sustainable design principles in buildings (Kim et al. 1998a). This work presents the importance of the LCA methodology as a competing issue to protect the built environment. It practices the integration of BIM models and LCA methodology to improve energy efficiency in buildings and evaluate the environmental impacts of construction materials. The result of this study is projected to allow the professionals in the construction sector to make a better understanding of the features of sustainable energy efficiency over the entire lifespan of buildings via the integration of BIM and LCA.

1.7.2. Practical Implication:

This work contributes to the body of knowledge to assist designers, engineers, and architects to develop a clear imagination with the proper decision tools to select construction materials that are assembling the building envelope for their projects in order to protect the built environment. It will provide professionals in the construction sector with a valuable framework to assess the energy consumption in buildings and evaluate the environmental impacts of building materials, as well as guiding the process of the selection of construction materials for the renovation and new buildings, especially in residential and office buildings.

1.8. Thesis organization

This work is organized through the following chapters:

Chapter Two is a literature review that conducts a bibliometric and bibliographic analysis about the recent implications that are contributed to the development of several applications and practices of sustainable energy life cycle assessment in buildings, and BIM and LCA integration in the construction sector.

Chapter Three describes the proposed methodology that can be used to implement the proposed integration between BIM tools and LCA methodology in order to enable the designers and architects to automate their design modeling within BIM tools and LCA methodology in order improve energy efficiency in buildings at an early designing stage.

Chapter Four includes the conclusion that describes the research contributions and limitations and it lists the future recommendations for future expansions and further enhancements for the research.

References that are used in the literature review and methodology Chapters.

Appendices include all technical papers that validate the objectives of this study.

2. CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

Sustainability success depends mainly on the combination of three interactive pillars: environment, economy, and society (Finkbeiner et al. 2010), which are highly influenced by the construction sector (Olawumi et al. 2018a). The first usage of LCA as an environmental management tool started in the 1960s. Since then and until the early 1990s, the LCA studies were concluded in different names and ways, such as the resource and environmental profile analysis, ecobalance, integral environmental analysis, and environmental profiles. However, in the 1990s there were publications presenting the methodology as it is currently known, such as "*Life-cycle Assessment: What Is and How to Do it*" that was published by the United Nations Environment Program, and "*Life-cycle Assessment: A Guide to Approaches, Experiences and Information Sources*" that was published by the European Environment Agency (Khasreen et al. 2009). This illustrates that several publications, working groups, conferences, and initiatives have been held showing the growing concern about sustainable development (Naves et al. 2018). The United Nations Environmental Programme (UNEP) highlighted the crucial need to consider the traditional focus on manufacturing processes and production sites at the environmental, economic, and social levels over the entire lifespan of a product, taking into consideration the energy consumption level (UNEP 2009b). Environmental impacts account for around 40% of the global impacts of materials and energy use in the construction sector (Kwok Wai Wong and Zhou 2015; Lassio et al. 2016; Lasvaux 2010; Schlueter and Thesseling 2009). The environmental performance of products has gained an increasing awareness of the development of the LCA and LCC methodologies (Swarr et al. 2011). it should match the requirements of users along with their personal comfort needs (Ahmad and Thaheem 2017).

Applying the methodology of LCA towards sustainability results in more extensive and complex studies, as well as more uncertainties will arise based on the diversity of stakeholders (Clímaco and Valle 2016). In these terms, several approaches can be integrated with LCA to empower the decision-making process in the construction sector such as the mathematical optimization (Hammad et al. 2018), BIM approach (Antón and Díaz 2014a; Santos et al. 2019), Multi-Criteria Decision Making analysis (MCDM) (Motuziene et al. 2016), and Life Cycle Thinking (LCT) tools (Marzouk et al. 2018).

This Section highlights the implications of BIM and LCA integration in the construction sector, as well as the recent publications related to the sustainable energy life cycle assessment in buildings. The reviewed publications are contributed to the development of several applications and practices and resulting in different streams related to the utilization of different methodologies (i.e. LCA and LCT) and approaches (i.e. BIM) in a way to cover the major aspects of a sustainable building and validate and justify the main conclusions. There are several methods to be applied when conducting a literature review. Utilizing these methods at the same time might results in uncertainty outcomes (Loli and Bertolin 2018), hence, it is important to choose the appropriate method for each analysis. This section illustrates the applied methods for this work, as presented in the flowchart analysis in **Figure 6**, where the input data starts in the Scopus Elsevier Database as the largest worldwide citation database (Aghaei Chadegani et al. 2013; Franceschini et al. 2016).

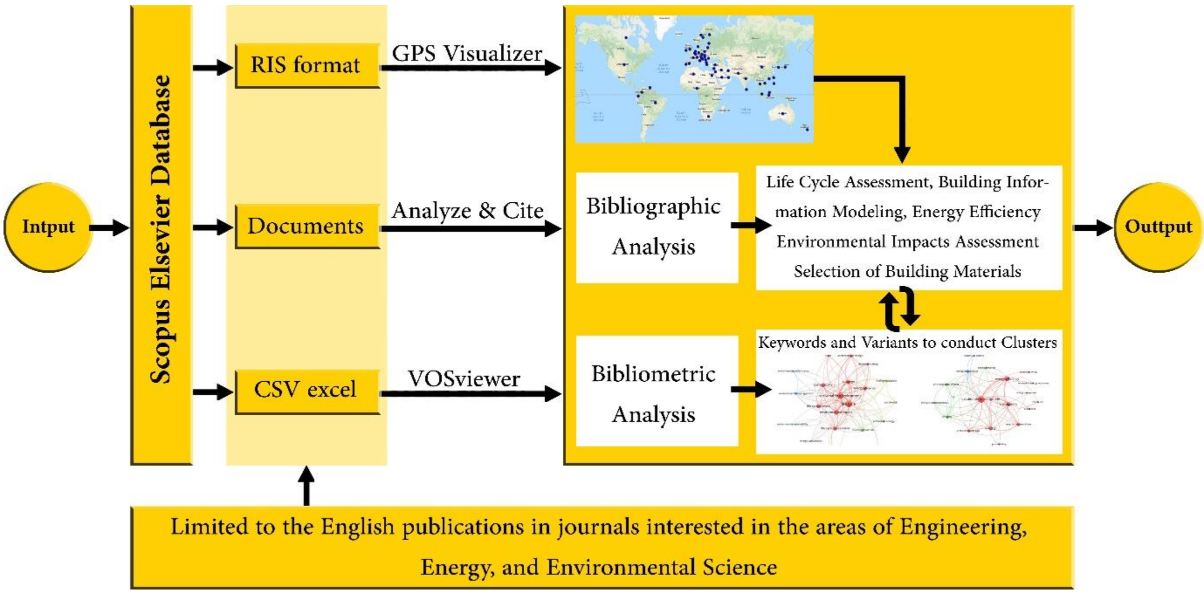

Figure 6. Flowchart analysis of conducting the literature review of this work.

2.2. sustainable energy life cycle assessment in buildings

The application of LCA methodology towards sustainable construction could result in complex studies (Clímaco and Valle 2016). In these terms, a literature review of sustainable energy life cycle assessment in buildings is conducted and discussed in **Appendix 10**.

2.3. The applications of BIM-LCA integration in construction

2.3.1. LCA framework applications in the construction sector

LCA is a methodology that aims to quantify the environmental impacts of products, taking into consideration the entire life cycle since the extraction of raw materials, manufacturing and transportation to the site, construction, operation, and maintenance, until end-of-life and recycling or demolition. This integrated methodology helps to develop and expand frameworks, impact assessments and data quality (Klöpffer 2006). In the second half of the 1990s, the International Standards Organization (ISO) published the most important recognized standards of LCA methodology (Khasreen et al. 2009), as presented in **Figure 7**: ISO 14040 Principles and framework, ISO 14041 Goal definition and inventory analysis, ISO 14042 Life-cycle impact assessment, and ISO 14043 Life-cycle interpretation.

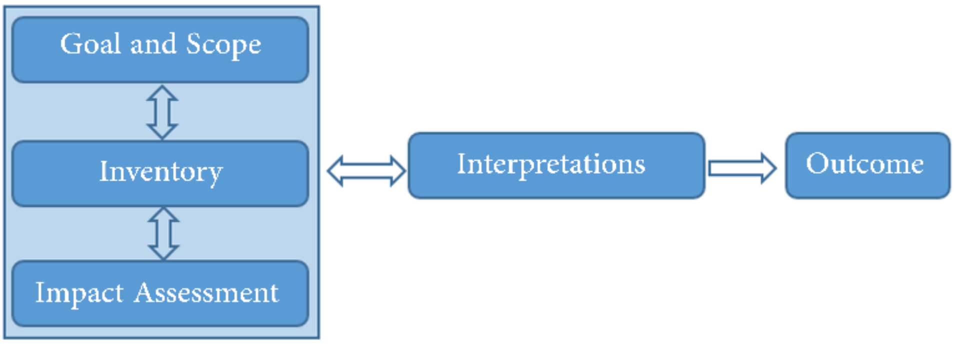

Figure 7. The framework of life cycle assessment

Energy-efficient building design necessitates conducting a multidisciplinary study over the entire lifespan phases (Yüksek and Karadayi 2017). **Table 1** highlights the energy consumption over the five main stages of buildings. The first stage, characterized as embodied energy, is the extracting and manufacturing phase of raw materials. The next stage is grey energy and it refers to the transportation phase of building materials from the production site to the construction site. The third and fourth stages are the actual energy used for construction and operation phases. The types of energy consumed in these two phases are known as induced energy and operation energy, respectively. The final stage is the energy used for demolition and recycling and it refers to the end-of-life phase of the building (Edge Environment Pty Ltd 2011; Haynes 2013; Kim et al. 1998b; Sartori and Hestnes 2007; UNEP 2007). Furthermore, studies show that the right choice of building materials can minimize embodied energy. Whereas, operational energy, which is considered as the main part of the total energy used in buildings for cooling, heating, ventilation, lighting, heating water, and power, can be saved by applying an energy efficient system that provides good indoor conditions while consuming less energy (UNEP 2007).

Table 1. LCA phases and relevant energy consumption

Life Cycle Phase	Activities	Relevant Contained Energy
Pre-Building Phase	extraction of raw materials, manufacturing, packaging, and transporting to the site	Embodied Energy is the energy consumed in the extraction and manufacture of construction materials. Grey Energy: is the energy consumed in transporting building materials from the factory to the construction site.
Building Phase	Construction, installation, operation, and maintenance	Induced Energy: Is the energy consumed in the construction and building steps. Operation Energy: Is the energy consumed in the operation of the building.
Post-Building Phase	Demolition and recycling	Disposal Energy: Is the energy consumed in the demolition and disposal of the building.

The methodology of LCA in the construction sector operates in four phases (Bayer et al. 2010; UNEP 2012): material, product, building, and industry. The first phase is considered as the core of the LCA process, while a group of materials is assembled into the final product. In this term, the building phase considers the whole building as one product. This phase helps LCA experts to understand the way of constructing buildings, the choice of construction materials, and the reasonable methods to operate buildings. The last phase, industry, is considered the best tool to evaluate the LCA process at a wide scale. It examines industrial production and economic output data. Furthermore, LCA methodology applies three levels of classification tools to simplify LCA analysis at the scale of buildings. The first level of these tools is interested in analyzing the LCA of construction materials. Examples of tools at this level include SimaPro, GaBi, Umberto, TEAM, LCE, Open LCA, BEES, LCAiT, and TAKE-LCA. The second level is interested in analyzing the LCA of the entire building. Examples of such classification tools include Athena Environmental Impact Estimator (EIE), BRI LCA (energy and CO2), EcoQuantum, Envest, LISA, Energy Plus, and Autodesk EcoTect & Green Building Studio level. The third level is interested in analyzing LCA of construction stage and concentrated on the three pillars of sustainability: environmental, economic and social. Examples of these tools include BREEAM, Green Globes, LEED, and GBTool (Abdulla and Jrade 2012).

The number of publications in the field of environmental LCA studies has increased significantly after the release of ISO 14040 and 14044 guidelines. The number of publications that could be found in Scopus up to 2011 was only 88 whereas this number raised up to 264 publications in 2015 (Anand and Amor 2017). Some works highlighted the importance of improving the application of LCA in the construction sector (Evangelista et al. 2018; Huang et al. 2015; Martínez-Rocamora and Solís-Guzmán 2016; Soust-Verdaguer et al. 2016). Additionally, numerous papers discussed the area of building LCA in case studies and analytical works (Aktas 2012; Asdrubali et al. 2013; Buyle et al. 2013; Caldas et al. 2015; Cole and Kernan 1996; Lassio et al. 2016; Mitterpach and Štefko 2016; Ramesh et al. 2010; Rodrigues et al. 2018; Sartori and Hestnes 2007; Thormark 2007).

2.3.2. BIM framework applications in the construction sector

The developments of computer aided design (CAD) software and Building Information Modeling (BIM) in the recent three decades have changed the traditional design formats and the set of communication patterns in the construction sector (Kwok Wai Wong and Zhou 2015; Penttilä 2006). BIM tools deliver an opportunity to achieve the standards of sustainable development in the construction sector (Azhar et al. 2010a; Kwok Wai Wong and Zhou 2015). Besides, they provide the ability to assess the three pillars of sustainability by using several BIM dimensions (Taher 2016). The success of BIM is profound as it has the ability to simplify the design process, allow a full energy examination, upsurge the accessibility of design information to stakeholders, and measure all sustainability dimensions (Ahmad and Thaheem 2017).

BIM tool provides an opportunity to communicate and generates the construction project decisions by generating intelligent and dynamic 3D models supported with associated statistics and precise geometry, which facilitate the design steps such as rendering, fabrication quantity and surveys and can be easily shared through the online system between project team members (Autodesk 2008; Dowhower 2010; Kwok Wai Wong and Zhou 2015; Li et al. 2008). Applying the technology of BIM models in the construction sector enhances both the project performance and quality. It facilitates the communication and transparency among stakeholders and design teamwork in order to save time and energy, reduce costs and wastes, minimize future errors and enhance the working and living conditions (Antón and Díaz 2014b). In addition to this, it offers a valuable opportunity to assess the environmental impacts generated and possible mitigation measures of these impacts in the construction sector (Autodesk 2008; Azhar et al. 2010b; Kwok Wai Wong and Zhou 2015).

The framework of BIM includes different models, taxonomies, and classifications (Porwal and Hewage 2013; Succar 2009). Succar in his work (Succar 2009) clarified three axes of BIM domain: BIM Fields, BIM Stages, and BIM Lenses, as shown in **Figure 8**. BIM Fields means to define all clusters, interactions and overlaps for the different technologies, processes, and policies. BIM Stages means build-up the inventory of database, 3D modelling, integration, and collaboration of the different construction objects and materials. BIM Lenses means to provide the output of BIM tools such as deliverables, 3D smart objects, energy simulations, and estimations of cost and time. In this term, several publications examined the application of BIM tools in the construction sector (Abanda et al. 2017; Eddy et al. 2008; Habibi 2017; Kota et al. 2014; Liu et al. 2017; Lu et al. 2017; Volk et al. 2014). Many researchers discussed the advantages of BIM as a building tool provides opportunities to explore the consumption of energy in construction projects at early stages of designing buildings (Antón and Díaz 2014a; Jrade and Jalaei 2014; Martino et al. 2015; Pinheiro et al. 2018; Wang et al. 2011). Others researchers suggested the use of BIM as a tool supports the decision-making process in the designing phase (Peng 2015; Shafiq et al. 2015).

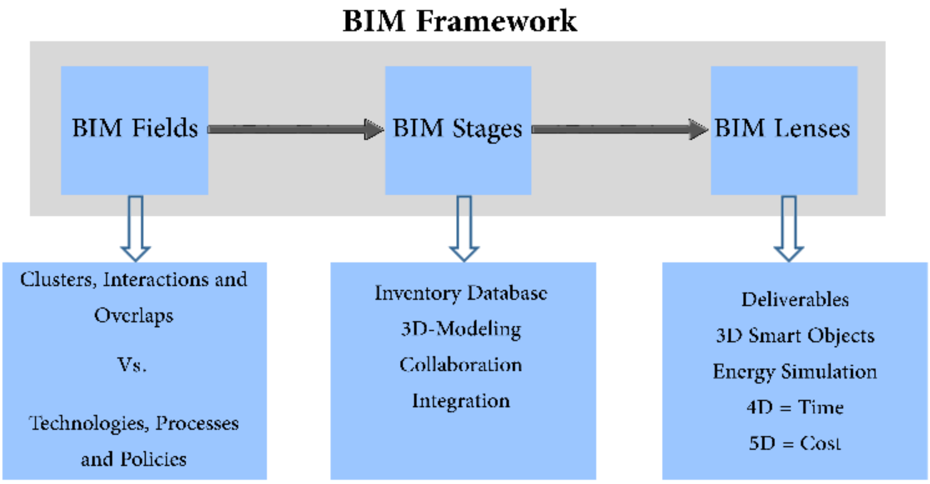

Figure 8. The framework for building information modeling

2.3.3. BIM-LCA integration in the literature

Using "Building Information Modeling" and "Life Cycle Assessment" as keywords in the Scopus Elsevier Database to conduct a search in the Title and Abstract field retrieved 254 documents published since 1997; the number of publications per year is presented in **Figure 9**.

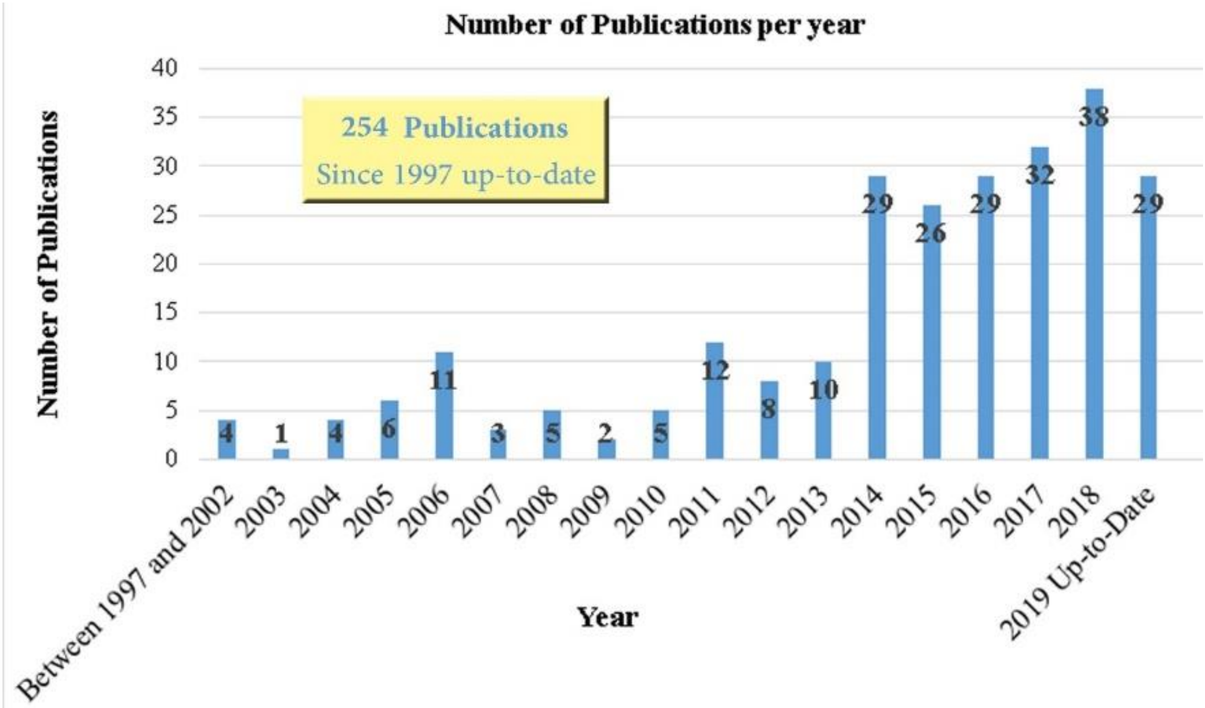

Figure 9. The number of publications per year according to the Scopus Elsevier Database.

An overview extracted from the Scopus Elsevier Database illustrates that Journal of Cleaner Production is the main source of these publications (17), followed by Journal of Automation in Construction and International Journal of Life Cycle Assessment within (11) and (10) publications, respectively. Furthermore, this analysis highlights that institutions with most of the publications are from the United States (40). While the next countries in a number of publications are United Kingdoms (22), China (19), and Germany (19). Australia (15), Italy (14), Switzerland (14), Canada (13), Spain (12), Sweden (12), Malaysia (10), and Austria (9) come next. Belgium, Denmark, and France (8 publications each), Brazil and Portugal (7 publications each), South Korea (6), Greece, Netherlands, Singapore, and Thailand (5 publications each). However, this work uses the GPS Visualizer (Global Positioning System) for the plotting of the Geo-location of publications and the countries of affiliation of the authors (Schneider 2002). It utilizes the extraction of data (i.e. country name) from the Scopus Elsevier Database and bibliometric software in the GPS Visualizer, as presented in **Figure 10**.

Figure 10. Plotting of the Geo-location of publications related to the sustainable energy life cycle in building extracted from the Scopus Elsevier Database.

2.3.3.1. Bibliometric analysis

Cluster analysis is conducted to perform the BIM-LCA integration in the literature in order to make the refinements of further searches. However, the initial results are presented in **Figure 11**, where the first cluster sorts out that the main concerns related to the BIM-LCA integration included 14 items, named architectural design, building information modeling, building life cycle, buildings, construction, construction projects, economic and social efficiency, energy efficiency, environmental assessment, green buildings, information theory, intelligent buildings, project management, and sustainable development. The second clusters included 10 items, named cost benefit analysis, costs, decision making, decision support systems, design, life cycle costing, risk assessment, sensitivity analysis, structural design, and uncertainty analysis. The third clusters included 9 items, named carbon dioxide, environmental impact, environmental impact assessment, environmental protection, life cycle analysis, life cycle assessment, modeling, recycling, and sustainability. The fourth clusters included 8 items, named building materials, carbon, carbon emissions, carbon footprint, database systems, gas emissions, greenhouse gases, and information management. The fifth clusters included 7 items, named climate change, computer software, energy conservation, energy utilization, environmental management, environmental performance, and housing.

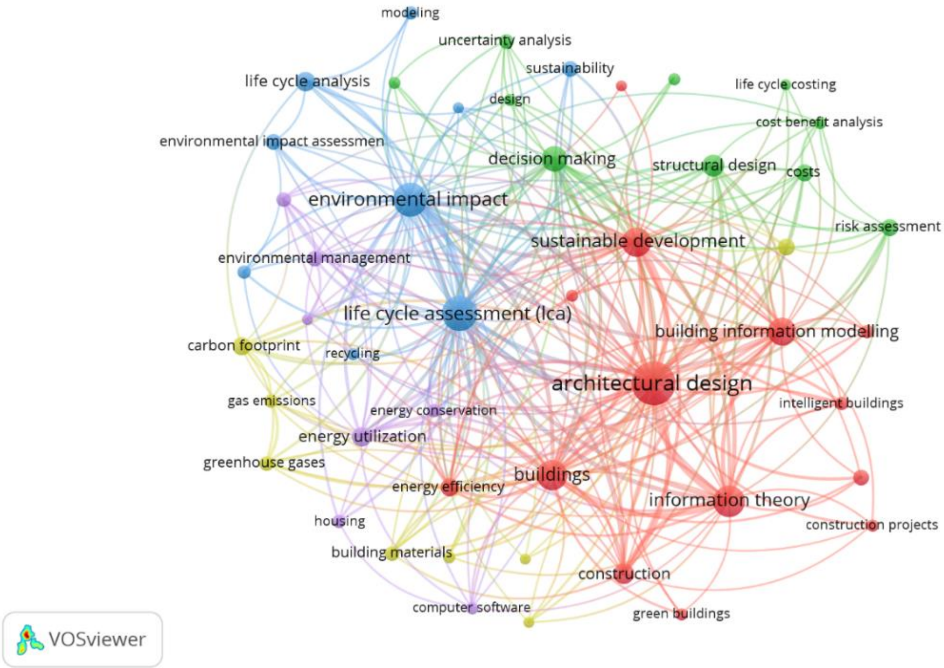

Figure 11. Network visualization of BIM-LCA integration and most related issues.

The high occurrence of the variants related to the BIM-LCA integration is presented in **Figure 12**, which shows the density visualization that allows concluding a strong relationship between the closely related issues in the BIM-LCA studies. It illustrates the items that have a wide density in the literature such as life cycle assessment, environmental impacts, and architectural design. Followed by building information modeling, information theory, sustainable development, decision making, structural design, and buildings. However, the other items have a minor density in the literature.

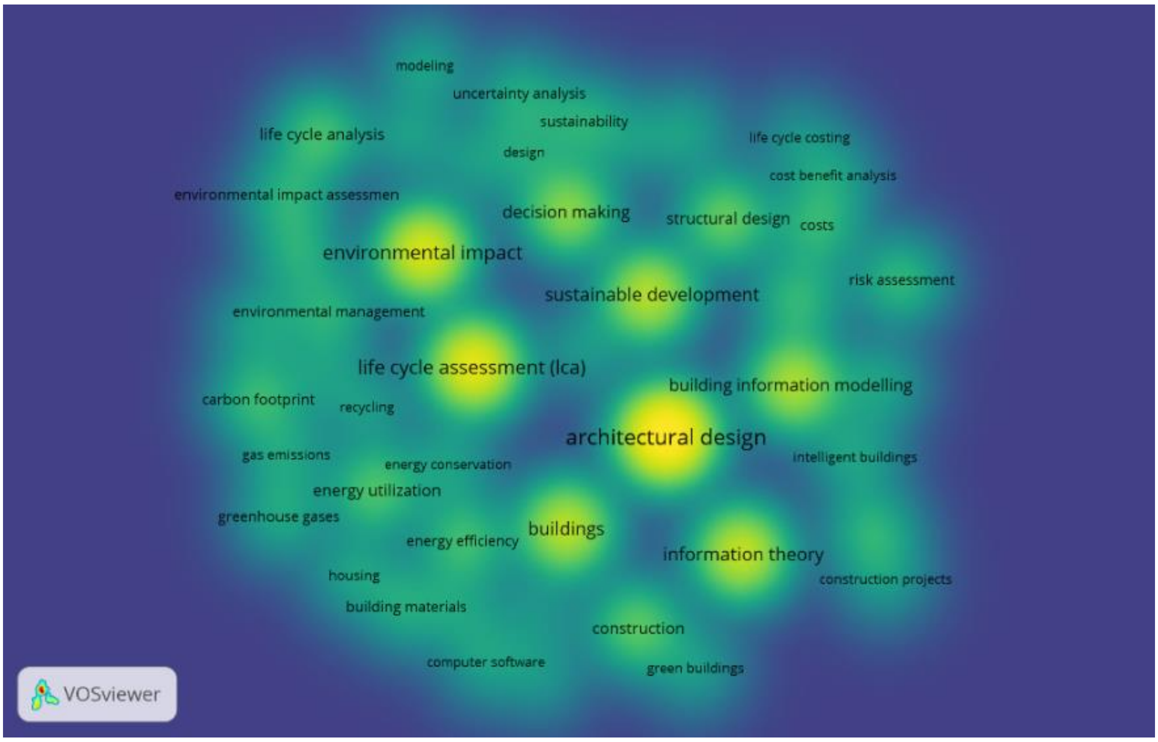

Figure 12. Density visualization of BIM-LCA integration and most related issues.

2.3.3.2. Bibliographic analysis

Sustainable construction is a practice that aims to raise the quality of life for residents by maintaining a balanced relation between the different demands of people and affordable possibilities (CIB and UNEP-IETC 2002). Agenda 21 on Sustainable Construction for Developing Countries defined sustainable construction as a complete approach that aims to preserve the relationship between the natural and built environment, and build settlements that protect human dignity and motivate equity (CIB & UNEP-IETC 2002). There are several barriers to achieve sustainability in the construction sector such as technological inertia, uncertain economic environment, poverty and low urban investment, insufficient data, lack of interest in the application of sustainability, and the absence of integrated studies (CIB and UNEP-IETC 2002). Many methods and systems have been applied in the construction sector in order to analyze sustainable construction practice and evaluate the environmental performance of buildings.

Soust-Verdaguer et al (Soust-Verdaguer et al. 2017) reviewed several case studies of integrated BIM and LCA in the construction sector and found that this integration simplifies quick and effective results during the early stages of design.

However, the decision-making process aims to raise the awareness of architects, designers, and builders to combat environmental problems. It involves many factors such as the selection of materials, building orientation, use of passive systems, and ventilation (Canarslan 2007). Two approaches were addressed by Anton and Diaz in a way to facilitate the integration between BIM tools and LCA methodology (Antón and Díaz 2014b). The first approach was *“Direct access to the BIM model information to calculate LCA performance”*. This approach considers BIM models that have been created in the early design phase as the main source of information needed to conduct a complete life cycle assessment of buildings. Besides, this approach helps to avoid manual data re-entry, improve environmental performance, evaluate LCA methodology, and empower the decision-making process. The second approach was *“Environmental properties included in the BIM objects”*. This approach means to create a strong connection between BIM tools and the environmental life cycle assessment database. It motivates designers, architects and engineers to incorporate the environmental criteria within the decision-making process. This approach is still considered as an insufficient way to evaluate LCA analysis in the construction sector. However, managing and reducing the energy consumptions and GHG emissions at an early stage of designing construction projects have been growing fast in the construction sector.

Estimating energy performance (input, output and flow) requires taking into consideration the operating energy (OE) and embodied energy (EE) over the entire LCA of buildings; OE is the energy needed for heating, cooling, ventilation, lighting, domestic hot water, appliances and auxiliary systems, while EE is the energy needed over the total life cycle phases of building materials (Chastas et al. 2016; Mithraratne and Vale 2004). In the literature, there are increasing efforts that aim to enhance the energy efficiency in buildings. For example, some authors analysed the diffusion and adaptation of building envelope technologies based on a Hype cycle diagram, which combines technologies lifecycle and adaptation of a technology (Aslani et al. 2019). Others discussed the increasing of energy efficiency in buildings by thermal insulation (Simona et al. 2017) and investigated the usefulness of gradual pattern mining to achieve this objective (Fan et al. 2018). The European Union set a long-term strategy and frameworks with the Energy Performance of Buildings Directive to reduce the consumption of energy in the construction sector (The European parlimant and the council of the European union 2010). Within the literature, several available strategies are discussed to construct a low energy building; these include accounting for factors such as location, climate, cost, and available sources (Moran et al. 2017). Other studies defined five guidelines that are providing a strong basis to achieve low energy buildings through smart design and innovative technologies, as follows: i) alternative energy source, ii) passive solar design, iii) high-performance building envelope, iv) lighting and daylighting, and v) low consumption technology and appliances (National Institute of Standards and Technology 2013; Sustainable Construction n.d.).

Several studies have addressed the aspects of energy consumption in buildings and examined the various possibilities in achieving a reduction in this consumption. For instance, Charisi (Charisi 2017) analysed the building envelope of a typical Greek residential building in four climate zones. The author found that efficient constructive solutions could vary for every climate zone based on the combinations of building parameters. The results of the research confirmed that the right combination might save energy consumption by 30% and reduce the annual energy demand for less than 50 kWh/m^2. Ascione et al (Ascione et al. 2016) discussed the design criteria for a residential building in the Mediterranean climate. Their work aimed to minimize the energy demands in winter and summer without compromising thermal comfort. However, the authors found difficulty in understanding the best trade-off between summer and winter performance. Giordano et al (Giordano et al. 2017) examined a case study since the earliest design stage, considering both the EE and OE. The authors developed a worksheet with over 65 materials to inspire designers to manage these issues. Loukaidou et al (Loukaidou et al. 2017) focused on the optimal thermal features of the building envelope in the climate conditions of Cyprus. The study included thermal insulation on the wall, roof, ground floor, and windows. The authors demonstrated that the cost-optimal energy performance levels in Cyprus are higher than the national minimum requirements and underlined the necessity of forming three independent climate zones in the country instead of the existing one. Kampelis et al (Kampelis et al. 2017) examined the operating energy in industrial, residential and tertiary sector buildings. The authors compared the energy dynamic and quasi-dynamic models with various data and environmental measurements. The authors highlighted the needs to address the performance gap between energy efficient prediction in the design phase and the evaluation measurements in the operational phase.

Many other studies examined the features of the Life Cycle Energy Assessment (LCEA). For instance, Moran et al (Moran et al. 2017) focused on the life cycle cost and environmental analysis of a number of case study buildings in Ireland. The authors used different sources for heating purposes such as a gas boiler, biomass boiler, domestic gas-fired combined heat, and power unit, heat pump and renewable technology. The authors found that future buildings should be super-insulated with higher air-tightness performance. In addition to this, the authors presented the benefits of operating low impact heating systems on the environment such as a biomass boiler or heat pump. Muñoz et al (Muñoz et al. 2017) assessed a new school building, considering the LCEA by taking into account the pre-use phase, use phase, and the estimated post-use phase. The authors found that the very low Primary Energy Consumption (PEC), less than 92 kWh m^{-2} $year^{-1}$, represents around 56% of the total demanded energy over the total LCA of the building. Chastas et al (Chastas et al. 2017) evaluated the LCEA of 90 residential case studies focusing on the normalization procedure that follows the principles of Product Category Rule 2014:02 for buildings. The authors found that applying different methods of Life Cycle Inventory (LCI) could lead to various values of EE and highlighted the necessity to consider LCEA in energy efficient regulations. Atmaca and Atmaca (Atmaca and Atmaca 2015) analysed the construction of two residential buildings in Gaziantep in Turkey, considering urban and rural buildings. The analysis includes the construction, operation and demolition phases over a 50-year lifespan. The authors found that the energy consumption in the operation phase is dominant in urban and rural buildings, and EE accounts for 24-27% of the total life cycle energy consumption, pointing out that the life cycle energy demand in rural residential buildings is 18% lower than urban residential buildings.

Mathematical optimization has also been adopted to enhance energy consumption efficiency in buildings. Bamdad et al (Bamdad et al. 2017) highlighted that the simulation-based optimization methods are widely employed in the design of low-energy buildings due to non-linear thermal behavior of buildings. The authors developed and applied an Ant Colony Optimization for a continuous domain to optimize a commercial building in Australia. Chen and Yang (Chen and Yang 2017) proposed a two-stage design optimization approach which is applied to prototype passively high-rise residential building in multiple building operation scenarios. Nguyen et al (Nguyen et al. 2014a) described the building design optimization techniques applied to build performance analysis. Ferrara et al (Ferrara et al. 2014) built a simulation model of a real high performing French single-family house for minimizing the global cost function. The authors found that the more efficient the energy system, the more cost impacting the envelop design. Yu et al (Yu et al. 2015) presented a multi-objective optimization model that assist green building design, using an improved multi-objective genetic algorithm as a theory basis. Fesanghary et al (M. Fesanghary et al. 2012) considered the design of low-emission cost-effective residential buildings to reduce the lifecycle cost and carbon dioxide emissions. The authors presented a multi-objective optimization algorithm based on the harmony search algorithm.

3. CHAPTER THREE: RESEARCH METHODOLOGY

3.1. Introduction

This work reviews LCA from a building perspective and highlights the importance of LCA in the construction sector. It targets the residential and office buildings in the construction market. The novelty herein is to enable decision-makers utilizing standard procedures to empower the process of sustainable energy efficiency in buildings and evaluate the environmental impacts of building materials and protect the built environment. However, evaluating the environmental impacts and simulating the energy performance of the construction components at the conceptual design stage are two motivated issues for designers and architects. This work proposes an automated model that links the tools of BIM and LCA, which evaluate the environmental impacts, simulate the energy performance and daylight analysis, and optimize the energy efficiency and renewable energy in buildings. This means to develop flowcharts that empower the decision support analysis in order to achieve the objectives of this work presented in Subsection 1.4. Various case studies of realistic and hypothetical construction projects will be examined to prove the workability of the proposed methodology. This work targets to deliver and explore the practical issues and constraints facing future construction automation for sustainability. It analyzes the current implementation and utilization of the various software, technologies, and tools in the rapidly developing BIM sphere. The scope of this work is to emphasis on the energy performance of the construction materials and components as a major discipline that causes most variations in the LCA and sustainability of buildings.

This research includes a theoretical framework and practical research elements to investigate the research hypothesis as follows:

- General and Theoretical framework:
  Concluding a deep review and gathering information about concepts and theories presented by researchers and academic centers using the following sources; printed journals, online journals, books, websites and articles in magazines and newspapers.
- Informational content:

- ✓ Collecting and analyzing data about BIM challenges and strategies, and evaluating the progression of BIM in the construction sector.
- ✓ Collecting and analyzing data about the methodology of LCA in buildings since the starting point of the project, stages of execution, until the final stage and delivery

- Practical research tool:
  Gathering information that proves the workability of the proposed methodology and frameworks by applying various case study buildings.

3.2. BIM and sustainable construction

Around 60% of the time is being lost at the early stages of designing construction projects. This comes back to the need of entering the same information for the same project up to seven times during its lifespan (Antón and Díaz 2014a). The role of BIM appeared to facilitate energy efficient design within the energy consumption assessment throughout the entire life cycle assessment of buildings (Häkkinen and Kiviniemi 2008). According to many researchers (Abdulla and Jrade 2012; Antón and Díaz 2014b; a; Jrade and Jalaei 2014; Kylili et al. 2015), one of the suggested solutions to assess environmental impacts in the construction sector is to incorporate BIM tools and LCA methodology. This integration could be achieved by combining the decision-making process with the sustainable design procedure. Hence, this work considers the important value of the early design stages of construction projects in terms of evaluating the environmental impacts of building materials particularly, in terms of the complexity of decisions facing designers performing LCA analysis at early design stages (Basbagill et al. 2013).

BIM software can be considered as the technical core of creating sustainable construction. It provides both intelligent modelling and information management (WSP 2013). BIM software such as Autodesk Revit is designed specifically to work in a BIM framework, with the ability to insert additional information like sustainability and maintenance information (Kymmell 2008). BIM tools provide an effective way to integrate the design of energy efficiency within the assessment of energy consumption over the entire life cycle of the building (Häkkinen and Kiviniemi 2008).

This work presents the ability of BIM tools to contribute to building sustainability and overall performance. Eventually, it is important to clarify that promoting the process of decision-making at the early stages of designing a construction project requires a strong connection between BIM tools and both decision making tools and sustainability metrics.

3.3. 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 in this work is formulated in order to increase the operating energy efficiency of building envelopes and enhance the constructability of the building. 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, as presented in **Appendix 2**. The objective functions are formulated to achieve the following:

- Minimize the cost of fuel and electricity expended in the operation of the building.

- Maximize the constructability of the building, by looking at the time and skill required to install a particular component in the building.

- Minimize the operational energy of the building.

Moreover, a number of constraints are formulated in order to delineate the feasible region of the optimization problem considered (Santos et al. 2014), as follows:

- Ensure that a single material is chosen for each building component in the building.
- Exclude certain selections of materials that can be impossible due to building restrictions.
- The condition where two building components cannot be directly linked together in the structure (i.e. roof and foundations).
- Compute the energy demand of the building based on heating, cooling and water requirements respectively.

The mathematical optimization model is a method that reformulates the given set of objective functions so that one is optimized whilst the rest are executed as constraints (Mavrotas 2009). The trade-off matrix representing the best values for each objective function is obtained. This requires the application of lexicographic optimization (Zykina 2004). 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 (Mavrotas 2009).

3.4. Proposed methodology of this work

The outcomes of this work are to establish a concrete contribution framework and propose an automated model that links BIM, LCA, energy simulation, and environmental evaluation tools with sustainable construction systems. This means to quantify the environmental impacts and simulate the energy performance of construction components at the conceptual design stage, as presented in **Figure 13**, in order to empower the decision-making process in terms of the selection of the best design alternative and construction materials that would lead to a more energy efficient building and protect the built environment. BIM offers designers the ability to assess different design alternatives over the entire LCA of buildings. The implementation is within developing decision-support frameworks based on three main modules that are capable of measuring the environmental impacts of construction components, assessing the energy performance of buildings, and optimizing the best alternatives for building design, as shown in **Figure 13**. This work facilitates identifying the potential energy efficiency in building as a whole and for each of its associated components.

Figure 13 illustrates the methodology of this work that aims to improve energy performance and protect the built environment at an early stage of designing construction projects. This process depends on integrating and exchanging data between BIM software and LCA application (Soust-Verdaguer et al. 2017). This work applies the methodological framework of LCA based on ISO 14040 and 14044 guidelines, taking into consideration the basic steps of LCA methodology, as shown in **Figure 13** (Bayer et al. 2010; UNEP 2012): Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations. Goal and scope level determines the functional unit, system boundary and the set of building materials. LCI is the most challenging level of LCA analysis due to the difficulty of collecting reliable and relevant data. The next step to LCI is LCIA, in which the quantities of materials, energy consumption, and resulting emissions are clustered using the indicators of sustainability. The final step, Interpretation, allows for the identification and evaluation of the results obtained from LCI and LCIA.

The framework of BIM is a structure that includes different models, taxonomies, and classifications (Porwal and Hewage 2013; Succar 2009). Succar (Succar 2009) in his work explained three main axes of BIM domain: BIM Fields, BIM Stages, and BIM Lenses, as shown in **Figure 13**. In this discipline, applying BIM framework at an early design stage of a construction project starts with BIM Fields. This means to conduct the required clusters, interactions and overlaps between the different parties of the applied technologies, processes and policies (Succar 2009). In other words, it means to determine the participants of BIM implementation (Zhou et al. 2017). BIM Stages determine the maturity level of BIM implementation (Succar 2009), or measurement methods (Zhou et al. 2017). At this level, BIM Stages is subdivided into different phases such as inventory database (LCI), 3D modeling, collaboration and integration of design based on the local environment of the construction project. While BIM Lenses provide the depth and breadth to identify and qualify BIM Fields and BIM Stages (Succar 2009), representing BIM benefits indicators (Zhou et al. 2017). These benefits might be the deliverables of BIM, 3D smart objects, estimations of energy simulation and time and cost schedules in order to achieve the objectives of the project such as achieving sustainability standards, time efficiency, and cost efficiency, etc.

Furthermore, the performance parameters step, presented in **Figure 13**, takes into consideration various building modifications and simulations for the design, orientation, materials selection , and the applied renewable energy sources (Barrios et al. 2017; Harish and Kumar 2016; Nguyen et al. 2014b; Østergård et al. 2016). Besides, building properties and Environmental data are two basic parameters at this level of the analysis. Building properties include the building geometry, which is associated with design factors such as the floor level, floor heated area, dimensions of the heated volume, and the respective space area of each construction component in the building (Zhang et al. 2017); building technologies relates to the calculation of the thermal transmittance of the utilized construction components and air change rate of the geographic location of the building (Bienvenido-Huertas et al. 2019); and building envelope that recognizes all construction components in a building; defining such parameters will facilitate evaluating the U-values (Thormark 2007). However, the environmental data parameter means to take into consideration the climate data, site topography, and urban surrounding of the construction site. In addition to this, this parameter means to assess the contrast between the inside air temperature and the external air temperature associated with the local climate zone of the building.

Defining the main three modules of the proposed methodology of this work is the next step herein. It can be conducted by developing decision-support frameworks that evaluate the environmental impacts, improve energy efficiency, and optimize the best design alternatives of construction projects, as shown in **Figure 13**. In these terms, developing frameworks that evaluate the environmental impacts means to consider the mid-points, as presented in **Appendix 1**, **Appendix 2**, **Appendix 3**, **Appendix 4**, and **Appendix 5**, and the end-points as presented in **Appendix 6**. While developing frameworks that improve energy efficiency in buildings means to consider the energy efficiency as presented in (**Appendix 1** to **Appendix 9**), daylight assessment as presented in **Appendix 5**, heat energy loss in buildings as presented in **Appendix 8**, energy efficiency in the applied renewable energy sources as presented in **Appendix 9**, and alternative construction components that are assembling the building envelope as presented in **Appendix 1**, **Appendix 2**, **Appendix 3, Appendix 4**, **Appendix 6**, and **Appendix 7**). Developing frameworks to optimize the best design alternatives and construction materials for construction projects means to optimize comparing different alternative designs and develop a database for sustainable construction materials.

The following step is to define the conceptual framework. At this step, a holistic approach of a summation of the interactions between the different performance parameters is conducted in a way to make a better understanding of the whole system in a multidimensional way (Spruill et al. 2001). This requires evaluating the collected results of different models of the performance parameters and validating the proposed framework on realistic case studies in a way to improve the energy efficiency in buildings and protect the built environment. This step of the suggested methodological framework of this work requires appraising and integrating the collected results in order to empower the decision-making process in the construction sector by categorizing the data sources, comparing and matching results, and proposing recommendations and new options of building design.

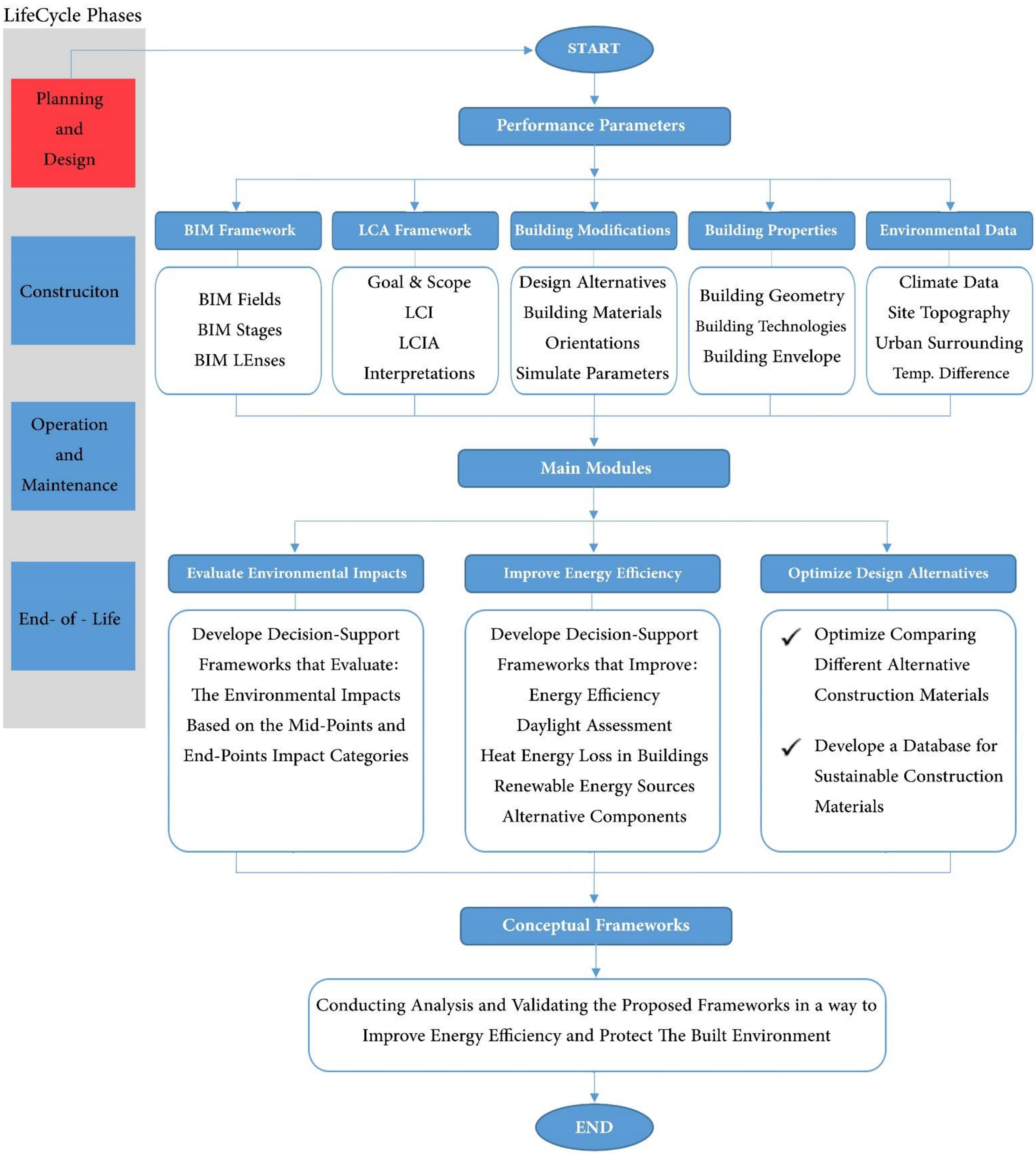

Figure 13. The proposed methodology of this work

4. CHAPTER FOUR: CONCLUSION

4.1. Research summary

The development and validation of this doctorate thesis are illustrated in the format of journal and conference papers. This work helps designers and architects to better understand the energy efficiency in buildings by highlighting the importance of Life Cycle Assessment methodology and Building Information Modeling tools in the construction sector. The novelty highlighted in this study is to enable decision-makers utilizing standard procedures to empower the process of sustainable energy efficiency in buildings and evaluate the environmental impacts of building materials and protect the built environment. The methodology of this work was developed based on three main modules of modifications and simulations; evaluate the environmental impacts, improve energy efficiency, and optimize comparing design alternatives. In other words, it establishes a concrete contribution and automated model that integrates the Life Cycle Assessment, Building Information Modeling, energy simulation, and environmental evaluation tools with the sustainable construction in a way to quantify the environmental impacts, perform the energy consumption in buildings, and optimize the best design alternatives at early design stages

4.2. Appendices summary and sub-objectives meeting

In this Subsection, a brief summary of all appendices is illustrated where the sub-objectives designed for this study, as presented in Subsection 1.4., are being achieved as follows:

4.2.1. Appendix 1

The motivation of this work is to empower the decision-making process and sustainability in the construction sector. The proposed framework aimed to integrate the framework of BIM within the LCA methodology, as well as the building modifications and environmental data, at an early designing process to estimate the energy efficiency in buildings and the environmental impacts of construction components that are assembling the building envelope. A case study building is applied to validate the proposed framework of this study. The output results of this work indicate that BIM-LCA integration is an optimal procedure towards achieving sustainable development and environmental protection, and empowers the decision-making process in the construction sector. Moreover, this work highlights the current limitations that are facing the proposed integration process and outlines that most of the passive environmental impacts are occurring during the manufacturing and operation phases. Finally, this work encourages reviewing the application of building materials in order to reduce the passive contribution to the environment. Hence, it can be clarified that this appendix aimed to achieve all the designed sub-objectives for this study.

4.2.2. Appendix 2

This work develops a novel framework for integrating the mathematical optimization, BIM, and LCA at an early designing step of construction projects to enhance the operating energy efficiency of the resulting building designs adopted, improve the building performance, optimize the alternative sustainable components, and empower the decision-making process and sustainability in the construction sector. The proposed framework has been validated on the building envelope of a realistic case study building in order to optimize the selection process of construction components, evaluate the environmental impacts and increase the operating energy efficiency in buildings towards producing energy efficient buildings. The output results of this work illustrate that all components are influencing the energy consumption in buildings, particularly, exterior walls and windows. This work insight that the optimal integration between BIM, LCA and the mathematical optimization could reduce the annual energy use intensity in buildings by about 45%, enhance the life cycle energy use and cost by more than 50%, and improve the environmental impacts such as acidification and global warming potential by more than 30%. Hence, it can be clarified that this appendix aimed to achieve all the designed sub-objectives for this study.

4.2.3. Appendix 3

This work evaluated the environmental impacts of the construction components that are assembling the building envelope of an office building in Brazil via the BIM-LCA integration in a way to empower the decision-making process and sustainability in the construction sector. It uses Autodesk Revit as a BIM tool, Autodesk Green

Building Studio as a BIM plug-in, and Tally as an LCA plug-in in Revit. The outcome results of this work illustrate that most of the passive environmental impacts are occurring during the manufacturing and operation phases, hence, it is important to apply the innovative techniques to produce energy efficient components that protect the built environment and the natural resources. The insight of this work recommend applying curtain wall systems instead of concrete systems on the exterior facades of office buildings in Brazil due to the low environmental impacts in the current climate classifications in Brazil. Hence, it can be clarified that this appendix aimed to achieve all the designed sub-objectives for this study.

4.2.4. Appendix 4

This paper examines various alternatives of building components that are assembling the envelopes of three typologies of residential buildings in Brazil based on a developed framework that integrates the framework of BIM with LCA methodology, as well as the environmental data and building modifications and simulations in order to empower the decision-making process and sustainable building design in the construction sector towards nearly Zero Energy Buildings. The outcomes of this work state that BIM-LCA integration is an ideal course towards reducing the operating energy in buildings. It considers all building components are influencing the consumption of energy in buildings, and supports increasing insulation and thickness of exterior walls and installing energy efficient windows in order to reduce the operating energy in the construction sector. Hence, it can be clarified that this appendix aimed to achieve the first, second, fourth, and sixth sub-objectives designed for this study.

4.2.5. Appendix 5

This work develops a framework that conducts a BIM-LCA integration to estimate energy consumption and daylight analysis in buildings, and empower the decision-making process and sustainable building design in the construction sector. The proposed methodology is validated on a case study building using Autodesk Green Building Studio plug-in as a BIM tool to estimate the energy consumption in buildings, and LEED plug-in to estimate the proportion of capturing the natural daylight. The results show that BIM-LCA integration is considered as an optimistic course in terms of sustainable development and decision-making process in the construction sector. Furthermore, it encourages reviewing the building orientation, HVAC systems and the construction of external walls and roofs in buildings at an early stage of design in order to increase energy efficiency and capturing of natural daylight in buildings. Hence, it can be clarified that this appendix aimed to achieve the first, second, fourth, and sixth sub-objectives designed for this study.

4.2.6. Appendix 6

This work targets empowering the decision-making process and sustainability in the construction sector through estimating the operating energy performance in buildings and evaluating the endpoint impacts of building materials at an early designing stage based on BIM-LCA integration. The proposed framework of this work has been validated on a hypothetical case study building taking into consideration two methods of construction; concrete construction and steel construction. Open LCA software is applied to estimate the endpoint categories using two assessment methods; Impact 2002+ and ILCD 2011. The outcome results of this work indicate that using steel construction instead of concrete construction is more environmentally friendly in such types of buildings. The insight of this work encourage the application of innovative techniques in the production process to protect the natural resources and the built environment, and reduce energy consumption in buildings. Hence, it can be clarified that this appendix aimed to achieve the first, second, and sixth sub-objectives designed for this study.

4.2.7. Appendix 7

This Appendix was first prepared as a conference paper, as presented in Appendix 7A. Then, it has been enlarged and developed, where the methodological framework was integrated and well validated and published as an article, as presented in Appendix 7B.

4.2.7.1. Appendix 7A

This work presents the interests of BIM tools in examining different design alternatives in order to improve energy performance in buildings. A novel framework is proposed to enhance the design of energy output in construction projects. This work empowers decision-making process and sustainability through a parametric analysis of the selection of construction building components. The methodological framework accommodates various performance parameters through the use of experimental design for improving energy efficiency of buildings. A case study with a group of construction materials for exterior walls and roofs as well as a set of the window-to-wall ratio are examined in different climate classifications. RStudio software is applied as a linear regression analysis to determine all the variables of the design factors. Autodesk Green Building Studio software is applied as the BIM tool to estimate energy use intensity (EUI) of the applied factorial designs. This study indicates that BIM modeling is an optimal procedure towards empowering both sustainability and decision-making process in the construction sector. Besides, this work shows that the design factor of the window-to-wall ratio is the main agent of influencing the energy consumption in buildings rather than any other building components, hence it suggests constructing buildings within minor opening spaces at any climate zone towards nearly Zero Energy Buildings (nZEBs). Hence, it can be clarified that this appendix aimed to achieve the first, fifth, and sixth sub-objectives designed for this study.

4.2.7.2. Appendix 7B

This study proposes a framework based on various performance parameters, environmental data, and building technologies to enable decision-makers utilizing standard procedures and software to empower the process of sustainable energy use and management in buildings, through a parametric analysis in different climatic conditions. The proposed methodology is validated on a case study building, sorting out the climate classification plays a fundamental role in the choice of design factors that are best suited for effective energy consumption in buildings. This work also finds that around 15% improvement in the energy consumption in buildings is noticed due to changes to the design factor such as the window-to-wall ratio. Insights that can be gleaned from this study include the impact of space area, exterior openings and material thickness and choice for the envelope of the building in all climate classifications, aiding in the design of low-energy buildings. Hence, it can be clarified that this appendix aimed to achieve the first, fifth, and sixth sub-objectives designed for this study.

4.2.8. Appendix 8

This work proposes a methodological framework that characterizes the Heat Energy Loss (HEL) in buildings during the operation phase, taking into consideration the local environmental data in which buildings are located, based on Ventilation Heat Loss (VHL) and Fabric Heat Loss (FHL) of construction components. The performance parameters of the proposed methodology included some important building properties such as building geometry, building technology, and building envelope. A case study building has been applied at this level of the analysis in a way to validate the proposed framework, where the results reveal that FHL is the main factor of the HEL in buildings; responsible for more than 81% of the total HEL in buildings. Openings and exterior walls play a significant role in curbing such energy loss; accounting for around 70% of the total FHL in buildings. This work points out that the percentage of energy efficiency improvement of FHL is similar and directly proportional to the percentage of reduction in U-values of building components. Besides, the analysis conducted indicates that lower air change rate would lessen the VHL in buildings. Hence, it can be clarified that this appendix aimed to achieve the first, fifth, and sixth sub-objectives for this study.

4.2.9. Appendix 9

This work empowers the decision-making process and sustainability through a parametric analysis of the installation of PV modules to increase their energy output towards nearly zero energy buildings. This work develops a framework that integrates different performance parameters through the use of an experimental design to expect all variables of installing PV modules via linear regression analysis. The outcome results demonstrate that the installation of PV modules on the mounted roof is better than elevations, where the vertical installation of modules is the worst possible inclination to maximize the yielded energy. The impact of inclination is higher than orientation in influencing the energy productivity of PV modules. The insight of this study specifies integrating PV modules mounted on roofs and elevations towards the equator line, by a proportion of inclination/latitude equal to 85 ± 3%, to maximize the energy output. Hence, it can be clarified that this appendix aimed to achieve the fifth, and sixth sub-objectives designed for this study.

4.2.10. Appendix 10

This work conducts a literature review to identify the close relationship between LCA and sustainable energy in buildings through a bibliometric and bibliographic analysis. The reviewed literature covers the major aspects of a sustainable building (i.e. energy efficiency, environmental impacts, and materials selection). The bibliometric analysis illustrates several clusters that make the refinements of further searches and classify the documents and the primary sources. The bibliographic analysis shows that the assessed methodologies and approaches facilitate the process towards sustainable energy life cycle assessment in buildings; giving the opportunity to evaluate the environmental impacts and improve energy efficiency in buildings.

4.3. Research contribution

The scientific contribution of this study is in developing a distinctive approach towards sustainable construction by integrating Building Information Modeling and Life Cycle Assessment for designing energy efficient buildings and identifies the existing gaps in such integration in order to empower the decision-making process and sustainable design procedure in the construction sector. This work targets developing a decision support system that estimates the energy efficiency and daylight assessment in buildings, and evaluates the environmental impacts of building materials in order to facilitate the selection of construction materials process at the conceptual stage of design. Besides, this study integrates the sustainable design models in a way to automate the process of improving the energy performance of buildings, taking into consideration the heat energy loss in buildings during the using phase, the affordable sources of renewable energy, and the application of alternative construction materials that are assembling the building envelope.

4.4. Limitations and future recommendations

The developed methodological framework can be applied to evaluate the energy consumption and environmental impacts over the entire lifespan of construction projects (i.e. residential buildings and office buildings) towards preparing the sustainable design. However, one of the most important limitations is that every model has been validated separately on a different case study building, as presented in the appendices. Hence, applying the whole modules and validating the results in a real building could be one of the recommendations for future works. Another limitation of this work is that it investigated the proposed integration between Building Information Modeling and Life Cycle Assessment from an environmental aspect, disregarding the other pillars of sustainability (cost and social), hence, integrating the proposed methodology within the Life Cycle Costing and Social Life Cycle Assessment could be another recommendation for future works that provide an effective way to visualize and assess the Life Cycle Sustainability Assessment in buildings. The third limitation is that the database developed in the most Appendices has been designed based on the collected data that is supported by Autodesk Revit as a Building Information Modeling software, which covers limited sustainable construction components. In these terms, investigating a wider range of sustainable construction components that are assembling the building envelope and considering an adapted climate data could be another recommendation for future studies.

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APPENDICES

APPENDIX 1

Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building

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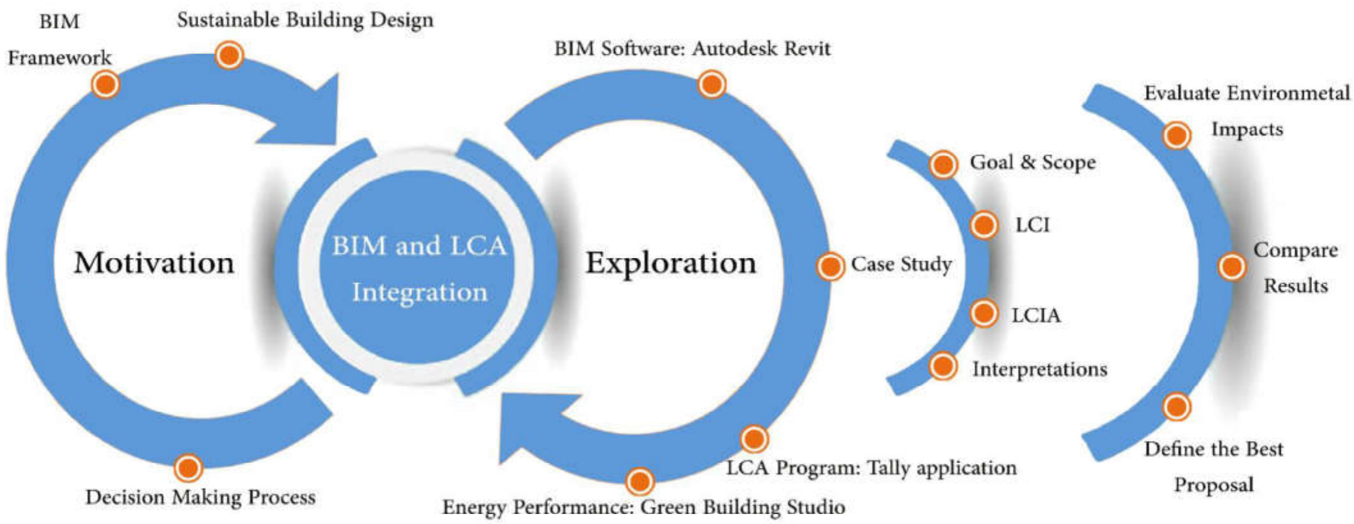
Graphical Abstract:



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Mohammad Najjar[a,*], Karoline Figueiredo[b], Mariana Palumbo[c], Assed Haddad[b,c]

[a] Programa de Engenharia Ambiental, Escola Politécnica da Universidade Federal do Rio de Janeiro, Athos da Silveira Ramos, 149, Ilha do Fundão, Centro de Tecnologia, Bloco A, Sala DAPG, Cidade Universitária, 21941-909 Rio de Janeiro, RJ, Brazil

[b] Departamento de Construção Civil, Escola Politécnica da Universidade Federal do Rio de Janeiro, Athos da Silveira Ramos, 149, Ilha do Fundão, Centro de Tecnologia, Bloco D, Sala 207, Cidade Universitária, 21941-909 Rio de Janeiro, RJ, Brazil

[c] Programa de Pós Graduação em Engenharia Civil, Universidade Federal Fluminense, Passo da Pátria, 156, 3° andar, Sala 365, Bloco D, São Domingos, 24210-240 Niterói, RJ, Brazil

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ABSTRACT

This work integrates Building Information Modeling (BIM) with Life Cycle Assessment (LCA), and presents the outcome of this integration in evaluating environmental impacts of building materials in the construction sector. A case study of a multi-story office building is applied to validate the development of design concepts and discuss the results generated by BIM and LCA tools. This research evaluates the LCA methodology of the case study based on ISO 14040 and 14044 guidelines within the available database, using Autodesk Revit as a BIM program and Green Building Studio and Tally applications in Revit as tools to achieve the objectives. This study indicates that BIM-LCA integration is an optimal procedure towards achieving sustainable development and environmental protection, and empowers the decision-making process in the construction sector. It sheds light on the current limitations that are facing the integration process. Moreover, this work outlines that most of the negative environmental impacts are occurring during the manufacturing and operation phases. Thus, it encourages reviewing the application of building materials in order to reduce the passive contribution to the environment.

1. Introduction

The world is observing a growing concern in the fields of energy and natural resources consumption, and environmental impacts. Environmentally intensive human activities such as the burning of fossil fuels, deforestation, and land use changes are producing harmful emissions that are passively affecting the environment [1]. The United States (U.S.) Energy Information Agency forecasts that by 2025 the global energy consumption will increase by 33% in developed countries, and 91% in developing countries [2]. The International Energy Agency (IEA) expects that between 2003 and 2030 the annual growth rate of energy consumption would reach the values of 1% and 3% in countries that are involved in the Organization for Economic Co-operation and Development Countries (OECD) and non-OECD countries, respectively [3]. The construction industry is one of the activities that are consuming energy, resources and affecting the environment [4–11]. Hence, it is important to increase innovations and solutions to achieve the sustainability standards in this field, principally in critical conditions: rising competition, running out of resources and lack of standards to protect the environment [12]. These factors play a basic role in affecting the built environment and energy consumption during the entire Life Cycle Assessment (LCA) of building materials, that is the extraction of raw materials, manufacturing, packaging and transportation to the site, construction and installation, operation, until demolition and recycling [13–16]. The novelty of this work is to illustrate the important role of integrating BIM and LCA at early design stages to evaluate environmental impacts in the construction sector.

New strategies such as green building approaches, sustainable materials practices and renewable energy systems are extensively required to reduce energy consumption, greenhouse gas (GHG) emissions, and environmental impacts of building materials in the construction sector [17]. The relationship between building materials and energy has improved in a complicated way in recent decades. This comes back to the modern technologies that explored the different properties and capabilities of these materials. Besides, the type of building, climate zone and the level of economic development are prominent factors playing role in determining the pattern of energy consumption in the construction sector [18]. LCA is one of numerous management tools that are used to evaluate the environmental impacts in the construction sector. The function of LCA appears as an eco-friendly methodology to

* Corresponding author.
E-mail addresses: mnajjar@poli.ufrj.br (M. Najjar), karolinefigueiredo@poli.ufrj.br (K. Figueiredo), mariana.palumbo@upc.edu (M. Palumbo), assed@poli.ufrj.br (A. Haddad).

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Integration of BIM and LCA: evaluating the environmental impacts of building materials at an early stage of designing a typical office building

Abstract: This work integrates Building Information Modeling (BIM) with Life Cycle Assessment (LCA), and presents the outcome of this integration in evaluating environmental impacts of building materials in the construction sector. A case study of a multi-story office building is applied to validate the development of design concepts and discuss the results generated by BIM and LCA tools. This research evaluates the LCA methodology of the case study based on ISO 14040 and 14044 guidelines within the available database, using Autodesk Revit as a BIM program and Green Building Studio and Tally applications in Revit as tools to achieve the objectives. This study indicates that BIM-LCA integration is an optimal procedure towards achieving sustainable development and environmental protection, and empowers the decision-making process in the construction sector. It sheds light on the current limitations that are facing the integration process. Moreover, this work outlines that most of the negative environmental impacts are occurring during the manufacturing and operation phases. Thus, it encourages reviewing the application of building materials in order to reduce the passive contribution to the environment.

Keywords: Environmental Impacts, Life Cycle Assessment, Building Information Modeling, Sustainable Building, Building Energy.

1. Introduction

The world is observing a growing concern in the fields of energy and natural resources consumption, and environmental impacts. Environmentally intensive human activities such as the burning of fossil fuels, deforestation, and land use changes are producing harmful emissions that are passively affecting the environment [1]. The United States (U.S.) Energy Information Agency forecasts that by 2025 the global energy consumption will increase by 33% in developed countries, and 91% in developing countries[2]. The International Energy Agency (IEA) expects that between 2003 and 2030 the annual growth rate of energy consumption would reach the values of 1% and 3% in countries that are involved in the Organization for Economic Co-operation and Development Countries (OECD) and non-OECD countries, respectively [3]. The construction industry is one of the activities that are consuming energy, resources and affecting the environment [4–11]. Hence, it is important to increase innovations and solutions to achieve the sustainability standards in this field, principally in critical conditions: rising competition, running out of resources and lack of standards to protect the environment [12]. These factors play a basic role in affecting the built environment and energy consumption during the entire Life Cycle Assessment (LCA) of building materials, that is the extraction of raw materials, manufacturing, packaging and transportation to the site, construction and installation, operation, until demolition and recycling [13–16]. The novelty of this work is to illustrate the important role of integrating BIM and LCA at early design stages to evaluate environmental impacts in the construction sector.

New strategies such as green building approaches, sustainable materials practices and renewable energy systems are extensively required to reduce energy consumption, greenhouse gas (GHG) emissions, and environmental impacts of building materials in the construction sector [17]. The relationship between building materials and energy has improved in a complicated way in recent decades. This comes back to the modern technologies that explored the different properties and capabilities of these materials. Besides, the type of building, climate zone and the level of economic development are prominent factors playing role in determining the pattern of energy consumption in the construction sector [18]. LCA is one of numerous management tools that are used to evaluate the environmental impacts in the construction sector. The function of LCA appears as an eco-friendly methodology to compute the environmental impacts of building materials. Despite the aim of LCA methodology is to evaluate the concept of sustainability in the construction sector, there are different challenges facing the application of LCA in this field. Examples of these challenges are the potential changes in the form and function of buildings during the entire lifespan, mostly more than 50 years, and the challenges of forecasting the whole life cycle and reducing the environmental loads of buildings [19]. In this context, the role of building information modeling (BIM) appears as a building tool that facilitates the application of LCA in the construction sector [20]. Using BIM at an early stage of designing construction projects empowers the decision-making process in the construction sector [21,22]. BIM provides designers, architects, and engineers with data required to evaluate energy consumption and environmental impacts in the construction sector throughout the entire lifecycle of building materials [10,23,24]. It can be considered that BIM harmonizes both the information of building materials and the evaluation of their environmental impacts [20].

The number of publications in the field of environmental LCA studies has increased rapidly since the release of ISO 14040 series. According to Anand and Amor, the number of publications that could be found in Scopus up to 2011 was only 88. This number increased to 264 publications in 2015 [20]. In this discipline, numerous papers discussed LCA methodology from a building perspective [25–30], while many other publications revised this methodology in analytical works and case studies. [11,13,31–39]. Furthermore, numerous publications examined the application of BIM methodology in the construction sector [40]. Some authors defined strategies that present the power of BIM [41]. Other authors conducted a review of numerous BIM publications in order to determine objectives and the potential of green BIM tools in the construction sector [9,42]. However, there is a growing concern in the field of BIM and LCA integration. Some authors considered this step as a promising opportunity in the Architectural, Engineering, and Construction (AEC) industry [43]. Other authors assessed this integration in a way to cover the three pillars of sustainable development; environment, social and economic at an early stage of design [24,44]. In addition, some authors analyzed the ability of such integration to evaluate the sustainability standards and building energy performance [23], while others attempted to maximize the benefits of this integration and achieve the most sustainable construction standards [45]. Despite these publications, one can perceive a gap in the field of BIM and LCA integration. This gap lies in the insufficient methodological details that are covered in this part of the study. In fact, the need for a systematically defined framework of BIM and LCA extends beyond knowledge inquiry and organization. This area needs to be addressed in order to support the decision-making process in the construction sector and to protect the built environment.

This work analyses the methodology of LCA from a building perspective and presents the role of BIM and LCA integration in evaluating the environmental impacts of building materials in order to enable both the decision-making process and sustainable design procedure in the construction sector. Thus, empowering the decision-making process aims to achieve more efficient, cost-effective, and sustainable design standards, particularly at early stages of designing construction projects [9]. The objective of this work is to motivate the integration of

BIM and LCA methodologies in an initial phase of the design of construction projects and to present the ability of such integration in evaluating the environmental impacts of construction materials. Besides, BIM-LCA integration shows the important role of sustainable construction in reducing the environmental impacts of building materials such as global warming potential, acidification potential, ozone depletion potential, eutrophication potential, smog formation potential, and non-renewable energy. The purpose of the paper is to synthesize the first stages of designing a typical multi-story office building in Brazil in order to achieve the objectives of the research.

2. Tools of the Integration Process

Sustainable construction is a practice that aims to raise the quality of life for residents by maintaining a balanced relation between the different demands of people and affordable possibilities [46]. Agenda 21 on Sustainable Construction for Developing Countries defined sustainable construction as a complete approach that aims to preserve the relationship between the natural and built environment, and build settlements that protect human dignity and motivate equity [47]. There are several barriers to achieve sustainability in the construction sector such as technological inertia, uncertain economic environment, poverty and low urban investment, insufficient data, lack of interest in the application of sustainability, and the absence of integrated studies [46]. Many methods and systems have been applied in the construction sector in order to analyze sustainable construction practice and evaluate the environmental performance of buildings. Examples of these methods include the Evaluation System of Environmental Efficiency (BREEAM) in the UK, Evaluation System of Sustainable Building (LEED) in USA, Evaluation System of the Environmental Performance of The Buildings (CASBEE) in Japan, Building Environmental Performance Assessment Criteria (BEPAC) in Canada, and Pearl Community Rating System (ESTIDAMA) in the UAE.

2.1. Life Cycle Assessment (LCA)

LCA is a methodology that aims to quantify the environmental impacts of products, taking into consideration the entire life cycle since the extraction of raw materials, manufacturing and transportation to the site, construction, operation and maintenance, until end-of-life and recycling or demolition. This integrated methodology helps to develop and expand frameworks, impact assessments and data quality [48]. In the second half of the 1990s, International Standards Organization (ISO) published the most important recognized standards of LCA methodology [19]: ISO 14040 Principles and framework, ISO 14041 Goal definition and inventory analysis, ISO 14042 Life-cycle impact assessment, and ISO 14043 Life-cycle interpretation. The methodology of LCA has been widely applied in the construction sector, since 1990, as an important tool to evaluate the environmental impacts of building materials over the different life cycle phases of the construction project [49]. LCA methodology recognizes and analyses the different possibilities that help to reduce energy and resource consumption and the environmental impacts of building materials. Building LCA has been divided into three main phases, as shown in Table 1; pre-Building Phase, building phase, and post-building phase. Each phase includes different activities, and the relevant contained energy has been classified according to the nature of each phase. Table 1 highlights the energy consumption of buildings over their life cycle in five main stages. The first stage, characterized as embodied energy, is the extracting and manufacturing phase of raw materials. The next stage is grey energy and it refers to the transportation phase of building materials from the production site to construction site. The third and fourth stages are the actual energy used for construction and operation phases. The types of energy consumed in these two phases are known as induced energy and operation energy, respectively. The final stage is the energy used for demolition and recycling and it refers to the end-of-life phase of the building [18,38,50–52]. Furthermore, studies show that the right choice of building materials can minimize embodied energy. Whereas, operating energy, which is considered as the main part of the total energy used in buildings for cooling, heating, ventilation, lighting, heating water, and power, can be saved by applying an energy efficient system that provides good indoor conditions while consuming less energy [18].

Life Cycle Phase	Activities	Relevant Contained Energy
Pre-Building Phase	extraction of raw materials, manufacturing, packaging, and transporting to the site	Embodied Energy: is the energy consumed in the extraction and manufacture of construction materials. Grey Energy: is the energy consumed in transporting building materials from the factory to the construction site.
Building Phase	Construction, installation, operation, and maintenance	Induced Energy: Is the energy consumed in the construction and building steps. Operation Energy: Is the energy consumed in the operation of the building.
Post-Building Phase	Demolition and recycling	Disposal Energy: Is the energy consumed in the demolition and disposal of the building.

(Table 1. LCA phases and relevant energy consumption)

The methodology of LCA in the construction sector operates in four phases [53,54]: material, product, building, and industry. The first phase is considered as the core of the LCA process, while a group of materials is assembled into the final product. In this term, the building phase considers the whole building as one product. This phase helps LCA experts to understand the way of constructing buildings, the choice of construction materials, and the reasonable methods to operate buildings. The last phase, industry, is considered the best tool to evaluate the LCA process at a wide scale. It examines industrial production and economic output data. Furthermore, LCA methodology applies three levels of classification tools to simplify LCA analysis at the scale of buildings. The first level of these tools is interested in analyzing LCA of construction materials. Examples of tools at this level include SimaPro, GaBi, Umberto, TEAM, LCE, Open LCA, BEES, LCAiT, and TAKE-LCA. The second level is interested in analyzing LCA of the entire building. Examples of such classification tools include Athena Environmental Impact Estimator (EIE), BRI LCA (energy and CO2), EcoQuantum, Envest, LISA, Energy Plus, and Autodesk EcoTect & Green Building Studio level. The third level is interested in analyzing LCA of construction stage and concentrated on the three pillars of sustainability: environmental, economic and social. Examples of these tools include BREEAM, Green Globes, LEED, and GBTool [43].

2.2. Building Information Modeling (BIM)

The set of communication patterns and traditional design formats in the construction sector have already been changed in the recent three decades after the enormous improvements of computer-aided design (CAD) software and building information modeling (BIM) [9,55]. BIM software is considered the technical core of BIM tools that deliver distinctive intelligent modeling and information management [56]. It is an effective generation of information technology in the building industry that intends to integrate building information and develop the field of knowledge in planning, designing, building, managing, and recycling during the different phases of the life cycle of a construction project [57,58]. The National Building Information Model Standard Project Committee in the United States defined BIM as [59]:

"*BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition".*

BIM aims to achieve the standards of sustainability and objectives of the construction project [41]. It provides an appreciated opportunity to perform the environmental performance analyses and sustainable development standards in the construction sector [9,60,61]. BIM tools help to generate construction project decisions by sharing the models and information between project team members through an online system [62,63]. Besides, BIM tools provide the ability to estimate costs of construction projects (4D) and imagine a logical order of timeline and steps of works (5D) [64]. However, the structure of BIM models has a positive effect on the three pillars of sustainability. BIM models have been used in the building industry in order to raise project performance and quality. It facilitates communication and transparency among stakeholders and design teamwork in order to save time and energy, reduce costs and wastes, minimize future errors and enhance working and living conditions.

Promoting the decision-making process at an early stage of designing a construction project necessitates a solid combination between BIM tools and sustainability standards in order to evaluate the various impacts in terms of design, operation, and maintenance in addition to applying multi-dimensional visualization technology that promotes the concept of sustainable built environment [65]. Moreover, this combination requires a better understanding of building materials that considerably affect the environment. Such combination facilitates the issues of assessing costs in the construction sector and reducing the consumption of both energy and resources [9]. Hence, it is important to declare that this combination could be a part of an integration procedure between BIM and LCA in order to appraise the decision-making process at an early stage of designing a construction project [66].

2.3. BIM and LCA Integration

BIM facilitates energy efficient design within the energy consumption assessment throughout the entire life cycle assessment of buildings [67]. According to many researchers [23,24,43–45], one of the suggested solutions to assess environmental impacts in the construction sector is to incorporate BIM tools and LCA methodology. This integration could be achieved by combining the decision-making process with sustainable design procedure. Soust-Verdaguer et al [68] reviewed several case studies of integrated BIM and LCA in the construction sector and found that this integration simplifies quick and effective results during the early stages of design. However, decision-making process aims to raise the awareness of architects, designers and builders to combat the environmental problems. It involves many factors such as the selection of materials, building orientation, use of passive systems, and ventilation [69]. It is important to highlight that it is estimated that around 60% of the time is being lost at the early stages of designing construction projects. This comes back to the need of entering the same information for the same project up to seven times during its lifespan [24]. Hence, this work considers the important value of the early design stages of construction projects in terms of evaluating the environmental impacts of building materials particularly, in terms of the complexity of decisions facing designers performing LCA analysis at early design stages [66].

Two approaches were addressed by Anton and Diaz in a way to facilitate the integration between BIM tools and LCA methodology [44]. The first approach was *“Direct access to the BIM model information to calculate LCA performance”*. This approach considers BIM models that have been created in the early design phase as the main source of information needed to conduct a complete life cycle assessment of buildings. Besides, this approach helps to avoid manual data re-entry, improve the environmental performance, evaluate LCA methodology, and empower the decision-making process. The second approach was *“Environmental properties included in the BIM objects”*. This approach means to create a strong connection between BIM tools and the environmental life cycle assessment database. It motivates designers, architects and engineers to incorporate the environmental criteria within the decision-making process. This approach is still considered as an insufficient way to evaluate LCA analysis in the construction sector. However, managing and reducing the energy consumptions and GHG emissions at an early stage of designing construction projects have been growing fast in the construction sector.

3. Methodological Framework of BIM-LCA Integration

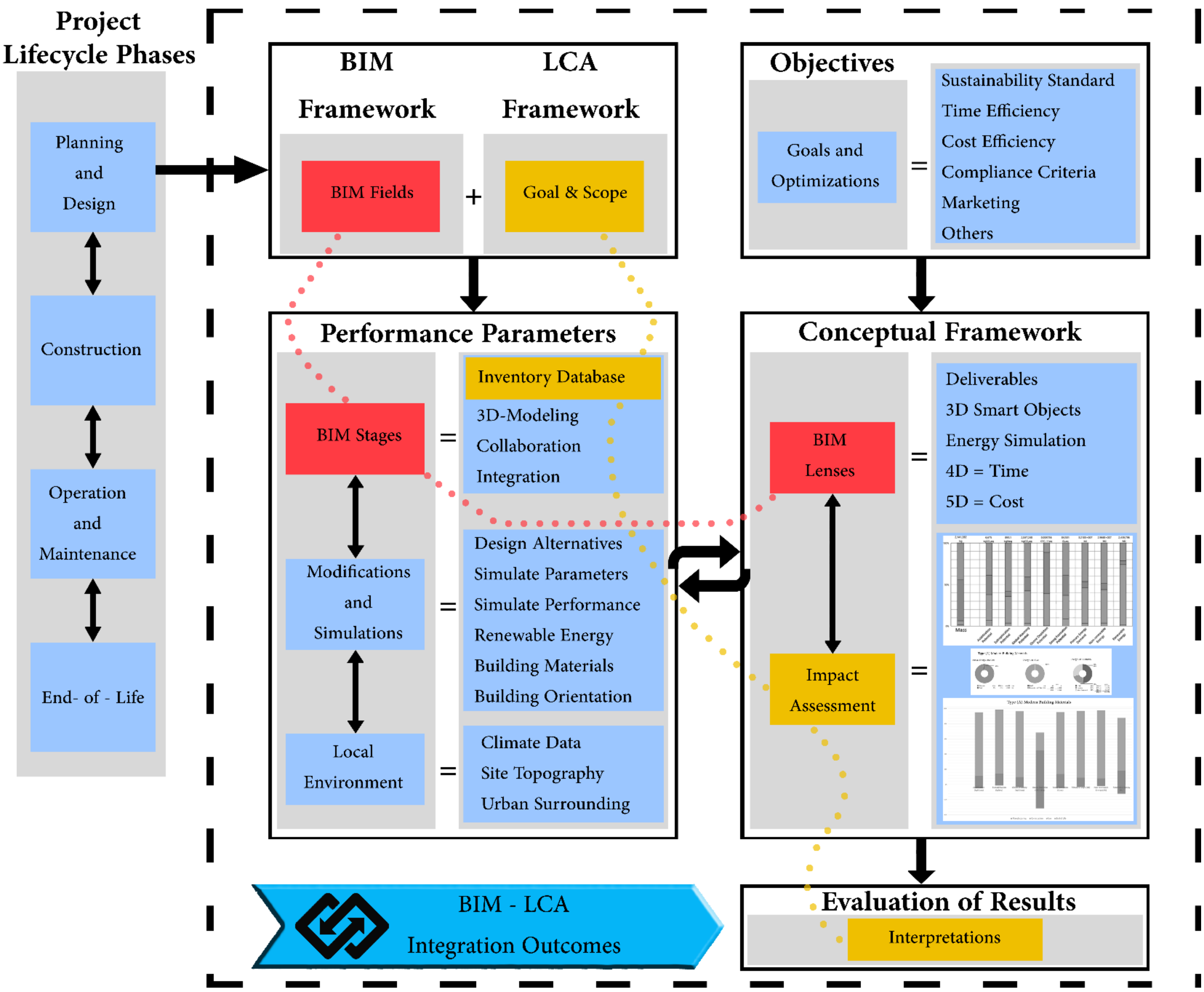
Integrating BIM and LCA attracts designers, engineers, architects and experts interested in sustainability and environmental engineering. On the first hand, BIM models produce integrated design and support information management and cooperation between stakeholders over the entire lifecycle of construction projects [24]. This gives the opportunity to provide design alternatives within all possible variations and design parameters during the early design stages of construction projects [70]. On the second hand, LCA is a suitable method to assess environmental impacts [71,72]. Hence, integrating BIM and LCA is considered as an urgent issue in achieving the sustainability standards in the construction sector and protecting the environment [73]. Such integration could be of great assistance in the field of sustainability [24]. It simplifies data acquisition of the building and provides a comprehensive feedback of projects [68]. This gives the opportunity to estimate energy consumption, environmental impacts, and therefore increase the ability to inform the decision prior to the decision making towards very low energy buildings and protect the surrounded environment [74].

3.1. Decision Support Analysis

This work provides a practical application of BIM-LCA integration and analyses the environmental impacts of building materials in the construction sector. It applies the methodological framework of LCA based on ISO 14040 and 14044 guidelines, taking into consideration the basic steps of LCA methodology, as shown in yellow boxes in Figure 1 [53,54]: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations. Goal and scope level determines the functional unit, system boundary and the set of building materials. LCI is the most challenging level of LCA analysis due to the difficulty of collecting reliable and relevant data. The next step to LCI is LCIA, in which the quantities of materials, energy consumption and resulting emissions are clustered using the indicators of sustainability. The final step, Interpretation, allows for the identification and evaluation of the results obtained from LCI and LCIA. On the other hand, The framework of BIM is a structure that includes different models, taxonomies and classifications [75,76]. Succar [76] in his work explained three main axes of BIM domain: BIM Fields, BIM Stages and BIM Lenses, as shown in the red boxes in Figure 1.

Figure 1 illustrates a flowchart of decision support analysis for BIM and LCA integration at an early stage of designing a construction project. This process depends on integrating and exchanging data between BIM software and LCA application [68]. In this discipline, applying BIM framework at an early design stage of a construction project starts with BIM Fields. This means to conduct the required clusters, interactions and overlaps between the different parties of the applied technologies, processes and policies [76]. In other words, it means to determine the participants of BIM implementation [40]. Meanwhile, applying LCA framework at an early designing stage comprises stating the goal and scope of the construction project. The next step is to determine performance parameters of the study by identifying BIM Stages that determine the maturity level of BIM implementation [76], or measurement methods [40]. At this level, BIM Stages is subdivided into different phases such as inventory database (LCI), 3D modeling, collaboration and integration of design based on the local environment of the construction project. Performance parameters step takes into consideration various modifications and simulations for the building design, orientation, materials, parameters and renewable energy [77–80].

The following step is to clarify the conceptual framework, as shown in Figure 1. At this step, the outputs of impact assessment analysis of LCA methodology is to be integrated with BIM Lenses, which provide the depth and breadth to identify and qualify BIM Fields and BIM Stages [76]. BIM Lenses represent BIM benefits indicators [40]. These benefits might be the deliverables of BIM, 3D smart objects, estimations of energy simulation and time and cost schedules in order to achieve the objectives of the project such as achieving sustainability standards, time efficiency, cost efficiency, compliance criteria, marketing, etc. Evaluating the results of the conceptual framework step, interpretations, is the later step that illustrates the outcomes of the BIM-LCA integration and empowers the decision-making process in the construction sector. However, the performance parameters step has an interconnected relationship with the conceptual framework step. This allows examining various modifications and simulations within different modeling and deliverables in order to determine the best proposal that serves the objectives of the project.



(Fig. 1: Flowchart of decision support analysis)

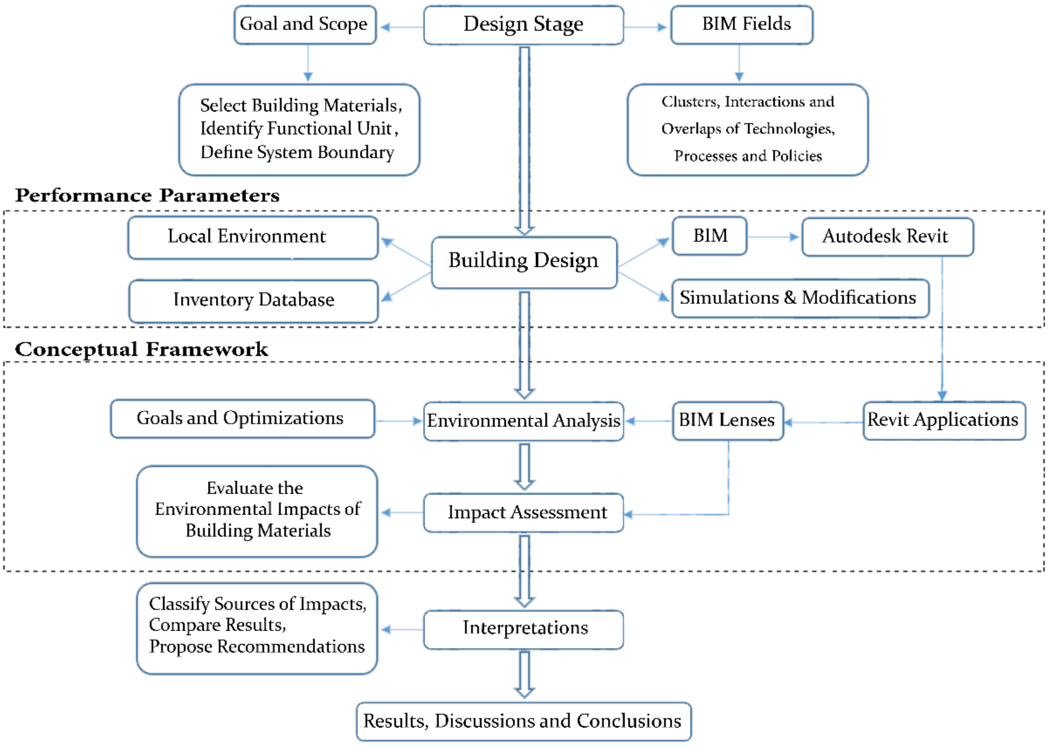
3.2. Application of Tools

This work uses the construction of a multi-story office building in Brazil as a case study to examine the validity and usability of BIM-LCA integration in evaluating the environmental impacts in buildings, clarifying the development of design concepts and discussing the results generated by BIM and LCA tools. The design of the building followed the traditional design methods of office buildings in Brazil, using two types of building materials:

- Type (A) includes modern building materials such as curtain wall system, reinforced concrete, masonry, metals and finishes.
- Type (B) includes typical building materials such as reinforced concrete, ceramic bricks and mortar, metals and finishes.

BIM models can perform various modifications and simulations, as previously discussed. In this discipline, using two types of building materials is considered as a single modification of BIM models in order to support the decision-making process and achieve the sustainability standards of construction projects. After stating the goal and scope of the work and defining the BIM Fields as shown in Figure 2, the performance parameters step is to be identified by designing the initial plans and models of the proposed building using Autodesk Revit program as a BIM software. Revit is used to conduct the 3D modeling of the case study considering the proposed modifications and inventory database of building materials, and the local climate data of the case study. Besides, Revit quantifies the amounts of building materials in the construction project. This work uses the advantages of Autodesk Revit to estimate the energy performance in buildings applying Green Building Studio application. Results at this step are required to build up life cycle energy analysis at the operation phase of buildings [81]. Besides, this work uses Tally application in Autodesk Revit as an LCA tool in order to evaluate the environmental impacts of building materials. It is important to acknowledge that Tally application is the first life cycle assessment tool in Autodesk Revit that aims to calculate the environmental impacts of the selected building materials [82]. LCI dataset in Tally is modeled using GaBi database [81]. Tally provides an effective and quick LCA feedback at the design phase of a construction project [83].

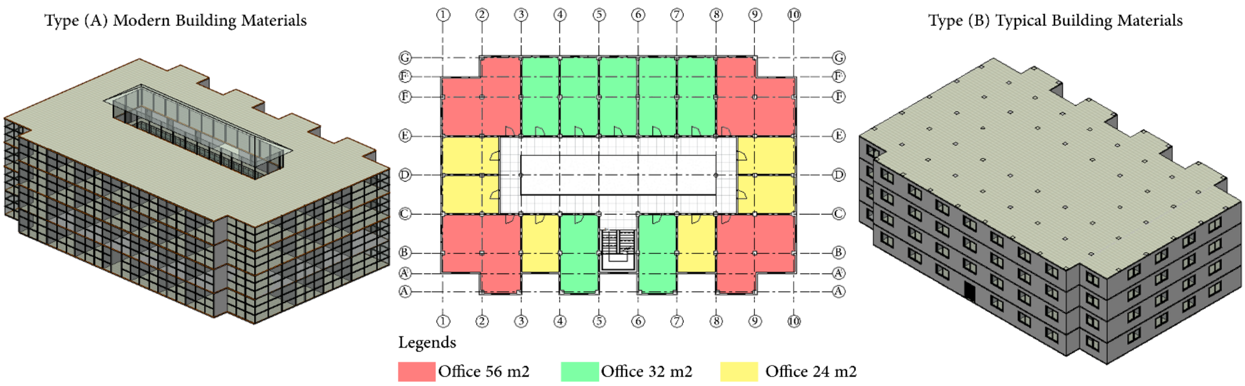
At the conceptual framework process, the benefit indicators and outputs of Revit, BIM Lenses, is to be integrated with the impact assessment (LCIA) of LCA methodology in order to achieve the objectives of the study. In this term, LCIA sorts out simpler understanding results by comparing the significance of the collected impacts with the elementary flows of data and emissions [53,54,84]. After that, the interpretation process starts by clarifying and classifying sources of impacts, comparing solutions, determining boundaries of analysis, and suggesting recommendations and new design options that may improve the design of buildings. "*This phase further comprises a review of the results by an independent expert, especially when the results of the comparisons are to be made public*" [84]. Finally, results are observed by discussing the work and presenting conclusions.



(Fig. 2: Research Methodology)

4. Case Study

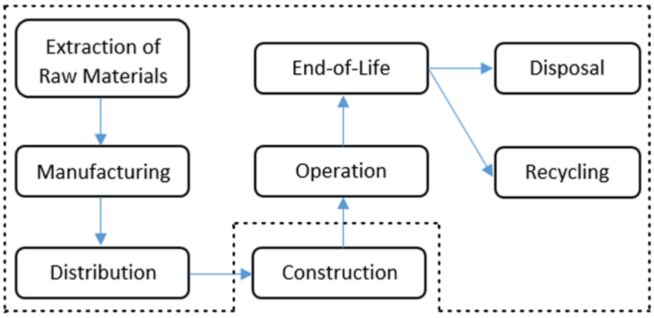
The design of the case study followed the traditional methods of designing a hypothetical multi-story office building in Brazil using two types of building materials: Type (A) and Type (B), as previously discussed. The assessed building composes of 67 offices with a total floor area of about 2730 m^2, divided into four floors. The proposed plan provides three different spaces to work (24 m^2, 32 m^2 and 56 m^2), as seen in Figure 3. This paper applies the LCA methodology based on ISO 14040 and ISO 14044 guidelines within the available databases in order to achieve the objectives of this work [53,54]. Autodesk Revit generates all graphs of environmental impacts and energy consumption presented in this work.



(Fig. 3: 2D plan and 3D modeling of the multi-story office building)

4.1. Goal and Scope

At this level, information needs to be chosen in details: system boundaries, variants and set of data, functional unit, type and impact of analysis, assumptions and limitation of the study. The system boundary refers to the size of LCA. In this work, the system boundary is focusing on several phases over the life cycle of the case study in terms of cradle to grave variant, including extraction of raw materials (cradle), manufacturing, operation, and end-of-life (grave). The system boundary excluded the construction phase, as seen in Figure 4. The end-of-life phase is distinguished by disposal and recycling because the majority of the construction waste in Brazil is disposed of in landfills and vacant lots whereas only 1% is being recycled [11].



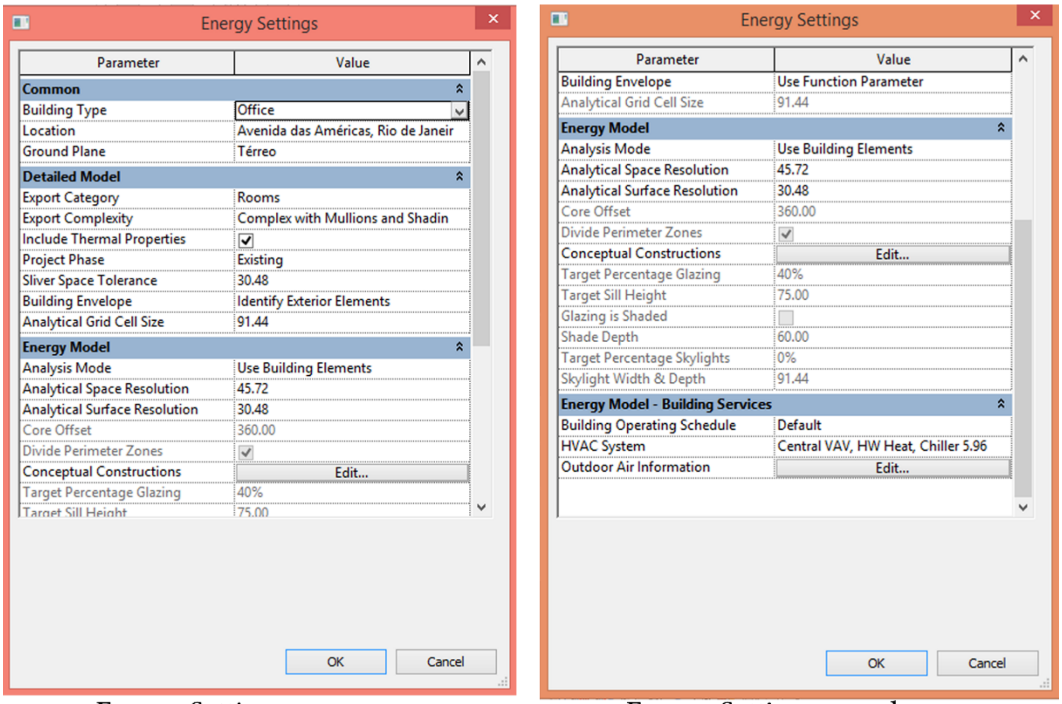
(Fig. 4: layout of the system boundary)

Attention is given to the list of impact categories in order to evaluate the real impact of building materials on the environment during the allocated system boundary of this study. The functional unit, which describes the evaluated product or system [53,54], considers the whole building as a single unit. According to the default technical standard, the average lifespan of an office building in this work is in range of 50 years [85]. However, the scope of this work is to consider the early design stages of constructing a multi-story office building in Brazil. It aims to evaluate the environmental impacts of building materials using the Tally application in Autodesk Revit. This means to quantify and measure midpoint categories based on the selected system boundary and functional units such as acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, primary energy demand, non-renewable energy, and renewable energy.

4.2. Life Cycle Inventory (LCI)

This phase includes details of environmental inputs of materials, energy, outputs in air, water and solid emissions. LCI is a group of elementary flows including all emissions released into and from the environment during the life cycle of a product [53,54]. In other words, this level considers all the inputs and outputs of the production system along the entire lifecycle. In this term, it is highly important to collect reliable and constant data, otherwise invalid results will be proposed at the end of LCA analysis [84]. "*An LCA is only as valid as the data it uses"* [86]. However, collecting a relevant and accessible LCI data is a difficult issue in the field of LCA studies.

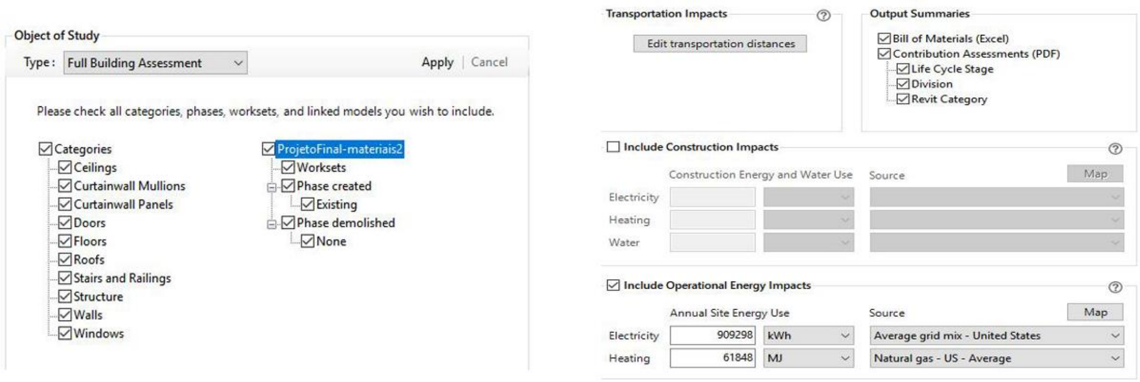
The initial plans and modeling of building materials are constructed in Autodesk Revit software. In this term, it can be considered that specifying the properties of building materials in terms of LCA analysis are not covering the entire lifespan of building materials and some information needs to be added manually. However, Autodesk Revit uses Green Building Studio application as an intelligent energy setting in order to estimate the energy performance in buildings. At this step, different assumptions and parameters are required to be filled-in precisely such as building type, location, thermal properties, project phase, building envelope, analysis mode, conceptual construction, building operating schedule, HVAC system (Heating, Ventilation and Air Conditioning), and outdoor air information, etc., as shown in Figure 5. In this discipline, heating is excluded from operating energy, as it is not commonly used in office buildings in Brazil. However, average distances of 10, 12 and 55 km for transporting materials to the construction site, landfilling wastes, and recycling purposes, respectively, were assumed [11].



Energy Setting, page up Energy Setting, page down

(Fig. 5. Energy consumption analysis in Autodesk Revit)

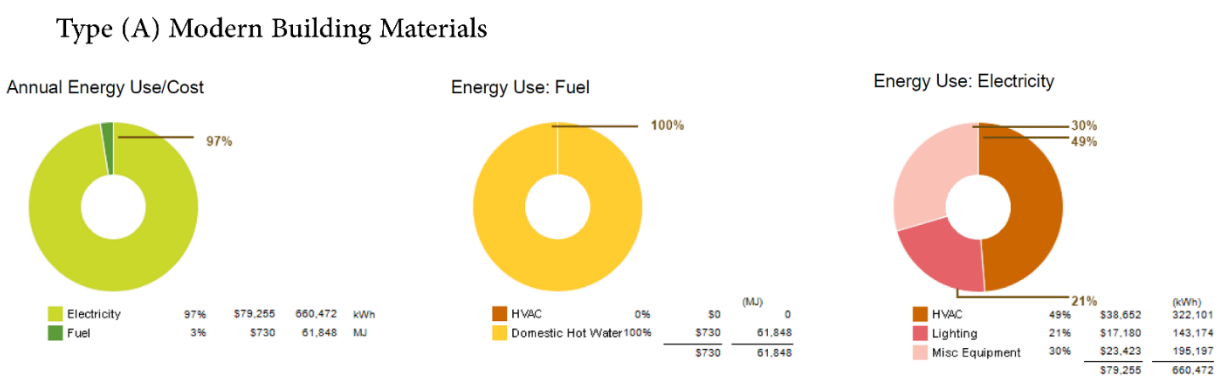
The next step is to transfer the results of energy use, and assumed distances of transportation of the case study into the Tally Application in order to complete the analysis properly and achieve the objectives of this work, as shown in Figure 6. In this discipline, there are some challenges facing the Tally application in the present moment. For example, modeled materials need to be identified properly and similar information is required to be entered for the same materials at every new analysis. As well, geographical sources are adapted for the US region only [68,81].



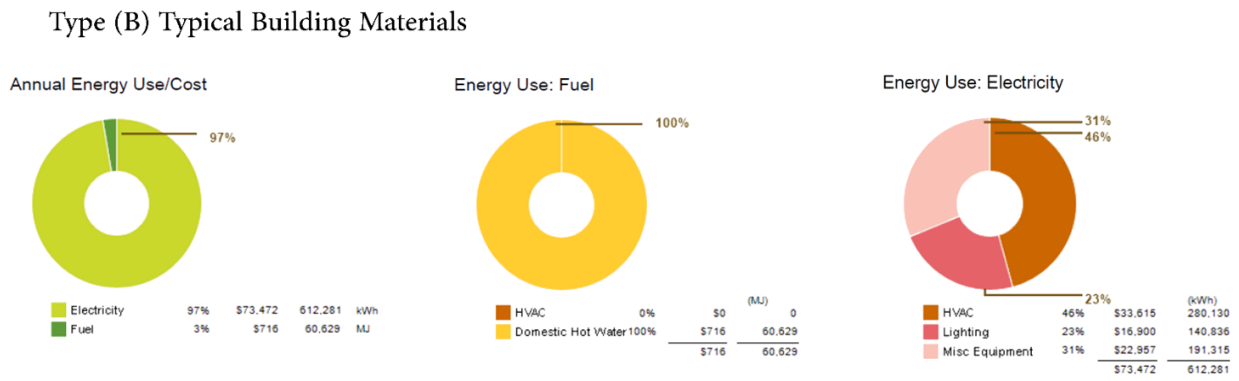
(Fig. 6. Environmental impacts analysis in Tally application)

4.3. Life Cycle Impact Assessment (LCIA)

In this phase, the findings of LCI having the help of impact assessment methods are translated into the impact categories in order to make an easier understanding of the results [87]. Environmental involvements such as the extraction of raw materials, emissions, physical modification of natural area, and noise are being translated into environmental impacts using impact assessment methods [88,89]. Results presented in this research are based on the analysis of building materials used in the functional unit of this work that considered the entire building as a single unit. One of the basic challenges at this step is the difficulty of comparing the different scenarios in such types of analysis. The comparison is manually conducted using Photoshop software to gather figures. However, performing energy consumption analysis is associated with annual energy use: electricity and fuel. The conceptual energy analysis in Figures 7 and 8 shows that consumption of electricity in such type of buildings accounts for 97% of total annual energy use. Type (A) consumes 660472 kWh/year while Type (B) consumes 612281 kWh/year of electricity. These values are distributed in three fields: HVAC system, lighting, and miscellaneous equipment with percentages of 49%, 21%, and 30%, respectively, in Type (A), and 46%, 23%, and 31%, respectively, in Type (B). Consumption of fuel accounts for 3% of total annual energy use, dedicated for domestic hot water in both Types.

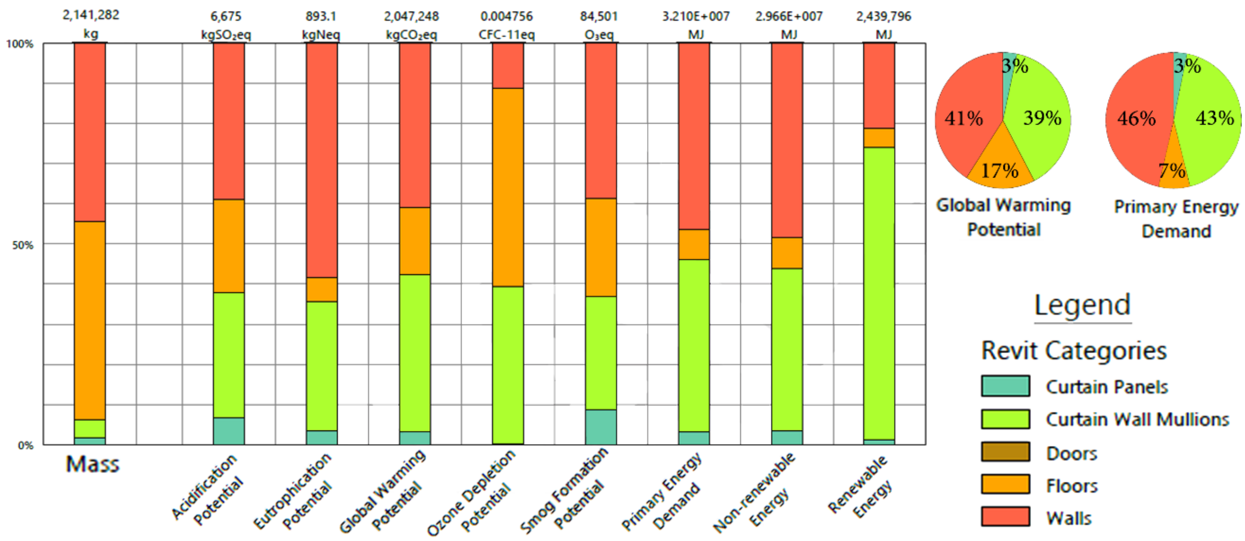


(Fig. 7. Annual Energy Use based on modern building materials)

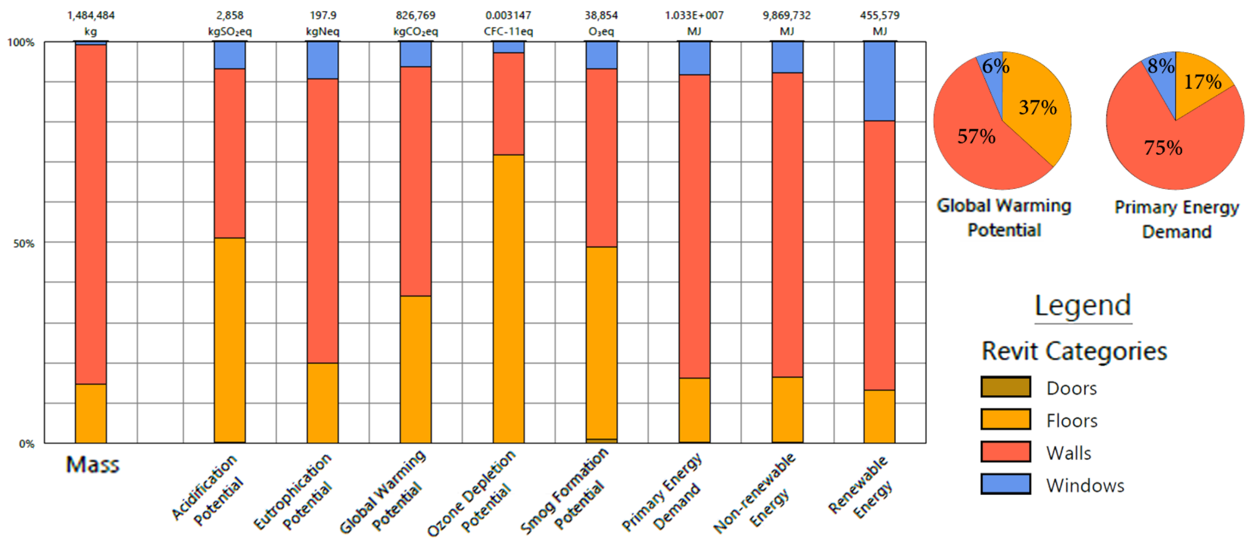


(Fig. 8. Annual Energy Use based on typical building materials)

Figures 9 and 10 show the various impacts of building materials applied in the case study building Type (A) and (B), respectively, and based on Autodesk Revit categories. Figure 9 illustrates the high impacts of curtain wall mullions, floors and walls in this type of construction on the one hand, and the low impacts of curtain panels on the other hand. Figure 10 clarifies the high impacts of floors and walls and the low influences of windows in such type of construction. In this discipline, walls in type (A) are constructed of masonry brick, mortar and paint, while they are constructed of ceramic, masonry brick and mortar in Type (B). Curtain wall mullions in Type (A) are made of aluminum whereas windows in Type (B) are made of aluminum frames and glass. Floors are constructed from reinforced concrete in both Types of buildings.

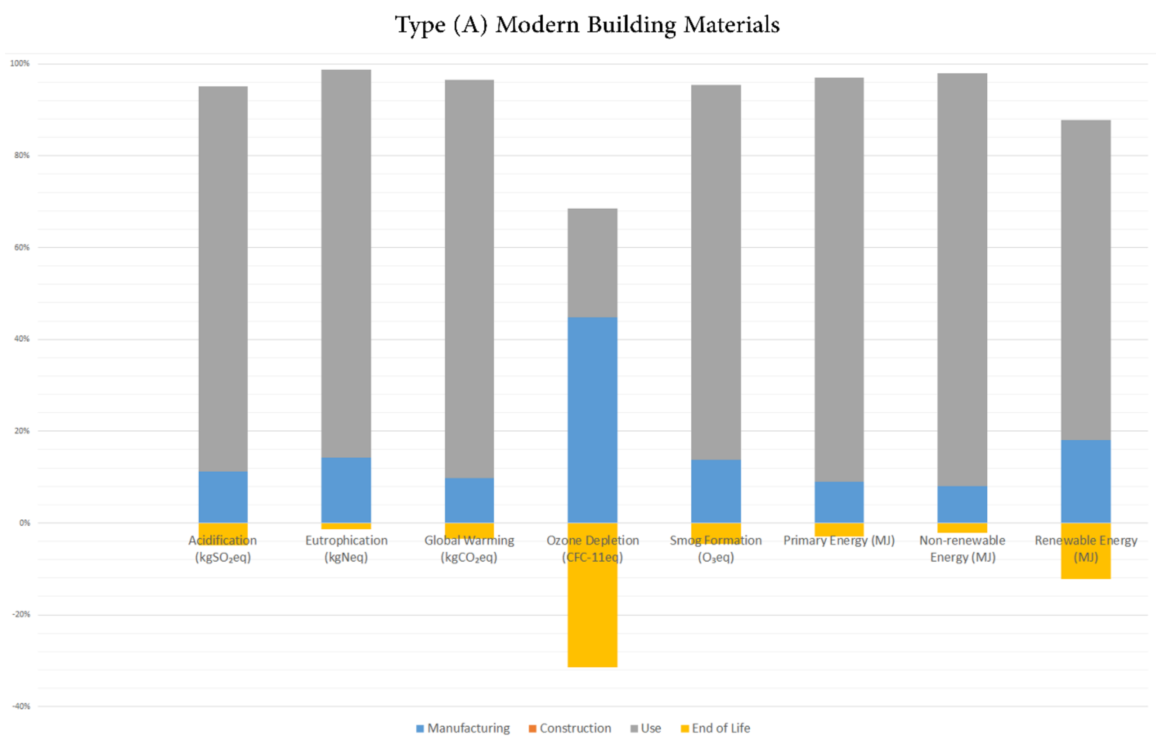


(Fig. 9: Environmental impacts per Autodesk Revit category based Type (A) building)

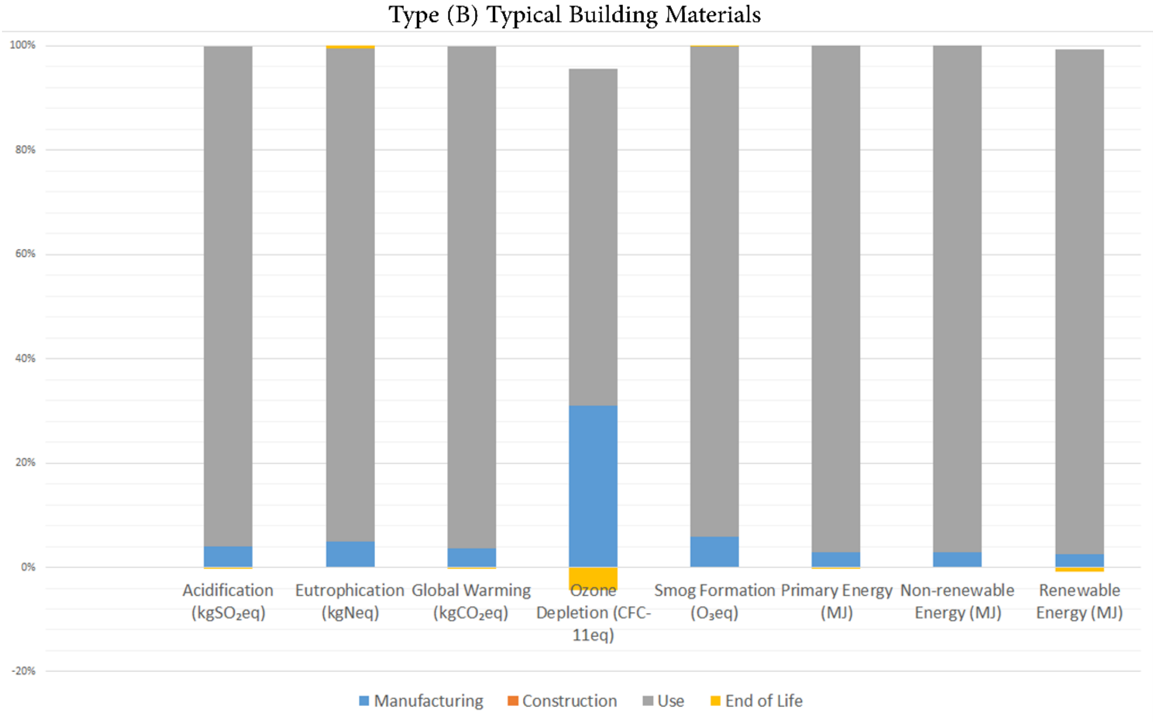


(Fig. 10: Environmental impacts per Autodesk Revit category based on Type (B) building)

Figures 11 and 12 present the total evaluation of environmental impacts of building materials in the case study, based on the life cycle phases assigned in the system boundary. This means to take into consideration each life cycle phase, separately, in order to evaluate the entire environmental impacts of building materials. Both Figures illustrate that this level of analysis considers operation phase as the main agent for the most of the impact categories in such type of buildings while manufacturing phase is considered as the second main agent. However, modern building materials used in Type (A) would positively influence the environmental impacts at the end-of-life phase rather than typical building materials used in Type (B).



(Fig. 11: Total environmental impacts of building materials of Type (A) building)



(Fig. 12: Total environmental impacts of building materials of Type (B) building)

4.4. Interpretations

The interpretations phase begins once one identifies and evaluates the indicators of LCI and LCIA. This phase aims to highlight the environmental issues and make an environmentally friendly decision [53]. Comparing the energy performance in Type (A) and (B) shows that using curtain wall system in office buildings in Brazil would consume more energy than using ceramic walls and normal windows. However, Type (A) reflects low environmental impacts of curtain panels compared to curtain wall mullions and other building materials such as floors and walls. For example, curtain wall mullions are responsible for the most of the impact categories in such type of buildings; particularly renewable energy, global warming potential, ozone depletion potential, primary energy demand and non-renewable energy. Walls and curtain wall mullions are responsible for 80% and 89% of the global warming potential and primary energy demand, respectively, whereas curtain panels are only responsible for 3% of these impact categories. Type (B) shows low environmental impacts of windows compared to floors and walls. Walls are responsible for the most of the impacts in such type of buildings; particularly those are related to eutrophication potential, primary energy demand, non-renewable energy, renewable energy and global warming potential. For example, walls are responsible for 57% and 75% of the global warming potential and primary energy demand, respectively, whereas windows are responsible for 6% and 8% of these impact categories, respectively.

Depending on that and analyzing the results of building materials per life cycle stages in Type (A) and (B), it can be realized that most of the environmental impacts are occurring during the operation phase, while the manufacturing phase is considered the second agent for most of the impacts. However, the end-of-life phase in Type (A) is evaluated with higher benefits to the environment than Type (B).

5. Results and Discussion

This paper illustrated the growing interest in integrating BIM models with LCA methodology. It aimed to evaluate environmental impacts of building materials in the construction sector by examining such integration at early design stages. However, this part of the study is divided into two sections:

5.1. Challenges facing the integration process

This work demonstrates the ability of BIM and LCA integration to evaluate environmental impacts at an early stage of designing buildings. On the one hand, BIM models have the ability to produce adjustable smart objects that are easy to modify and allow the use of different building materials within various design parameters and elements at the designing phase in order to estimate energy performance. On the other hand, LCA is a methodology that aims to evaluate environmental impacts over the entire lifespan of building materials. Thus, integrating BIM tools with LCA methodology is considered as an optimistic course to protect the environment, and empower both sustainability and decision-making processes in the construction sector.

There are some constraints facing BIM-LCA integration in the construction sector such as the insufficient BIM database that needs to be improved at the early design stages of construction projects in terms of developing the LCA application [90]. Hence, more information about material properties should be adapted in BIM models in terms of LCA analysis. Another challenge is that users of the Tally application must define materials properly to the buildings under study. Hence, more effort is desirable to utilize technologically similar entries to the modeled materials. As well, geographical sources in Tally need to be adapted to cover more regions worldwide. There is a limitation of data that are related to building elements in BIM, and the difficulty of comparing scenarios are additional challenges facing this type of integration [20]. The proposed implementation of BIM tools requires more evolving technologies in response to the limitation of knowledge in order to support the sustainable construction and decision-making processes in the construction sector [9,91].

5.2. Evaluation of environmental impacts in the case study

The analyzed case study shows that all building materials are accountable for impact categories in such type of buildings, particularly curtain wall mullions in Type (A) and walls in Type (B). As previously discussed, this study considers that curtain wall mullions in Type (A) are made of aluminum whereas walls in Type (B) are built of ceramic, masonry brick and mortar. It is extremely important to recognize the environmental impacts of such building materials as a prior step to invest in this type of construction in Brazil. In other words, great efforts should be devoted to reduce the impact categories of building materials throughout the entire life cycle stages, particularly at the manufacturing and operation stages. It is important to understand that reducing the environmental impacts of building materials in the construction sector at an early stage of designing buildings requires taking into consideration the technological improvements that have been made in some of these materials [71,72]. This means to review the manufacturing stage of materials that are constructing the elevations of buildings such as curtain wall system and ceramic walls. Moreover, it is well noted that most of the impact categories are occurring during the manufacturing and operation phases. Thus, it is important to revise the installation of building materials in construction projects in a way to enhance energy performance and protect the environment. However, the operation phase of buildings consumes most of the non-renewable energy such as electricity and fuel. Therefore, it is extremely important to emphasize installation of renewable energy systems in such types of buildings in order to increase energy efficiency.

6. Conclusion

This paper examines sustainable construction in terms of BIM-LCA integration at early design stages of construction projects. BIM models allow using local and non-local materials within various design parameters, while LCA is a complicated methodology to evaluate the environmental impacts of building materials. Hence, this work aimed to demonstrate the benefit of the proposed integration between LCA methodology and BIM tools by evaluating environmental impacts and empowering decision-making process in the construction sector. Moreover, this work shed light on the current limitations of data and tools that are passively influencing the integration process.

A case study is presented in a way to apprise designers, architects and engineers about the methodological framework of the integrating process, and evaluate the environmental impacts of building materials over the entire life cycle assessment of buildings. This work reports on an analysis of the different lifespan phases of a typical multi-story office building in Rio de Janeiro in Brazil, using modern building materials, Type (A), and typical building materials, Type (B). Using two types of building materials illustrates a single modification that BIM models could perform to support the decision-making process and sustainability standards in construction projects. The novelty of this work is that it presents the important role of BIM and LCA integration at early design stages in order to evaluate the environmental impacts of building materials assessed in the functional unit of the case study. Autodesk Revit was applied as a BIM tool in order to design the proposed plans of the case study, and justify the inventory level. Then, Green Building Studio and Tally applications in Autodesk Revit were used as tools to estimate the significance of impacts on the elementary flows, measure solutions and advise recommendations.

This work highlighted critical points such as the high impact of the manufacturing and operation phases of building materials on the environment, particularly the passive contribution to acidification potential, global warming potential, ozone depletion potential, and wasting of renewable energy. Thus, this work encourages reviewing the application of building materials in order to reduce the negative contribution to the environmental impacts. Additionally, it recommends installing renewable energy systems in such type of buildings in Brazil in order to reduce the energy consumption and protect the environment. The results indicate that integrating BIM models with the LCA methodology is an optimal procedure towards achieving a sustainable development and environmental protection, and empowering the decision-making process in the construction sector. The methodology proposed can be used to determine which building elements have major importance in the LCA. In the case study, these were curtain wall mullions and ceramic walls as they were responsible for most of the total impacts. Accordingly, it is highly important to review the application of building materials that are constructing such items at an early designing phase and to minimize the passive environmental loads of buildings.

A recommendation for future work is to investigate elementary flow integration between BIM tools and LCA methodology due to the limitation of data and knowledge and the challenges of comparing different scenarios. Considering a wider range of building materials using the experimental design methodology is another recommendation for future work. This recommendation could help to evaluate energy performance, CO_2 production and environmental impacts of a wider range of building materials over the entire life cycle assessment of buildings.

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APPENDIX 2

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

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

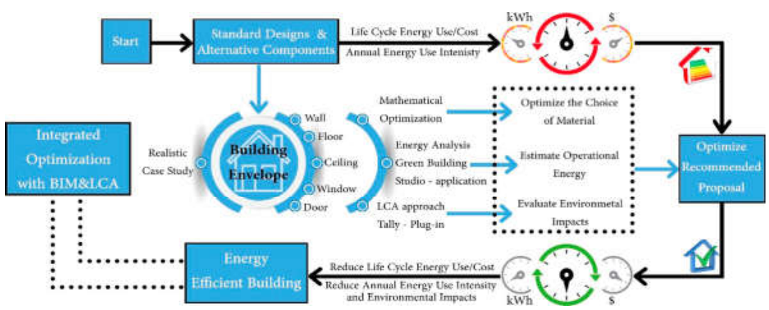
Mohammad Najjar[a], Karoline Figueiredo[a], Ahmed W.A. Hammad[b], Assed Haddad[a,*]

[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



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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).

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Integrated Optimization with Building Information Modeling and Life Cycle Assessment for Generating Energy Efficient Buildings

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.

Keywords. *Building information modeling; Life cycle assessment; Energy consumption; Sustainable construction; Environmental impacts.*

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:

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

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% to 90% of the life-cycle energy consumption [8], while embodied energy accounts for around 10% to 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 **Figure 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 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 **Figure 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.

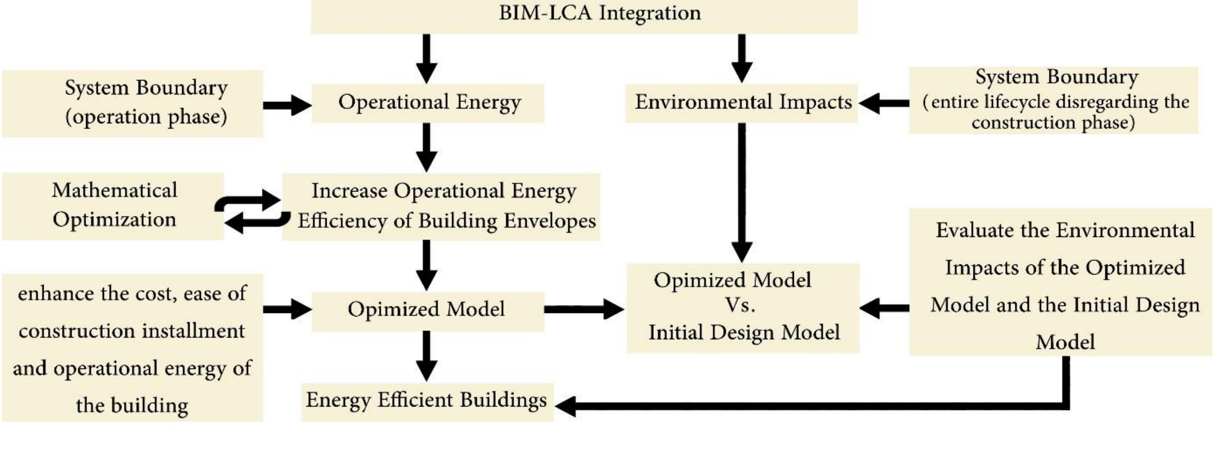


Figure 1. A general stream of this work

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 **Figure 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.

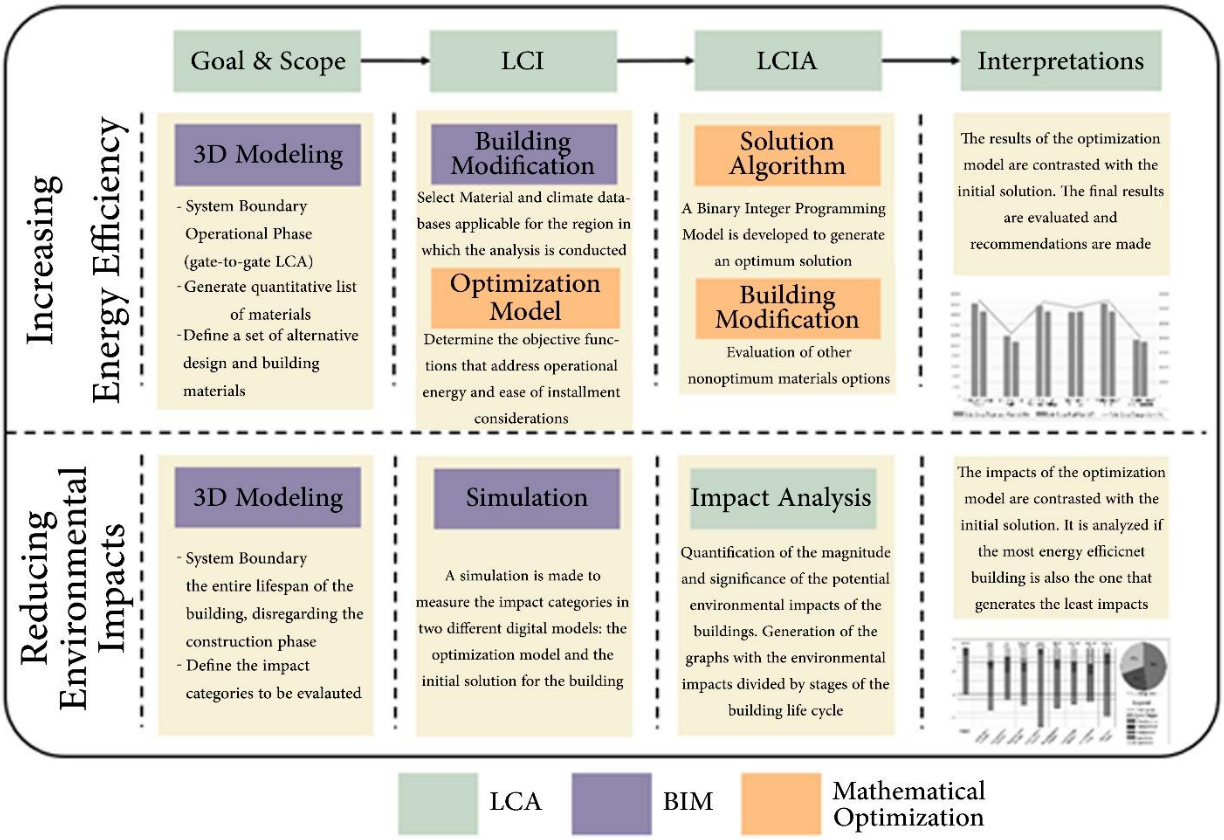


Figure 2. Flowchart of decision support analysis

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 **Figure 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:

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

In particular, the interaction between two components linked together in the building, namely c and $\tilde{c}$ is assessed, in terms of the easiness of installing the components together via the ease of installment matrix, $I_{m,c,\tilde{m},\tilde{c}}$. 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 $\tilde{c}$, where material m and material $\tilde{m}$ 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, iv) the extent of training required for construction technicians, and v) 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:

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

The first term, $Q_{Heat,c}^m x_c^m$ computes the total energy expended on heating the building, as influenced by the choice of material m for component c. The second term $Q_{Cool,c}^m x_c^m$ 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), $Q_{DHW,c}^m x_c^m$, 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:

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

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:

$$x_c^m = 0, \forall (c, m) \in Exclusion\_List \qquad (5)$$

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:

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

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

$$Q_{Heat,c}^m = (Q_{Heat,tr,c}^m + Q_{Heat,ve,c}^m) - \vartheta_{Heat,c}^m \times Q_{Heat,gn,c}^m \qquad (7)$$

$$Q_{Cool,c}^m = Q_{Cool,gn,c}^m - \vartheta_{Cool,ls,c}^m \times (Q_{Cool,tr,c}^m + Q_{Cool,ve,c}^m) \qquad (8)$$

$$Q_{DHW,c}^m = 4.182 \times V_{W,c}^m \times (\theta_{w,t} - \theta_{w,0}) \qquad (9)$$

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:

$$x_c^m \in \{0,1\}, \forall\, m \in M, \forall\, c \in C \qquad (10)$$

2.2.3. Solution approach

To determine the Pareto optimal solutions for the multi-objective optimization problem Eq (1) to Eq. (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 **Figure 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 **Figure 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 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 **Figure 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].

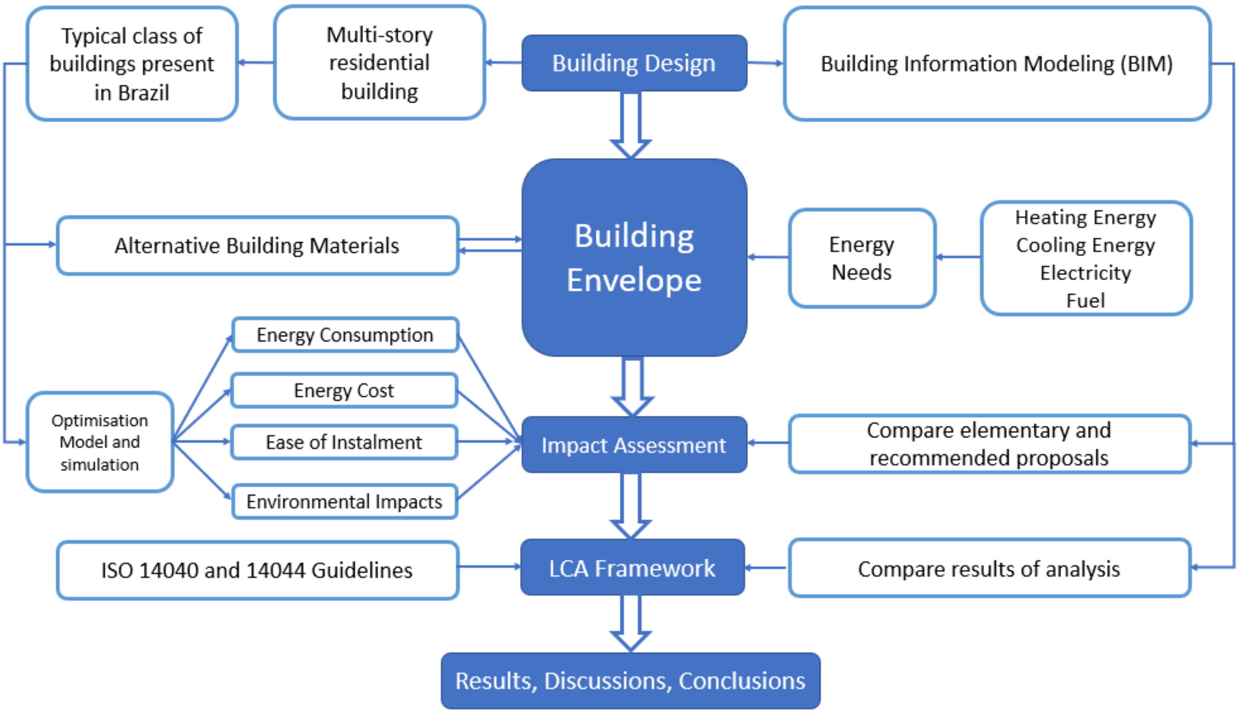


Figure 3. The methodology of this work

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 **Figure 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 seconds.

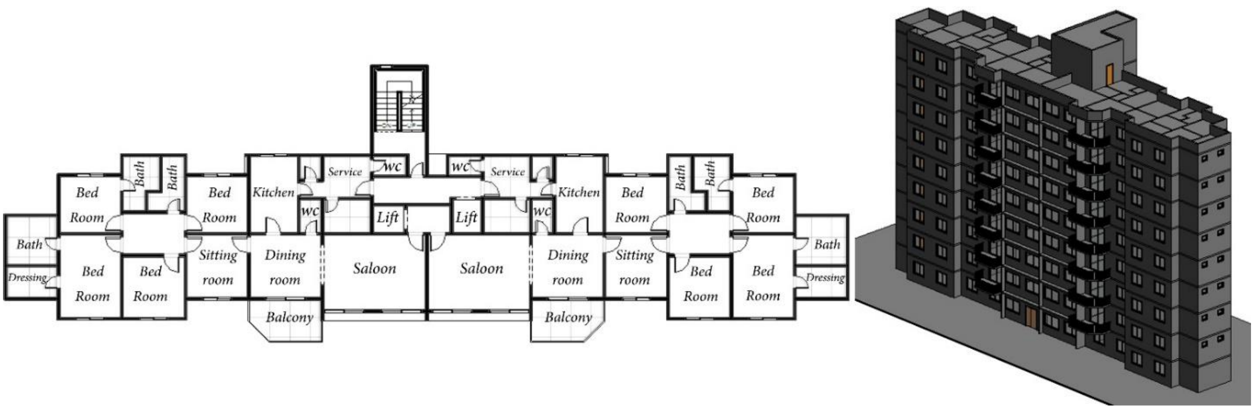
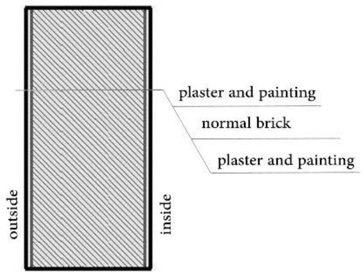
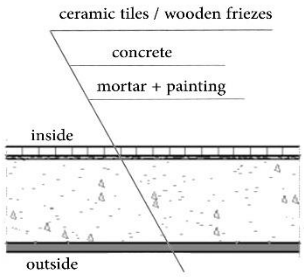
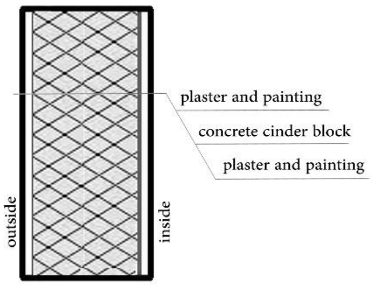
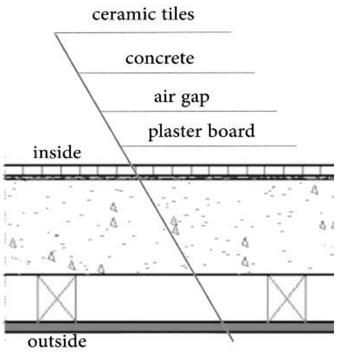
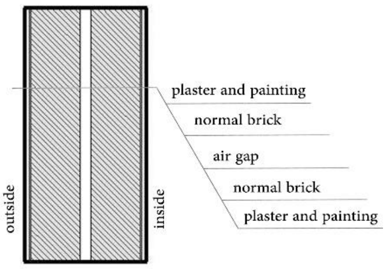
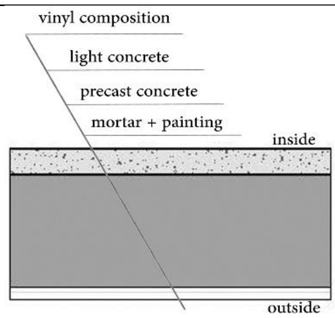
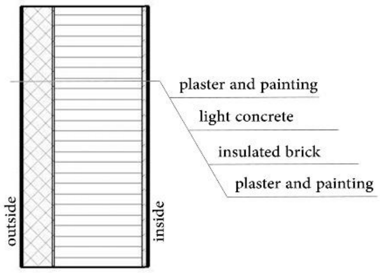
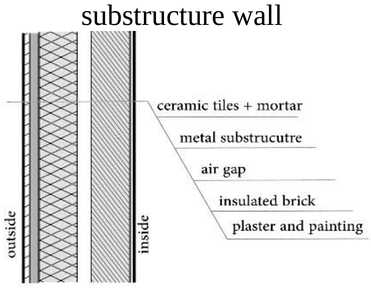


Figure 4. 2D and 3D plan of the multi-story residential building used as a case study

The first building components utilized were based on the regulation of the Brazilian Standard ABNT NBR 12721:2007, presented in Minas 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 26ºC 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 1. Standard design and alternative materials for the building components in the case study

	Exterior Walls	**Floors**	**Windows**	**Doors**
Standard Design	Ceramic masonry block 9cm x 19cm x 19cm  U-Value: 2.48 W/m².K	Concrete floor with mixed of Wooden friezes and ceramic tiles  U-Value: 2.64 W/m².K	Sliding window 1.20m x 1.20m Aluminum frame, brass color, with glass 4 mm U-Value: 3.58 W/m².K	Waxed solid wood U-Value: 3.00 W/m².K
Material Alternative 1	Concrete block wall  U-Value: 2.22 W/m².K	Suspended concrete floor  U-Value: 2.37 W/m².K	Sliding Birchwood window 1.20m x 1.20m U-Value: 3.67 W/m².K	Wood with stainless steel U-Value: 3.12 W/m².K
Material Alternative 2	Double brick cavity wall	Precast concrete platform slab	Double casement aluminum window 1.20m x 1.20m	Wood and EPS door

	 U-Value: 1.50 W/m^2.K	 U-Value: 1.98 W/m^2.K	U-Value: 2.02 W/m^2.K	U-Value: 3.27 W/m^2.K
Material Alternative 3	Insulated brick and light plaster wall  U-Value: 1.20 W/m^2.K	X	Sliding Pinewood window 1.20m x 1.20m 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  U-Value: 1.88 W/m^2.K	X	Standard window 1.00m x 1.20m (narrow size) U-Value: 3.58 W/m^2.K	Steel galvanized with insulation glazed U-Value: 2.40 W/m^2.K

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 2534630 (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 149893 ($). 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 Subsection 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 **Figure 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**.

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

Building Component: 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**	**Ease of Instalment**

						(kWh/m^2)	
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

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 **Figure 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.

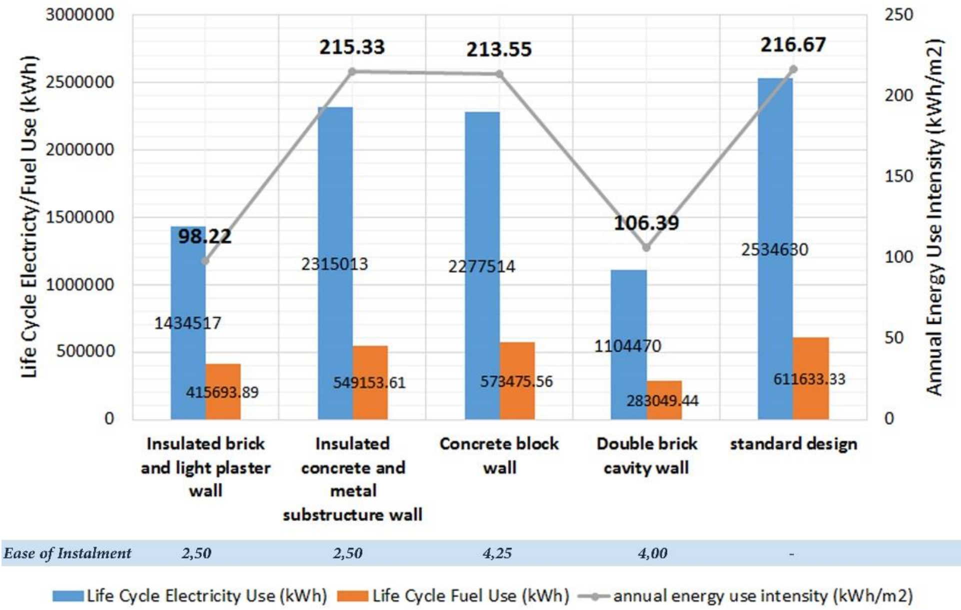


Figure 5. Comparison of the exterior wall components applied in the case study

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**.

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

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 **Figure 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.

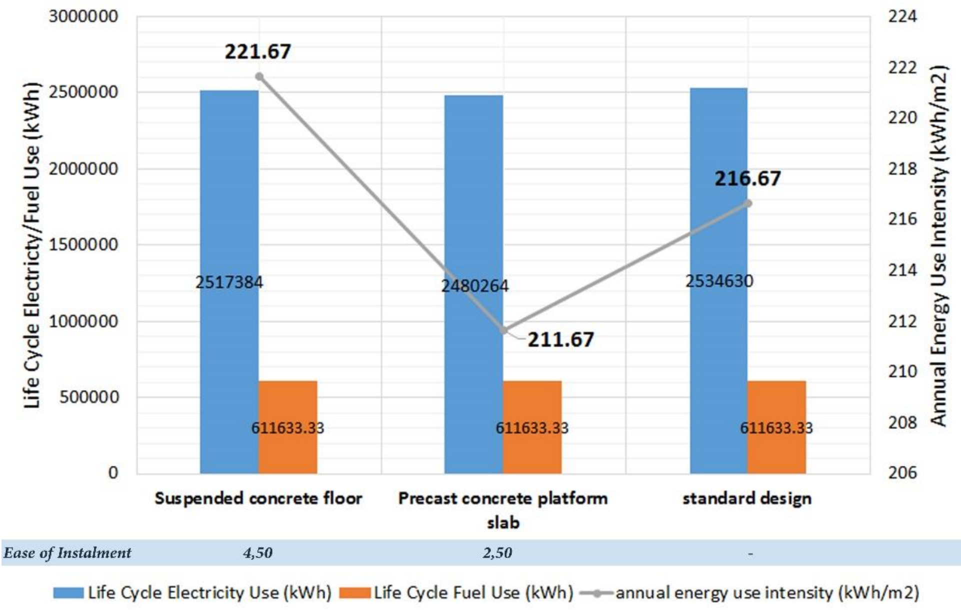


Figure 6. Comparison of the floor and ceiling components applied in the case study

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**.

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 1.20x1.20 m.	2.579.977	611.633,33	152.363	177	41,67	218,67	2,25
Double casement aluminum window 1.20 x 1.20 m	2.178.083	611.633,33	130.468	149	41,67	190,67	3,50
Sliding Pinewood window 1.20 x 1.20 m.	2.137.651	611.633,33	128.265	145	41,67	186,67	2,25
Standard window 1.00 x 1.20 m. (narrow size)	2.381.870	611.633,33	141.570	163	41,67	204,67	4,25

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 **Figure 7**. The presented results show that the life cycle energy use of sliding birchwood window (1.20mx1.20m) is the worst among the other alternatives, while the life cycle energy use of sliding pinewood window (1.20mx1.20m) could be the most energy efficient window component in such types of buildings that could result in a better operational energy savings, leading to more energy efficient buildings.

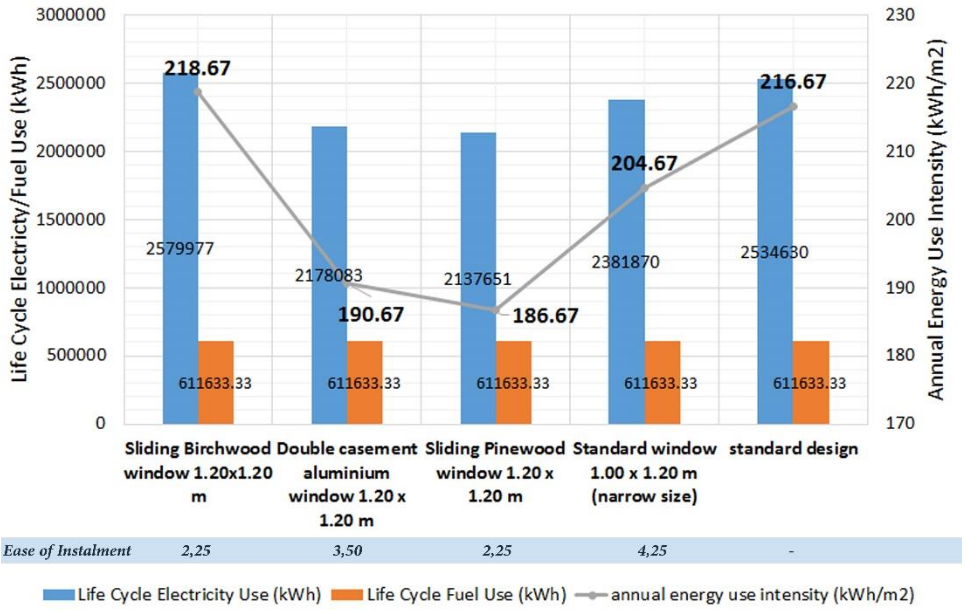


Figure 7. Comparison of the window components applied in the case study

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**.

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/m²)**	**Annual FUI (kWh/m²)**	**Annual Energy Use Intensity (kWh/m²)**	**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

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 **Figure 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.

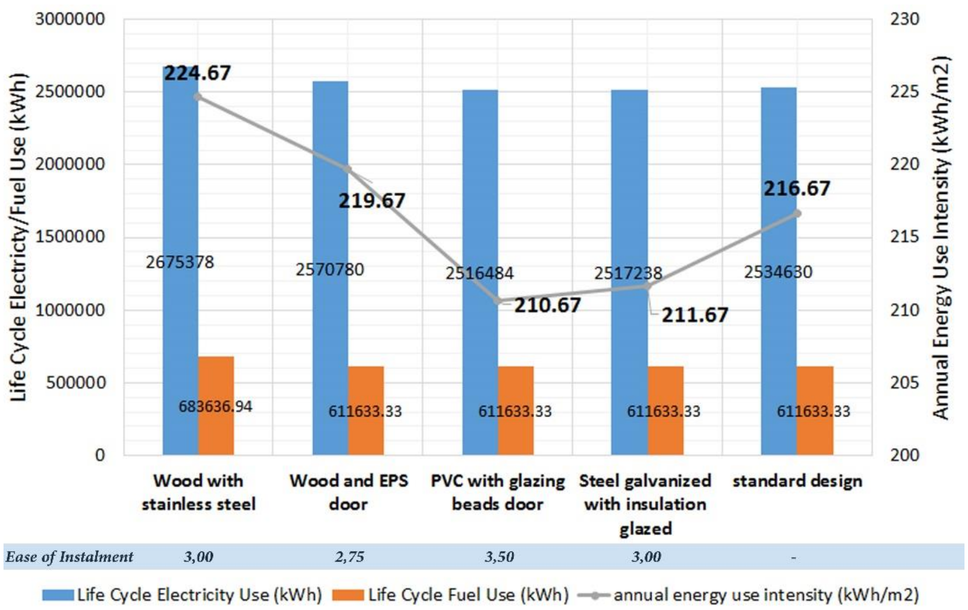


Figure 8. Comparison of the door components applied in the case study

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 1099673 (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 62494 ($). 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.

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/m2)	41,67	23,05
Annual electricity use intensity (kWh/m2)	175	96

Annual energy use intensity (kWh/m2)	216,67	119,05
Life cycle electricity use (kWh)	2534630	1099673
Life cycle fuel use (kWh)	611633,33	283049,44
Life cycle energy cost ($)	149893	62494

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 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 **Figure 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**, 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 **Figure 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.

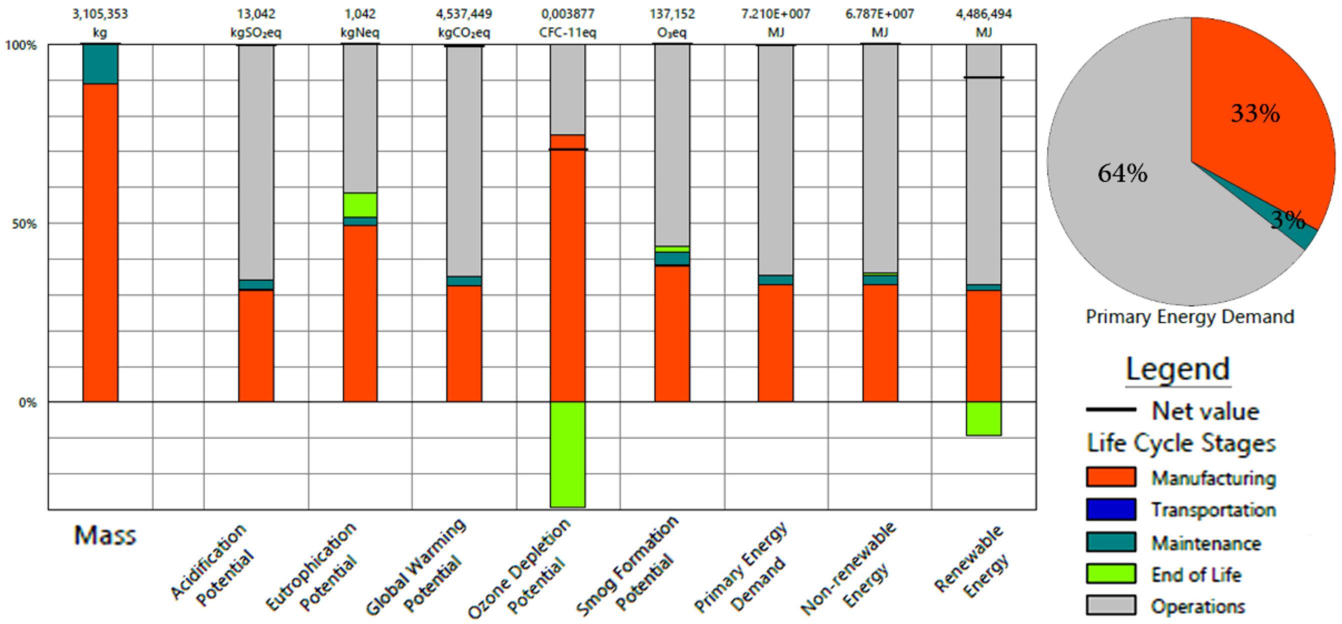


Figure 9. Environmental impacts of the building based on a standard design

The evaluation of the environmental impacts of the case study building based on the recommended proposal is presented in **Figure 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.

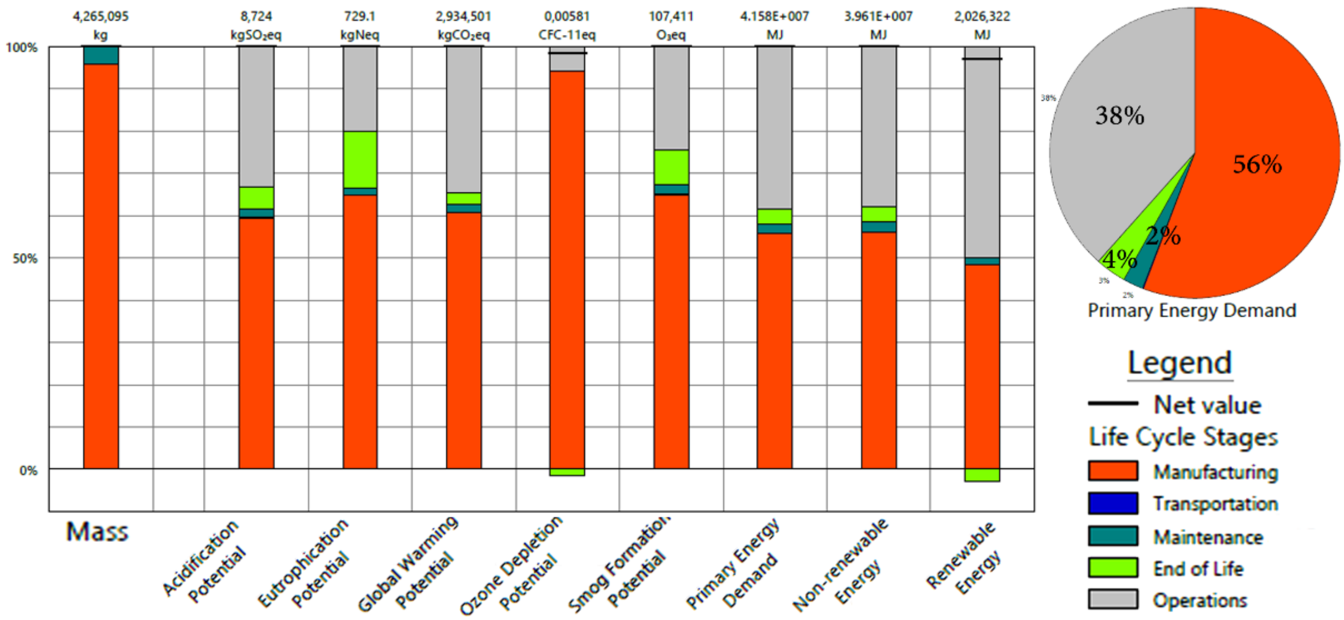


Figure 10. Environmental impacts of the building based on a recommended proposal

The acidification potential decreased from 13,042 kg SO_2 equivalent in the standard design model to 8,724 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.

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 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 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.

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

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 **Figure 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.

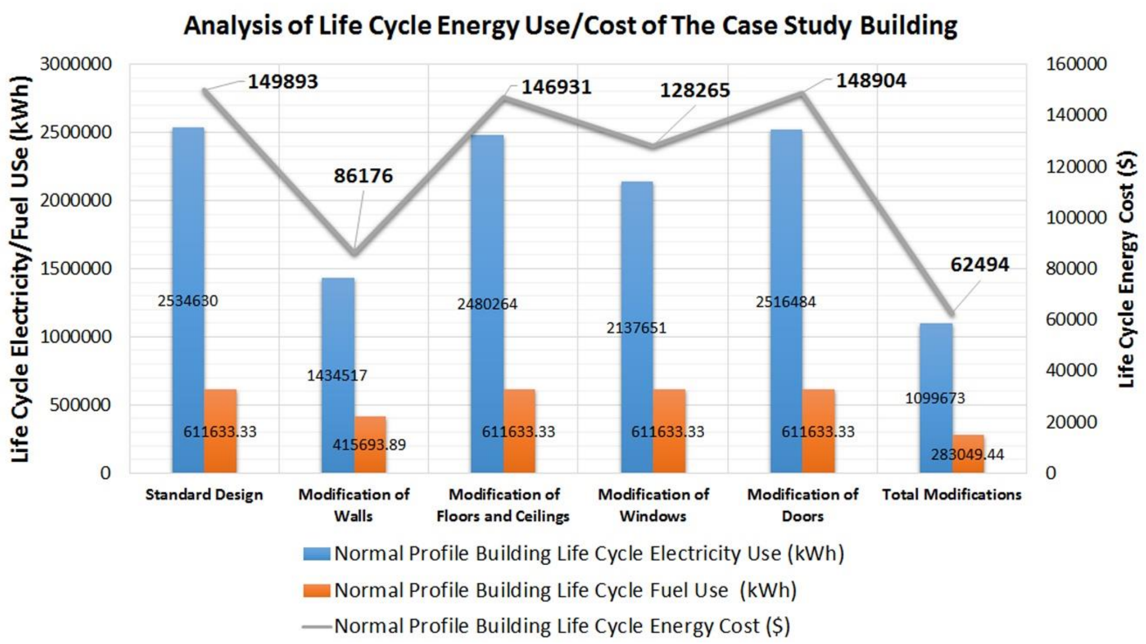


Figure 11. Analysis of lifecycle energy use/cost in the case study

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 14040 and 14044 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.

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Appendix

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/m³ 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)

APPENDIX 3

Evaluation of Environmental Impacts of Building Materials in the Construction Sector Integrating BIM and LCA

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Evaluation of environmental impacts of building materials in the construction sector integrating BIM and LCA

Mohammad Najjar;mnajjar@poli.ufrj.br
Universidade Federal do Rio de Janeiro
Karoline Figueiredo - karolinefigueiredo@poli.ufrj.br
Universidade Federal do Rio de Janeiro
Alex Ximenes Naves - axnaves@id.uf.br
Universidade Federal Fluminense
Dieter Boer - dieter.boer@urv.cat
Universitat Rovira i Virgili
Assed Haddad - assed@poli.ufrj.br
Universidade Federal do Rio de Janeiro

Abstract
Reducing the environmental impact of construction materials is a crucial issue over the life cycle assessment, particularly in manufacturing, operation and end-of-life phases of these materials. This study aims to integrate building information modeling with life cycle assessment in order to incorporate the decision-making process and the design of sustainable buildings. This research targets to evaluate the life cycle methodology of office buildings based on ISO 14040 and 14044 guidelines within the available database. Autodesk Revit software is applied as a building information modeling program, while Tally application is used as an evaluation method to estimate the environmental impacts. This paper recommends that designers and engineers use curtain wall system for the exterior facades instead of concrete and metals, due to the low environmental impact of using this type of system in Brazilian construction. Furthermore, this work points out the passive influence of the manufacturing and operation phases on the environment.

Keywords
Life Cycle Assessment; Building Information Modeling; Environmental Impact; Sustainable Building

Evaluation of environmental impacts of building materials in the construction sector integrating BIM and LCA

TS11 – Sustainable materials and building technologies
CT8 - Construction

Introduction

The construction sector is considered as an activity that consumes energy, natural resources and passively affects the environment [1]. It is highly important to assess the need for innovations and solutions to achieve sustainability standards in construction, particularly in serious circumstances such as rising competition, depletion of resources and deficiency of standards that protect the environment [2]. These circumstances are influencing the energy consumption over the entire Life Cycle Assessment (LCA) of construction materials since the extraction of raw materials, manufacturing, packaging and transportation to the site, construction and installation, operation, until demolition and recycling [3,4]. The novelty of this work is to integrate BIM and LCA at an early designing stage of a construction project in order to evaluate the environmental impacts of building materials in the construction sector.

The methodology of LCA is divided into three main phases, as shown in Figure 1, based on the activities included in each phase; pre-building phase, building phase and post-building phase. The pre-building phase includes the activities since the extracting of raw materials, manufacturing and transporting to the construction site. The building phase includes both the construction and operation periods of the building. The post-building phase refers to the end-of-life time of the building. Besides, the energy consumption of buildings over their entire lifespan is divided into five main stages, as shown in Figure 1. The first stage, characterized as embodied energy, comprises the extracting and manufacturing phase of raw materials. The next stage is grey energy. It refers to the transportation phase of building materials from the factory to the construction site. The third and fourth stages are the actual energy used for construction and operation phases. The energy consumed in these two phases so called as induced energy and operation energy, respectively. The final stage is the energy used for demolition and recycling at the end-of-life phase of the building [5-7].

Figure 1 – LCA phases and relevant energy consumption

LCA is a technique that evaluates the environmental impacts of construction materials over the different lifespan phases of buildings. The number of publications in this field has rapidly increased from only 88 in 2011 to 264 in 2015 [8]. Several types of research discussed the methodology of LCA from a building perspective and revised this methodology in case studies [9-13]. Building Information Modeling (BIM) is an operative generation of information technology that intends to integrate the building information and the field of knowledge in planning, designing, building, managing, and recycling over the different lifecycle phases of construction projects [14]. There are different publications that examined the application of BIM methodology in the construction sector and highlighted the objectives and the potential of green BIM tools in the construction sector [15,16]. However, some publications praised the role of BIM and LCA integration as a promising opportunity in the Architectural, Engineering, and Construction (AEC) industry, and evaluated the ability of such integration to cover the three pillars of sustainable development; environment, social and economic [17-19]. Other works evaluated the role of BIM-LCA integrations in the sustainability standards and energy performance in the construction sector [20,21]. Many publications considered this integration as a valuable solution to assess the environmental impacts in the construction sector and empower the decision-making process and the design of sustainable buildings [19,20,22]. Decision-making process raises the awareness of the architects, designers and builders to address the environmental issues [22,23], and achieve efficient, cost-effective, and sustainable design standards at early stages of designing construction projects [15].

This work analyses LCA methodology from a building perspective and highlights the role of BIM and LCA integration in evaluating the environmental impacts of construction materials, and empowering the decision-making process and sustainable design procedure in the construction sector. The objective of this work is to motivate the integration of BIM and LCA methodologies at early designing stages of construction projects and present the interests of such integration in assessing the environmental impacts of construction materials. Besides, this work shows the role of sustainable construction in reducing the environmental impacts such as global warming potential, acidification potential, ozone depletion potential, eutrophication potential, smog formation potential, and non-renewable energy. This work proposes the use of Autodesk Revit as a BIM modeling software and Tally plug-in in Revit as an LCA tool in order to achieve the objectives of this work.

Materials and Methods

BIM and LCA integration attracts experts interested in sustainability and environmental engineering. This comes back to the ability of BIM models to produce integrated design and support information management and cooperation between stakeholders in the construction sector [19], and provide several design alternatives during the early design stages [22,24]. LCA appears as a suitable method assessing environmental impacts [25,26]. Thus, it can be considered that BIM and LCA integration is an urgent course aims to achieve the sustainability standards and protect the environment [19,22,27]. Such integration relies on exchanging data between BIM software and LCA application. It simplifies database and provides an inclusive feedback of construction projects [28]. BIM modeling gives the opportunity to produce various modifications and simulations for the building design, orientation, materials, parameters and renewable energy [29-32], and evaluate the environmental impacts of building materials and protect the built environment [33].

The methodological framework of LCA based on ISO 14040 and 14044 guidelines is applied in this work, taking into consideration the basic steps of LCA methodology, as shown in Figure 2 [34,35]: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations. Goal and scope step identifies the functional unit, system boundary and the set of construction materials. The next step is LCI that is the most challenging level of LCA methodology due to the difficulty of collecting modeling data. At the LCIA step, all the quantities of materials, energy consumption and resulting emissions are assessed using the indicators of sustainability. Interpretation is the final step that allows for the identification and evaluation of the results acquired at the LCI and LCIA steps. Furthermore, this work uses the construction of a multi-story office building in Brazil as a case study to examine the validity of BIM-LCA integration in order to evaluate the environmental impacts of construction materials. The design of the case study building followed the traditional design methods of office buildings in Brazil, using curtain wall system as a covering material for the exterior facades. In addition to materials such as concrete, masonry, metals, and finishes.

Figure 2 shows that the first step in such analysis is to design the initial plans and models of the proposed building using Autodesk Revit software. Revit conducts the 3D modeling of the case study building taking into consideration the inventory database of construction materials, local climate data, and quantities of construction materials. Besides, Revit assesses the conceptual energy performance in buildings using Autodesk Green Building Studio. Results of energy at this step are highly required to set up a life cycle energy analysis at the operation phase of buildings [36]. Additionally, this work uses Tally plug-in in Autodesk Revit as LCA tool. Tally is the first life cycle assessment plug-in in Revit that evaluates the environmental impacts of the construction materials [37] and provides an effective feedback of LCA at the designing phase of a construction project [38]. As previously discussed, the first step to analyze LCA methodology starts by determining the goal and scope of the work before building up the LCI. However, the inventory of data set in Tally is modeled using GaBi database [36]. The next step is to integrate outputs of Revit with the LCIA in order to sort out simpler understanding results and achieve the objectives of this work, before conducting the interpretation process by classifying sources of impacts, comparing solutions, and suggesting recommendations that may improve the design of buildings. Finally, results are observed by discussing the work and presenting conclusions.

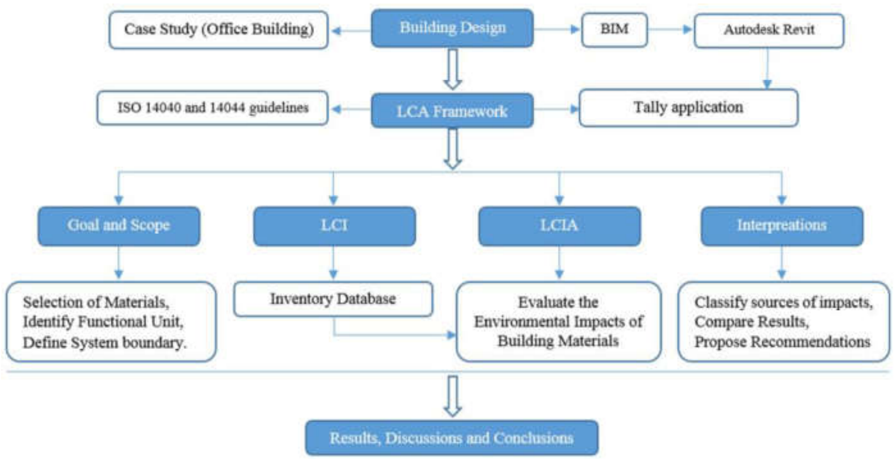

Figure 2 – Research methodology

Case Study

The assessed building is a multi-story office building composes of 4 floors with a total floor area of about 2730 m^2. The proposed plan includes three different spaces to work (24 m^2, 32 m^2 and 56 m^2), as shown in Figure 3. Autodesk Revit generates all graphs of environmental impacts and energy consumption presented in this work. However, this paper applies the LCA methodology based on ISO 14040 and ISO 14044 guidelines in order to evaluate the environmental impact of construction materials in a typical office building in Brazil [34,35]:

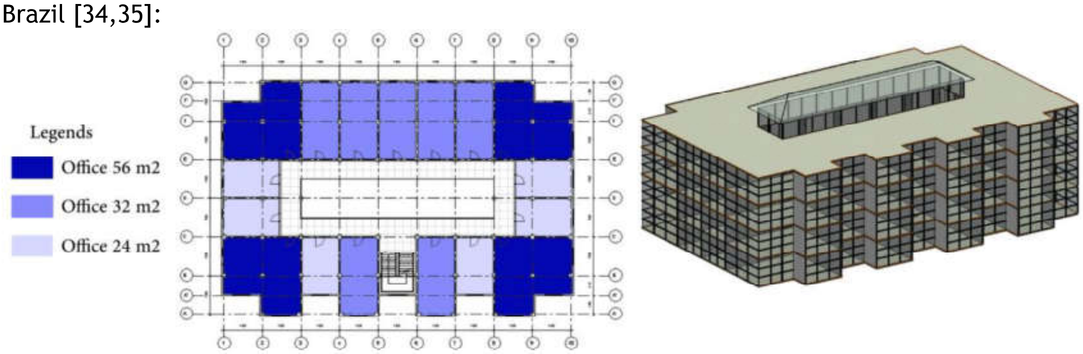

Figure 3 – 2D plan modeling of the case study

Goal and scope. At this level, information needs to be chosen in details: system boundaries, functional unit, type and impact of analysis, assumptions, and limitation of the study. The functional unit of this work considers the whole building as a single unit. The system boundary focuses on several phases of the life cycle of the case study, including extraction of raw materials, manufacturing, operation and end of life, and excluding the construction phase, as shown in Figure 4.

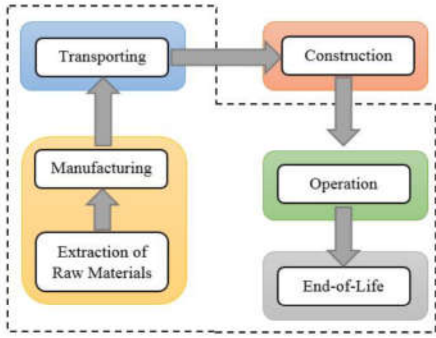

Figure 4 - System boundary of the case study

Attention is given to the list of impact categories in order to evaluate the real impacts on the environment during the allocated system boundary of this study. According to the default technical standard, the average lifespan of an office building in this work will be in a range of 50 years [39]. Autodesk Revit automatically calculates the quantities of construction material for the modeling of buildings, as shown in Table 1. However, the scope of this work is to evaluate the environmental impacts of construction materials at the early design stages of constructing a multi-story office building in Brazil.

Table 1- quantities of construction materials

Material	Quantity (kg)
Glazing	36,133.90
Aluminium	98,079.70
Concrete	1,016,580.20
Brick	511,019.50
Steel	42,151.30
Mortar	68,212.90
Paint	2,673.20

Life Cycle Inventory (LCI). This phase includes details of environmental inputs of construction materials and energy and outputs in the air, water and solid emissions. LCI is a group of elementary flows including all emissions released into and from the environment during the life cycle of a product. However, unreliable and inappropriate inventory database of LCA methodology will cause prejudice and disadvantages impact assessment results [40].

This study uses Autodesk Green Building Studio in Autodesk Revit as an intelligent application estimates the energy consumption in buildings. At this level of analysis, several assumptions and parameters are required to be filled-in sufficiently and build-up reliable inventory data. These are building type, location, thermal properties, project phase, building envelope, building zone and spaces, building surfaces and openings, building operating schedule, HVAC system (Heating, Ventilation and Air Conditioning), and outdoor air information, etc. However, heating demands are not used in office buildings in Brazil and excluded from operating energy in this analysis.

Moreover, this study applies Autodesk Revit to construct the initial plans and properties of construction materials. Besides, it applies Tally plug-in in Autodesk Revit to evaluate the environmental impact. However, collecting a relevant and accessible LCI data is a difficult issue in the field of LCA studies. Thus, the inventory database in Tally, GaBi, is used as a background data to evaluate the LCA of the case study. Finally, average distances of 10, 12 and 55 km for transporting materials to the construction site, landfilling wastes and recycling purposes, respectively, were assumed in order to build-up a relevant and reliable database [9].

Life Cycle Impact Assessment (LCIA). In this phase, the findings of LCI with the help of impact assessment methods are translated into the impact categories. In other words, the quantities of construction materials, energy consumption and released emissions are to be evaluated in order to generate simpler understanding results [41]. At the energy analysis level, the results presented in this work and generated by Autodesk Revit are estimated based on the analysis and comparison of building components used in the functional unit of the case study. However, this part of the analysis is basically associated with annual energy use: electricity and fuel. Figure 5 presents that the annual consumption of electricity in such types of buildings accounts for 660472 kWh/year whereas the consumption of fuel accounts for 61848 MJ/year. Figure 5 illustrates that such building consumes fuel for domestic hot water purposes only, while electricity is used for HVAC, lighting and miscellaneous purposes with percentages of 49 %, 21 % and 30 %, respectively.

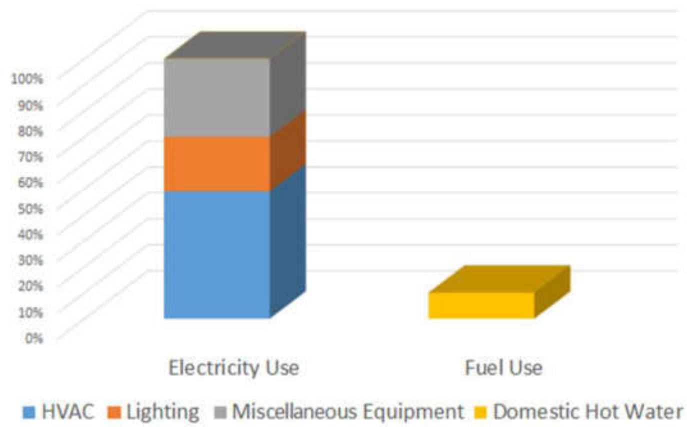

Figure 5 – Annual energy consumption

According to the results obtained in Tally, this paper examines the impact categories of construction materials as seen in Figure 6, which illustrates the low environmental impacts of opening and glazings compared to metals, finishes and concrete.

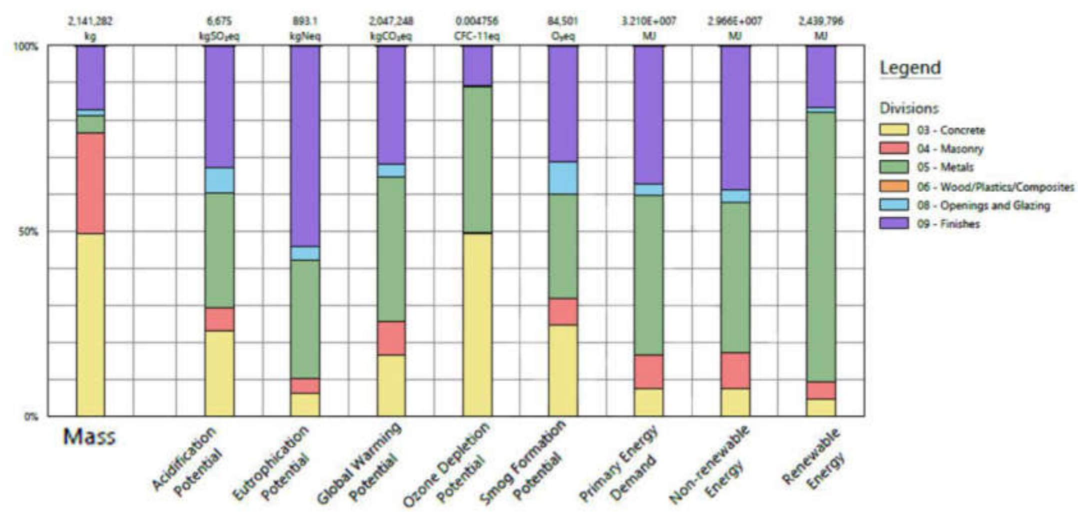

Figure 6 – Impact categories per construction materials

Besides, this paper highlights and calculates the environmental impacts of construction materials at each life cycle stage: manufacturing, transportation, operation and end-of-life, as shown in Figure 7. This means to take into consideration each life cycle stage, separately, in order to evaluate the entire environmental impacts of materials assessed in the functional unit of this work.

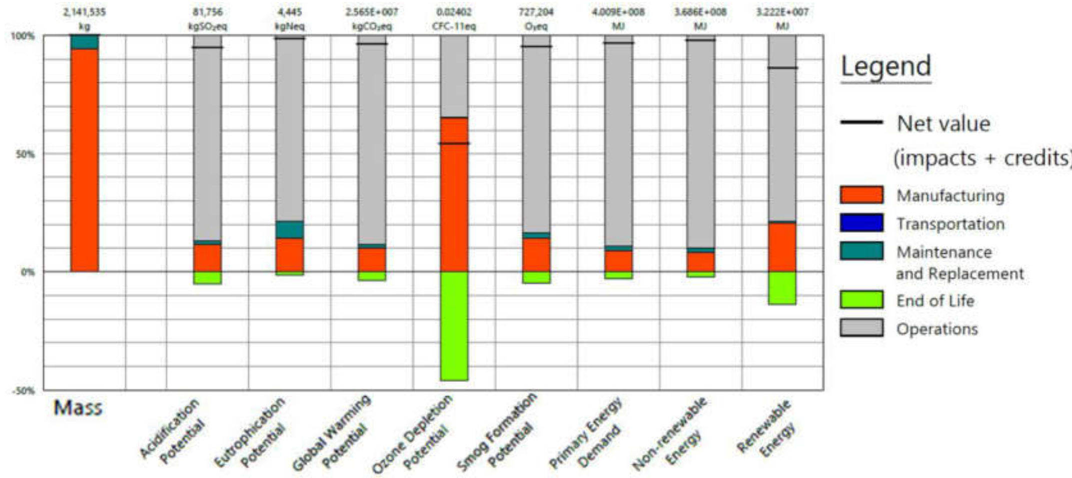

Figure 7 – impact categories per life cycle stages

This research conducts a detailed comparison of the environmental impact categories of construction materials over the different life cycle stages. Figure 8 highlights the individual impact of each material on the environment throughout the different life cycle phases. This means to take the life cycle stages, individually, in order to evaluate the environmental impacts of each construction materials in the case study. This figure identifies that most of the environmental impacts of curtain wall mullions, floors and walls are occurring throughout the manufacturing and operation stages of the total life cycle assessment of these materials.

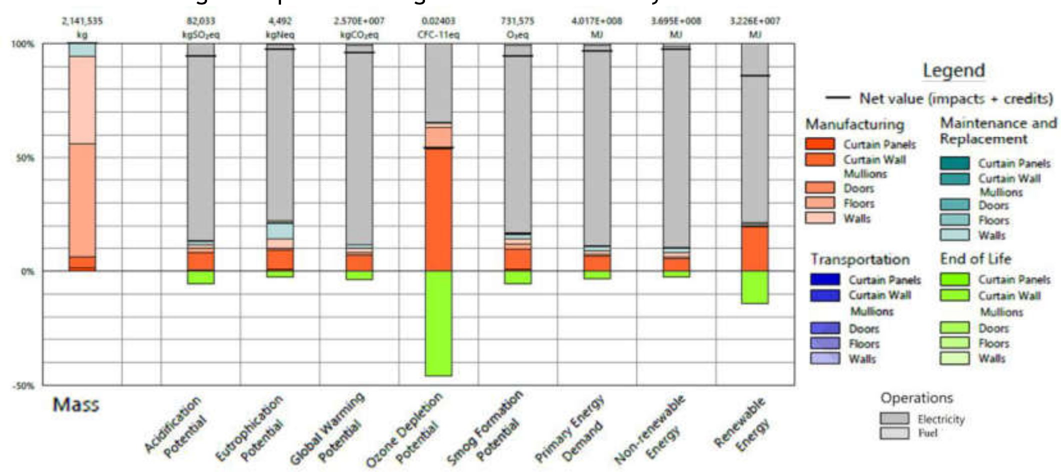

Figure 8 – Impact categories per construction materials over the life cycle stages

Interpretations. This step aims to highlight the environmental issues and make an environmentally friendly decision [34]. As shown in Figure 5, electricity is considered as the main source of energy consumption in such types of buildings. Almost 70% of the consumption of electricity modeling is dedicated for HVAC and lighting purposes in such types of buildings. The results collected in Figure 6 illustrates such a low impact of glazing, in a curtain wall system, in comparison with other construction materials, particularly on eutrophication potential, global warming potential, ozone depletion potential, and primary energy demand, non-renewable energy, and renewable energy. This analysis shows the high environmental impact of some building materials such as metals, finishing and concrete.

Analyzing the LCA of construction materials in Figure 7 clarifies that manufacturing and operation stages are the main agents for the most of the impact categories in such types of buildings. In other words, it can be modeling that most of the environmental impacts occur during the operation phase whereas the manufacturing phase is the second agent for most of the impacts. However, the maintenance and replacement stage is distinguished with a minor effect on most of the impact categories. In more details, Figure 8 presents high environmental impacts of some construction materials such as curtain wall mullions, floors and walls over the manufacturing and maintenance and replacement phases of buildings. On the other hand, it presents the slight impacts of curtain wall panels over the entire life cycle assessment of the functional unit considered in the case study.

Discussion

This work examined the BIM-LCA integration at early design stages and evaluated the environmental impacts of construction materials over their entire lifespan. In this discipline, BIM models allow using various construction materials within different parameters and estimate the energy performance in buildings at the designing phase. LCA methodology evaluates the environmental impacts over the entire lifespan of construction materials. It can be notified that BIM and LCA integration is an optimistic course aims to evaluate the environmental impacts of construction materials and protect the built environment.

The results of this work show that all building materials are passively affecting the environment in such types of buildings. It is clear that curtain wall mullions, walls, and floors are the main agents for the most of the environmental impacts. Hence, it is enormously essential to identify the environmental impacts of such construction materials as a concrete step to invest in this type of construction in Brazil. In other words, engineers and designers should dedicate great efforts to assess the impact categories of construction materials at early stages of designing office buildings in order to increase energy efficiency and protect the environment.

Furthermore, reducing the environmental impacts of modern construction such as curtain wall systems requires taking into consideration the improvement industries of these materials. This means to appraise the manufacturing stage of constructing walls and floors such as concrete, masonry, metals, and finishes. In addition to curtain wall mullions such as aluminum. Besides, it is important to highlight the very low environmental impacts of curtain panels building material over its entire lifecycle. Hence, it is extremely imperative to highlight the installation of curtain panels such as glass at a wider scale instead of concrete and metals in term of reducing the environmental impacts in the construction sector.

Conclusions

This study stimulates the sustainable construction concept and environmental protection and empowers the decision-making process in terms of BIM-LCA integration at early stages of designing construction projects. It conducts an analysis on the different phases of the life cycle of construction materials in order to consider the environmental impacts in a typical multi-story office building in Brazil. This work upraises the negative impacts of the manufacturing and operation phases of construction materials on the environment. It presents the important role of taking sustainable measurements in order to increase energy efficiency in buildings and supports the installation of renewable energy systems in generating energy rather than obtaining power from the electricity network only. Furthermore, this paper states that curtain wall mullions, walls and floors are the main responsible for the most of the impact categories in such types of buildings. Thus, it is highly important to evaluate the environmental impacts of such construction materials at an early designing stage in a way to protect the built environment. Besides, this work recommends that designers and engineers review the installation of curtain panels at a wide range as an environmental friendliness building material in the construction sector.

Acknowledgments

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APPENDIX 4

Increasing energy efficiency of building envelopes towards nearly zero energy buildings integrating BIM and LCA

(A conference paper in 1st Latin American Conference on Sustainable Development of Energy, Water and Environment Systems, Rio de Janeiro, Brazil, 2018)

Best Paper Award

The Organizing Committee of
The 1st Latin American SDEWES Conference
FMENA, University of Zagreb
Ivana Lučića 5
HR-10000 Zagreb
CROATIA

To:
Mr. MOHAMMAD NAJJAR
Universidade Federal do Rio de Janeiro,
RIO DE JANEIRO,
Brazil

This letter confirms that ***Mr. MOHAMMAD NAJJAR*** has the following submissions reviewed by the editors and accepted for presentation and publication on digital proceedings of the 1st Latin American SDEWES Conference on Sustainable Development of Energy, Water and Environment Systems to be held from January 28 - 31, 2018 in Rio, Brazil:

Archival oral presentation(s) (with the possibility of publishing the paper in an archival journal)
LA.SDEWES2018-0106 **Increasing energy efficiency of building envelopes towards nearly zero energy buildings integrating BIM and LCA**
by Mohammad Najjar, Karoline Figueiredo, Assed Haddad*

The oral presentations will be conducted in the 15 minutes presentation plus 5 minutes discussion fashion.

This letter **DOES NOT** serve for getting entry visa to Brazil!

For any communication please use the following e-mail address: sdewes2018@sdewes.org

Sincerely yours,

Prof. Neven Duić
CoChairman of Local Organizing Committee

1st Latin American Conference on Sustainable Development of Energy, Water and Environment Systems – LA SDEWES

January 28 – 31, 2018, Rio de Janeiro, Brazil

BEST PAPER AWARD

presented to

Assed Haddad

For an outstanding presentation of the submission titled

Increasing energy efficiency of building envelopes towards nearly zero energy buildings integrating BIM and LCA

Mohammad Najjar, Karoline Figueiredo, Assed Haddad*

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January 2018

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Increasing energy efficiency of building envelopes towards nearly zero energy buildings integrating BIM and LCA

Mohammad Najjar*
Programa de Engenharia Ambiental, Escola Politécnica
Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil
e–mail: mnajjar@poli.ufrj.br

Karoline Figueiredo, Assed Haddad
Programa de Engenharia Ambiental, Escola Politécnica
Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil
e–mail: karolinefigueiredo@poli.ufrj.br, assed@poli.ufrj.br

ABSTRACT

The methodology of this work aims to integrate Building Information Modeling (BIM) with Life Cycle Assessment (LCA) in order to empower the decision-making process and sustainable building design in the construction sector towards nearly Zero Energy Buildings (nZEB). This paper examines various alternatives of building components that are assembling the envelopes of three typologies of residential buildings. It evaluates the LCA methodology based on ISO 14040 and 14044 guidelines within the available database, using Autodesk Revit as a BIM software, and Green Building Studio and Tally applications in Revit as tools to achieve the objectives. This work states that BIM-LCA integration is an ideal course towards reducing the operating energy in buildings. It considers all building components are influencing the consumption of energy in buildings, and supports increasing insulation and thickness of exterior walls and installing energy efficient windows in order to reduce the operating energy in the construction sector.

KEYWORDS

Building information modeling, Life cycle assessment, Energy consumption, Sustainable construction, Environmental impacts, nearly zero energy buildings.

INTRODUCTION

The construction industry is an activity that consumes energy, natural resources and affects the environment [1–8]. International Energy Agency (IEA) expected that the global annual growth rate of energy consumption would be around 1% between 2003 and 2030 in countries that are involved in the Organization for Economic Co-operation and Development Countries (OECD), while this figure would increase to reach 3% in non-OECD countries within the same period [9]. Energy consumption in the building sector accounts for around 40% of global CO_2 emissions and consumes 40% of natural resources [4–7]. The United States Energy Information Administration (EIA) 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; from 61% in 2012 to 75% in 2040 [10]. Thus, it is essential to apply new strategies such as green building, sustainable materials usage and integrating renewable energy systems, and dedicated efforts to reduce the energy consumption and greenhouse gas (GHG) emissions. Many countries are aiming to follow the

* Corresponding author

path towards a reduction in GHG emission such as the UK that intends an 80% reduction in CO_2 emissions by 2050 [11], and Brazil that intends a 36,1% to 38,9% reduction of the estimated GHG emissions by 2020 [12]. In the meantime, the concept of "nearly Zero Energy Building" (nZEB) has been studied and implemented to reduce the energy consumption in the construction sector [13–17]. The Energy Performance of Buildings Directive (EPBD) considered nZEB as an imperative energy performance, and the nearly-zero or very low demands of energy could be covered by generating energy from renewable sources [15].

Energy consumption in buildings result in direct and indirect impacts over their entire lifespan, however, increasing energy efficiency in the construction sector is becoming a priority in energy procedures and strategies [18]. This comes back to the fact that several prominent factors are playing fundamental roles in determining the patterns of energy consumption in the building sector such as the type of building, climate zone, level of economic development and modern technologies that explored the different properties and capabilities of construction materials [19]. Evaluating energy consumption over the life cycle assessment (LCA) of buildings requires a specific determination of building envelopes such as exterior walls, windows, doors, roof, and ground floor [20]. Furthermore, introducing and stimulating LCA in the construction sector necessitates an integration with the tools of building information modeling (BIM) [21,22]. The potential BIM-LCA integration in construction projects could make a wider approach towards covering the three pillars of sustainability: environment, social, and economic [23,24]. BIM tools facilitate estimating energy consumption of construction materials [8,23–25] and empower the decision-making process at the designing phase of construction projects [24,26,27] in order to evaluate the environmental impacts and energy consumption patterns based on LCA [28]. However, one can recognize a gap lies in the inadequate methodological details that are covering BIM-LCA integration. In fact, this part of study needs to be systematically defined and addressed in a more comprehensive way in order to empower the decision-making process in the construction sector and protect the surrounded environment.

This study appraises the awareness of designers, architects, and engineers to the energy consumption in the construction sector, and stimulates the optimistic application of BIM tools and LCA methodology in a way to increase energy efficiency towards nZEB. In this work, LCA is revised from a building perspective, considering the possible benefits of integrating with BIM tools and sustainability in a way to empower decision-making process in the construction sector. To achieve the objectives of this work, the construction of three typical multi-story residential buildings in Brazil within three different profiles of building envelopes (low profile, normal profile, and high profile) have been analyzed [29]. The design of these buildings represents the typical class of designing such types of buildings in Brazil. This work examines the construction of building envelopes for each building typology based on the standard designs. It modifies the parameters of the applied construction materials with a view to reduce the annual operating energy consumption in buildings. The novelty of this work is that it examines the operating energy performance of building envelopes and evaluates the environmental impacts of construction materials at the designing phase of construction projects with the aid of BIM and LCA in order to improve building performance and identify alternative sustainable designs towards nZEB.

LITERATURE REVIEW

Estimating energy performance (input, output and flow) requires taking into consideration the operating energy (OE) and embodied energy (EE) over the entire LCA of buildings; OE is the energy needed for heating, cooling, ventilation, lighting, domestic hot water, appliances and auxiliary systems; EE is the energy needed over the total life cycle phases of building materials [30–32]. In literature, there are increasing efforts that aim to upgrade the energy efficiency in buildings such as the minimized energy demands, airtightness of a passive house, low energy buildings, energy efficient goal, and nZEB. Until 2014, only few member states provided a definition and quantified parameters towards nZEB. However, recent reports show a kind of positive obligations and requirements of the member states [30]. According to EPBD, the concept of nZEB has been identified as "*A building that has a very high energy performance and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*". The European Union set a long-term strategy and frameworks with the EPBD in order to reduce the consumption of energy in the construction sector. The Directive (2010/31/EU) clarified that achieving nZEB is the main goal in the energy performance of buildings. EPBD requires all new construction to be nZEB by the end of 2020 [33]. Such scheme can be achieved by renovating existing buildings or constructing new buildings that satisfy the requirements of nZEB [34]. There are several of available strategies to construct a low energy or nZEB including a high number of factors such as location, climate, cost, and available sources [35]. Other strategies defined five guidelines that are providing a strong basis to achieve nZEB through smart design and innovative technologies: alternative energy source, passive solar design, high-performance building envelope, lighting and daylighting, and low consumption technology and appliances [36,37]. However, the intensive use of construction materials towards nZEB shows a substantial increase in the embodied life cycle energy in buildings [38–42].

Several studies have addressed the aspects of energy consumption in buildings and examined the various possibilities in achieving the concept of nZEB. For instance, Charisi [43] analyzed the building envelope of a typical Greek residential building in four climate zones. The author found that the efficient constructive solutions could vary for every climate zone based on the combinations of parameters. The results of this research confirmed that the right combination might save the energy consumption by 30% and reduce the annual energy demand for less than 50 kWh/m^2. Ascione et al [44] discussed the design criteria for a residential nZEB in the Mediterranean climate. Their work aimed to minimize the energy demands in winter and summer without compromising thermal comfort. However, the authors found a difficulty in understanding the best trade-off between summer and winter performance. Giordano et al [45] examined an nZEB case study since the earliest design stage, considering both the EE and OE. The authors developed a worksheet with over 65 materials in order to inspire designers to manage these issues. Loukaidou et al [46] focused on the optimal thermal features of the building envelope in the climate conditions of Cyprus. The study included the thermal insulation on wall, roof, ground floor and windows. The authors demonstrated that the cost-optimal energy performance levels in Cyprus are higher than the national minimum requirements, and underlined the necessity of forming three independent climate zones in the country instead of the existing one. Kampelis et al [47] examined the operating energy in industrial, residential and tertiary sector buildings designed toward nZEB. The authors compared the energy dynamic and quasi-dynamic models with various data and environmental measurements. However, the authors highlighted the needs to address the performance gap between energy efficient prediction in the design phase and the evaluation measurements in the operational phase.

Moreover, many other studies examined the features of Life Cycle Energy Assessment (LCEA) towards nZEB. For instance, Moran et al [35] focused on the life cycle cost and environmental analysis of a number nZEB case study buildings in Ireland. The authors used different sources for heating purposes such as a gas boiler, biomass boiler, domestic gas-fired combined heat, and power unit, heat pump and renewable technology. The authors found that future buildings should be super-insulated with higher air-tightness performance. In addition to this, the authors presented benefits of operating low impact heating systems on the environment such as a biomass boiler or heat pump. Muñoz et al [48] assessed a new school building, considering the LCEA by taking into account the pre-use phase, use phase, and the estimated post-use phase. The authors found that the very low Primary Energy Consumption (PEC), less than 92 kWh m^{-2} $year^{-1}$, represents around 56% of the total demanded energy over the total LCA of the building. Chastas et al [49] evaluated the LCEA of 90 residential case studies focusing on the normalization procedure that follows the principles of Product Category Rule (PCR) 2014:02 for buildings. The authors found that applying different methods of Life Cycle Inventory (LCI) could lead to various values of EE, and highlighted the necessity to consider LCEA in energy efficient regulations towards nZEB. Atmaca and Atmaca [50] analyzed the construction of two residential buildings in Gaziantep in Turkey, considering urban and rural buildings. The analysis includes the construction, operation and demolition phases over a 50-year lifespan. The authors found that the energy consumption in the operation phase is dominant in urban and rural buildings, and EE accounts for 24-27% of the total life cycle energy consumption. Moreover, the authors pointed out that the life cycle energy demand in rural residential buildings is 18% lower than urban residential buildings.

DECISION SUPPORT ANALYSIS

BIM-LCA integration is a vital process that could achieve the sustainability standards in the construction project and protect the environment [51]. 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 [23] in order to provide several design alternatives within various parameters at an early stage of designing construction projects [52]. On the second hand, LCA methodology helps to evaluate the environmental impacts and estimate the energy performance in the construction sector [53,54]. Hence, it can be considered that such integration procedure empowers the decision-making process towards very low energy buildings and protect the surrounded environment [24,55]. This work applies the methodological framework of LCA based on ISO 14040 and 14044 guidelines, as shown in yellow boxes in Figure 1 [56]: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations. Besides, it applies the BIM framework based on three main axes of BIM domain, as shown in red boxes in Figure 1 [57]: BIM Fields, BIM Stages, and BIM Lenses.

Figure 1 presents a flowchart of decision support analysis of integrating BIM and LCA at an early stage of designing a construction project. In this discipline, the first step in the integration process starts by design parameters. This means to identify both the BIM Fields and the Goal and Scope of the study. BIM Fields means conducting the required clusters, interactions and overlaps between the different players of the applied technologies, processes and policies, while Goal and Scope mean determining the functional unit, system boundary, the scope of the work and the set of building materials. The next step is to define the performance parameters of the study. This means to identify the BIM stages including inventory database (LCI), 3D modeling, collaboration and integration of design taking into consideration the surrounded environment of the construction project [24,57].

The third step is to get benefit from the input data in the previous step in clarifying the conceptual framework of the study by integrating and exchanging data between the outputs of impacts assessment (LCIA) and BIM Lenses. This step presents the integrations process between BIM and LCA, as shown in Figure 1. In these terms, LCIA provides an evaluation of the significance of impacts within the elementary flows whereas BIM Lenses delivers 3D smart objects, estimation of energy performance and time and cost schedules. The final step in this flowchart is to interpret the output of data. This means to evaluate and compare the collected results from LCI and LCIA, classify sources and propose recommendations in order to achieve the objectives of the study. However, it is important to highlight that there is an interconnected relationship between the performance parameters and conceptual framework steps allowing the examination of numerous modifications that simulate the building design, orientation, materials, parameters and renewable energy [24,58–61] in order to facilitate the best proposal that serves the objectives of the construction project.

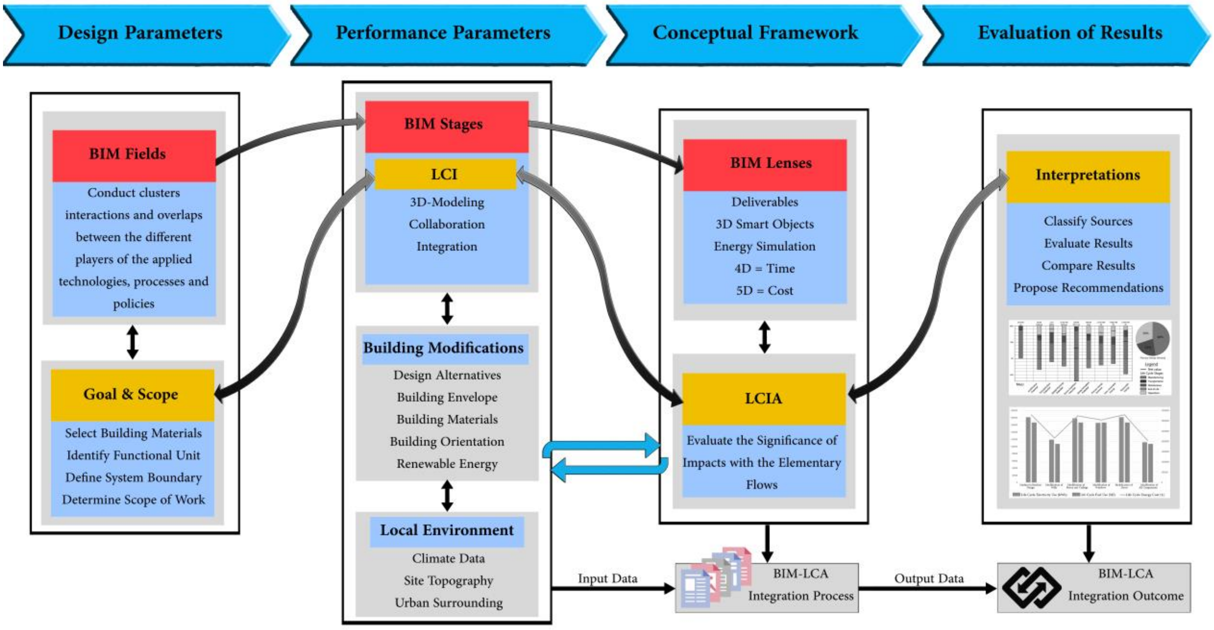

Figure 1. Flowchart of decision support analysis

Application of tools

BIM models are able to implement several modifications and simulations, as previously discussed. This work aims to examine the building envelope as a single modification of BIM models in order to support the decision-making process and achieve the sustainability standards of construction projects. This work 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 towards nZEB. Accordingly, the chosen case studies for this work are the plans of typical multi-story residential buildings, considering three profiles of building typologies: low profile, normal profile, and high profile. 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 [29]. Figure 2 shows the flowchart of research methodology of this work, clarifying that the first step is to design the models of each building typology using the Autodesk Revit as a BIM software. As well, Autodesk Revit defines the parameters and quantifies the construction materials of the buildings. Besides, it classifies the parametric building elements in categories, families, and types; a category is a group of elements that are modeling a building design; family classifies categories with common properties, identical use, and similar graphical representation; type classifies families based on size or style [62]. Besides, Autodesk Revit analysis the energy consumption in buildings using conceptual masses or building elements [63]. It assesses the energy performance using the thermal zones value providing a simple mass with large forms to represent major parts of the design [64].

The scope of this research is to reduce the consumption of the operating energy to a very low value or nZEB. Thus, it investigates the operating energy needs and consumption for each building, considering the building envelope and the designed construction materials. The building design and the related conceptual construction materials are affecting the construction and operation consumption and costs of buildings [65]. In the recent 50 years, the building energy simulations and tools such as BLAST, Energy Plus, QUEST, TRACE, DOE2, Ecotect, and Integrated Environmental Solution (IES-VE) have been developed and applied widely in the construction industry [66,67]. This work estimates the annual operating energy consumption in each case study building, separately, using Autodesk Green Building Studio application in Autodesk Revit, as shown in Figure 2. This application is considered as an intelligent energy setting that facilitates the performance of building simulations and optimizes operating energy efficiency in buildings [68]. It uses DOE2 as a proven and validated simulation engine to provide results related to energy use, water use, and carbon emissions [69]. The results at this level of analysis are evaluated under ANSI/ASHRAE Standard 140 [70]. The Green Building Studio application produces various simulations for buildings, considering the modeling, specifications, and orientation of buildings and properties of construction materials. Results at this step help assembling the life cycle energy analysis at the operation phase of buildings [71]. Autodesk Green Building Studio is a reliable database of local weather data for both site studies and energy analysis for construction projects, taking into account a 30-year life of building within 6,1% discount rate for costs [72]. Besides, this application considers several parameters that are essential to be filled-in precisely in order to get realistic results. These parameters 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 project phase at this level of the study focuses on the operation stage only of construction projects, while the thermal properties consider the thermal zoning for energy analysis. It is important to declare that Autodesk estimates the emissions of CO_2 by applying the utility emissions data according to the U.S. Environmental Protection Agency (EPA) for projects in the U.S. whereas it applies Carbon Monitoring for Action (CARMA) data for projects outside the U.S. Moreover, Autodesk considers the way of generating electricity at the location of the project as a basic step to evaluate emission data [73].

The obtained results in such kind of energy analysis include figures related to the energy consumption and breakdowns of depletions and loads [74]. Autodesk indicates that Revit considers all roof surfaces are using photovoltaic (PV) panels to produce electricity [75]. However, this work eliminates the role of PV panels and focuses only on the alternative options of construction materials. This work modifies alternative options of construction materials that are assembling the building envelopes of the three building typologies based on the local materials in the construction market in Brazil. 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 standard design proposals in order to conduct a conceptual energy consumption analysis for each building typology, separately.

The next step is to calculate the impact assessment and conduct interpretation [56] in order to recommend a set of construction materials that are forming the envelopes of the assessed buildings and reduce the annual energy consumption. Then, this research compares the LCA of the applied case studies based on the standard designs on the one hand, and the recommended proposals on the other hand. This step compares the environmental impacts of construction materials in terms of reducing energy consumption and GHG emissions. The system boundary at this level of the study considers the entire lifecycle stages of construction materials, excluding the construction stage. The inventory of data at this step is constructed based on the amount of construction materials and the application of Tally plug-in that is powered by GaBi database [76]. This plug-in is the first LCA tool in Autodesk Revit that calculates the environmental impacts of construction materials [77]. It delivers an operative feedback at the designing phase of the total LCA of construction projects [78]. Eventually, this work reviews the work, observes results and discussions, suggests recommendations, and presents conclusions.

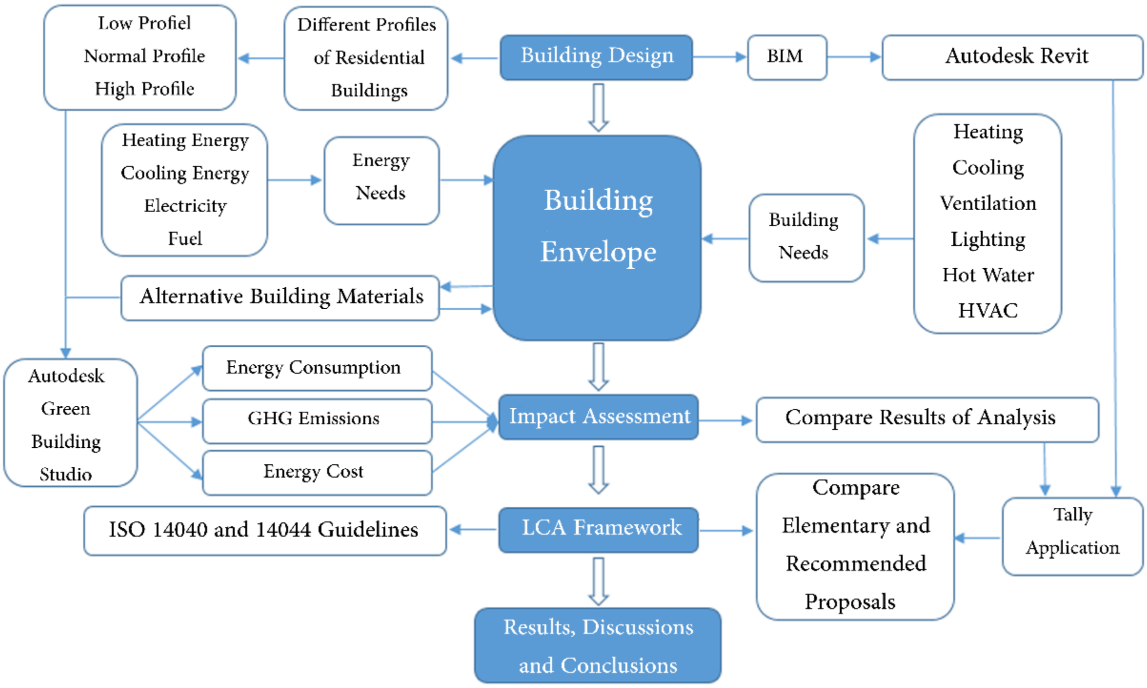

Figure 2. Methodology of this work

CASE STUDY

The designed envelopes of the case study buildings applied in this work are developed and presented as an actual building design in Minas Gerais SINDUSCON MG publication [29], as shown in Table 1. The first case study, low-profile building, consists of 10 levels (ground floor, 8 floors, and a roof), with a total floor area of (1558 m^2), including 36 residential apartments. Each apartment consists of two bedrooms, sitting room, kitchen, bathroom, and service area, as seen in Figure 3. The second case study, normal profile building, consists of 11 levels (basement, ground floor, 8 floors, and a roof), with a total floor area of (2920 m^2), including 32 residential apartments. Each apartment consists of three bedrooms, sitting room, kitchen, two bathrooms, toilet, balcony, and service area, as seen in Figure 4. The third case study, high-profile building, consists of 11 levels (basement, ground floor, 8 floors, and a roof), with a total floor area of (2352 m^2), including 16 residential apartments. Each apartment consists of four bedrooms, sitting room, dining room, saloon, kitchen, three bathrooms, two toilets, balcony, dressing room, and service area, as seen in Figure 5. However, Autodesk Revit generates all graphs of energy consumption and environmental impacts presented in this work.

Table 1. Designed building materials in the selected case studies

Building Component	**Low Profile Building**	**Normal Profile Building**	**High Profile Building**
Exterior Walls	Ceramic masonry block 9 cm x 19 cm x 19 cm	Ceramic masonry block 9 cm x 19 cm x 19 cm	Ceramic masonry block 9 cm x 19 cm x 19 cm
Floors	Concrete floor with ceramic tiles	Concrete floor with ceramic tiles	Concrete floor with mixed of Wooden friezes and ceramic tiles
Ceilings	Plate and single mass	Plate and single mass	Plate and single mass
Windows	Sliding window 1.20 m x 1.20 m. Sheet metal rail, for painting, with smooth glass 4 mm.	Sliding window 1.20 m x 1.20 m. Aluminium frame, natural color, standardized, with glass 4 mm.	Sliding window 1.20 m x 1.20 m. Aluminium frame, brass color, with glass 4 mm.
Doors	Wood, semi-hollow, 3.5 cm thickness, unpainted finishing	smooth plywood, 3.5 cm thickness, painting	Waxed solid wood

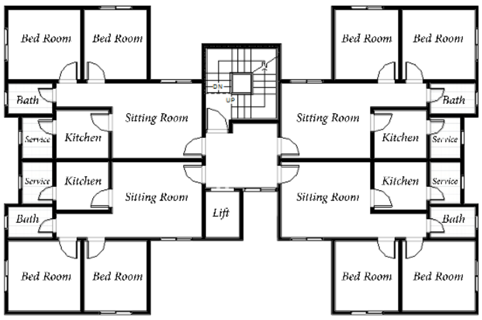

Figure 3. 2D plan of the low profile multi-story residential building

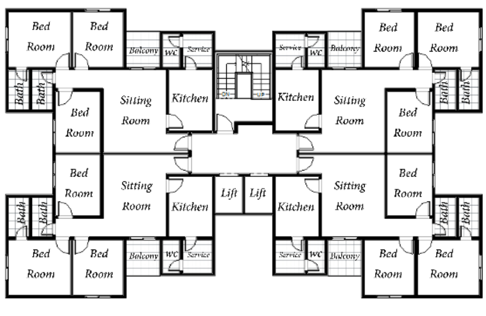

Figure 4. 2D plan of the normal profile multi-story residential building

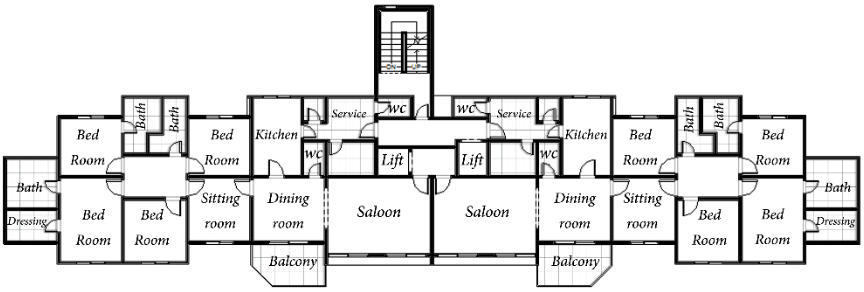

Figure 5. 2D plan of the high-profile multi-story residential building

Estimating the annual operating energy consumption and cost based on the standard designs

Evaluation of energy consumption in the case study buildings is assessed based on the life cycle energy use and cost and the annual energy use intensity; electricity use intensity (EUI) and fuel use intensity (FUI). Autodesk Revit estimates the performance of energy in buildings using the thermal zones value. It considers a value of 0.12 $/kWh for electricity consumption and 0.01 $/MJ for fuel consumption in order to assess the life cycle energy cost in such types of analysis. Figure 6 shows the estimation of the annual energy use intensity and the life cycle energy use and cost of construction materials used in the functional unit of each building typology, taking into consideration every building as a single unit.

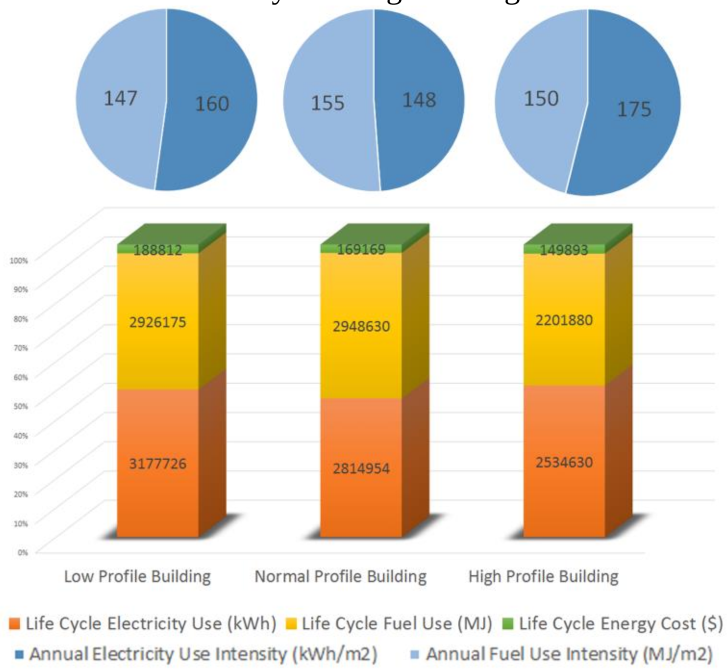

Figure 6. Energy use and cost based on standard designs

Estimating the annual operating energy consumption based on the modified building materials

Each case study building has been constructed using different building materials, as previously mentioned. At this step, alternative options of construction materials that are forming the building envelopes are to be modified based on the local materials that are available in the construction market in Brazil. The profile measurement at this level is to increase insulation thickness of exterior components and examine the energy efficient of doors and windows in order to achieve more efficient and high-performance components. The idea is to examine each alternative of construction material individually within the standard designs in order to examine 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.

<u>Modification of exterior walls.</u> Alternative options of construction materials, as seen in Figure 7, such as concrete block wall, double brick cavity wall, insulated concrete and metal substructure wall, and insulated brick and light plaster wall are to replace the standard design of building materials that are forming the components of exterior walls in the three case studies. However, applying different insulation materials in the construction of exterior walls such as stone wool and air gap would give the opportunity to identify better energy performance materials within the elementary structure for each building. Results of the life cycle of energy use and cost are presented in Table 2.

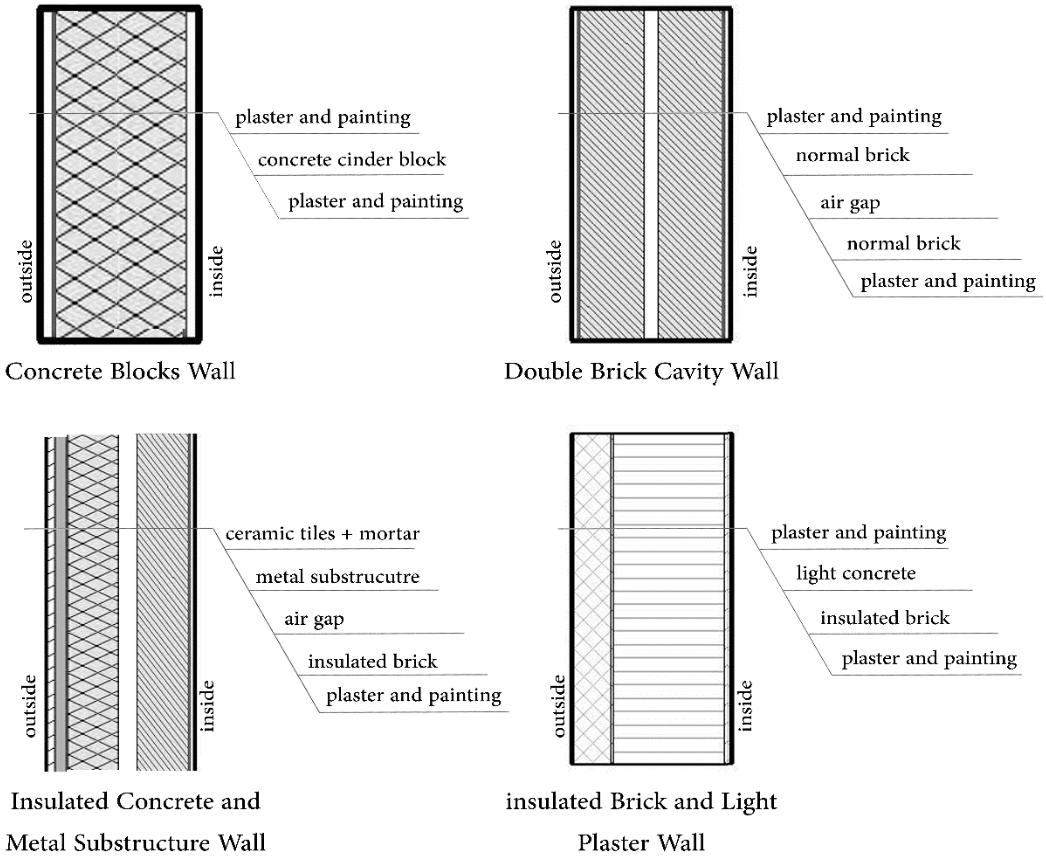

Figure 7. Alternative options of construction materials for exterior walls

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

Building Component (Exterior Walls)	**Case Study Buildings**				
	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (MJ)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (MJ/m^2)
Low Profile Building					
Concrete block wall	2507509	1998643	165333	165	133
Double brick cavity wall	2090637	1886185	124011	148	130
Normal Profile Building					
Insulated brick and light plaster wall	2708954	2826000	162736	144	152
Concrete block wall	3280704	3002859	194834	174	161
Double brick cavity wall	2464499	2106544	147169	118	110
High Profile Building					
Insulated concrete and metal substructure wall	2315013	1976953	136722	177	138
Concrete block wall	2277514	2064512	135148	173	146
Double brick cavity wall	1104470	1018978	69651	85	77

The results show that concrete block wall is more energy efficient component compared with the designed plans in low and high profile buildings. Meanwhile, the annual energy use intensity and the life cycle of energy in normal profile building that applies this type of wall would consume more energy than using ceramic masonry block wall. Additionally, insulated brick and light plaster wall, and insulated concrete and metal substructure wall are more energy efficient when applied in normal and high profile buildings, respectively, in comparison with the standard designs. The application of double brick cavity wall as an alternative component of exterior walls would provide a noticeable estimation of the life cycle energy consumption and cost in the three profiles of buildings than any other wall components in this part of the analysis. In this term, it can be said that the application of double brick cavity wall in these types of buildings would reduce the annual energy use intensity in such types of building typologies.

Modification of 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 three profile buildings, as seen in Figure 8. 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. Such modification of materials gives the opportunity to investigate the capability of these materials to reduce the consumption of energy. Table 3 shows the total life cycle of energy use and cost in such type of analysis.

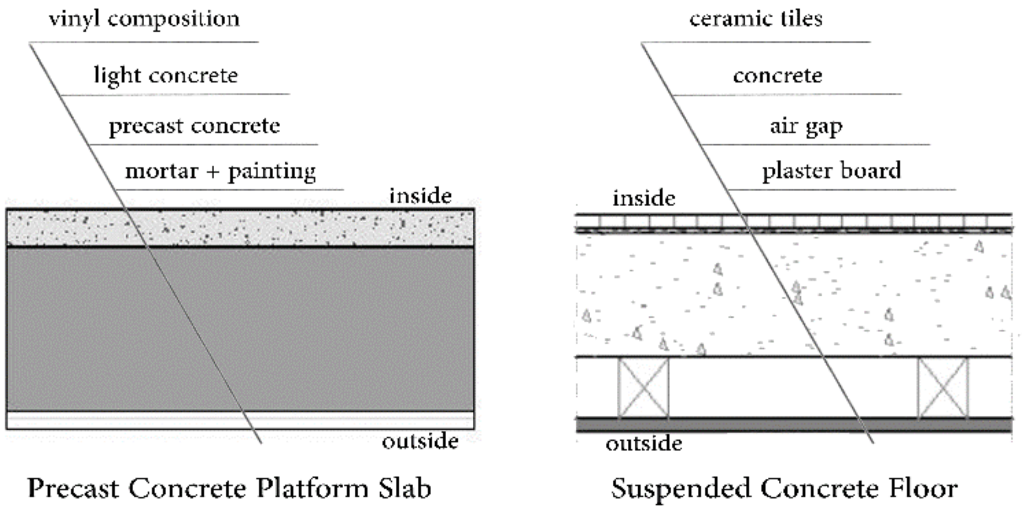

Figure 8. Alternative construction materials for floors and ceilings

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

Building Component (Floors and Ceilings)	**Case Study Buildings**				
	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (MJ)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (MJ/m^2)
Low Profile Building					
Suspended concrete floor	3122919	2926175	185826	155	147
Precast concrete platform slab	3143157	2926175	186929	160	147
Normal Profile Building					
Suspended concrete floor	2866039	2948630	171952	202	155
Precast concrete platform slab	2800729	2948630	168394	140	155
High Profile Building					
Suspended concrete floor	2517384	2201880	148953	180	150
Precast concrete platform slab	2480264	2201880	146931	170	150

The results show that the application of two alternative options of construction materials are more energy efficient than the standard designs in low and high profile buildings. At this time, the annual energy use intensity and the life cycle of energy use and cost in normal profile building that applies suspended concrete floor would consume more energy than the elementary components. However, it can be said that the life cycle of energy in the low-profile building that applies suspended concrete floor would increase the energy efficiency in such types of construction, while buildings that apply precast concrete platform slab would be more energy efficient than any other applied materials for floors and ceilings in normal and high standard buildings.

Modification of Windows. Alternative options of windows such as sliding PVC window, sliding birch wood window, double casement aluminum window, sliding pine wood window and the same windows in standard designs with narrower sizes are replacing the construction materials that are structuring the components of windows in the three profile buildings. This examines the impacts on the consumption of energy in buildings as a reason to the wide range of alternative materials with different thermal parameters and dimensions. For example, the application of sliding pine wood window in the high-profile building is proposed to be protected by the vinyl exterior, stainless steel finishing, and low-emissivity glass. However, Table 4 presents results of the life cycle energy use and cost in the three case study buildings.

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

Building Component (windows)	**Case Study Buildings**				
	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (MJ)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (MJ/m^2)
Low Profile Building					
Sliding PVC window 1.20 x 1.20 m.	3035130	2926175	181043	154	147
Standard window 1.00 x 1.20 m. (narrow size)	2906541	2926175	174038	149	147
Normal Profile Building					
Sliding Birchwood window 1.20x1.20 m.	2834286	2948630	170222	151	155
Double casement aluminium window 1.20 x 1.20 m.	2573399	2948630	156009	141	155
Standard window 1.00 x 1.20 m. (narrow size)	2698931	2948630	162848	146	155
High Profile Building					
Sliding Birchwood window 1.20x1.20 m.	2579977	2201880	152363	177	150
Double casement aluminium window 1.20 x 1.20 m	2178083	2201880	130468	149	150
Sliding Pinewood window 1.20 x 1.20 m.	2137651	2201880	128265	145	150
Standard window 1.00 x 1.20 m. (narrow size)	2381870	2201880	141570	163	150

The results show that the life cycle of energy in normal and high profile buildings that apply sliding birch wood window would consume more energy than any other options of construction materials. On the other hand, applying other types of windows, analyzed in this work, would evaluate the life cycle of energy in low, normal and high profile buildings. However, it can be said that applying the same standard specification of windows with narrower sizes would be more energy efficient in the low-profile building. Besides, double casement aluminum window illustrates better energy efficient in normal profile building, and sliding pine wood window would increase the operating energy efficiency in high profile building.

Modification of Doors. Different options of doors such as PVC door, bamboo plywood sliding door, wood and EPS door and insulation glazed with the steel galvanized door are replacing the standard components of doors in the three profile buildings. The wide range of alternative options of materials with different thermal parameters would affect the consumption of energy in buildings. For example, the application of PVC door considered the economic factor for each profile of buildings; in low-profile building applied PVC door only, while in normal and high profile buildings added plastic and double glazed beams to this type of doors. Moreover, the application of EPS (expanded polystyrene insulation materials) in doors would provide more energy efficient and soundproofing in buildings [79]. However, Table 5 shows results of the life cycle of energy use and cost in the three case study buildings.

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

Building Component (Doors)	**Case Study Buildings**				
	Life Cycle Electricity Use (kWh)	Life Cycle Fuel Use (MJ)	Life Cycle Energy Cost ($)	Annual EUI (kWh/m^2)	Annual FUI (MJ/m^2)
Low Profile Building					
PVC door	3176364	2926175	188738	159	147
Wood with stainless steel	3180954	2926175	188988	161	147
Normal Profile Building					
PVC and plastic door	2810782	2948630	168941	147	155
Oakwood, 3.5 cm thickness, painting	2807450	2948630	168760	145	155
Wood and EPS door	2840983	2948630	170587	152	155
High Profile Building					
PVC with glazing beads door	2516484	2201880	148904	169	150
Steel galvanized with insulation glazed	2517238	2201880	148945	170	150
Wood and EPS door	2570780	2201880	151862	178	150

The results show that the life cycle of energy in buildings that apply wood with stainless steel door and wood and EPS door would consume more energy than the standard components. On the other hand, applying other options of materials, assessed in this work, would increase the energy efficiency in the three profiles of buildings. To sum up, the annual energy use intensity and the life cycle of energy in buildings that apply PVC door and PVC with glazing beads door is more energy efficient in low and high profile buildings, respectively, than any other components of doors whereas oak wood painting door would be more energy efficient in normal profile building.

Total Modifications. The last step of this section is to review the previous results and investigate the modifications of components and profiles. This means to present the implications of all alternative options of components on the annual operating energy consumption in order to build up a recommendation of building components that would evaluate the life cycle energy in the three profiles of buildings, Table 6.

Table 6. Recommended building components for the final proposals

Building Component	**Recommended Construction materials**		
	Low Profile Building	**Normal Profile Building**	**High Profile Building**
Exterior Walls	Double brick cavity wall	Double brick cavity wall	Double brick cavity wall
Floors and Ceilings	Suspended concrete floor	Precast concrete platform slab	Precast concrete platform slab
Windows	Standard window 1.00 x 1.20 m. (narrow size)	Double casement aluminium window 1.20 x 1.20 m.	Sliding Pinewood window 1.20 x 1.20 m.
Doors	PVC door	Oakwood, 3.5 cm thickness, painting	PVC with glazing beads door

Estimating the operating energy based on recommended proposals

Based on the previous step, this work conducted a conceptual energy analysis for each building typology, taking into consideration the recommended construction materials of the final proposals, using the application of Autodesk Green Building Studio in Autodesk Revit as shown in Figure 9.

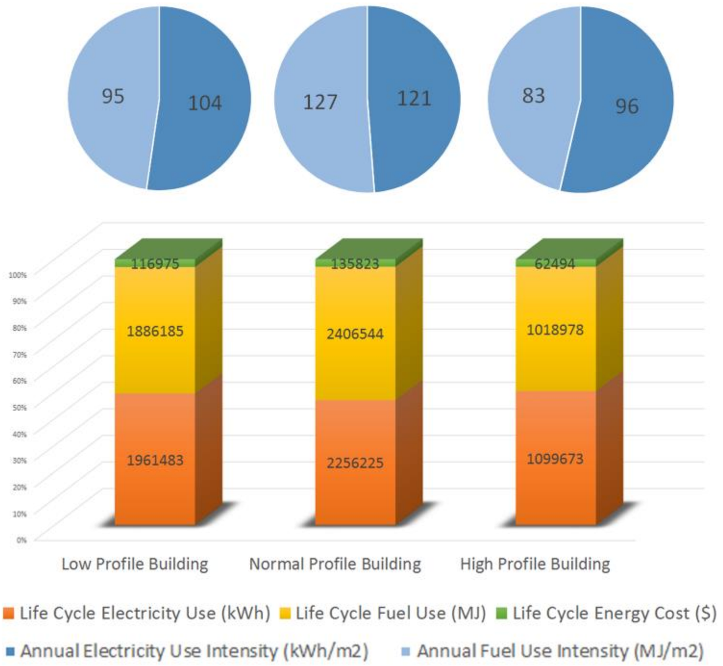

Figure 9. Energy use and cost based on the recommended construction materials

Evaluating the environmental impacts of the standard designs and recommended proposals of the case study buildings

At this level, attention is given to the list of impact categories for each case study, considering both the standard designs and recommended proposals in order to evaluate the environmental impacts of building components. This analysis targets to measure the variables of impacts throughout the operation stage of buildings, particularly primary energy demand, and evaluate the different outcomes achieved based on different building components in each case study.

The functional unit that defines the assessed product or system [56,80], considers every building typology as a single unit. The system boundary includes the entire lifespan of construction materials, disregarding the construction phase. After calculating the quantities of construction materials in Autodesk Revit, Tally software is used in order to measure the impact categories based on the selected system boundary and functional unit such as acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, primary energy demand, non-renewable energy, and renewable energy. Moreover, this work considers that roads are the main transportation model 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 [7]. At this step of the analysis, the operating phase is considered to combine both the operation and maintenance periods of buildings.

Figure 10 illustrates the environmental impacts of the low-profile building based on the standard designs. The results show that operation stage accounts for substantial values of the total impact categories. These values would be more than 50% of some impacts such as eutrophication potential, global warming potential, primary energy demand, and non-renewable energy. For instance, the primary energy demand in this type of buildings would account for 52% and 48% for the operation stage and manufacturing stage, respectively.

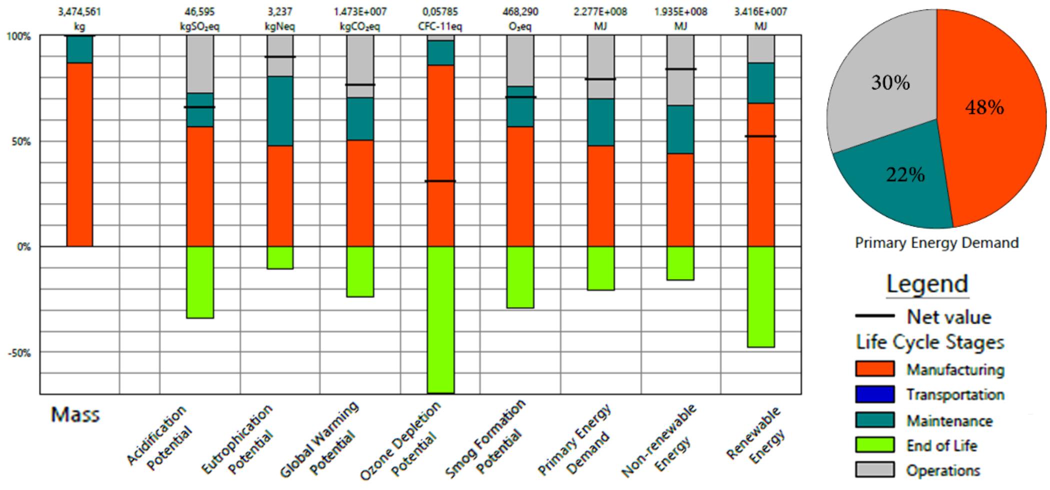

Figure 10. Environmental impacts of low-profile building based on standard design

Figure 11 illustrates the environmental impacts of the low-profile building based on the recommended proposal in this work. Results show that operation stage accounts for fewer values of the total impact categories than the standard design. The values of some impacts such as eutrophication potential, global warming potential, and primary energy demand would be less than 50%. For instance, the primary energy demand would account for 47% at the operation stage and 53% at the manufacturing stage.

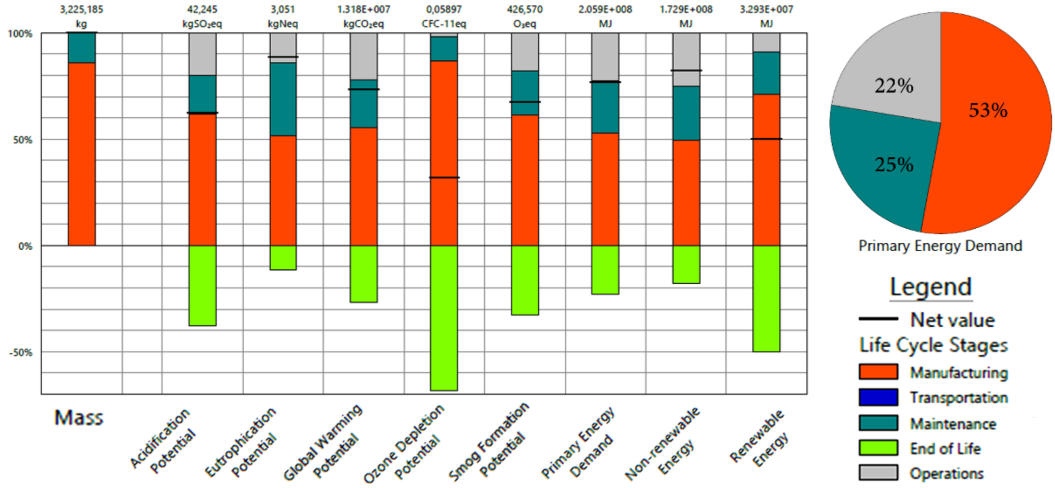

Figure 11. Environmental impacts of low-profile building based on recommended proposal

Figure 12 illustrates the environmental impacts of normal profile building based on the standard design. The results show that operation stage accounts for greater values of the total impact categories. These values would be between 40% and 60% for some impacts such as acidification potential, eutrophication potential, global warming potential, smog formation potential primary energy demand, and non-renewable energy. For instance, the primary energy demand in this type of buildings would account for 51% and 49% for the operation stage and manufacturing stage, respectively.

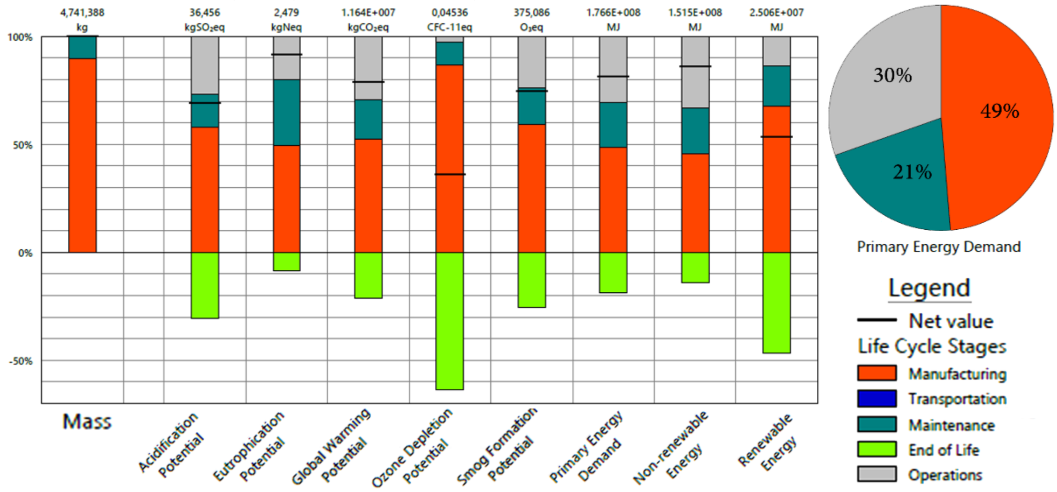

Figure 12. Environmental impacts of normal profile building based on standard design

Figure 13 illustrates the environmental impacts of normal profile building based on the recommended proposal in this work. Results show that operation stage accounts for fewer values of the total impact categories than the standard design. The values of some impacts such as acidification potential, global warming potential, smog formation potential and primary energy demand would be 40% or less. For instance, the primary energy demand would account for 40% at the operation stage and 60% at the manufacturing stage.

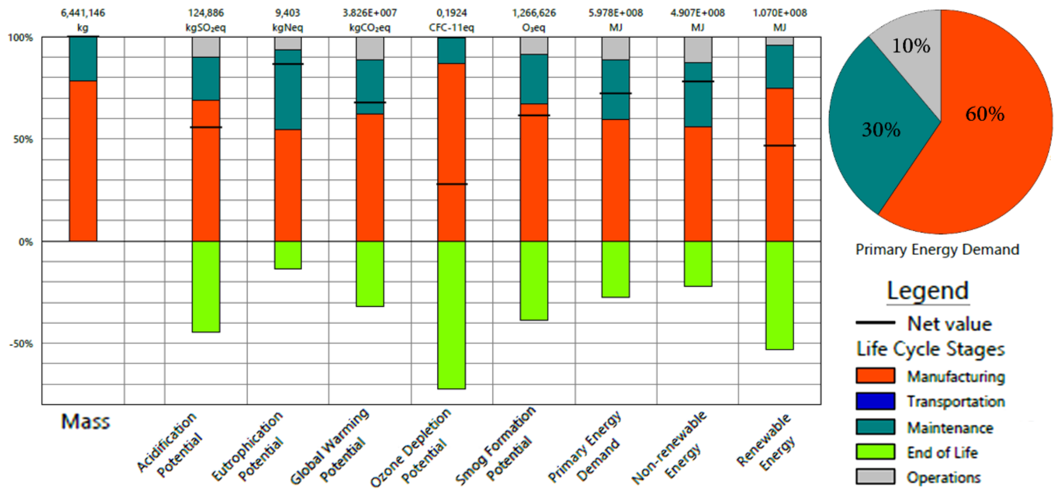

Figure 13. Environmental impacts of normal profile building based on recommended proposal

Figure 14 illustrates the environmental impacts of the high-profile building based on standard design. Results show that operation stage accounts for considerable values of the total impact categories. These values would be more than 60% of some impacts such as acidification potential, global warming potential, primary energy demand, non-renewable energy, and renewable energy. For instance, the primary energy demand in this type of buildings would account for 67% and 33% for the operation stage and manufacturing stage, respectively.

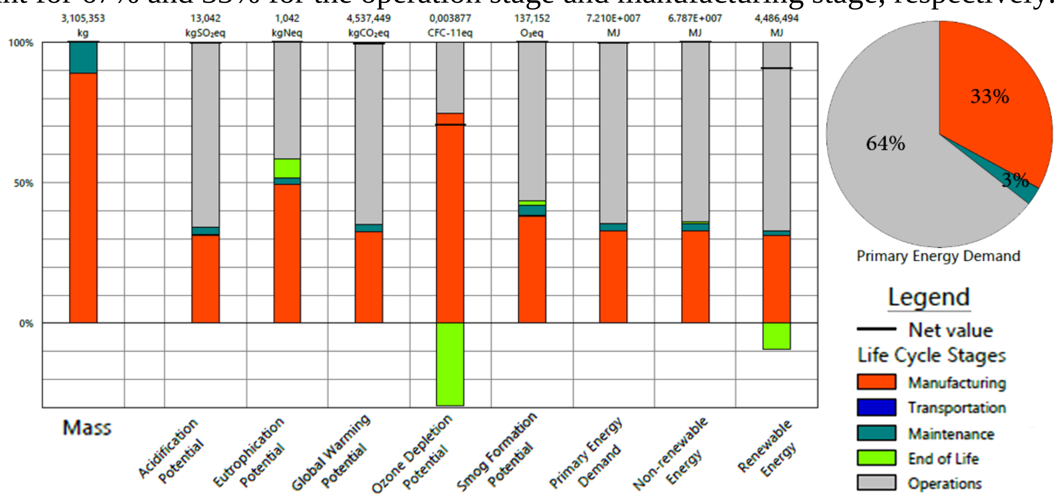

Figure 14. Environmental impacts of high-profile building based on standard design

Figure 15 illustrates the environmental impacts of the high-profile building based on the recommended proposal in this work. Results show that operation stage accounts for fewer values of the total impact categories than the standard design. The values of some impacts that accounted for more than 60% of impacts in the standard design would be around 50% or less. For instance, the primary energy demand would account for 40% at the operation stage, 56% at the manufacturing stage, and 4% at the end of life stage.

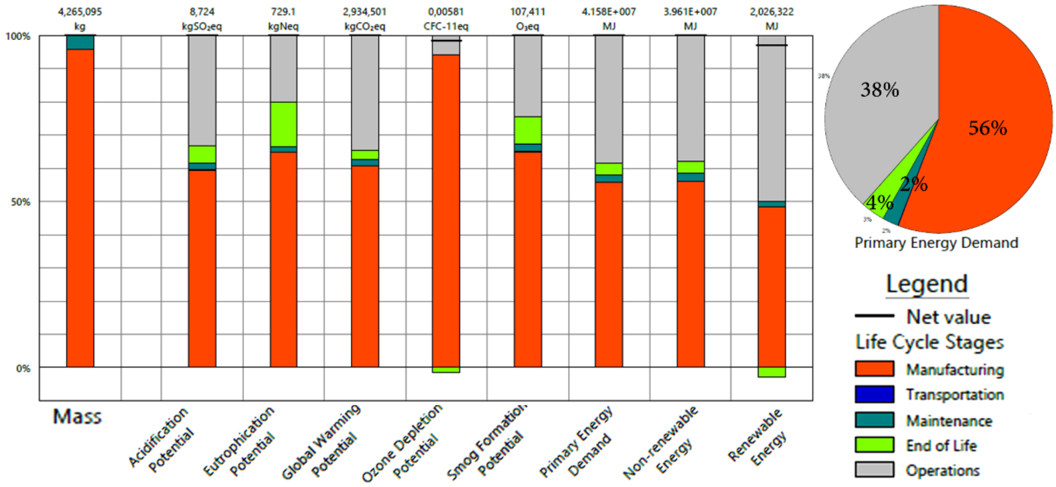

Figure 15. Environmental impacts of high-profile building based on recommended proposal

RESULTS AND DISCUSSION

The three profiles of buildings were simulated using Autodesk Revit as a BIM software, and the consumption of operating energy was estimated for each case study 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 applied to the standard designs, individually, and a conceptual energy consumption analysis is being conducted after every single modification for each building typology in order to identify components that are affecting the energy efficiency of building envelopes. Then, this work compared the acquired results within the standard designs in order to recommend the most efficient components that would reduce the consumption of operating energy in buildings.

This paper illustrates that BIM models allow using various construction materials within different performance parameters at early stages of designing buildings in order to empower the decision-making process in the construction sector. It shows that 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 BIM-LCA integration in order to analyze construction projects from a sustainable perspective, using the tools that allow the creation of different simulations in a short period. It built up a new proposal for each profile of building typology and compared the potential reduction in energy consumption. 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 building and essential services. However, Table 7 shows the annual energy use intensity; electricity use intensity (EUI per kWh/m^2) and fuel use intensity (FUI per MJ/ m^2) for the all variants within the respective performance of building components, based on the three building typologies applied in this work. This table helps drawing a better understanding of the annual energy use intensity of the building components applied in this work. Consequently, the following Figures 16, 17 and 18 illustrate the analysis of the life cycle of the operating energy consumption and cost in the three building typologies of this work based on the recommended building components of the final proposals.

Table 7. Annual energy use intensity for all variants based on the three building typologies

Building Components		Low Profile Building		Normal Profile Building		High Profile Building	
		Annual EUI	*Annual FUI*	*Annual EUI*	*Annual FUI*	*Annual EUI*	*Annual FUI*
Exterior Walls	*Concrete block wall*	165	133	174	161	173	146
	Double brick cavity wall	148	130	118	110	85	77
	Insulated brick and light plaster wall	*x*	*x*	144	152	*x*	*x*
	Insulated concrete and metal substructure wall	*x*	*x*	*x*	*x*	177	138
Floors and Ceilings	*Suspended concrete floor*	155	147	202	155	180	150
	Precast concrete platform slab	160	147	140	155	170	150
Windows	*Sliding PVC window 1.20 x 1.20 m.*	154	147	*x*	*x*	*x*	*x*
	Standard window 1.00 x 1.20 m. (narrow size)	149	147	146	155	163	150
	Sliding Birchwood window 1.20x1.20 m.	*x*	*x*	151	155	177	150
	Double casement aluminium window 1.20 x 1.20 m.	*x*	*x*	141	155	149	150
	Sliding Pinewood window 1.20 x 1.20 m.	*x*	*x*	*x*	*x*	145	150
Doors	*PVC door*	159	147	*x*	*x*	*x*	*x*
	Wood with stainless steel	161	147	*x*	*x*	*x*	*x*
	PVC and plastic door	*x*	*x*	147	155	*x*	*x*
	Oakwood, 3.5 cm thickness, painting	*x*	*x*	145	155	*x*	*x*
	Wood and EPS door	*x*	*x*	152	155	178	150
	PVC with glazing beads door	*x*	*x*	*x*	*x*	169	150
	Steel galvanized with insulation glazed	*x*	*x*	*x*	*x*	170	150

It can be seen that using double brick cavity walls in all profiles would significantly evaluate the life cycle of energy consumption and cost in comparison with the standard designs. Moreover, using suspended concrete floor would result in more energy efficient than standard components in the low-profile building, while precast concrete platform slab would be the most energy efficient component than the standard designs in normal and high profile buildings. At the windows level, it is clear that applying the standard components of windows with narrower sizes would significantly reduce the life cycle of energy consumption and cost in low-profile building whereas double casement aluminum window and sliding pine wood window would be the most efficient energy components in normal and high-profile buildings, respectively. At the doors level, PVC doors, oak wood doors, and PVC with the glazing beads door are the best alternative components that would enhance the life cycle of energy consumption and cost in low, normal and high-profile buildings, respectively. However, forming components that give the best results in terms of energy consumption in the three case study buildings, as mentioned before in Table 6, would result in a substantial reduction in the life cycle of energy use and cost compared with the standard designs.

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 in the three profiles of buildings. Hence, it is highly important to recognize the construction materials that are forming such components as a prior step to invest in such types 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.

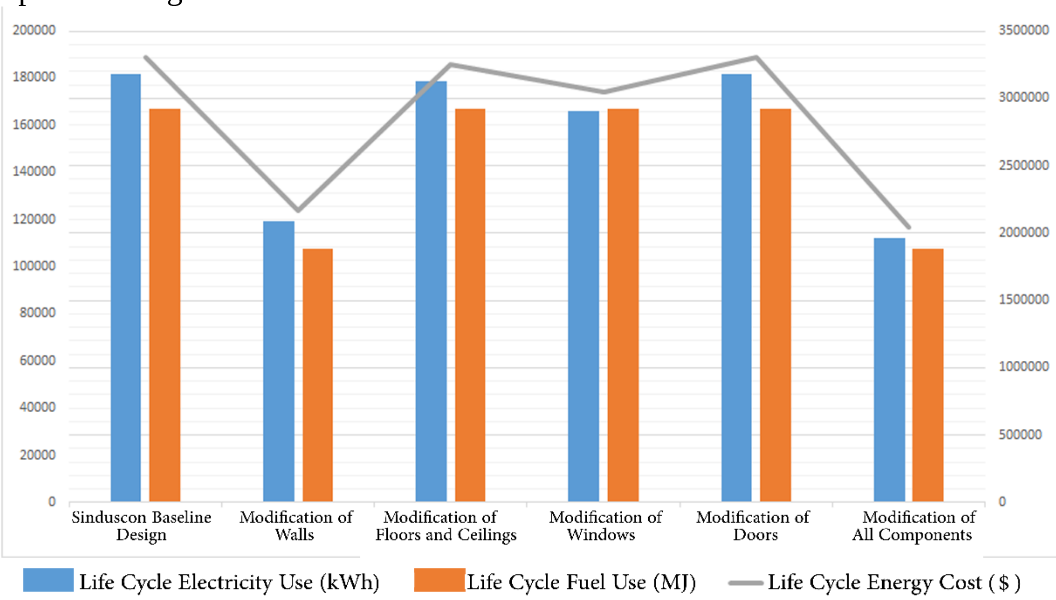

Figure 16. Analysis of lifecycle energy use/cost in low-profile building

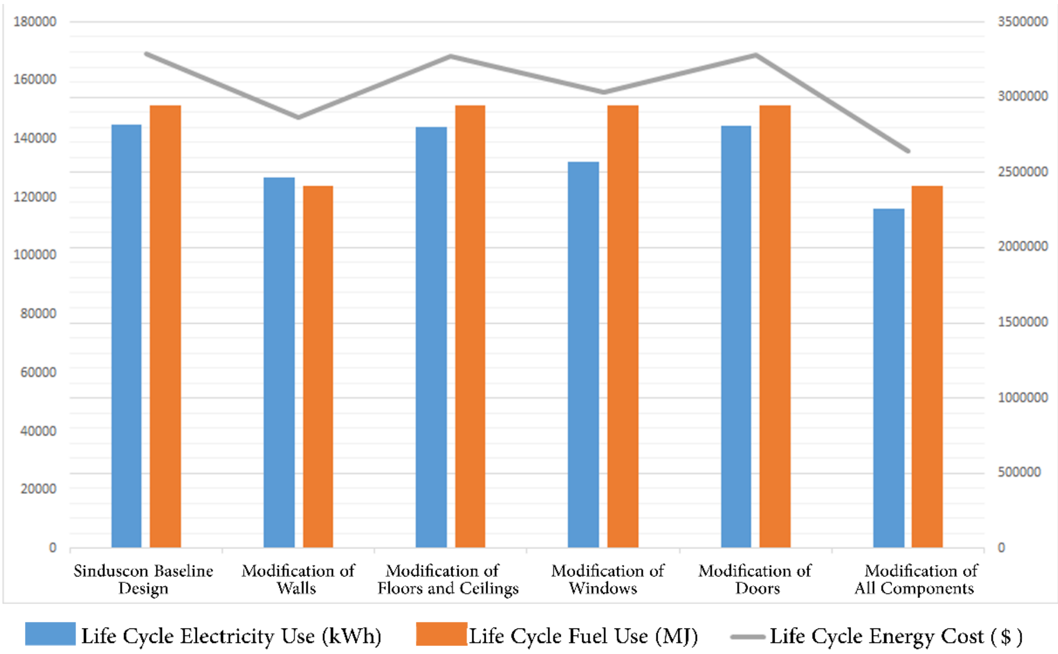

Figure 17. Analysis of lifecycle energy use/cost in normal profile building

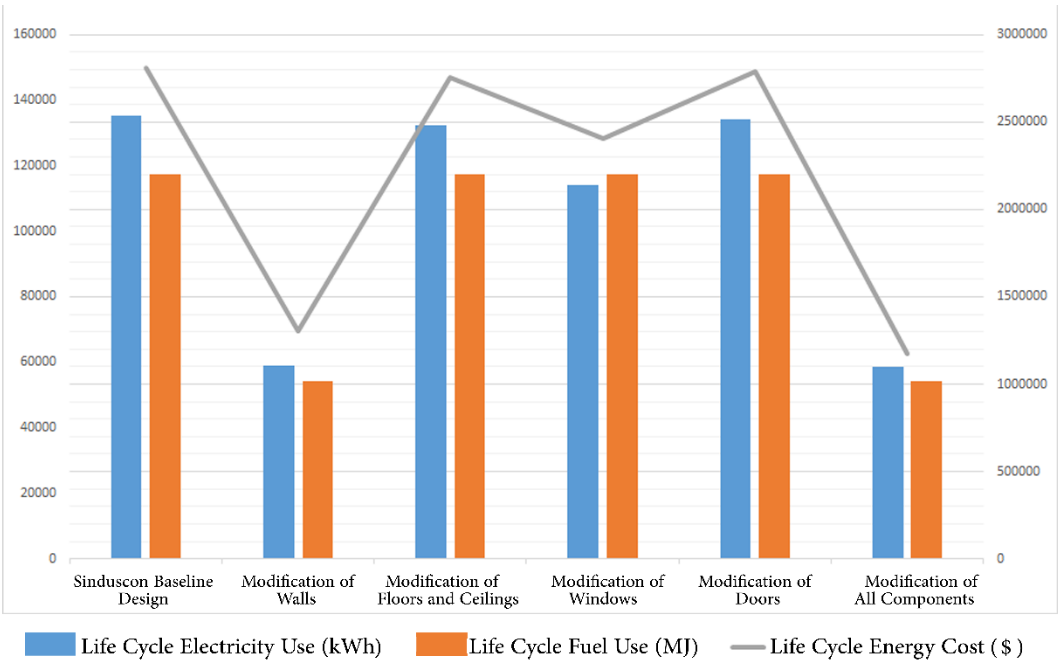

Figure 18. Analysis of lifecycle energy use/cost in high-profile building

According to the environmental impacts analysis for both standard designs and recommended proposals, the results show that the recommended building proposals in this work for such types of buildings can considerably reduce the impact categories at the operation stage. In other words, operation stage accounts for significant values of the total impact categories in standard designs compared with recommended proposals in the three case study buildings. For example, comparing the primary energy demand based on the standard designs and recommended proposals clarifies that the significance of such impact would reduce by around 5%, 11% and 27% in low, normal and high-profile buildings, respectively. On the other hand, the significance of impacts at the manufacturing stage would considerably increase.

CONCLUSIONS

This work analyses the construction of multi-story residential buildings in Brazil. It stimulates the concept of sustainable construction and empowers the decision-making process. Additionally, it targets the integration process between BIM and LCA methodologies towards nZEB with a great ambition to examine alternative options for building components that are forming the building envelopes and reduce the consumption of energy and the production of GHG emissions. LCA seems to be one of the most complex applications to analyze buildings. Henceforth, this work aimed to integrate this methodology with BIM tools in order to investigate the effectiveness of different combinations of materials in various building components to decrease the consumption of operating energy in buildings. This work suggested sustainable solutions of building components that have been proven effective in reducing the consumption of energy in the analyzed case studies.

Three multi-story residential buildings were presented in this work in order to evaluate the understanding of designers, architects, and engineers to answer the current urgent calls to reduce energy consumption and cost in the construction sector and promote the decision-making process towards nZEB. The novelty of this work is that it presents the important role of BIM and LCA integration in order to examine the operating energy performance of building envelopes and evaluate the environmental impacts of construction materials, using three building typologies: low, normal and high profile buildings. This study applied Autodesk Revit as a BIM tool in order to satisfy the progression of this work and used Autodesk Green Building Studio application in Revit to estimate the consumption and cost of operating energy in buildings. The next step was to examine the construction of building envelope for each case study. At this step, this work suggested a group of alternative options of building components that are structuring exterior walls, floors and ceilings, windows and doors in the local market in Brazil. The aim of this step was to estimate the consumption of energy and figure out the most energy efficient components towards nZEB. The recommendations of building components are proposed for each building typology, individually, based on the estimation of the differences in energy consumption. This work followed the LCA methodology based on ISO 14040 and 14044 guidelines to assess the importance of impacts and elementary flows, compare solutions, and propose commendations. Tally plug-in is applied to evaluate the environmental impacts of building components and compare the LCA of the standard designs and the recommended proposals.

The results of this work present that integrating BIM models with LCA methodology is an optimal procedure to estimate the energy use and cost in the construction sector and evaluate the environmental impacts of construction materials towards nZEB. The methodology proposed for this work can be applied to identify which building components are consuming the most of the energy. For the three building typologies, these were exterior walls and windows as they were the agents of the most of operating energy and the total impact categories. Accordingly, it is highly important to review the application of construction materials that are forming such components at an early designing phase in order to evaluate the environmental loads and operating energy in buildings. Eventually, this work supports increasing the insulation and thickness of walls, floors and ceilings, and installing more energy efficient doors and windows. A recommendation for future work is to consider the development of the elementary flow of information between LCA methodology and BIM tools as a reason to the shortage of data in BIM when comparing various scenarios. Another recommendation is to consider the renewable energy components in these types of Brazilian residential buildings such as photovoltaic panels and wind turbines. This means to examine the reduction of energy consumption and environmental impacts in buildings towards nZEB.

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APPENDIX 5

Daylight Assessment and Energy Consumption Analysis at an Early Stage of Designing Residential Buildings Integrating BIM and LCA

(A book chapter in Innovative Production and Construction, World Scientific,
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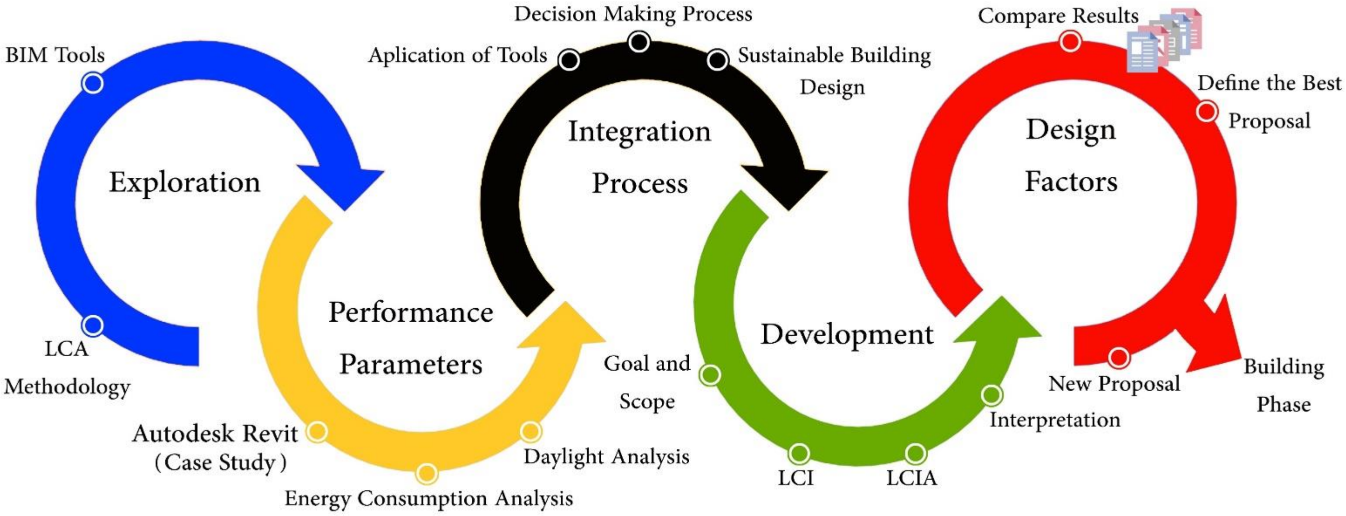
Graphical Abstract:



DAYLIGHT ASSESSMENT AND ENERGY CONSUMPTION ANALYSIS AT AN EARLY STAGE OF DESIGNING RESIDENTIAL BUILDINGS INTEGRATING BIM AND LCA

Mohammad Najjar [1], Karoline Figueiredo [2], and Assed Haddad [3*]

[1] Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil.
[2] Departamento de Construção Civil, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil.
[3] Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil.
[*] Corresponding Author (assed@poli.ufrj.br)

ABSTRACT

Building Information Modeling (BIM) tool provides a distinctive way of observing and estimating energy consumption and daylight analysis in buildings. Integrating this tool with Life Cycle Assessment (LCA) empowers the decision-making process and sustainable building design in the construction sector. This work presents the interests of BIM-LCA integration in examining different design alternatives and orientations in order to increase daylight efficiency and energy performance in buildings at an early designing phase. This work encourages improving the construction options by showing a methodology and tools capable of facilitating decision-making in the designing phase of sustainable projects. It evaluates the LCA methodology of residential buildings based on ISO 14040 guidelines within the available database. The methodology of this work aims to conduct a conceptual energy consumption analysis using Autodesk Green Building Studio, a plug-in that allows designers to perform building performance simulations in a cloud-based service to optimize energy efficiency, testing different possibilities for the construction. Besides, this work uses the advantages of Autodesk Revit software to assess the impact of natural daylight analysis using LEED daylight plug-in. The results show that BIM-LCA integration is considered as an optimistic course in terms of sustainable development and decision-making process in the construction sector. Furthermore, it encourages reviewing some critical factors such as building orientation, HVAC systems and the construction of external walls and roofs in the construction projects at an early stage of design in order to increase energy efficiency and capturing of natural daylight in buildings.

Keywords. *Building Information Modeling, Sustainability in Construction, Life Cycle Assessment, Daylight Analysis, Energy Consumption.*

1. Introduction:

The construction industry is an activity that consumes energy and natural resources. It is known as *"the industry of 40%"* (Lasvaux, S., 2010). This comes back to the fact that the life cycle of buildings produces nearly 40% of CO2 emissions, 40% of waste generation, and consume 40% of natural resources (Lassio et al., 2016; Kwok Wai Wong and Zhou, 2015). The world is witnessing an increasing concern in the field of energy efficiency, particularly non-renewable energy. Thus, advanced solutions are required to achieve the sustainability standards in this field, particularly in serious circumstances such as deteriorating of natural resources and insufficient criteria to protect the environment (Šaparauskas and Turskis, 2006). Such circumstances are affecting the surrounded environment and energy consumption over the entire Life Cycle Assessment (LCA) of construction materials (Buyle, Braet and Audenaert, 2013; Gustavsson, Joelsson and Sathre, 2010).

Several tools and methods have been assessed to support the implementation of sustainable strategies in the built environment (Kang, 2015; Azhar, Carlton, Olsen and Ahmad, 2011; Alwan, Jones and Holgate, 2017). One of these methods is LCA methodology which is considered as a complete process to evaluate the sustainability of buildings over their entire lifespan (Asdrubali, Baldassarri and Fthenakis, 2013). It is highly important to declare that the number of publications in the field of environmental LCA studies have increased significantly after the release of ISO 14040 series. The number of publications that could be found in Scopus up to 2011 was only 88 whereas this figure raised up to 264 publications in 2015 (Anand and Amor, 2017). Some works highlighted the importance of improving the application of LCA in the construction sector (Martínez-Rocamora and Solís-Guzmán, 2016; Huang, Xing and Pullen, 2015; Soust-Verdaguer, Llatas and García-Martínez, 2016). However, applying LCA in the construction sector requires an integration with building tools (Anand and Amor, 2017). In this discipline, Building Information Modeling (BIM) is being discussed as a building tool that optimizes the application of LCA (Soust-Verdaguer, Llatas and García-Martínez, 2016). It provides opportunities to estimate the energy consumption of buildings in the designing stage (Jrade and Jalaei, 2014; Antón and Díaz, 2014), and empowers the decision-making process (Shafiq, Nurrudin, Gardezi and ABin Kamaruzzaman, 2015; Peng, 2015). Despite of these publications, it can be recognized that there is a gap lies in the insufficient methodological framework in the field of BIM and LCA integration. This part of study needs to be addressed in a comprehensive way to support the decision-making process in the construction sector.

The novelty of this work is to present the interests of integrating BIM tools with LCA methodology at early design stages in order to empower the decision-making process and sustainable design procedure in the construction sector. This work reviews LCA from a building perspective and examines the integration process at designing residential buildings. It aims to evaluate the benefits of such integration to conduct a daylight analysis using LEED daylight plug-in in Revit, and estimate the consumption of energy at the operating phase based on different design alternatives and orientations using Autodesk Revit and Autodesk Green Building Studio. In this discipline, design alternatives mean modifying parameters of HVAC systems, and construction of external walls and roofs, while design orientations mean rotating buildings in different directions with the intention of achieving the objectives. This work applies one of the typical multi-story residential buildings in Brazil, recognized as a low profile construction building, as a case study to validate the methodological framework of BIM-LCA integration and achieve the objectives of the research.

2. Methodological Framework of BIM-LCA Integration:

2.1. Decision Support Analysis

Integrating BIM and LCA is an urgent process that achieves sustainability standards (Antón and Díaz, 2014), and protects the environment (Eleftheriadis, Mumovic and Greening, 2017). This process depends on exchanging data between BIM software and LCA application (Soust-Verdaguer, Llatas and García-Martínez, 2017). It gives the opportunity to estimate energy performance, evaluate environmental impacts, and empower the decision-making process in the construction sector (Shadram et al., 2016). This work applies the methodological framework of LCA based on ISO 14040 as shown in Figure 1 (UNEP, 2012): Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations. Besides, It considers the different models, taxonomies and classifications of BIM framework (Porwal and Hewage, 2013; Succar, 2009), based on the main axes of BIM domain as shown in Figure 1 (Succar, 2009): BIM Fields, BIM Stages and BIM Lenses. However, Figure 1 shows that the first step at an early designing stage of a construction project is to determine design parameters. This means to recognize BIM Fields by conducting the required clusters, interactions and overlaps between the different players of the applied technologies, processes and policies. Moreover, it means to define the goal and scope of the construction project by stating the functional unit, system boundary and the set of building materials (UNEP, 2012).

The next step is to state the performance parameters of the study by classifying BIM Stages that reflect the maturity level of BIM implementation (Succar, 2009). BIM Stages is divided into different steps such as inventory database (LCI), 3D modeling, collaboration and integration of design, considering the local environmental data of the construction project. In this discipline, LCI is the most challenging step of LCA methodology due to the difficulty of accumulating reliable and relevant data (UNEP, 2012). However, performance parameters step considers the possible modifications and simulations, orientations, and materials of building design (Østergård, Jensen and Maagaard, 2016; Barrios et al., 2017; Harish and Kumar, 2016; Nguyen, Reiter and Rigo, 2014). In this study, design alternatives mean adjusting parameters of HVAC systems, and the construction of exterior walls and roofs

The following step is clarifying the conceptual framework, as shown in Figure 1. This is an important step in the integration process where the outputs of the lifecycle impact assessment (LCIA) analysis integrates with BIM Lenses. In this term, LCIA is the total sum of the quantities of materials, energy consumption and resulting emissions (UNEP, 2012) such as daylight study, cooling and ventilation analysis, energy performance estimation and environmental impacts evaluation. On the other hand, BIM Lenses provide the required indicators to classify BIM Fields and BIM Stages (Succar, 2009) Such as the deliverables of BIM, 3D smart objects, estimation of energy simulation and time and cost schedules. The last step in the integration process is the evaluation of results, interpretation, in order to define the best proposal at an early stage of designing buildings, as seen in Figure 1. Interpretation identifies and evaluates the results obtained from LCI and LCIA (UNEP, 2012). However, there is an interconnected relationship between the performance parameters and conceptual framework. This allows observing several modifications and simulations within different modeling and deliverables in a way to figure out the best proposal that serves the objectives of the project.

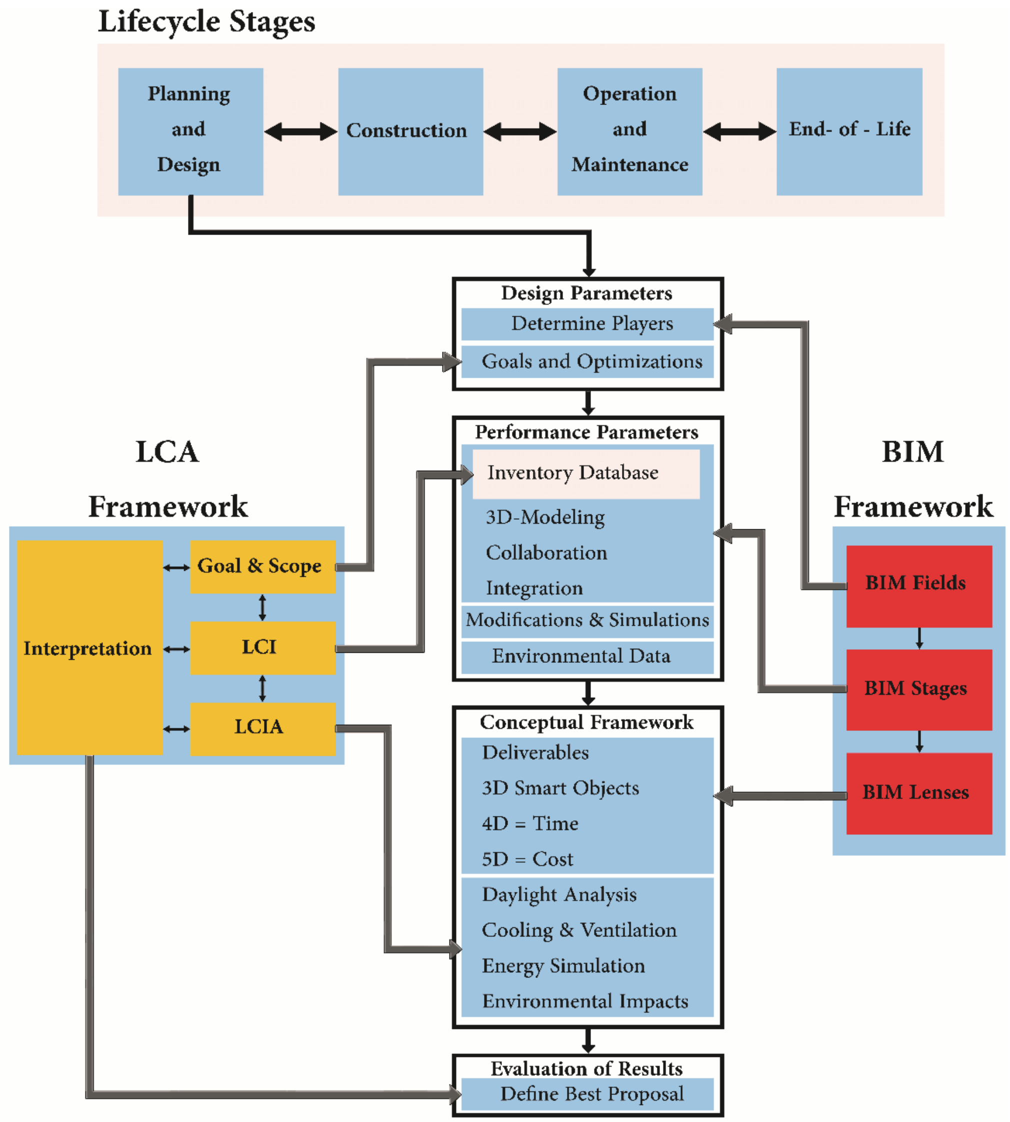


Fig. 1. Decision Support Analysis

2.2. Application of Tools

This work illustrates the BIM-LCA integration within the available database in order to conduct a daylight assessment and energy consumption analysis based on different design alternatives and orientations of residential buildings in Brazil. It targets the early designing phase of construction projects when the model encloses only basic geometry and spaces, construction cost is characteristically low with an excess of alternative designs and prospects to reduce the consumption of operating energy and improve the daylight efficiency in buildings (Liu, Osmani, Demian and Baldwin, 2011; Azhar et al., 2011). This work uses the construction of a multi-story residential building in Brazil as a case study to examine the validity and usability of BIM-LCA integration in evaluating the daylight analysis, estimating energy performance and clarifying the development of design concepts generated by BIM and LCA tools.

The first step of this work is to state the goal and scope of the work and define BIM Fields. Next, the performance parameters are to be identified by defining BIM Stages, and considering the possible simulations and environmental issues. This means to define the parameters, conduct the 3D modeling of the building, recognize the various design alternatives, build up the inventory database of construction materials and consider the local climate data of the case study using Autodesk Revit as a BIM software. The next step is to integrate the benefit indicators and outputs of Revit, BIM Lenses, with the impact assessment (LCIA). At this step, LEED daylight plug-in is applied to assess the potential impact of natural daylight analysis, and Autodesk Green Building Studio is used to conduct a conceptual energy consumption analysis of the building. Results at this step are required to build up life cycle energy analysis at the operation phase of buildings (KT Innovations, Thinkstep and Autodesk, 2016). Such results are evaluated and met the criteria under ANSI/ASHRAE Standard 140 (Autodesk, 2014). However, Green Building Studio could produce various simulations for buildings, taking into consideration the building modeling, various specifications and orientation of the building and properties of construction materials. After that, this work assesses the impacts by evaluating the significance of the outputs with the elementary flows in order to make simpler understanding results (UNEP, 2012). The following step is interpretation. This means to present the results, classify the sources of the impacts, compare solutions, and suggest recommendations (UNEP, 2012). The last step is to discuss the results, review the work, and present the conclusion.

3. Case Study:

This work examines the structure of a multi-story residential building recognized as a low profile construction based on the regulations of the Union of the Civil Construction Industry to model the case study building. The modeling of the building consists of 10 levels with a total floor area of (1558 m^2), including 36 residential apartments, as shown in Figure 2. The construction materials that are applied in the case study building as mentioned in SINDUSCON (SINDUSCON-MG, 2007) are: ceramic masonry block for exterior walls; concrete floor with ceramic tiles for floors; plate and single mass for ceilings; sheet metal rail (120 cm x 120 cm) with smooth glass for windows; and solid concrete flat slab for roof. However, Autodesk Revit generates all graphs of energy consumption analysis and daylight assessment presented in this work.

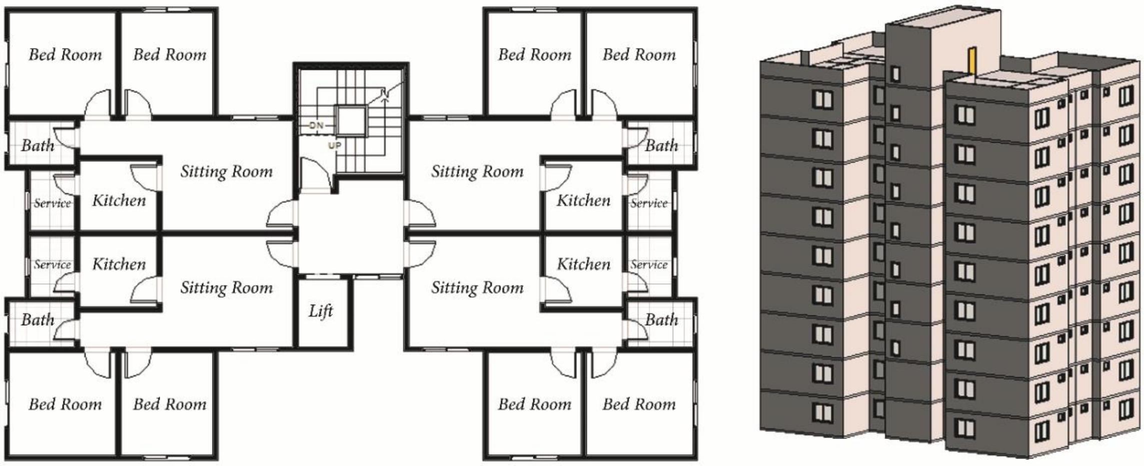


Fig. 2. 2D plan and 3D modelling of the multi-story residential building

3.1. Goal and Scope:

This work targets the early designing phase of construction projects. Despite of this, the system boundary that refers to the size of LCA focuses on the operation phase only, neglecting all other phases of LCA. In this work, the entire building is considered as a single unit and the analysis of the functional unit concentrated on the parameters of the design alternatives and orientations. According to the default weather stations in Autodesk Green Building Studio, the average lifespan of energy consumption analysis is limited in a range of 30-years of weather data (Autodesk, 2011). The scope of this work is to examine different design alternatives and orientations in order to increase daylight efficiency and reduce consumption of energy in such types of buildings at an early designing phase.

3.2. Life Cycle Inventory (LCI):

The modeling of the case study building and specifying the properties of building materials are constructed in Autodesk Revit software, which uses Green Building Studio application as an intelligent energy analysis engine in order to estimate the energy performance in buildings (Autodesk Revit, 2017). Different assumptions and parameters are required to be filled-in precisely in this application such as 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, etc., as shown in Figure 3.

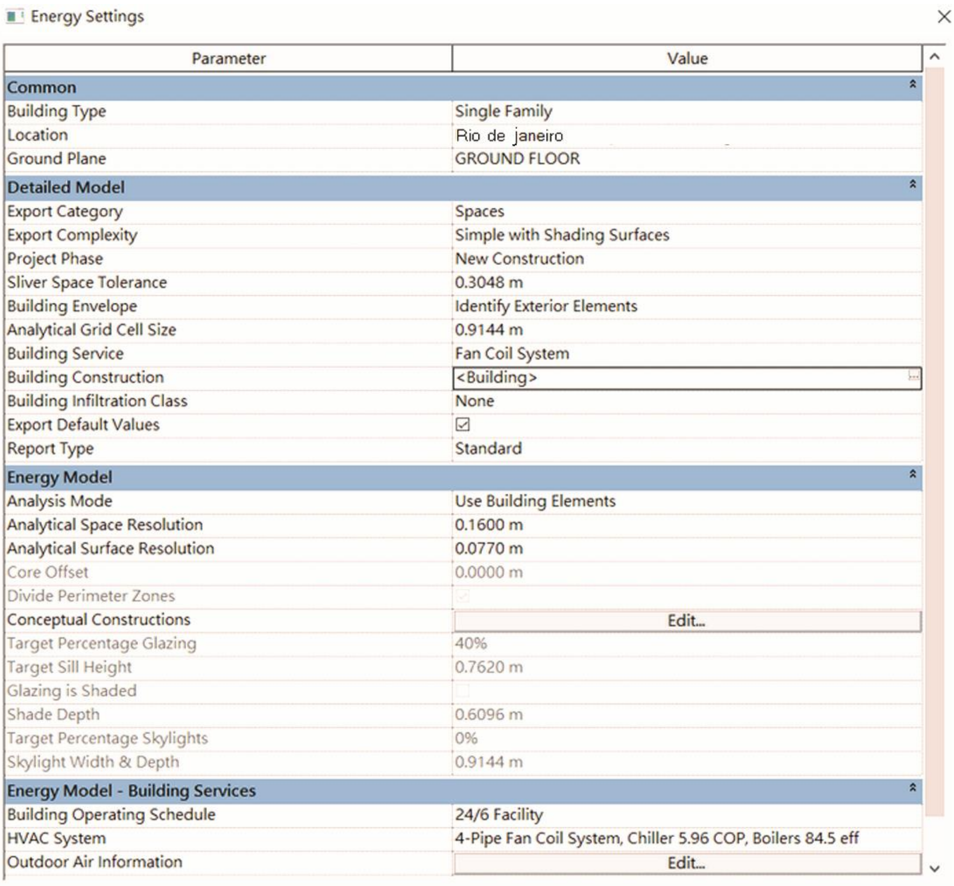


Fig. 3. Energy consumption analysis in Autodesk Revit

Such assumptions and parameters give the opportunity to examine the suggested design alternatives of this work by adjusting parameters of HVAC systems and the construction of exterior walls and roofs as shown in Table 1. However, the alternative HVAC systems chosen in this work are provided as residential options in Green Building Studio application. Besides, the alternative construction materials of external walls and roofs chosen for this work aim to show the important role of the thickness form and the insulation process using different types of materials.

Table 1. Adjusting parameters of the case study building

HVAC System		**Construction of External Walls**		**Construction of Roofs**	
No.	**Type**	**No.**	**Type**	**No.**	**Type**
1	Residential 14 SEER/0.9 AFUE Split/Packaged Gas <5.5 ton	**8**	Insulated Concrete Form Wall, 10" thick form	**15**	Wood Frame Roof with Super High Insulation
2	Residential 14 SEER/8.3 HSPF Split Packaged Heat Pump	**9**	Insulated Concrete Form Wall, 12" thick form	**16**	Wood Frame Roof without Insulation
3	HP, 13 SEER, Electric Heat, Residential	**10**	Insulated Concrete Form Wall, 14" thick form	**17**	Metal Frame Roof with Super High Insulation
4	Residential 17 SEER/9.6 HSPF Split HP <5.5 ton	**11**	Metal Frame Wall with Super High Insulation	**18**	Metal Frame Roof without Insulation
5	Residential 14 SEER/0.9 AFUE Split/Packaged Gas <5.5 ton	**12**	Metal Frame Wall without Insulation	**19**	Continuous Deck Roof with Super High Insulation
6	Residential 17 SEER/0.85 AFUE Split/Pkgd <5.5 ton	**13**	Massive Wall with Super High Insulation	**20**	Continuous Deck Roof without Insulation
7	PSZ, ASHRAE 90.1-2007, 11 EER, 78% AFUE, Residential	**14**	Massive Wall without Insulation	**-**	-

Autodesk Revit gives the opportunity to rotate modeling in different directions. Besides, it uses LEED daylight plug-in to perform daylighting simulations in the cloud (Autodesk, 2017). In this discipline, LEED v4 plug-in in Revit has adopted two important metrics, which are spatial daylight autonomy (sDA) and annual sunlight exposure (ASE), in order to help designers and engineers understanding annual daylight availability and quality, as well as glare and overheating potential within their construction projects (Autodesk, 2016). The assumptions at this level of study are based on the local environmental issues, illumination settings and cloud credits, as shown in Figure 4. Such assumptions give the opportunity to automate daylight simulations and improve design decisions. Figure 4 clarifies that the time range is automatically simulated for 10 hours per day, from 8 am to 6 pm, covering 3650 hours over a full annual simulation. LEED requires that DA achieves for at least 55% or 75% regularly occupied floor area within ASE of no more than 10% for the occupied daylit floor area per sDA. However, both metrics require a resolution of at least 24 inches analysis grid at the cloud credit level.

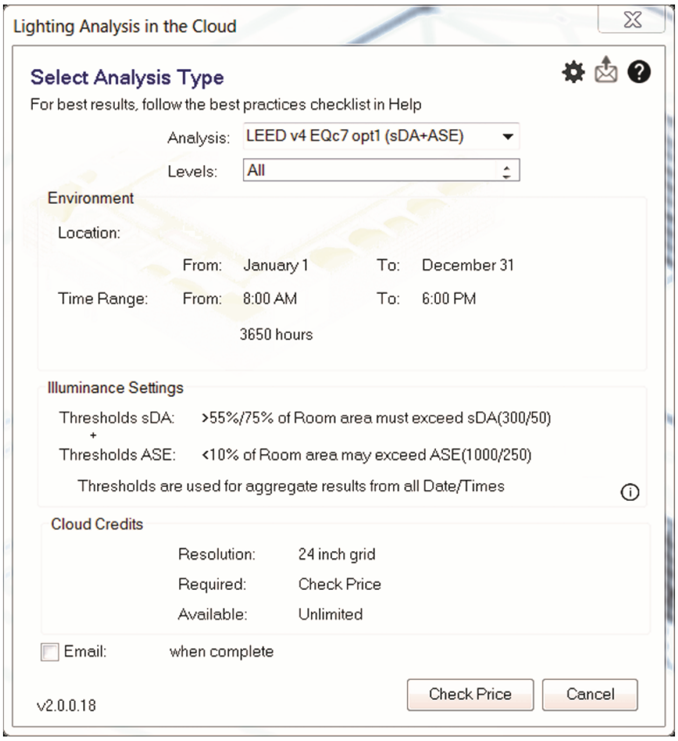


Fig. 4. Lighting analysis in Autodesk Revit

3.3. Life Cycle Impact Assessment (LCIA):

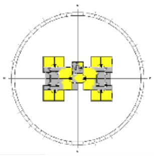
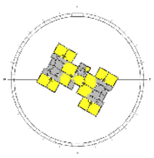
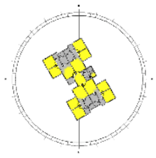
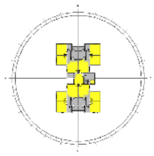
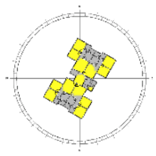
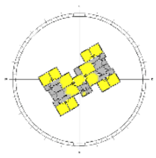
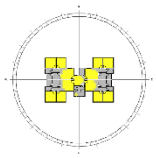
The presented results at this level of analysis are based on the evaluation of construction materials used in the functional unit of this work that considered the whole building as a single unit. The conceptual energy analysis of the case study building shows that the consumption of electricity and fuel account for 97%, and 3%, respectively. Results show that the case study building consumes 96,293 kWh of electricity per year, however, Table 2 presents the values of electricity consumption based on the adjustment of parameters.

Table 2. Energy consumption based on adjustment of parameters

HVAC System		Construction of External Walls		Construction of Roofs	
No.	**Electricity Consumption (kWh / year)**	**No.**	**Electricity Consumption (kWh / year)**	**No.**	**Electricity Consumption (kWh / year)**
1	121,801	**8**	97,747	**15**	95,108
2	117,347	**9**	97,340	**16**	101,684
3	87,509	**10**	95,820	**17**	95,624
4	76,550	**11**	99,104	**18**	102,488
5	121,801	**12**	122,977	**19**	95,708
6	77,234	**13**	99,189	**20**	101,343
7	121,801	**14**	104,938	**-**	-

According to the LEED daylight analysis, the results presented in this research are based on the building orientation within 180º. This comes back to the symmetric design of the case study building. Hence, this analysis considers seven basic cases to rotate the building between 0º and 180º within a variation of 30º, as shown in Table 3. Case (A) assumes that the longer side of the building is oriented to the east-west axis directly, while Cases (B, C, D, E, F and G) reflect a rotation of the main axis within 30º, 60º, 90º, 120º, 150º, and 180º, respectively.

Table 3. LEED daylight analysis of the case study

	Case (A)	Case (B)	Case (C)	Case (D)	Case (E)	Case (F)	Case (G)
Building Orientation							
sDA +ASE	33 %	30 %	15 %	15 %	21 %	25 %	33 %

3.4. Interpretation:

Comparing the energy performance in the case study building and adjustment parameters show that using particular HVAC systems or some alternative construction materials for exterior walls and roofs would influence the energy efficiency in buildings, as shown in Figures 5. In terms of HVAC systems, it can be seen that types numbers (3, 4 and 6) could reduce the consumption of electricity whereas types numbers (1, 2, 5 and 7) would dramatically increase this issue. In terms of construction materials of external walls and roofs, it is clear that applying super high insulation process on the different construction materials such as types numbers (11, 13, 15, 17 and 19) would increase the energy efficiency in buildings. Furthermore, reducing the thickness of insulated concrete walls would result in more energy consumption, and vice versa. This point is approved in types numbers (8, 9 and 10).

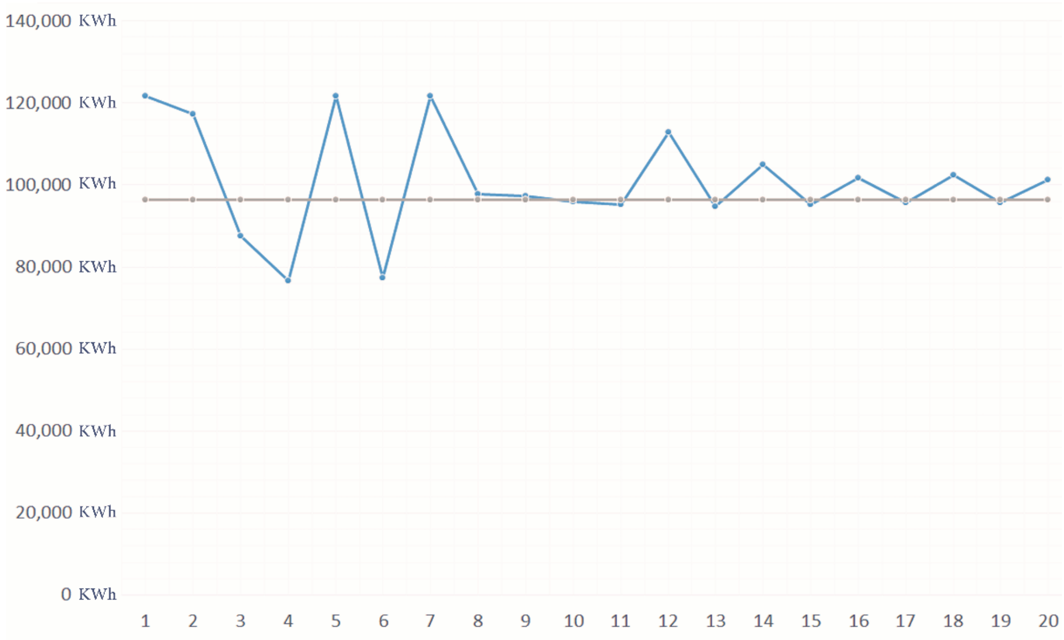


Fig. 5. Annual electricity consumption of the building and adjusting parameters

On the other hand, the collected outcomes of LEED daylight analysis as shown in Table 2 illuminate that Cases (A and G) would achieve the best results ever in terms of sDA and ASE, clarifying that 33% of building area would meet the required percentage hours of sDA in rooms within less than 10% of area above ASE. However, Case (B) presents the second best standard of the building that meets sDA and ASE requirements with a value of 30%. Besides, Cases (E and F) illustrate lower standards in terms of sDA and ASE with values of 21% and 25%, respectively. On the other hand, Cases (C and D) demonstrate the worst standards for such types of buildings with a value of 15%, each.

4. Discussion:

This paper highlights the growing interest in the field of BIM-LCA integration and evaluates the natural daylight assessment and energy consumption in buildings based on different design alternatives and orientations at an early stage of designing residential buildings. It clarifies that BIM models allow using various construction materials within different performance parameters at the designing phase in order to empower the decision-making process. Besides, this paper shows that LCA methodology aims to evaluate the influence of such estimations over the entire lifespan of the construction project. This work presents a BIM-LCA integration framework in order to analyze construction projects from a sustainable perspective, applying tools that allow the creation of different simulations in a short period. It presents the difficulties in comparing the different scenarios of energy and daylight analysis in such integration course (Anand and Amor, 2017).

The analyzed case study shows that there are different factors influencing energy efficiency in buildings such as the type of HVAC system and the application of the insulation process and the thickness form of the construction of external walls and roofs. The results show that the appropriate choice of such factors would reduce waste generation and environmental impacts. The applied tools at this step of analysis provide a wider vision of examining various alternatives to construction materials at an early designing stage in order to increase energy efficiency in the construction sector. However, climate data is a critical input to validate building performance analysis. This work presents an uncertainty issue facing this study in terms of the applied climate database in Green Building Studio that comes back to the year 2006. This means that the data might be outdated or does not reflect the reality of the region today.

Furthermore, this work shows that the building design and orientation factor play a fundamental role in controlling the capacity of natural daylight, glare and overheating potential in buildings. In other words, such factors are largely influencing the design decisions in such types of construction projects. The results show that orienting the long axis of the building towards the east-west direction, as shown in Cases (A and G), would achieve the highest inducing results in capturing the natural daylight potential. On the other hand, orienting this axis towards the north-south direction, as shown in Case (D) would achieve the lowest inducing results in these terms. However, rotating this axis with 30º, 120º or 150º degrees, as shown in cases (B, E and F), would expose the building to less natural daylight compared with Cases (A and G).

5. Conclusions:

This paper motivates the sustainability in terms of BIM-LCA integration at an early designing stage of construction projects. BIM models allow using various conceptual parameters, while LCA methodology evaluates the impact these parameters in the construction sector and on the environment. Thus, this work presents a methodological framework for the proposed integration between LCA methodology and BIM tools and analyzes a case study building in a way to achieve the objectives of this research by assessing the energy consumption and daylight analysis based on different design alternatives and orientations at an early stage of designing residential buildings. Besides, the tools presented in this work help architects, designers and engineers making more conscious choices in terms of natural daylight analysis and energy efficiency.

This work presents some critical points such as the difficulties of comparing the different scenarios of BIM tools in such integration course. On the other hand, it encourages reviewing the building orientation, the application of HVAC systems and the construction of external walls and roofs in the construction projects at the initial stages of design in order to increase energy efficiency and ventilation in buildings. In the light of results, integrating BIM models with the LCA methodology is considered as an optimal procedure towards achieving a sustainable development and empower the decision-making process in the construction sector. The proposed methodology helps to increase both energy efficiency capturing of natural daylight over the entire lifespan of buildings.

Acknowledgments

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APPENDIX 6

Life Cycle Assessment Methodology Integrated with BIM as a Decision-Making Tool at Early Stages of Building Design

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Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design

Mohammad K. Najjar, Karoline Figueiredo, Ana Catarina Jorge Evangelista, Ahmed W. A. Hammad, Vivian W. Y. Tam & Assed Haddad

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Life Cycle Assessment methodology integrated with BIM as a decision-making tool at early-stages of building design

Abstract. Climate change is one of the major concerns worldwide and greenhouse gas emissions plays an important role in increasing the temperature of the earth's atmosphere. Furthermore, the construction industry is one of that presents a considerable environmental impact as it consumes large amounts of natural resources and energy. Aiming to investigate the environmental impacts, Life Cycle Assessment (LCA) methodology evaluates products and services showing the similarities and differences in evaluating midpoint and endpoint impact categories. This study reviews LCA from a building perspective and empowers the decision-making process and sustainable building design in the construction sector. The novelty is to estimate the operating energy performance and evaluate the endpoint impacts of building materials at an early designing stage, considering two methods of construction; concrete construction and steel construction. This work follows the methodological framework of LCA based on ISO 14040 and 14044 guidelines within the available database, using Autodesk Green Building Studio application in Autodesk Revit and Open LCA software based on two assessment methods: IMPACT 2002+ and ILCD 2011. A case study of a multi-story office building is applied to achieve the objectives of this work. The building is structured at four levels of subsystems and associated construction materials: basic structure, walls, finishing, and windows. Results indicate that using steel construction instead of concrete construction is more environmentally friendly in such types of buildings. It encourages the application of innovative techniques in the production process to protect natural resources, reduce energy consumption, and protecting the built environment.

Keywords Life Cycle Assessment; Sustainable Building Design; Construction Materials; Damage Impact Categories; Environmental Impacts; Building Energy.

1 - Introduction

Energy consumption and greenhouse gas (GHG) emissions are becoming a key concern globally **(1)**. The world is witnessing a depletion in both natural resources and nonrenewable energy (Krantz et al. 2015; Tam *et al.*, 2019). The construction sector is considered as an activity that consumes energy and resources (Lasvaux 2010) **(2)** **(3)**. This highlights the crucial needs to find solutions to meet the standards of sustainability in construction, principally in serious circumstances such as growing competition, deteriorating of resources and deficiency of standards to protect the environment (Šaparauskas 2006). These factors play a basic role in damaging the surrounded environment and energy consumption during the entire Life Cycle Assessment (LCA) of construction materials. They may result in different areas of damage categories, endpoints, such as human health, ecosystem quality, and resources depletion (LCA guide 1998). The intensive environmentally human activities are producing harmful emissions that affect the environment. For example, the burning of fossil fuels, deforestation, and land use changes build up a long-term of GHG emissions such as (CO2, CH4, N2O, etc.) in the higher layer of atmosphere and result in global warming (Buchanan 1994). Experts warned that taking insufficient actions to reduce GHG emissions by 50% may increase the global surface temperature between 1.1 °C and 2.4 °C by the end of this century (Steffe and Fenwick 2016).

LCA t is an eco-friendly methodology object that computes the damage impact categories of building materials. LCA analyzes the different lifecycle phases of products since the extracting of raw materials and manufacturing, packaging and transporting to the site, constructing and installing, operating, until demolition and recycling (Buyle et al. 2013). Applying the methodology of LCA in construction projects at the designing phase gives the opportunity to increase energy efficiency and sustainability in buildings **(4)**. This comes back to the low cost of construction at this phase with a high potential to change the design and building materials (Liu et al. 2011). The novelty of this work is to estimate the operating energy performance and evaluate the damage categories of building materials at the early stages of designing buildings to increase energy efficiency and reduce GHG emissions in buildings.

This study evaluates the awareness of designers, architects, and engineers to the potential negative impacts of energy consumption and GHG emissions. Besides, it stimulates the optimistic application of LCA in the construction sector in a way to protect the natural resources and the built environment. The framework focuses on early design stages of constructing multi-story office buildings, considering two methods of construction:

- Case (A) concrete construction: using typical building materials such as reinforced concrete, brick, ceramics, and wood window frames.
- Case (B) steel construction: using steel beams, drywalls, clay plaster, and curtain wall systems.

This paper estimates the lifecycle energy use of the case study building as a prior step to evaluate the lifecycle of construction materials. It reviews the methodology of LCA from a building perspective using two assessment methods: IMPACT2002+ and ILCD2011. As a result, this work aims to integrate LCA methodology in the design process of buildings and evaluate the environmental performance of construction materials. This gives the opportunity to support proper environmentally oriented design choices and reduce both energy consumption and GHG emissions at the initial phases of design. This analysis intends to evaluate the damage impact categories of building materials, empower the decision-making process, and authorize the procedure of sustainable and environmental design in the construction sector. The objective of this work is to present the important role of sustainable construction in reducing the damage impacts of construction materials.

2 - Literature Review

The application of LCA methodology in the construction sector reflects the high quality of this tool as a reputable way to assess lifecycle in buildings (Sharma et al. 2011; Basbagil et al. 2012). LCA empowers the decision-making process and practices of sustainable buildings (Vandenbrouck et al. 2015; Najjar et al. 2017) . This work presents the three main phases of LCA: pre-building phase, building phase, and post-building phase, as shown in Figure 1. The pre-building phase starts by extracting raw materials, manufacturing and transporting to the site. Building phase includes the construction and the operation and maintenance periods of buildings. Post-building phase means the end of life and demolition of buildings (UNEP 2007).

Figure1. Life cycle building phase

Efforts to improve the implementation of operative practice and accelerate improvements in LCA continue to pose challenges for researchers. Academic and scientific research and, in particular, case studies of LCA from a building perspective proposed method to improve the understanding and practical application level for the development of theories in the field of the construction sector and might guide improvement strategies for LCA of building materials. Some studies underlined the understanding of established assessment methods and data quality in building LCA research

(Crawford and Stephan 2013; Wiedmann 2011). Other researches discussed the role of LCA to inform decision-making in the construction sector (Oregi et al. 2015; Stage et al. 2017). Further studies addressed various aspects of the construction sector from the methodological perspective of LCA (Cabeza et al. 2014Bastos et al. 2016; Crawford et al. 2016; Stephan and Athanassiadis 2016; Ingrao et al. 2016; Jalaei, Zoghi and Khoshand, 2019). Despite these publications, one can perceive a gap in the field of midpoint and endpoint categories based on various assessment methods. This gap lies in the inadequate analytical details that are covering this part of the study. In fact, the need for a systematically defined analysis extends beyond the knowledge inquiry and organization. This area needs to be handled in a more comprehensive way to empower the decision-making process in the construction sector and protect the built environment.

The comprehensive application of assessment methods at the Life Cycle Impact Assessment (LCIA) step is a major challenge that is facing the employment of Life Cycle Assessment (LCA) in the construction sector. Examples of these assessment methods are CML, EDIP, EPS, Cumulative Energy Demand, Cumulative Exergy Demand, Cumulative Exergy Consumption, Eco-indicator 99, IMPACT 2002+, Ecological Scarcity Method, ReCiPe,Japan Environmental Policy Priorities Index(JEPIX), LIME (Japanese LCIA Methodology based on Endpoint Modeling), LUCAS (LCIA method used for a Canadian context) (International Reference Life Cycle Data System (ILCD 2011), TRACI (Tool for ther and cssessment of chemical and other environmental Impacts), USEtox (scientific model endorsed by the UNEP/SETA), Methodology study for Ecodesign of Energy-using Product (MEEup), Building for Environmental and Economic Sustainability (BEES), Ecological footprints, Emergy Analysis, Cumulative Exergy Extraction from the Natural Environment (CEENE), and Intergovernmental Panel on Climate Change (IPCC) (Menoufi 2011; Acero et al. 2015; ILCD/GreenDaelta 2017; Jolliet et al. 2003; Halleux et al. 2006). In this study, two assessment methods are applied to meet the objectives of this work: IMPACT 2002+ and ILCD 2011, as shown in Figure 2. The last step in this flowchart is evaluating results. This means to address and classify the impact categories of construction materials.

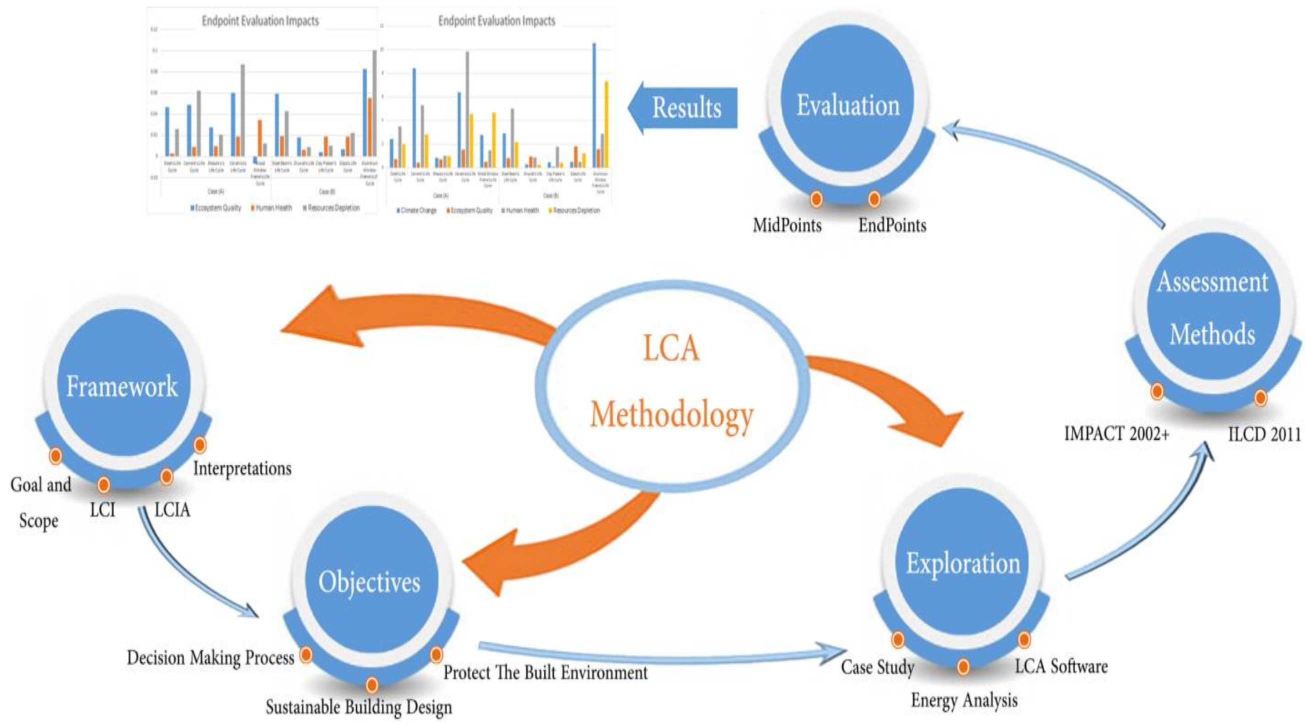

Figure 2. Flowchart of decision support analysis

Figure 2 illustrates a flowchart of decision support analysis to evaluate the impact categories of construction materials at an early stage of designing a construction project. This analysis depends on analyzing the lifecycle of energy use in buildings and transferring data of construction projects to LCA software to empower the decision-making process, achieve sustainability standards, and protect the built environment. Recently, several computer tools based on LCA methodology have been developed to simplify the LCA analysis for products and systems at the scale of the construction materials such as SimaPro, GaBi, TEAM, LCE, and Open LCA (Abdulla and Jrade 2012)]. In this work, Open LCA is applied as LCA software to simplify the endpoint categories of construction materials.

3 – Methodology

This study performs a practical application of LCA methodology to evaluate the damage impact categories of construction materials. It applies the methodological framework of LCA based on ISO 14040 and 14044 guidelines, taking into consideration the basic steps of LCA methodology, as shown in Figure 2 that is presented and developed in this work: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. Goal and scope step identifies the functional equivalent, system boundary and the set of building materials. LCI is the most inspiring step of LCA analysis. This comes back to the difficulty of collecting consistent and applicable data. The next step is LCIA where the quantities of materials, energy consumption, and input data are assembled using the indicators of sustainability. The final step is Interpretation that allows for the evaluation of the results achieved from LCI and LCIA (UNEP/SETAC 2010; Bayer et al. 2010). In this study, Open LCA is applied as LCA software to simplify the endpoint categories of construction materials.

This paper illustrates the classification of different midpoint impacts that lead to endpoint categories, as shown in Figure 3 (a, b, and c), based on two assessment methods that are applied in this analysis (ILCD 2010; Jolliet et al. 2003; Wolf et al. 2011; ILCD 2012; UNEP 2003; Yi et al. 2014; Sharaai et al. 2010). The midpoint characterization has a strong relation to the elementary flows with a lower modeling uncertainty whereas the endpoint characterization has a strong relation to the areas of protection. Hence, it can be recognized that the endpoint categories provide easier understandable information on the environmental relevance of the characterized flows (UNEP/SETAC 2012). As shown in Figure 3, it can be recognized that IMPACT 2002+ considers climate change as an endpoint category, while ILCD (2011) considers climate change as a midpoint impact leads to human health. In terms of ecosystem quality and resources depletion impacts, it can be seen that IMPACT 2002+ and ILCD 2011 are almost considering different midpoint impacts leading to such endpoints. In fact, this variety and differences in midpoint impacts for each endpoint category give the opportunity to achieve a comprehensive and wider vision for the evaluation of the environmental impacts. Hence, this work applies these two assessment methods in building up this analysis.

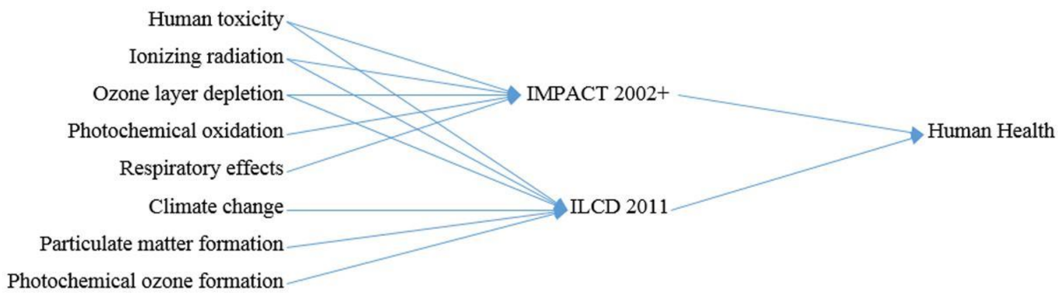

Figure 3 (a). Environmental impacts that lead to Human Health

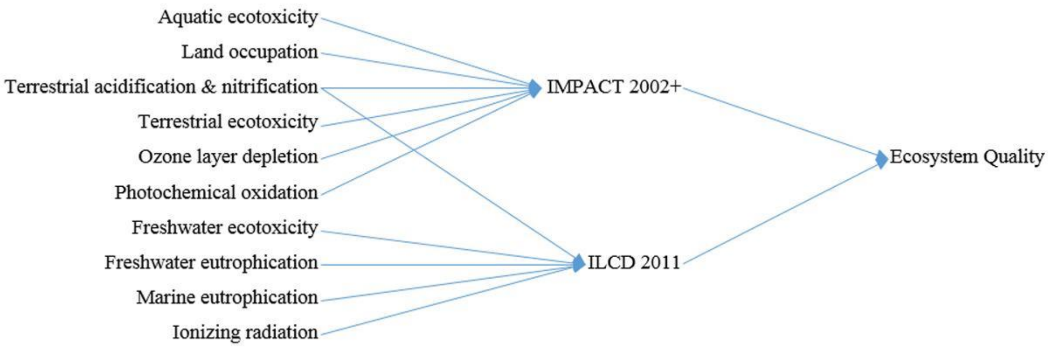

Figure 3 (b). Environmental impacts that lead to Ecosystem Quality

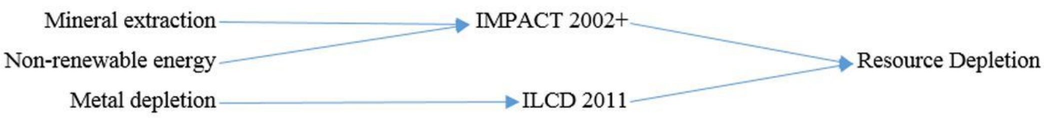

Figure 3 (c). Environmental impacts that lead to Resources depletion

The calculation of the impact assessment (LCIA) depends mainly on the evaluation of significance and elementary flows of these impacts towards drawing simpler understanding results (UNEP/SETAC 2012; Bayer et al. 2010; Bragança and Mateus n.d.) Elementary flows mean all inputs and outputs that the production system does in the entire lifecycle (UNEP/SETAC 2012; European Commission 2016). To sum up, this work builds up the results of LCA methodology based on each assessment method by determining boundaries, comparing results, identifying sources of impacts and recommendations, as shown in Figure 4.

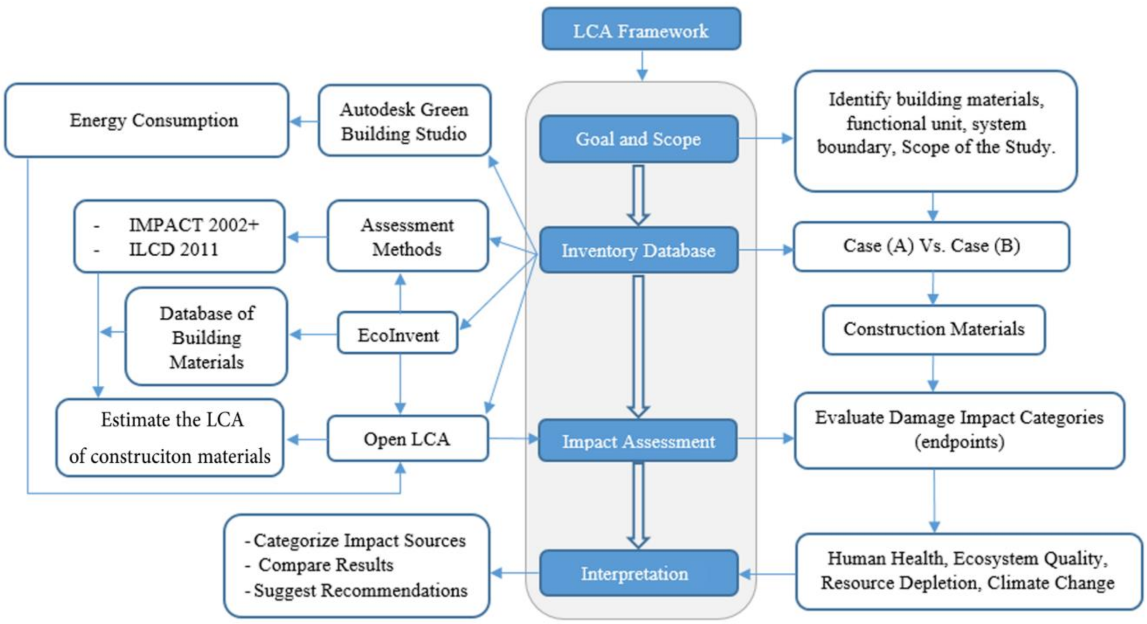

Figure 4. Research framework

4 – Case study – LCA applied to a multi-store building

The selected case study is a proposal of a typical multi-story office building in Brazil, considering two methods of construction in design: concrete construction (Case A) and steel construction (Case B). Figure 4 presents the methodological framework of LCA and clarifies that the first step is to identify the goal and scope of the case study before establishing the inventory of data. This work uses the Ecoinvent database, version 3.1, as an international database to build up the inventory of construction materials in the case study. This version of Ecoinvent is a comprehensive and transparent LCI database and allows applying several system models that are used to create fully independent model implementations out of the same unlinked Ecoinvent data (Ecoinvent guideline 2013). It uses several data provider toolkits that provide users with all relevant information and tools required. Examples of these toolkits are ecoSpold2 data format that creates the lifecycle inventories for Ecoinvent version 3 (Ecoinvent ecoSpold2 n.d.) and ecoEditor freeware that creates, edits, reviews, and uploads datasets for the future versions of the Ecoinvent database (Ecoinvent ecoEditor n.d.). However, the LCI is described in Ecoinvent based on single figures per input or output flow, which contain a level of uncertainty (Brocéliande n.d.). Hence, this version applies Pedigree Matrix approach to all types of distributions allowed by the ecoSpold2 data format (Muller 2014). This approach was modified to assess the quality of data in LCA and developed to derive uncertainty factors from a qualitative assessment of the data (Brocéliande n.d.; Muller 2014).

This study uses the Autodesk Green Building Studio application in Autodesk Revit as a tool to estimate the operating energy consumption and monthly cooling loads in the case study building. The design of the building and the conceptual construction materials are influencing the energy consumption in the construction sector (Grobler 2005), however, several energy simulations and tools such as BLAST, Energy Plus, QUEST, TRACE, DOE2, Ecotect, and Integrated Environmental Solution (IES-VE) have been developed and applied in buildings (Crawley 2008; Jalaei and Jrade 2014). In this discipline, Green Building Studio application is considered as a powerful building performance analysis platform that greatly simplifies the task of conducting the building performance using DOE2 as a proven and validated simulation engine to provide results related to energy use, water use, and carbon emissions (Autodesk 2013). The provided results at this level of analysis are evaluated and met the criteria under ANSI/ASHRAE Standard 140 (Autodesk 2014). However, Autodesk has identified the Green Building Studio application as a flexible cloud-based service that runs building performance simulations to optimize energy efficiency and heating and cooling loads at the designing process of construction projects (Autodesk Green Building Studio n.d). It produces various simulations for buildings, considering the modeling, specifications, and orientation of the building and properties of construction materials. Results at this step help assembling the life cycle energy analysis at the operation phase of buildings (Tally 2016).

Additionally, this research uses Open LCA software to integrate the statistics and collected results with the performance parameters of the software itself based on the applied assessment methods to achieve the objectives of this work, as shown in Figure 4. Open LCA evaluates the damage impact categories and compares the reflection of these categories on the life cycle of building materials selected in the case study based on various assessment methods. This open source software facilitates the process of accessing data at different stages of analysis, provides a systematic and transparent way to analyze complex life cycles, categorizes the hotspots in all aspects of the supply chain, and evaluates the environmental impacts and damage categories of products and services across all life cycle stages (Ciroth 2014).

The first used assessment method in this work is IMPACT 2002+. The collaboration of this assessment method is collected based on the adaptation of some existing characterization methods such as Eco-indicator 99 and CML 2002. This assessment method provides classification factors for around 1500 LCI-results. It distributes a reference substance for all midpoint scores and connects them to four endpoint categories: human health, ecosystem quality, climate change, and resources depletion

(Humbert et al. 2012; SimaPro Database Manual 2016). The second assessment method is the International Reference Life Cycle Data System 2011 (ILCD 2011). This method is the result of a project directed by Joint Research Center (JRC) of the European Commission and aimed to examine several life cycle impact assessment methodologies in order to achieve an agreement on the recommended method for each environmental impact category (Wolf et al. 2011, SimaPro Database Manual 2016; my EcoCost 2011). It is important to declare that this method targets the life cycle impact assessment of products in the European context. Besides, it supports the accurate use of characterization factors and motivates future improvements by developers of LCIA methods (ILCD 2012). The next step is to conduct the life cycle impact assessment (LCIA) by evaluating the damage impact categories (endpoints) of construction materials applied in the case studies (A) and (B). The last is the interpretation of impacts by comparing results and suggest recommendations.

The designing of the multi-story office building in the case study followed the traditional methods of designing such types of buildings in Brazil. It consists of 67 offices divided into four floors, with a total floor area of about 3424 m^2. The building takes the rectangular form (36 m x 24 m) with a total height of 12 m, providing three different spaces to work for companies and individual businesses: 24 m^2, 32 m^2, and 64 m^2, as seen in Figure 5. However, figures of operating energy presented in this work are generated by Autodesk Revit software, while figures of damage categories are generated by Open LCA software based on the two applied assessment methods and the inventory of data for each building material.

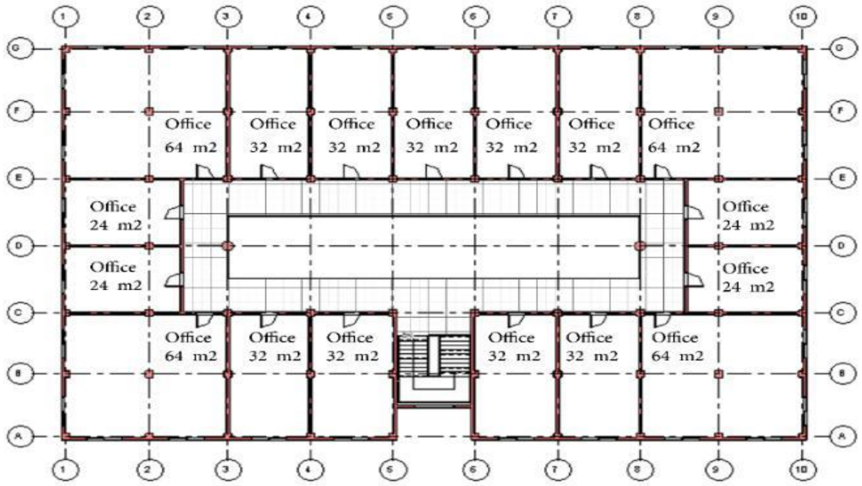

Figure 5. Proposal plan of the multi-story office building

Goal and Scope

This work adopts the methodology of LCA on the assessed case study at an early designing stage, considering the system boundary as the entire life cycle of building materials since the extraction of raw materials, manufacturing, distribution, construction, operation, and end-of-life phases. It is important to mention that the end-of-life phase in Brazil is distinguished by disposal and recycling. This comes back to the fact that only 1% of the construction waste is recycled in Brazil, whereas the majority is disposed of in landfills and vacant lots (Lassio et al. 2016).

Significant attention is given to the endpoint categories during the assigned system boundary of this work. The functional equivalent, which is a description of the evaluated product or system at the building level, considers the entire building as a single product. The functional equivalent at this level of the analysis takes into consideration the technical and functional requirements of the building and forms a basis for comparisons of the results of the assessment (BS EN 15643-2 2011). However, the examination of the functional equivalent focuses on the basic structure, exterior walls and finishing, jackets, partition walls, and windows of the building based on the subsystems applied and the quantities of construction materials, as shown in Table 1.

Autodesk Revit automatically produces the quantities of building material for each case study modeled. The scope of this work is that it targets two construction methods in designing an office building in Brazil. It intends to quantify and measure the damage categories such as human health, ecosystem quality, resources depletion, and climate change of building materials based on two different assessment methods. Each assessment method considers different midpoint indicators and uses different characterizations, normalization, and weighting factors to estimate the endpoint categories of building materials. Hence, this work applies two different assessment methods as a simple simulation that could enrich the total comprehension of the elementary flows of building materials and environmental impacts in terms of the selected system boundary.

Table 1. Subsystems and associated construction materials

	Case (A)			Case (B)		
	Subsystem applied	**Material**	**Quantity**	**Subsystem applied**	**Material**	**Quantity**
Basic Structure	reinforced concrete structure	cement	118,750 kg	steel structure; steel beams	steel beams	324,580 kg
		steel	28,858 kg			
Walls	masonry; brick blocks	brick	589,615 kg	drywall partitions; gypsum, plaster, and foam	drywall	211,019 kg
Finishing	ceramics	ceramics	170,785 kg	clay plaster	clay plaster	14,673 kg
Windows	window frame; wood	wood	260 m^2	curtain wall; aluminum and glass	glazing	1,440 m^2
					Aluminum	98,352 kg

Life Cycle Inventory (LCI)

The second step of LCA is Life Cycle Inventory (LCI) where the information on building materials, energy consumption, and emissions are collected. The database at this level is considered as a group of elementary flows including all emissions released into and from the environment for each unit process in the production system (UNEP/SETAC 2012; Baye et al. 2010). In other words, it means all inputs and outputs that a production system does in the entire lifecycle. LCI database must be reliable and consistent, otherwise inappropriate data will cause prejudice and disadvantages results (Bragança and Mateus n.d.). Building effective LCA models require transparent, high quality, and widely accepted inventory data; "*An LCA is only as valid as the data it uses*" (SimaPro 8 2014).

This work uses the Autodesk Green Building Studio application in Autodesk Revit software to estimate operating energy efficiency and cooling loads of the case study building. At this step, different assumptions are required to be filled-in precisely in order to achieve reliable results such as building type, location, thermal properties, project phase, building envelope, building zone and spaces, building surfaces and openings, building operating schedule, HVAC system (Heating, Ventilation and Air Conditioning), and outdoor air information, etc. In this analysis, heating is excluded from operating energy, as it is not used in office buildings in Brazil.

Moreover, this work applies Open LCA 1.5.0 as a life cycle software to evaluate the damage impact categories for each case study building. It uses Ecoinvent database version 3.1 to build up the inventory of data of the construction materials in the analysis, considering two assessment methods: IMPACT2002+ and ILCD2011. Open LCA offers full and valid access to the Ecoinvent database in order to build up the inventory of data for production systems and projects (GreenDelta n.d.). At this step, three main navigations are required to be identified accurately: flows, processes and production systems. Besides, categories and quantities of construction materials and the consumption of energy are to be filled-in properly in input and output parameters in order to build up a reliable inventory database and achieve the objectives of this work. Additionally, information about the transportation of construction materials is essential to complete parameters analysis in Open LCA. This work considers that roads are the main transportation model for all construction phases in Brazil using lorries with capacities of 16 and 32 metric tons. Additionally, the average distances of manufacturers in most Brazilian cities are ranging from five to fifteen kilometers. On average, if you choose one specific point you will be most likely a ten kilometer away from one of them. Hence, this work proposes some distances to build up a complete inventory database in Open LCA. These distances were previously proposed in other case study works in Rio de Janeiro in Brazil as followings (Lassio et al. 2016; Najjar et al. 2017).

- At the manufacturing phase, the construction site is considered the same location for construction and extraction of raw materials.
- At the distribution phase, the distances between existing suppliers nearby the construction site are in a range of 10 km.

At end-of-life phase: the construction waste is destined for a landfill with displacements of 12 km, or to be processed for recycling with displacements of 55 km.

Life Cycle Impact Assessment (LCIA)

The third step of LCA is the Life Cycle Impact Assessment (LCIA). At this step, quantities of building materials, energy consumption, and emissions are being calculated in a way to create simpler sympathetic results (Cabeza te al 2014).. Moreover, environmental intervention findings of LCI level such as raw material extraction, emissions and physical modification of natural area with the help of impact assessment methods are translated into environmental impacts. The emissions in air, water or soil could be organized according to both quantity and weight (Menoufi 2011; Humbert et al. 2012; Margni et al. n.d.). As previously discussed, this work considers practicing two assessment methods in order to evaluate LCIA and transform the results and findings of the inventory step depending on the midpoint impact.

According to the energy analysis in Autodesk Revit, the results presented in this research are based on the comparison and analysis of the building components used in the functional equivalent of this work that considered the whole building as a single unit. However, estimating the life cycle of energy consumption analysis in Autodesk Green Building Studio application is associated with annual energy use: electricity and fuel. The conceptual energy analysis shows that electricity is the major source of operating energy consumption in such type of buildings. Figure 6 shows that the life cycle of electricity use in case (A) accounts for 18,572,661 kWh whereas in case (B) accounts for 20,018,373 kWh. On the other hand, the life cycle of fuel use in case (A) accounts for 1818885 MJ whereas in case (B) accounts for 1855468 MJ.

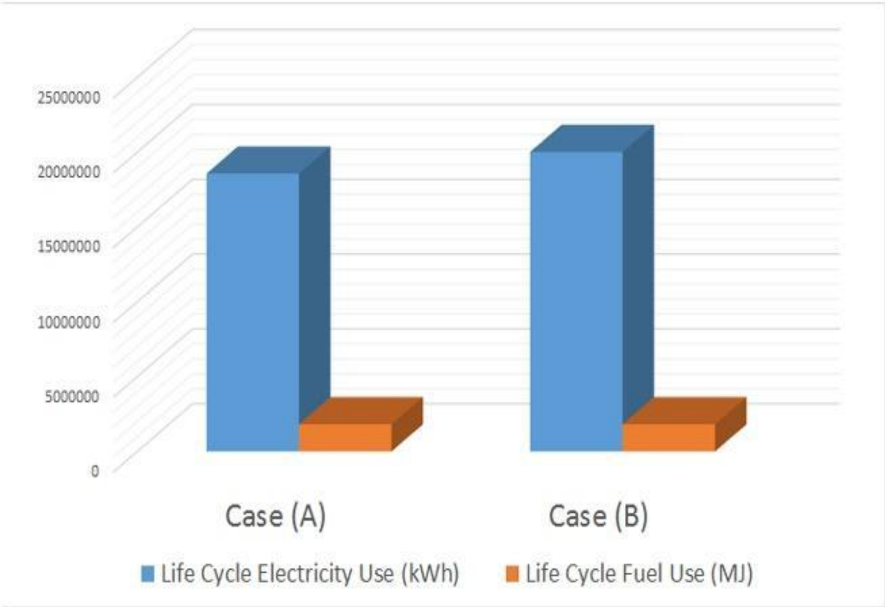

Figure 6. Life cycle energy use in the case study

Figure 7 presents the character of monthly cooling loads of the selected functional equivalent in the case study. In this part of the analysis, Autodesk points out that positive values reflect the cooling demands that are required to be satisfied by cooling systems or other means, while negative values reflect the loss of cooling values (Autodesk. Monthly Cooling Load 2016). Accordingly, the largest cumulative cooling loads in both case studies occur in January, February, March, April, and December, with the extreme contribution from walls in case (A) and windows in case (B).

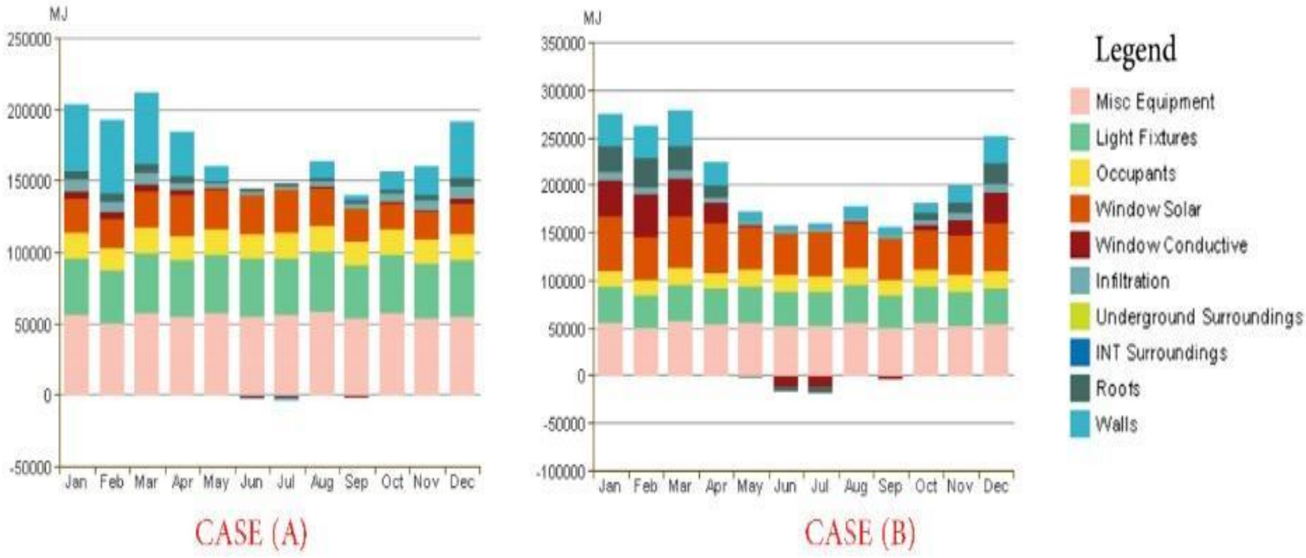

Figure 7. Monthly cooling loads

Furthermore, Figures 8 and 9 reflect a comparison of the damage impact categories of the life cycle of construction materials used in the functional equivalent in case studies (A) and (B) using Open LCA software based on IMPACT2002+ and ILCD2011 assessment methods, respectively.

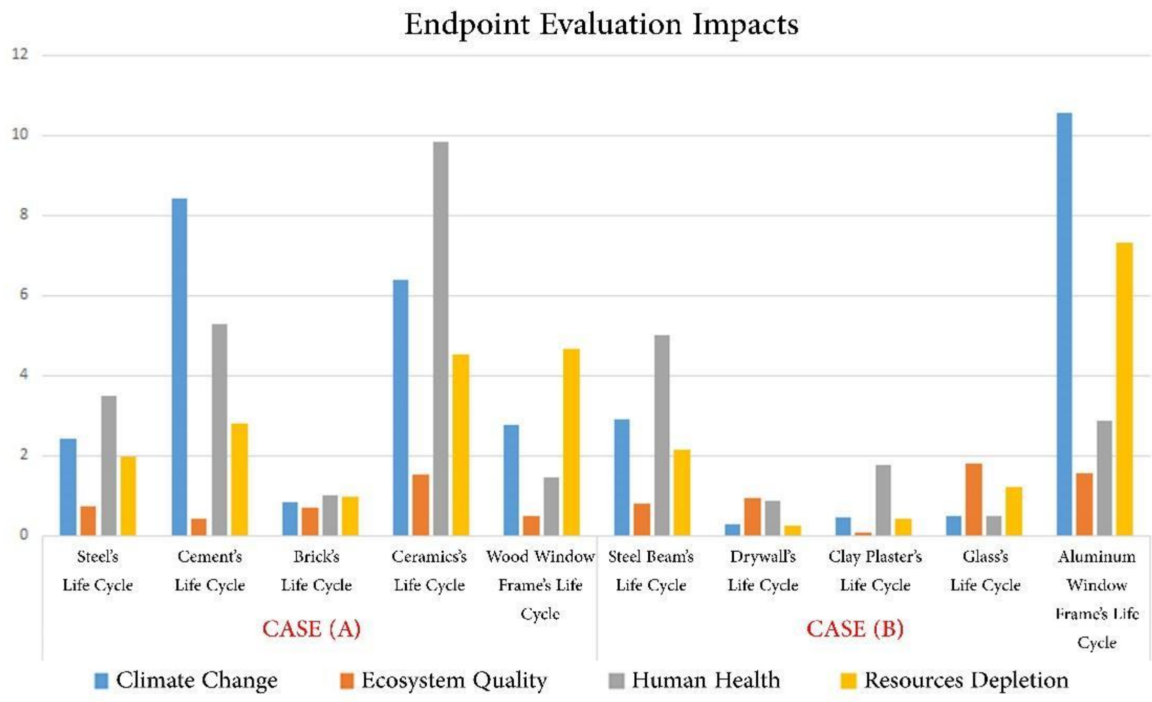

Figure 8. Endpoints comparison of construction materials based on IMPACT2002+

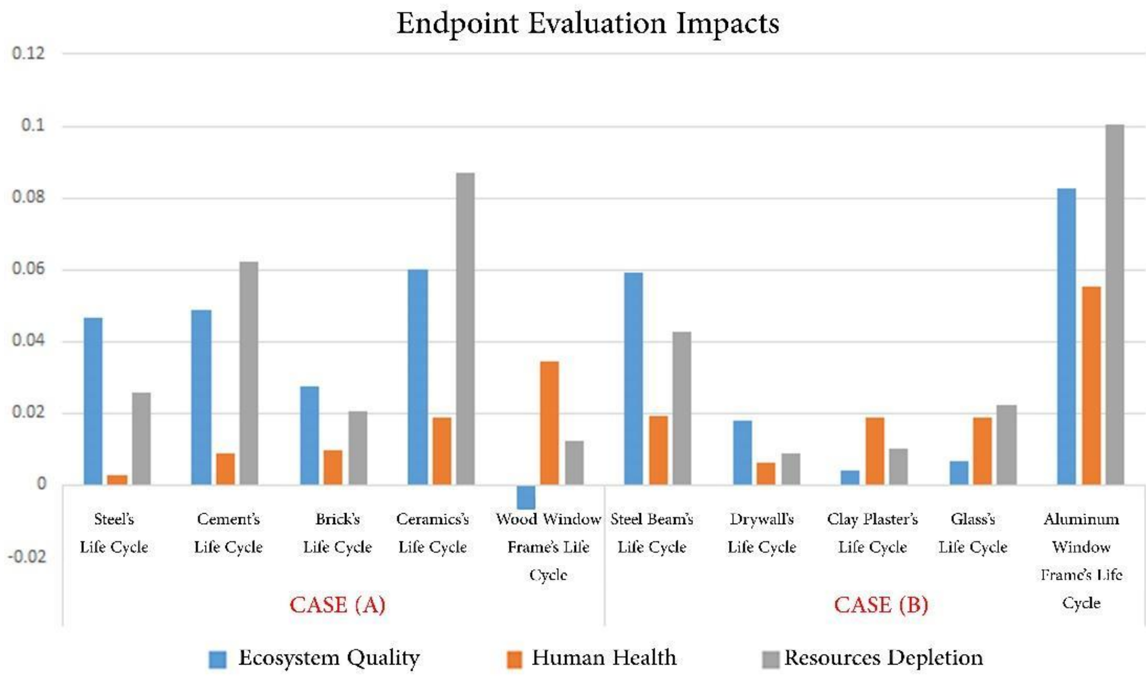

Figure 9. Endpoints comparison of construction materials based on ILCD2011

Interpretation

The last step of LCA methodology is Interpretations. This step originates conclusions and recommendations, stands out the environmental issues, and creates environmentally friendly decisions (UNEP/SETAC 2012). It comes directly after quantifying, identifying and evaluating the findings and indicators of LCI and LCIA. Besides, this step gives the opportunity to classify the source of impacts, compare solutions, clarify boundaries of the analysis, and propose recommendations [55]. However, comparing the life cycle of the operating energy use in Figure 6 shows that steel construction building would consume higher energy than concrete construction, while Figure 7 illustrates more monthly cooling loads in case (B) than case (A).

Analyzing the lifecycle of construction materials in the two assessment methods applied in this work, as seen in Figures 8 and 9, highlighted that the life cycle of aluminum and ceramics are the master agents of the analyzed damage categories. However, the life cycle of brick, drywall, clay plaster, and glass perform the least inspiration contributor among the assessed building materials in the functional equivalent. Figure 8 shows that LCA analysis of the case (A) considers cement and ceramics as substantial agents for climate change and human health damage categories whereas brick is considered as the least building materials that passively affect these damage impacts. Besides, the life cycle of both ceramics and wood play fundamental roles in raising the damage category of resources depletion. On the other hand, the analysis of case (B) considers aluminum as the substantial agent for climate change and resources depletion impact categories whereas steel beam is the main agent for human health impact category. However, it can be recognized that IMPACT 2002+ give a low ecosystem quality impact for all assessed building materials.

Additionally, Figure 9 presents that LCA analysis of the case (A) considers ceramics and wood as substantial agents for human health damage category whereas brick, cement, and steel are the least building materials that passively affect this damage impact. Besides, the life cycle of both cement and ceramics play a fundamental role in raising the damage impact category of resources depletion. The life cycle of these two materials, in addition to steel, are considered the main agents for the ecosystem quality damage category whereas the life cycle of wood has a positive influence on such damage impact. On the other hand, the analysis of the case (B) considers aluminum as the substantial agent for ecosystem quality, human health, and resources depletion damage categories. Besides, the life cycle of steel beam is considered the second agent for the same damage categories.

5. Discussions

The relationship between construction materials and energy has improved in a complicated way in recent decades. This comes back to the modern technologies that explored the different properties and capabilities of these materials. At the level of the environmental impact, this work underlines that IMPACT2002+ assessment method performs a strong combination of midpoints and endpoints. It aims to evaluate the results of the LCI step by combining midpoint impacts with their related damage categories (Menoufi 2011, Jollietet al. 2003) Besides, this work shows that the ILCD 2011 assessment method develops a group of intermediate endpoint categories based on the environmental impacts (Wolf et al. 2011; my EcoCost n.d.). Furthermore, IMPACT2002+ assessment method considers climate change as an endpoint impact whereas ILCD2011 assessment method considers this impact as a midpoint factor results in the human health category. This issue has been clarified when IMPACT2002+ underlined the high impact of the life cycle of aluminum at the climate change category, while still has a low impact on the human health category. Meanwhile, ILCD2011 raised up the high impact of the life cycle of aluminum at the human health category.

This study analyses the lifecycle of operating energy consumption and the cooling loads in such types of buildings. According to the collected outcomes, the results show that exterior façades are the main agents for cooling loads in such type of buildings. Thus, it is highly important to review the improvement industry of building materials before investing in the construction sector. Aiming to dedicate efforts to satisfy cooling demands in buildings and increase energy efficiency. For example, most of the cooling loads in steel construction would be in window solar and window conductive. This means that curtain wall systems are the major responsibilities of the loss of cooling values in such type of construction. On the other hand, most of the loss in cooling demands in concrete construction would be on walls and windows, with a minor significance of infiltration. This means that the construction of exterior walls and the installation of windows are the major responsibilities of the loss of cooling values in such type of construction. However, it can be considered that raising cooling demands will necessitate increasing values of energy consumption, particularly for HVAC systems, to satisfy the cooling conditions of buildings. In this context, comparing four external walls presenting different systems and materials, Igrao et al. (2016) highlighted the influence of this composnent on energy and environmental impact showing positive benefits selecting ventilated facades. As a result, this work shows that using steel beams with curtain wall systems might end-up in very high cooling loads compared to concrete construction. In this discipline, reducing the cooling loads in buildings would increase the energy efficiency in buildings and, consequently, minimize the passive environmental impacts in the construction sector(

Additionally, this work integrates the methodology of LCA in the design process of buildings in a way to evaluate the environmental performance of construction materials analyzed in the case study. In this discipline, the results of evaluating the life cycle of construction materials would vary based on the applied assessment method. This clarifies that the methodology of LCA presents the similarities and differences between assessment methods in evaluating midpoint and endpoint impact categories Several reseachers have been IMPACT 2002+ and/or ILCD 2011 to evaluate wall with different constructions materials (de Souza et al. 2016; Lassio et al. 2016; Cabeza et al. 2014) . For instance, the analysis that uses IMPACT 2002+ as an assessment method raises up the high impacts of aluminum, cement, and ceramics at the climate change and resources depletion levels . Additionally, it shows a high impact at the human health level in terms of the life cycle of ceramics, cement, steel beam and steel. This assessment method underlines a low impact at the ecosystem quality level in terms of the life cycle of all construction materials assessed in the functional equivalent. On the other hand, the analysis that uses ILCD 2011 as an assessment method highlights the high impact of the life cycle of aluminum, ceramics, cement, steel beam and steel at the resources depletion and ecosystem quality levels. Hence, this paper recommends applying the best techniques and innovations in a way to increase energy efficiency, protect the natural resources and surrounded environment. In this discipline, this work shows that the production process of building materials is affecting the natural resources and ecosystem quality. Thus, it suggests the usage of the best techniques and innovations that could save resources and protect the environment.

It is highly important to note that achieving the objectives of this paper requires comparing the life cycle of construction materials and examining the different damage impact categories based on two assessment methods. This work underlines that designers, architects, and engineers should review the methods of construction in their designs, taking into consideration the applied subsystems and associated construction materials. Besides, it shows that applying steel structure in this type of construction would be more environmentally friendly than concrete structure in terms of installing high-efficiency curtain wall systems, corroborating to previous research findings (Najjar 2017).The focus of this paper is on the whole life cycle assessment of construction materials rather than splitting the results for each phase. Hence, this part of the analysis is evaluated in four levels of subsystems and their associated materials over the entire lifecycle assessment, as follows:

A. Basic structure level, the life cycle of assessed construction materials: concrete construction and steel construction, shows that cement and steel have higher impacts than the steel beam. This means that steel structure in such types of buildings is more environmentally friendliness than reinforced concrete structure. In another study considering Brazilian data, De Souza et al. (2016) reported that concrete manufacturing process has a significant impact on resource depletion and climate change.

B. Walls level, the life cycle of assessed construction materials: brick and drywall, shows that brick has a slightly higher impact than drywall, however, both building materials have minor inspirations on damage impact categories. Similar finding was stated by Condeixa el al (2014) Lassio et al. (2016) as ceramics materials dependend on burning fossil fuels, which are used in manufacturing process , distribution, transport, and utilization.Thus, the selection of the proper building material at this level depends on the function, space, and total loads of buildings. In the case of using brick in exterior walls, it is important to realize the infiltration rate to minimize cooling loads and reduce energy consumption.

C. Finishing level, the life cycle of assessed construction materials: ceramics and clay plaster, shows that ceramics has a higher impact than clay plaster. This reflects the positive application of clay plaster as a finishing material in such types of construction.

D. Windows level, the life cycle of assessed construction materials: wood window frame and curtain wall systems, shows that aluminum has passive impacts on the environment than wood whereas glass is considered as an environmental friendly material. This offers two different options in design. The first option is to install high-efficiency wood window frames, while the second option is to install curtain wall systems taking into consideration expanding the space area of glass and minimizing the sections of mullions. In both options, it is highly important to consider the window conductive factor to reduce the consumption of energy and protect the environment.In this context (integration BIM-LCA), Crippa et al. (2018) presented similar results, as wood frame arose as the most sustainable option.

6. Conclusion

This study compared the LCA of building materials that are assembling the construction of multi-story office buildings in Brazil considering two methods of construction in design, based on two assessment methods: IMPACT2002+ and ILCD2011. It empowers decision-making process and concepts of sustainable and environmental construction. A case study of a typical multi-story office building is assessed in a way to appraise the comprehension of designers, architects, and engineers to the endpoint categories of construction materials such as human health, ecosystem quality, resources depletion, and climate change. The novelty of this work is to estimate the operating energy performance and evaluate the damage categories of building materials in order to increase energy efficiency and reduce GHG emissions in the construction sector at the early stages of design. This work considered the important selection of database and assessment methods in order to estimate damage categories and achieve the objectives. It followed the LCA methodological framework based on ISO 14040 and 14044 guidelines to evaluate the importance of impacts with the elementary flows, suggest solutions, and advise recommendations.

The inventory of data was built based on two construction methods of designing office buildings in Brazil, case studies (A) and (B), and the Ecoinvent database of the selected construction materials. It intends to estimate the life cycle energy use and cooling loads in the case study building using Autodesk Green Building Studio application in Autodesk Revit. Such assumption gives the opportunity to build up a reliable database and figures out the building components that are passively influencing the consumption of energy. Then, it applied Open LCA software to estimate the endpoint categories of the life cycle of construction materials based on each assessment method. The findings of this paper illustrate the ability of LCA to promote the comprehensive application of different database and methods that aim to assess the environmental loads of components and techniques over the entire lifecycle of products. In other words, LCA methodology presents the similarities and differences among the several assessment methods in evaluating various impacts at both midpoint and endpoint levels. This work presents that each assessment method considers different midpoint indicators and uses different factors to estimate the endpoint categories of building materials. In this term, using two assessment methods is considered as a simple simulation enriching the total comprehension of the elementary flows of building materials in the construction industry.

This work highlights the imperative necessities to use suitable materials in terms of fewer energy and resources consumption, ecosystem friendliness and less impact on human health. This study suggests that designers, architects, and engineers review the methods of construction in their designs, including the subsystems and the selection of building materials. This research shows that applying steel construction in such types of buildings is more environmentally friendly than concrete construction. Moreover, brick and drywall have such a low inspiration on the endpoint categories. In this term, this work highlights that using brick as an exterior wall material depends mainly on the infiltration rate that could reduce both cooling loads and energy consumption. At the finishing level, this research presents that applying clay plaster instead of ceramics could reduce environmental impacts in such types of buildings. Finally, this research analyzes the selection of construction materials at the windows level in two possibilities. It suggests considering the window conductive element as the main factor that could reduce the cooling loads in such type of buildings. The results show that using wood window frames is more environmentally friendliness than aluminum in such types of buildings in Brazil. However, installing curtain wall systems could be environmentally friendly in some conditions such as expanding space area of glass and minimizing sections of mullions.

The production process of construction materials is affecting natural resources and ecosystem quality. Hence, this paper encourages using the best techniques and innovations to save resources and protect the environment. Additionally, it recommends that contractors and architects review the lifecycle of the selected building materials in their projects, taking into consideration the imperative requirements to lessen environmental impacts of these materials in all phases of building construction, particularly at early designing phase. At this phase, there is a high potential to reduce the weight and quantities of building materials that will passively affect the environment in the operation or end-of-life phases.

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APPENDIX 7

APPENDIX 7A

Parametric Analysis to Improve Energy Performance of Construction Projects

(A conference paper)

APPENDIX 7B

Integrating Parametric Analysis with Building Information Modeling to Improve Energy Performance of Construction Projects

(A Journal publication)

APPENDIX 7A

Parametric Analysis to Improve Energy Performance of Construction Projects

(A conference paper in 1st International Conference on Construction Project Management and Construction Engineering, Sydney, Australia, 2018)

Parametric analysis to improve energy performance of construction projects

Mohammad Najjar[1], Ahmed W A Hammad[2], Vivian W. Y. Tam[3], Ana Catarina Jorge Evangelista[4], Assed Haddad[5]

[1]Ph.D Candidate, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
[2]Lecturer, UNSW Sydney, Sydney, Australia
[3]Professor, Western Sydney University, Sydney, Australia
[4]Research Fellow, Western Sydney University, Sydney, Australia
[5]Professor, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
Corresponding author's E-mail: assed@poli.ufrj.br

Abstract

Building Information Modeling (BIM) tools provide a distinctive way of observing and estimating energy consumption in construction projects. This work presents the interests of BIM tools in examining different design alternatives in order to improve energy performance in buildings. A novel framework is proposed to enhance the design of energy output in construction projects. This work empowers decision-making process and sustainability through a parametric analysis of the selection of construction building components. The methodological framework accommodates various performance parameters through the use of experimental design for improving energy efficiency of buildings. A case study with a group of construction materials for exterior walls and roofs as well as a set of the window-to-wall ratio are examined in different climate classifications. RStudio software is applied as a linear regression analysis to determine all the variables of the design factors. Autodesk Green Building Studio software is applied as the BIM tool to estimate energy use intensity (EUI) of the applied factorial designs. This study indicates that BIM modeling is an optimal procedure towards empowering both sustainability and decision-making process in the construction sector. The results show that the climate data plays a fundamental role in determining the energy consumption in construction projects. Besides, the design factor of the window-to-wall ratio is the main agent of influencing the energy consumption in buildings rather than any other building components, hence it suggests constructing buildings within minor opening spaces at any climate zone towards nearly Zero Energy Buildings (nZEBs).

Keywords: Building Information Modeling; Sustainable Construction; Energy Use Intensity.

1. INTRODUCTION

The world is witnessing an increasing concern in the field of energy efficiency. Advanced solutions are required to achieve the sustainability standards in this field (Šaparauskas & Turskis 2006). Several tools and methods are assessed to support the implementation of sustainable strategies in the built environment. In this discipline, Building Information Modeling (BIM) is being discussed as a building tool that evaluates energy performance in the construction sector, providing users with the ability to explore the different alternatives to increase energy efficiency in buildings (Najjar et al. 2017).

The novelty is to propose a framework that utilizes BIM tools in order to improve energy performance of buildings. It is envisaged that the proposed method will empower decision-making process and sustainability of designing construction projects. The Energy Use Intensity (EUI) is evaluated, taking into consideration the building components that are constructing the envelop of buildings, window-to-wall ratio, and the installed capacity. Experimental design, which involves a systematic collection of data, is utilized to focus on the planning of the selection process itself rather than the analysis of the results, based on a linear regression analysis (Nist Sematech 2012). The methodological framework developed accommodates various global climates, in response to the consensus worldwide on the need for improving energy consumption in buildings and enhancing the sustainability of the built environment. The output results from the process modeling of the experimental design are conducted in order to evaluate the energy performance towards nearly Zero Energy Buildings (nZEBs). A case study example of a single-family house is examined in different cities with varying climate data in order to validate the developed methodological framework.

2. FOCUS AND METHODOLOGY

The methodology proposed in this paper simulates the energy performance of construction projects, considering the EUI as one of the key metrics to benchmark the energy performance in buildings. It is calculated by dividing the total annual energy consumed in the building by the total gross floor area.

2.1. Decision Support Analysis

The initial step in the proposed approach is the integration of a number of performance parameters that influence the energy consumption during the operation phase of buildings, such as building modeling and climate data, as shown in Figure 1. The design factors relevant to the building modeling parameter include the identification of the function and use of the building, type of energy use and consumption, CO_2 production, exterior area of roof and walls and the exterior space of openings associated with the building (Perrone & Filiatrault 2017). These factors need to be combined together with the design features of the climate data parameter at the construction site of buildings.

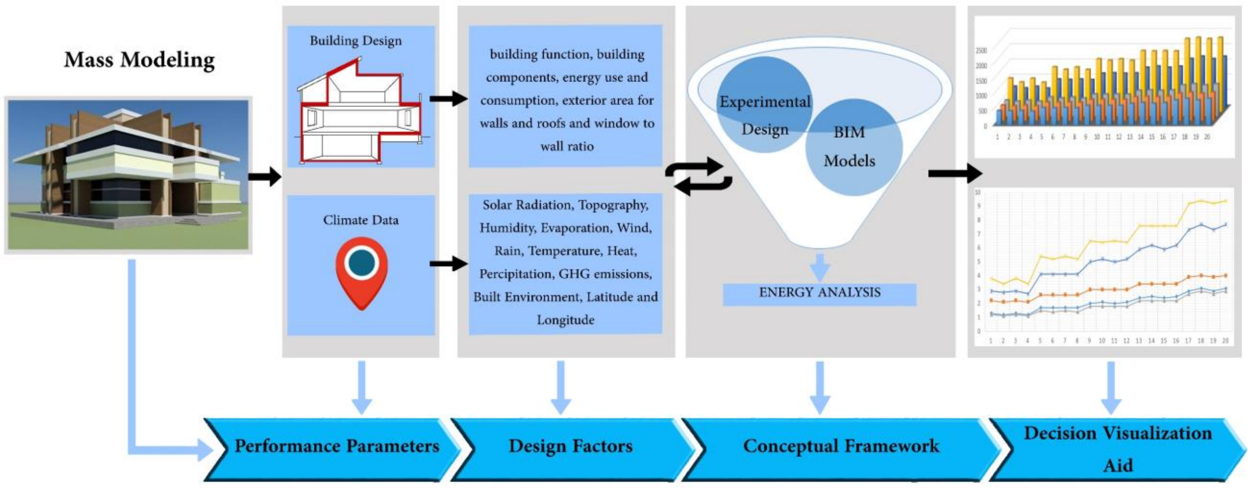

Figure 1. Decision support analysis

The evaluation process of the collected database starts by measuring the energy consumption, using BIM models as an indicator of sustainability. The methodology makes use of an experimental design procedure to indicate the best building component and window-to-wall ratio that could improve energy efficiency in buildings based on the different climate data and annual average temperature. The experimental design work is based on a parametric analysis that examines different values for several design factors. Such a process provides the maximum information at the minimum experimental cost (Callao 2014). The last step of the methodological framework of this study is to analyse and evaluate the collected results in order to simulate the energy performance in construction projects. This process starts by classifying sources of data, comparing results, and suggesting recommendations.

2.2. Linking framework components

The first step is to identify the size of the case study, which means identifying the amount, weight and quality of the specific product investigated, as shown in Figure 2. The second step is to build the inventory of database by estimating all the expected variables in an experimental design work using a parametric analysis based on a linear regression. RStudio is used for determining all the variables of the experimental design work through a regression analysis (RStudio n.d.). Autodesk Green Building Studio is adopted as an intelligent BIM model performs and estimates the energy performance in buildings (Abdulla & Jrade 2012). The third step is to evaluate the collected database for each mas modeling. At this level of the analysis, the collected EUI results in Autodesk Green Building Studio are evaluated in order to specify the impact of building components and window-to-wall ratio on energy consumption in buildings. Conducting such an analysis demands a parametric analysis involving gradual increments of the window-to-wall ratio and various building components.

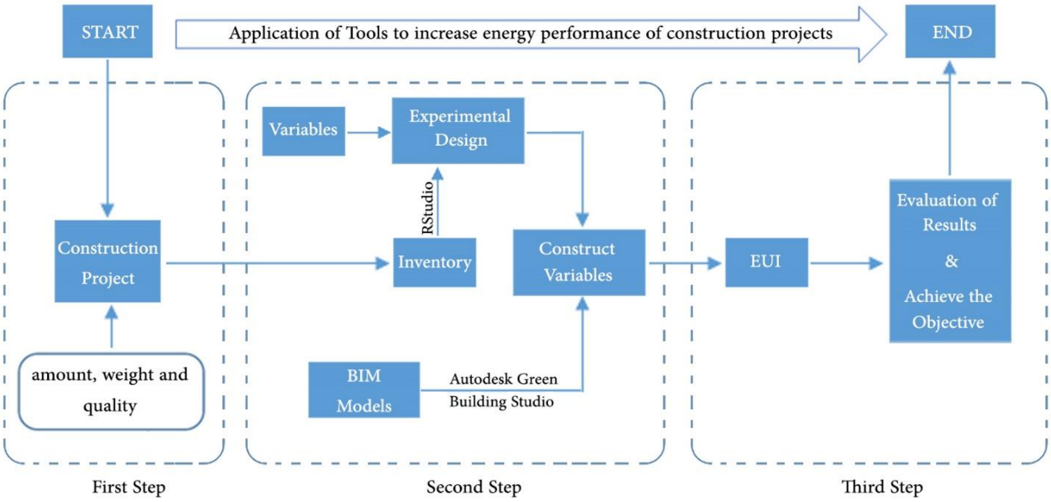

Figure 2. Linking framework components

3. CASE STUDY: VALIDATING THE METHODOLOGICAL FRAMEWORK IN A SINGLE-HOUSE FAMILY

The applied case study aims to validate the proposed framework used to model the decisions involved in choosing the building materials for construction projects. In order to showcase the versatility of the proposed framework, the proposed analysis is conducted in six different cities with different climate data. The chosen cities include Dubai in United Arab of Emirates, Moscow in Russia, Mount Wellington in Australia and Porto in Portugal that are located in dry climates, continental climates, polar climates, and mild temperate climates, respectively. In addition to this, there are Kuala Lumpur in Malaysia and Rio de Janeiro in Brazil that belong to the tropical climates within different sub-type classifications; tropical rainforest climate and tropical savanna climate, respectively.

3.1. Size of the case study

The case study of this work examines the energy efficiency of a single-family house, within a total floor area of a 60 m^2, consuming the energy for purposes of heating, cooling, lighting, equipment, pumps and hot water. The analysis takes into consideration two types of building materials that are constructing the exterior walls and roof, namely Insulated Concrete Form (ICF) wall, 10 thick form, and Insulated Concrete Form (ICF) wall, 14 thick form for walls. While Continuous Deck Roof with Code Compliant Insulation and Continuous Deck Roof with Super High Insulation for the roof. Additionally, the parametric analysis considers a range of different window-to-wall ratio (15%, 30%, 40%, 50%, and 65%).

3.2. Inventory of database

The inventory of database focusses on the operation phase of the case study and is constructed through two main steps. The first step is that the assigned design factors determined in the case study, Table 1, are integrated into a linear statistical regression, in order to cover all the expected variables of the experimental design. Applying the experimental design work, outlined in the proposed framework, to estimate the EUI, is known as mixed-level design or general full factorial design. Mixed-level design or general full factorial design allows the consideration of different levels for each factor (Nist Sematech 2012). In this study, three factors with different levels are incorporated. The first factor is the wall type (C_W), consisting of two levels. The second factor is the roof type (C_R), consisting of two levels as well. The third factor is the window-to-wall ratio (C_{WR}), which is associated with five levels, as displayed in Table 1.

Table 1. The applied alternatives of construction objects in the functional equivalent

Wall (C_W)	Roof (C_R)	window-to-wall Ratio (C_{WR})
- Insulated Concrete Form (ICF) wall, 10 thick form (1). - Insulated Concrete Form (ICF) wall, 14 thick form (2).	- Continuous Deck Roof with Code Compliant Insulation (1). - Continuous Deck Roof with Super High Insulation (2).	- 15% (1) - 30% (2) - 40% (3) - 50% (4) - 65% (5)

The model for such an experiment analysis is presented in Equation (1). The number of sequences will be the result of multiplying the number of levels associated with each factorial design considered within a single analysis together (Nist Sematech 2012; Collins et al. 2009). As an example, the number of sequences that are required to cover all the expected variables is 20 ($2 x 2 x 5$).

$$E = \beta 0 + \beta 1.CW + \beta 2.CR + \beta 3.CWR + \beta 1\,2.CW * CR + \beta 1\,3.CW * CWR + \beta 2\,3.CR * CWR + \beta 1\,2\,3.\ CW * CR * CWR + \epsilon \quad (1)$$

The second step is to apply the Autodesk Green Building Studio to estimate the EUI based on the running sequences that were previously built in the regression model. At this step, the database for each sequence is constructed individually. This means that 20 separate analysis is performed in Autodesk Green Building Studio application.

3.3. Assessment of design factors

The experimental design is applied at this level of the analysis to clarify the various effects of the assigned design factors. **Table 2** presents the estimated values of the EUI of the case study based on the examined cities in this work.

Table 2. Experimental design outputs

NO	Factorial Design			Energy Use Intensity (MJ/m2/year)					
	C_W	C_R	C_{WR}	Dubai	Kuala Lumpur	Moscow	Mount Wellington	Porto	Rio de Janeiro
1	1	1	1	497.1	502.2	1,091.7	679.6	517.0	462.2
2	1	2	1	472.4	489.8	963.0	621.0	481.0	450.5
3	2	1	1	496.5	502.7	1,085.8	675.8	513.4	462.1
4	2	2	1	471.2	489.3	955.4	616.2	476.9	439.0
5	1	1	2	597.9	574.5	1,460.7	916.0	619.2	558.1
6	1	2	2	586.5	562.1	1,380.6	900.2	583.3	548.5
7	2	1	2	597.8	575.7	1,457.2	912.1	616.3	557.2
8	2	2	2	586.8	563.7	1,375.5	896.4	580.0	547.7
9	1	1	3	685.1	629.3	1,727.2	1,108.1	715.6	628.4
10	1	2	3	688.3	626.9	1,681.1	1,120.9	710.5	629.0

11	2	1	3	685.6	630.7	1,724.9	1,103.9	713.1	627.3
12	2	2	3	688.4	627.5	1,677.6	1,116.7	708.2	627.9
13	1	1	4	770.0	681.4	1,995.9	1,302.5	834.0	697.5
14	1	2	4	786.4	696.6	1,985.2	1,341.2	847.0	720.7
15	2	1	4	770.4	682.8	1,994.6	1,299.3	832.1	696.5
16	2	2	4	786.3	698.2	1,982.4	1,337.5	845.0	719.9
17	1	1	5	888.1	765.4	2,394.2	1,590.0	1,015.3	810.8
18	1	2	5	925.3	796.2	2,430.7	1,665.0	1,051.6	859.5
19	2	1	5	888.1	766.9	2,393.4	1,587.5	1,013.8	809.7
20	2	2	5	925.1	797.3	2,429.5	1,662.2	1,050.2	858.9

Table 2 shows that installing the case study within a window-to-wall ratio of 15% in Rio de Janeiro disregarding any other components of walls and roofs, and in Dubai using super high insulation for roofs would consume almost the same EUI. While disregarding the insulation factor for roofs would consume more energy in Dubai than in Rio de Janeiro. Moreover, installing the case study within a window-to-wall ratio of 15% in Mount Wellington would consume almost the same EUI compared to the same installation within a window-to-wall ratio of 30% in Dubai and Porto. Installing the case study in Moscow within a window-to-wall ratio of 15% would cause the same consumption in Dubai within a window-to-wall ratio of 65%. While installing the case study within a window-to-wall ratio of 40% in Dubai and Porto would consume the same EUI in Kuala Lumpur and Rio de Janeiro within a window-to-wall ratio of 50%, disregarding all other building components.

3.4. Evaluation of Results

The analysis of the collected results sorts out that there are several performance parameters to be considered in order to increase energy efficiency in construction projects such as insulation and thickness of the building components, a space area of the exterior openings and climate data. The results show that the same building would consume high energy in continental climates and polar climates whereas the consumption would reduce dramatically in other climate classifications such as dry climates, tropical climates, and mild temperate climates. For example, EUI of the case study installed in Kuala Lumpur and Rio de Janeiro are slightly different, while the consumption of energy differs noticeably between the other cities located in different climate classifications. This proves that the sub-type climate classification plays a minor role in determining the energy efficiency whereas the climate group is the main agent of manipulating the energy consumption in construction projects.

After classifying and evaluating the results collected in the previous section, the aim is to increase the energy efficiency in construction projects, while highlighting the building components that could affect the consumption of energy in the case study is a secondary objective. The results of Table 2 illustrate that constructing buildings within minor openings (window-to-wall ratio) using different building components for walls and roofs consume less EUI than using wide opening spaces. In other words, using super high insulation building materials and increase the thickness of building components would slightly reduce the consumption of energy in buildings, however, the space area of the exterior openings is the main building component influences the energy consumption at this level of the analysis. Besides, Table 2 shows that sequences (2 and 4) maximize the efficiency of EUI of the case study building in the six examined cities whereas sequences (18 and 20) consume the most EUI.

4. DISCUSION AND CONCLUSION

A framework to increase the energy efficiency of construction projects was proposed, simulating the ability of BIM models and considering the building components that are constructing the building envelop, window-to-wall ratio, and the installed capacity. An integrated methodological framework was presented based on the experimental design to enhance the decision-making process and sustainability in buildings. The framework determined various performance parameters related to several design factors to maximize the energy efficiency, based on a parametric analysis. RStudio was utilized to conduct a linear regression analysis to cover all the possible variables of the assigned design factors. Besides, Autodesk Green Building Studio application was adopted as a BIM model to analyse and estimate the consumption of energy. This study points out that BIM models are optimal procedure towards empowering both sustainability and decision-making process in the construction sector.

A case study of a single-family house was examined in six cities, each with a different climate classification. Cities analysed included Dubai, Kuala Lumpur, Moscow, Mount Wellington, Port, and Rio de Janeiro. The results of this work indicate that the performance parameters suggested in the framework significantly influence the energy consumption in buildings. These parameters include the type of building design and the climate data and integrated through the use of experimental design and BIM models. The results also display that applying high insulation and increase the thickness of building components would slightly impact the energy efficiency in construction projects, while the design factor of the window-to-wall ratio plays a major role in influencing the energy consumption towards nZEBs. However, this work suggests constructing buildings within minor opening spaces in order to improve energy efficiency. Another result of this work is that it proved that the sub-type climate classifications have a minor role in influencing the energy consumption in buildings, while the climate group plays a fundamental role in determining this fact in construction projects.

5. ACKNOWLEDGEMENTS

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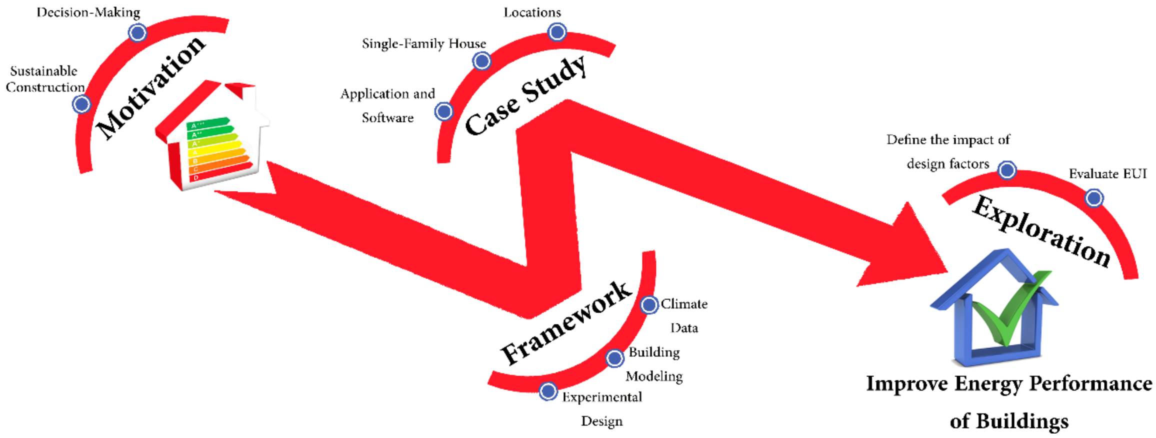
APPENDIX 7B

Integrating Parametric Analysis with Building Information Modeling to Improve Energy Performance of Construction Projects

(Published in Journal Energies, MDPI, DOI 10.3390/en12081515)

Graphical Abstract:



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MDPI

Article

Integrating Parametric Analysis with Building Information Modeling to Improve Energy Performance of Construction Projects

Mohammad K. Najjar [1,*], Vivian W. Y. Tam [2], Leandro Torres Di Gregorio [1], Ana Catarina Jorge Evangelista [3], Ahmed W. A. Hammad [4] and Assed Haddad [1,*]

1. Program de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-901, Brazil; leandro.torres@poli.ufrj.br
2. School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW 2751, Australia; vivianwytam@gmail.com
3. School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW 2751, Australia; ana.evangelista@westernsydney.edu.au
4. Faculty of Built Environment, New South Wales University, Sydney, NSW 2052, Australia; a.hammad@unsw.edu.au

* Correspondence: mnajjar@poli.ufrj.br (M.K.N.); assed@poli.ufrj.br (A.H.)

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Abstract: Buildings demand a significant amount of energy during their life cycles, hence, effective design measures need to be adopted to ensure efficient energy usage and management in buildings. This study proposes a framework based on various performance parameters to enable decision-makers utilizing standard procedures and software to empower the process of sustainable energy use and management in buildings, through a parametric analysis in different climatic conditions. Experimental design is adopted within the framework via the use of various performance parameters related to the building design (i.e., construction materials for exterior walls and roofs, as well as a set of window-to-wall ratios). Results indicate that climate data plays a fundamental role in the choice of design factors that are best suited for effective energy consumption in buildings. In particular, sub-type climate classifications, as opposed to the primary climate group, have a minor influence. Around 15% improvement in the energy consumption in buildings is noticed due to changes to the design factor such as the window-to-wall ratio. Insights that can be gleaned from this study include the impact of space area, exterior openings and material thickness and choice for the envelope of the building in all climate classifications, aiding in the design of low-energy buildings.

Keywords: energy in buildings; building management; building information modeling; sustainable construction; experimental design

1. Introduction

The construction industry consumes significant energy and natural resource levels and is commonly known as "the industry of the 40%" [1], due to the fact that buildings produce nearly 40% of overall CO_2 emissions, 40% of overall waste generation and consume 40% of overall natural resources over their entire lifespans [2]. The world is witnessing an increase in awareness with regards to enhanced energy efficiency in construction [3,4], specifically due to the fact that the majority of the energy in the construction sector is consumed during the operating phase of buildings (i.e., for heating, cooling, lighting and hot water equipment) [5]. As a result, modeling energy performance is a critical issue to perform and manage the energy efficiency in buildings [6,7]. Several tools and methods have been assessed to support the implementation of sustainable strategies in the built environment. In particular, Building Information Modeling (BIM) has been proposed as an innovative approach with many useful tools that can effectively evaluate energy performance in buildings [8], by harmonizing information of building material and facilitating the calculation of their environmental impacts [9].

Some factors play an important role in determining the energy-use patterns in buildings, such as building type, climate zone and level of economic development [10]. BIM offers the opportunity to save time that is consumed by designers, engineers and architects to account for all building geometry and the necessary information to complete an energy analysis [11,12]. The collected results at this level of the analysis include statistics related to energy use and breakdowns of consumption and loads [13]. Furthermore, BIM plays a fundamental role in automation in construction [14]; various dimensions of BIM (nD), including cost and time control, design and simulation enable effective building control over the entire life-cycle phase of construction projects [15].

A current gap exists in the literature for utilizing BIM as an approach that aids designers in adopting a strategic energy-use plan over the operation phase of buildings. As a result, the novelty of the research presented herein is to propose a framework that integrates different performance parameters, such as the building design, climate data, along with design factors, including building components, energy use and consumption, utilizing 3D modeling and sustainability as nD BIM dimensions in order to improve the energy performance of buildings. The aim is to make the work readily available to practitioners and experts in the construction sector using standard procedures and software. It is envisaged that the proposed method will empower the decision-making processes and sustainability of designing construction projects. The Energy Use Intensity (EUI) is evaluated, taking into consideration the building components that comprise the envelop of buildings, relevant measures including the window-to-wall ratio and of the energy consumed for heating, cooling, lighting and equipment purposes.

Throughout this study, the proposed framework involves incorporating different design parameters and visualization-aid tools that prove the ability to improve energy performance in buildings. Enhancing the energy performance in construction projects is conducted through a simulation and parametric analysis approach, where the construction materials of exterior walls and the roof of a building, as well as a set of window-to-wall ratios, are all examined. An experimental design, which involves a systematic collection of data, is utilized to focus on the planning of the selection process of construction materials, based on a linear regression analysis [16]. The methodological framework developed accommodates various global climates, in response to the consensus worldwide on the need for improving energy consumption in buildings and enhancing the sustainability of the built environment. The tools of BIM are applied to evaluate and improve the energy performance towards low-energy buildings using simulation data and sustainability as BIM dimensions. A case study of a single-family house is examined in six cities with varying climate data and annual average temperature to validate the developed methodological framework.

This paper is organized as follows: in Section 2, some background on BIM and its use for sustainable design are presented. Next, in Section 3, the methodology of this work is explained in detail, while Section 4 illustrates the linking of the framework's components. In Section 5, a case study is examined to validate the proposed methodology.

2. Background

2.1. BIM Dimensions

In the BIM approach, the modelling is multidimensional. In fact, it incorporates all required design information over the entire life span of construction projects. The so-called BIM n-D models are commonly defined as shown in Figure 1: 3D modeling, 4D (Time), 5D (Cost), 6D (Operation), 7D (Sustainability) and 8D (Safety) [17].

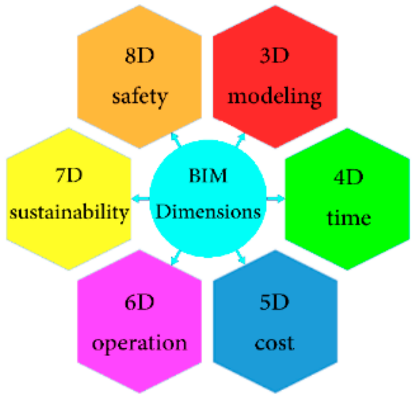


Figure 1. Building Information Modeling (BIM) dimensions.

3D BIM is the most familiar dimension adopted for the designing process of creating graphical and non-graphical information that is shared in a common data environment [17]. The level of importance of this dimension peaks at the planning and designing phase of the construction project, then it reduces gradually until the end of the operation and maintenance phase, as seen in Figure 2. This comes back to the fact that such dimension enables providing various design alternatives at this phase of the project life cycle [18]. 4D dimension is a planning process that binds the set of data in the 3D modeling with project programming and scheduling data [17]. It accelerates the simulation analysis of construction activities [19,20]. Hence, the important role of this dimension starts at a point somewhere at the designing phase, peaks during the construction phase, before reducing gradually during the next life cycle phases of construction projects, as seen in Figure 2. Such a dimension provides an opportunity for participants of a construction project to effectively visualize, analyze and communicate various aspects of construction progress over the entire life span of buildings. 5D dimension integrates 4D dimension with cost data such as quantities and prices [17]. It facilitates the accuracy of both quantity and cost estimation [19,21]. The important role of this dimension grows gradually from the starting point of the planning and designing phase, peaks during the construction phase, then reduces during the operation and end-of-life phases, as seen in Figure 2. Such a dimension provides an opportunity for cost consultants to improve the value of construction projects. 6D dimension extends BIM for facilities management [17], which is considered an integrated approach to maintain, improve and adapt buildings [22]; this dimension represents the as-built model that is used during the operational phase of construction projects [23], providing an opportunity for an integrated description of a building during its usage phase. The important role of this dimension starts by the end of the construction phase and lasts over the entire operation and maintenance phase of construction projects, as shown in Figure 2. 7D dimension incorporates components of sustainability within BIM [17]; the different BIM dimensions are stored in a "BIM knowledge repository" [24]. At this level of the analysis, 3D, 4D and 5D BIM dimensions enable designers to compare different alternatives, make a quick modification of building modeling and management and validate the decision-making towards meeting the sustainable requirements of construction projects [24]. Such requirements can be achieved during the designing and construction phases of construction projects, while the chance to meet the sustainability requirements reduces gradually in the next life cycle phase until it ends up at a point somewhere during this phase, as shown in Figure 2. 8D dimension incorporates different aspects of safety in construction projects during the designing and construction phases [17], as shown in Figure 2. To sum up, BIM provides an opportunity to optimize, simulate and visualize building design and therefore deliver high quality construction documentations [14]. Figure 2 illustrates the level of importance of BIM dimensions over the entire life span of construction projects.

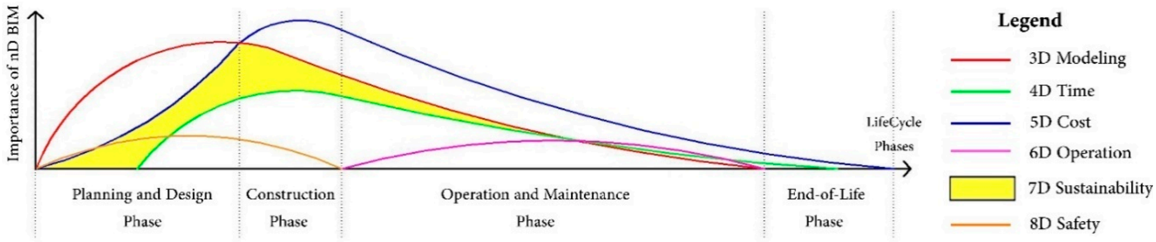


Figure 2. Level of importance of BIM dimensions over the entire life-cycle phases.

2.2. Climate Zone Classification

Climatic conditions are known to impact the energy performance of a building [25,26]. There are several schemes to classify climates into similar regimes such as plant hardiness, evapotranspiration and Köppen-Geiger climate classification, being the one that is the most widely applied to classify climate zones [27,28]. Köppen classification scheme analyzes average monthly temperature and precipitation for 1901–2010 at all grid points on Earth. It divides climate zones into five major groups, namely Tropical Climates (A), Dry Climates (B), Mild Temperate Climates (C), Continental Climates (D) and Polar Climates (E) [29,30]. According to the Köppen-Geiger classification scheme, such five major climate groups are subdivided into 31 sub-types [29–32]:

A. Tropical Climates, which is covering more than 20% of surface area, is subdivided into Tropical rainforest climate (Af), Tropical monsoon climate (Am) and Tropical savanna climate (Aw or As). The average temperature of the coldest month of the year for Tropical Climates is more than 18 °C.
B. Dry Climates, which is covering more than 27% of surface area, is subdivided into Hot desert climate (BWh), Cold desert climate (BWk), Hot semi-arid climate (BSh) and Cold semi-arid climate (BSk). The average annual temperature for Dry Climates is between 20 and 35 °C.
C. Mild Temperate Climates, which is covering more than 15% of the surface area, is subdivided into Humid subtropical climate (Cfa), Temperate oceanic climate (Cfb), Subpolar oceanic climate (Cfc), Monsoon-influenced humid subtropical climate (Cwa), Subtropical highland climate (Cwb), Cold subtropical highland climate (Cwc), Hot-summer Mediterranean climate (Csa), Warm-summer Mediterranean climate (Csb) and Cool-summer Mediterranean climate (Csc). The average annual temperature for Mild Temperate Climates is between −3 and 18 °C.
D. Continental Climates, which is covering more than 21% of the surface area, is subdivided into Hot-summer humid continental climate (Dfa), Warm-summer humid continental climate (Dfb), Subarctic climate (Dfc), Extremely cold subarctic climate (Dfd), Monsoon-influenced hot-summer humid continental climate (Dwa), Monsoon-influenced warm-summer humid continental climate (Dwb), Monsoon-influenced subarctic climate (Dwc), Monsoon-influenced extremely cold subarctic climate (Dwd), Mediterranean-influenced hot-summer humid continental climate (Dsa), Mediterranean-influenced warm-summer humid continental climate (Dsb), Mediterranean-influenced subarctic climate (Dsc) and Mediterranean-influenced extremely cold, subarctic climate (Dsd). The average annual temperature is less than −3 °C.
E. Polar Climates, which is covering up to 16% of the surface area, is subdivided into Tundra climate (ET) and Ice cap climate (EF). The lowest temperature ever recorded is −89.2 °C.

2.3. Related Literature

BIM as an approach can be utilized in the construction sector to increase the energy performance of construction projects and, consequently, enhance the sustainability of the built environment [8,11]. In the literature, several publications examined the important role of BIM towards achieving the objectives of construction projects. For example, Azhar and Brown [33] highlighted and investigated the viability of BIM towards sustainable design. The authors collected data via a questionnaire survey, a case study and semi-structured interviews in order to identify the benefits of BIM in the field of sustainability analysis; this was achieved by evaluating different software that analyzes building performance and developing a conceptual framework to incorporate BIM and Life Cycle Assessment in the field of sustainability analysis. Jeong and Son [34] presented an algorithm that translates the BIM building topology into an object-oriented physical using an object-oriented programming approach. GhaffarianHoseini et al. [14] focused on energy efficiency in buildings. The authors reviewed 96 papers and suggested a system called *Integrated Knowledge-based Building Management System* (BIM-IKBMS) using nD BIM applications in order to advance the successful implementation of sustainable building performances during the post-construction building lifecycle. Azhar et al. [35] examined the ability of BIM to empower sustainable building design and decision-making processes. They found that BIM optimizes building design and performs complex building analysis. In addition to this, BIM generates the necessary documentation for Leadership in Energy and Environmental Design (LEED), which is a green building rating system applied in the USA and saves considerable time and resources as a result.

Chong et al. [36] examined the ability of BIM development for sustainability. The authors found that there are insufficient works in the field of BIM application at the refurbishment and demolition phases. Besides, it was concluded that: (i) assessing sustainability criteria requires new tools of BIM; (ii) the integration between BIM software and energy simulation tools needs to be improved; (iii) the efficient steps are required to apply BIM into various aspects of refurbishment and demolition phases successfully; and (iv) the innovative system is required to adapt social sustainability into the project. Ilhan and Yaman [37] integrated BIM and sustainable data model for the designing stage of a construction building, considering Industry Foundation Classes (IFC) that is the main standard for BIM. The authors presented GBAT as a Green Building Assessment Tool to extract the green rating score table based on BREEAM (Building Research Establishment Environmental Assessment Method) applied on materials, inform the design and provide feedback for further evaluation. Azhar et al. [38] considered that BIM increases the productivity and quality of construction projects. The authors discussed the benefits of BIM by presenting two case studies demonstrating the different tangible and intangible benefits that could be achieved by all stakeholders in the Architecture, Engineering and Construction (AEC) industries.

As can be noticed from the literature, even though the applicability of BIM for sustainable analysis and design of buildings was discussed, there is still a lack of methods in developing large energy efficient projects, given the limited availability of data and materials [39]. Hence, this work aims to propose a framework that could aid the practitioners in the construction sector to accommodate various construction components that compose the building envelop to improve the energy efficiency of buildings, hence leading to low-energy building construction projects.

The focus of the proposed method is placed on examining the design requirements in buildings, considering the EUI as a helpful metric to benchmark the energy performance based on design goals in buildings [40]. As a result, this work provides an integrated and systematic methodological framework to improve energy efficiency in buildings that aligns with the environmental conditions and demand expectations of a given building project. In this section, an in-depth explanation of the EUI, design requirements and decision support analysis are presented.

EUI articulates the energy efficiency in buildings as a function of its size or other characteristics such as the building function and occupation density and daily and yearly using periods [41]. It is expressed as energy per square meter per year and is calculated by dividing the total energy consumed by the building in one year by the total gross floor area of the building [42,43]. The current focus on increasing energy use efficiency in buildings has made the use of EUI popular by governmental organizations, non-government organizations and building industry groups, including American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [40]. Figure 3 gives an example of the calculation process of EUI in residential buildings, highlighting that the energy consumed in buildings could be the result of heating, cooling, lighting, equipment, pumps and hot water requirements. Energy consumption in buildings certainly depends on the type of building itself;

low values of EUI signifies good levels of energy efficiency measures implemented in the building under consideration [44]. It is important that the domestic appliances that will consume energy are considered early on, at the design phase of construction projects; designers have to realize the energy impacts of the heating, cooling, lighting and other equipment that will be installed and used by the occupants [5]. Some methods have been proposed to reduce EUI in buildings. For instance, ensuring the proper maintenance of equipment to improve the efficiency of operation, installing motion activated lights or occupancy sensors, incorporating the use of natural sunlight into the design of occupied spaces, providing a means for passive heating and cooling of interior spaces and developing on-site renewable energy generation [44].

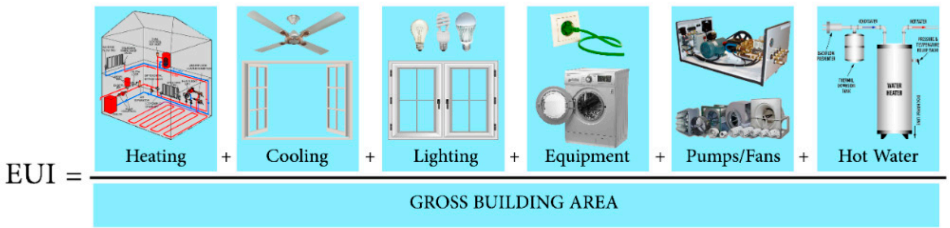


Figure 3. Energy use intensity in residential buildings.

In the next section, the design requirements for sustainable construction and the decision-support analysis are demonstrated within the full framework proposed.

3. Materials and Methods

The methodology proposed in this paper simulates the energy performance of construction projects, through integrating parametric analysis with BIM approach.

3.1. Design Requirements for Sustainable Construction

Construction projects are increasingly constrained by a set of functional requirements that result from higher standards of living [45]. In literature, the design requirements for sustainable construction are outlined in three basic analysis [46,47]; energy analysis, architectural analysis and comfort analysis, as seen in Figure 4. In these terms, designing for better energy performance is one of the key issues of sustainable construction [4,48], which involves a holistic approach to energy consumption and emissions to encourage environmental friendliness in buildings [49]. This way of creating buildings that are energy efficient [32,49], appropriately and architecturally designed for their context of use [50] and comfortable for occupation by people [51]. The majority of energy consumption in buildings is caused by heating, cooling and lighting purposes [52]. For example, the consumption of electricity is the main agent of high levels of CO_2 emissions in buildings [53]. Second, architectural analysis refers to predicting post-occupancy performance in buildings at an early stage of design, to optimize the project and understand the required decisions that could significantly affect the carbon footprint of buildings [54]. This involves studying the building form and typology within the built environment, considering the interaction of people and the evolution of the concept of building design from the first conception to production [55]. Third, comfort analysis means to raise the issue of a sustainable environment by expressing satisfaction with the thermal environment and is estimated by subjective evaluation [56].

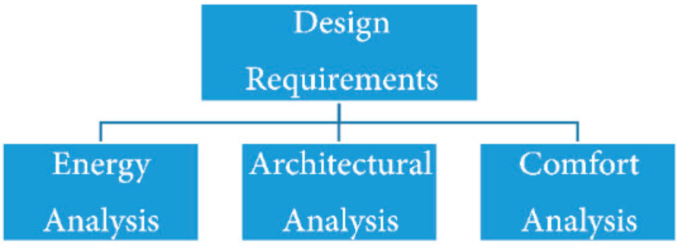


Figure 4. Design requirements for sustainable construction.

3.2. Decision Support Analysis

BIM is an approach that enables the creation of intelligent models used to design and manage buildings and cooperate the designing process [57]. Such approach can significantly reduce the opportunities for errors when revising or modifying the model information [58]. The initial step in the developed approach requires the input of a 2D and 3D model of the building. This way of defining the parameters that are influencing the consumption of energy during the operation phase of the building such as building properties (i.e., space area and basic appliances), type of energy use and define the building components. In addition to this, it requires classifying the climate database of the region where the construction project is to be constructed. Figure 5 highlights the developed framework in this study, which links performance parameters and design factors.

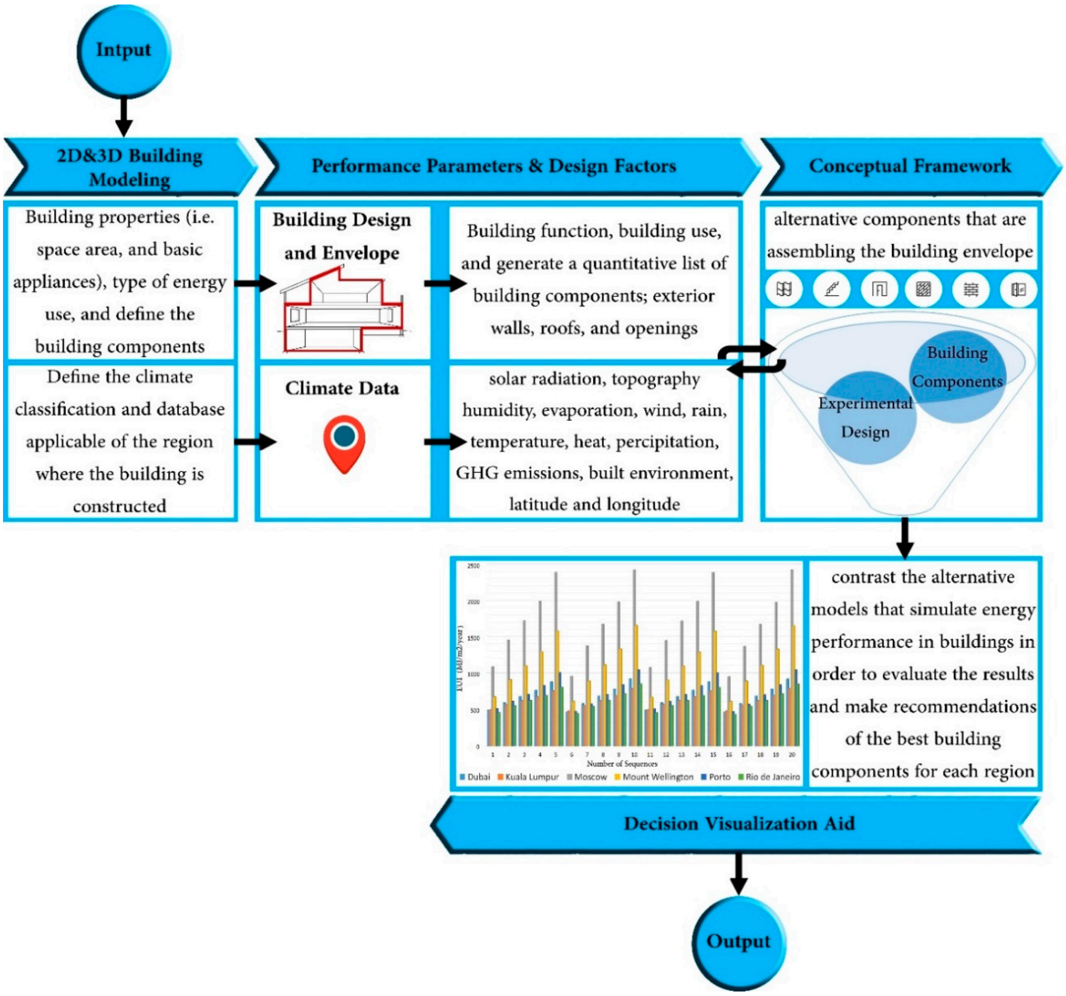


Figure 5. A methodological framework for increasing energy performance in construction projects.

The modeling of buildings requires identifying various performance parameters and their associated design factors. Performance parameters refer to the information that defines and classify a particular system in the model, while design factors are features (variables) that define the performance parameters, as depicted in Figure 5. The choice of performance parameters is based on implications that are highly affecting the energy consumption of construction projects, namely the building design and envelope [59,60], along with the climate classification in which the building is located [25,26]. Climate data as a performance parameter, the associated design features include solar radiation, topography, humidity, evaporation, wind, rain, temperature, heat, precipitation, greenhouse gas (GHG) emissions, built environment, latitude and longitude [61,62]. The features of the performance parameter Building Design and Envelope include identifying the function, use of the building and generate a quantitative list of building components that are assembling the building envelope such as exterior walls, roofs and openings of the building [40,63]. In these terms, the proposed methodological framework of this analysis can accommodate a large number of construction components, however, some specific components are chosen in the case study, Section 5, just to validate the framework.

The next step is to define the conceptual framework of the study. It starts by assessing the collected data using the indicators of sustainability in a way to empower the decision-making process. Conducting this step requires make reliable information that are simpler and available to policy makers. However, the evaluation process of the collected database starts by enrolling all or part of the generated building components of the construction project and estimating the consumption of energy, using BIM approach as a platform for quantifying the sustainability in buildings. The methodology of this study makes use of an experimental design procedure to identify all the expected variables in order to indicate the best building components and effective window-to-wall ratios that will improve energy efficiency in buildings, based on different climate data and annual average temperatures.

The experimental design work is applied via linear regression that defines the impact of several design factors and a parametric analysis that examines different values for these factors. The experimental design provides the maximum information at the minimum experimental cost [64]. Hence, this work evaluates and generates the variables collected at the experimental design phase, in BIM-related tools in order to integrate the construction of buildings and consequently achieve the objectives of the study. The last step of the methodological framework of this study is to assess the output results. At this level of the analysis, this work recommends contrasting the alterative models that simulate the energy performance in construction projects in a way to analyze and evaluate the collected results and define the best construction components that could improve the energy efficiency in buildings. This process starts by classifying sources of data, comparing and matching results and suggesting recommendations.

4. Linking Framework Components

In terms of the required analysis, three basic steps are required to improve the energy performance in buildings, as shown in Figure 6. The first step is to identify the performance parameters and the design factors of the construction project, which means identifying the building design and climate data. For this work, Autodesk Revit is applied as a BIM software to achieve the aim of this step by creating a BIM model and considering the database of the various climate classifications. The climate server in Revit enables climate database from several sources such as *Green Building Studio* weather station, which accommodates around 1.6 million virtual weather stations and allows better and accurate climate simulations [65].

The second step is to build up the inventory of the database. The proposed framework applies the experimental design to estimate all expected variables via linear regression. At this level of the analysis, the interaction effects are found by the use of a statistical factorial design technique [66]. This requires running a full complement of all possible factor combinations of the components of the building envelop, as a basic parameter influencing energy performance in buildings [59]. Interaction effects between components that define the number of factors (κ) (i.e., window-to-wall ratio, building components, etc.) and the desired range of their investigated levels that could influence the overall

EUI are also investigated [67]. In these terms, a factorial design model in this study is analyzed via regression analysis and is presented in Equation (1) to allow the estimation of all coefficients $\{\beta_0, \ldots, \beta_\kappa\}$ [68,69].

$$Y = \beta_0 + \beta_1 \cdot \chi_1 + \beta_2 \cdot \chi_2 + \ldots + \beta_\kappa \cdot \chi_\kappa + \epsilon \quad (1)$$

Equation (1) calculates all the actual responses and interactions of the expected variables [69]; in the experimental design, errors are inevitable [70]. As a result, the second step is conducted in two phases. The first phase is to use a software namely, Minitab to determine all the variables of the experimental design work through a linear regression analysis and reduce the regression errors and uncertainty [71]. The second phase involves adopting the tools of BIM to simulate the determined variables and estimate the energy performance in buildings. This work uses Autodesk Green Building Studio as a BIM tool to assess the sustainability of the design [72]. The analysis requires taking into consideration the different assumptions and parameters that are required to be filled-in precisely such as building type, location, thermal properties, project phase, building envelope, analysis mode, conceptual construction, building operating schedule, HVAC system (Heating, Ventilation and Air Conditioning) and outdoor air information. The third step is to evaluate the collected database for each modeling. At this level of the analysis, the collected EUI results in Autodesk Green Building Studio are evaluated in order to specify the impact of building components and window-to-wall ratio on energy consumption in buildings [73]. Conducting such an analysis demands a parametric analysis involving gradual increments of the window-to-wall ratio and various building components. Furthermore, Minitab software conducts the main effects plot, as presented in the supplementary file, by creating graphs that use data means. This analysis is vital for examining the differences between levels for one or more design factor [74].

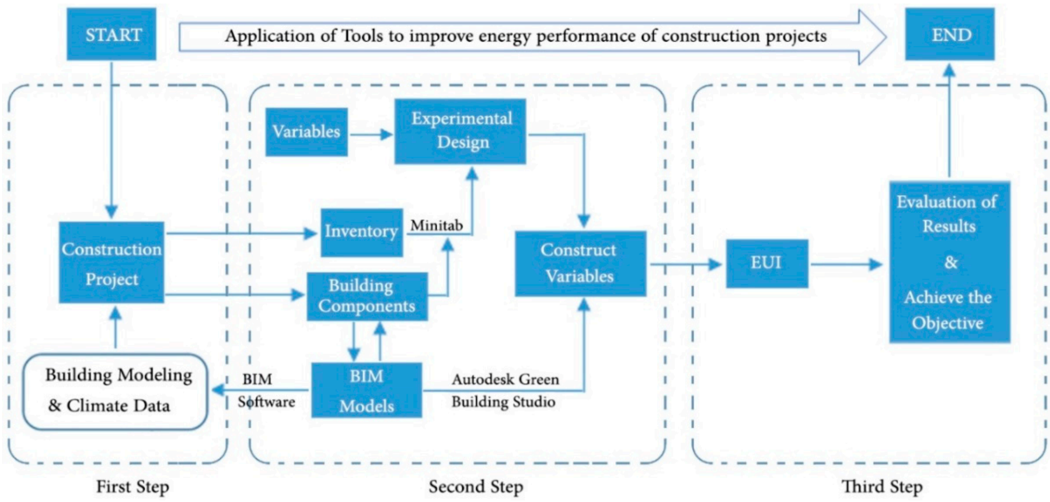


Figure 6. Linking framework components.

The proposed framework presented in Figure 5 and the linking component of this framework presented in Figure 6, can accommodate a large number of construction materials for exterior walls, roofs, window-to-wall ratio and any other component of the building envelop (i.e., windows, doors, floors and ceilings). However, the case study of this work will consider the exterior walls and roofs components and the window-to-wall ratio. This comes back to the fact that the exterior walls are responsible for the internal thermal comfort of occupants in buildings [75], while roofs are the part of buildings that receive the largest amount of solar radiation per square meter annually [76]. In addition to this, the window-to-wall ratio plays a basic role in heating loss and gain that could affect the thermal comfort of buildings [77]. The next section highlights the procedure in a case example.

5. Case Study: Validating the Methodological Framework in a Single-Family House

The applied case study aims to validate the proposed framework, which is the novelty of this work, used to model the decisions involved in choosing the building components (i.e., exterior walls and roofs) and window-to-wall ratio for construction projects. In order to showcase the versatility of the proposed framework, the proposed analysis is conducted in six different cities with different climates, as shown in Table 1. The chosen cities include Dubai in United Arab of Emirates, Kuala Lumpur in Malaysia, Moscow in Russia, Mount Wellington in Australia, Porto in Portugal and Rio de Janeiro in Brazil. The choice of cities is made to ensure a comprehensive consideration of various climatic conditions. Rio de Janeiro and Kuala Lumpur belong to the Tropical Climates within different sub-type classifications, Tropical savanna climate and Tropical rainforest climate, respectively as shown in Table 1. The characterizations of Dubai, Moscow, Mount Wellington and Porto are Dry Climates, Continental Climates, Polar Climates and Mild Temperate Climates, respectively.

Table 1. Selected cities for this analysis [28–31,78].

City	Climate Group	Sub-Type Classification
Dubai	Dry Climates	Hot desert climate (BWh)
Kuala Lumpur	Tropical Climates	Tropical rainforest climate (Af)
Moscow	Continental Climates	Warm-summer humid continental climate (Dfb)
Mount Wellington	Polar Climates	Tundra climate (ET)
Porto	Mild Temperate Climates	Warm-summer Mediterranean climate (Csb)
Rio de Janeiro	Tropical Climates	Tropical savanna climate (Aw or As)

5.1. Size of the Case Study

The case study of this work examines the energy efficiency of a one-floor single-family house, consisting of three bedrooms, bathroom, kitchen and living room with a total floor area of 60 m^2, using the basic appliances for heating and cooling (i.e., fan and heat pump), lighting (i.e., bulbs and plugs), equipment (refrigerator, cooker and washing machine) and hot water purposes (i.e., boiler. The plan layout of the house is shown in Figure 7. The selection of the case study is developed based on the ability to accommodate different construction materials that are assembling the building envelop. This could foster the simulation process of construction components and provide the basis for the application and extension of building materials. However, Autodesk Revit is used as a BIM software to build the modeling of the case study. This software enables the use of the model information database to perform different climate classifications of the examined cities presented in Table 1 and also to model the different alternative materials of the construction components that are assembling the building envelope.

The analysis takes into consideration two types of building materials for constructing the exterior walls and roof, namely Insulated Concrete Form (ICF) wall with 10-inch-thick form and ICF wall with a 14-inch-thick form for walls. Such types of walls are hollow foam blocks stacked into the shape of the exterior walls of a building, reinforced with steel rebar and filled with concrete. They combine one of the finest insulating materials such as expanded polystyrene, with one of the strongest structural building materials such as steel reinforced concrete, giving a wall system of unmatched comfort, energy efficiency, strength and noise reduction [79]. Continuous Deck Roof with Code Compliant Insulation and Continuous Deck Roof with Super High Insulation is considered for the roof; such types of roofs have a flat surface that is capable of supporting weight and providing noise and fire insulation [80]. The selection of two materials for each building component is for demonstration purposes; the proposed framework can accommodate a large number of construction materials for each building component, as previously discussed in Section 4. Additionally, the parametric analysis considers a range of common window-to-wall ratios, including 15%, 30%, 40%, 50% and 65%.

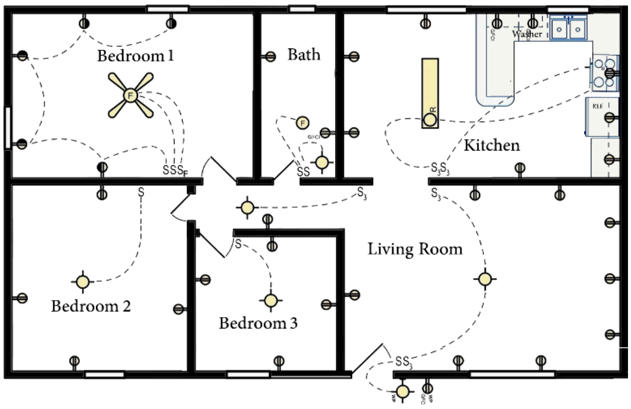


Figure 7. 2D plan of the single-family house.

5.2. Inventory of Database

The inventory of the database focusses on the operation phase of the building and is constructed through the three main steps highlighted in Section 4.

The first step is that the assigned design factors determined in the case study, Table 2, are integrated into a linear statistical regression, in order to cover all the expected variables of the experimental design. Application of the experimental design work outlined in the proposed framework is known as mixed-level design or general full factorial design, which allows the consideration of different levels for each factor [16]. In this study, three factors with different levels are incorporated: (i) the first factor is the wall type (C_W), consisting of two levels, which considers two insulated concrete form walls; (ii) the second factor is the roof type (C_R), consisting of two levels for the two types of continuous deck roof; (iii) the third factor is the window-to-wall ratio (C_{WR}), which is associated with five levels considering various values of window-to-wall ratio, as displayed in Table 2. The selection of the construction components of the walls and roofs in the case study follows the necessity of increasing energy efficiency and insulation in construction projects as an introduction of advanced low energy cooling concept and a high efficiency heating concept [81].

Table 2. The applied alternatives of construction objects.

Wall (C_W)	Roof (C_R)	Window-to-Wall Ratio (C_{WR})
Insulated Concrete Form (ICF) wall, 10-inch-thick form. Insulated Concrete Form (ICF) wall, 14 inch thick form.	Continuous Deck Roof with Code Compliant Insulation. Continuous Deck Roof with Super High Insulation.	15% 30% 40% 50% 65%

The model for such an experimental analysis is presented in Equation (2). The number of sequences will be the result of multiplying together the number of levels associated with each factorial design considered within a single analysis [16,82]. As an example, the number of sequences that are required to cover all the expected variables in the case example examined is 20 (2 × 2 × 5). The format of Equation (2) applied in the case study example of this work is as follows:

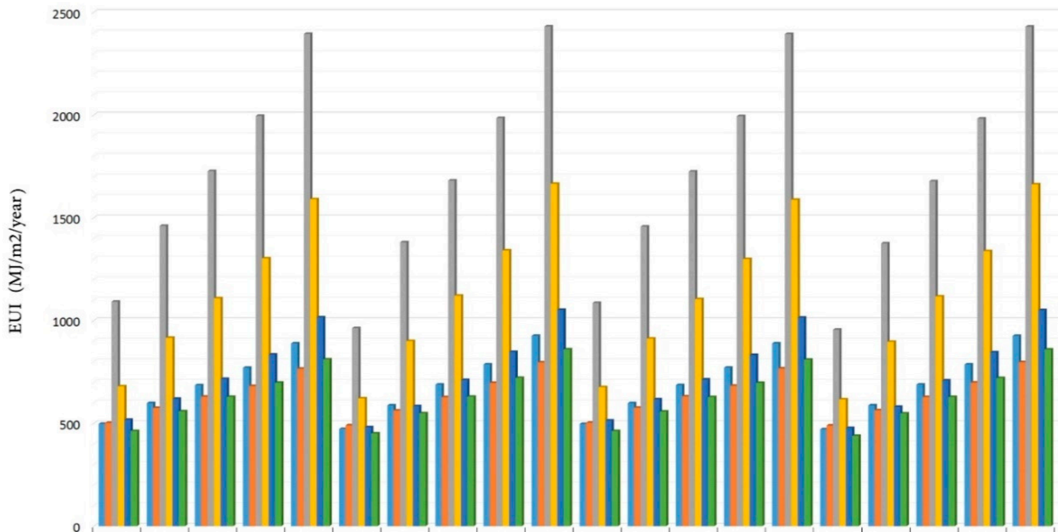
$$E = \beta_0 + \beta_1 \cdot C_W + \beta_2 \cdot C_R + \beta_3 \cdot C_{WR} + \beta_{12} \cdot C_W \cdot C_R + \beta_{13} \cdot C_W \cdot C_{WR} + \beta_{23} \cdot C_R \cdot C_{WR} + \beta_{123} \cdot C_W \cdot C_R \cdot C_{WR} + \epsilon \quad (2)$$

An interaction between the assigned factors that are defining the building is achieved to simulate all expected variables through the use of a statistical factorial design technique [66]. The energy analysis response (E) based on the main effects of C_W, C_R and C_{WR}, as defined in Table 2, is captured in terms of ($C_W \cdot C_R$), ($C_W \cdot C_{WR}$), ($C_R \cdot C_{WR}$) and ($C_W \cdot C_R \cdot C_{WR}$); these terms are included to consider all possible interactions between the main variables. The constant β_0 is the response of energy analysis when all main effects are equal to zero, while β_1, β_2, β_3, β_{12}, β_{13}, β_{23} and β_{123} denote the unknown parameters to be estimated; the variable ϵ refers to the experimental error. Table 3 illustrates the experimental design analysis of the applied design factors.

The next step is to apply Autodesk Green Building Studio to estimate the EUI based on the running sequences that were previously built in the regression model of the experimental design. At this step, the database for each sequence is constructed individually. This means that a total of 20 separate analysis are performed in Autodesk Green Building Studio for each city. The third step involves the collection of the results in Autodesk Green Building Studio and integrating them into Minitab software, in order to evaluate the collected data and to estimate the main effects of the various design factors, based on the energy simulation in the chosen cities.

5.3. Assessment of Design Factors

The experimental design is applied at this level of the analysis to clarify the various effects of the assigned design factors. Figure 8 presents the estimated values of the EUI of the case study based on the examined cities in this work.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Dubai	497.1	597.9	685.1	770	888.1	472.4	586.5	688.3	786.4	925.3	496.5	597.8	685.6	770.4	888.1	471.2	586.8	688.4	786.3	925.1
Kuala Lumpur	502.2	574.5	629.3	681.4	765.4	489.8	562.1	626.9	696.6	796.2	502.7	575.7	630.7	682.8	766.9	489.3	563.7	627.5	698.2	797.3
Moscow	1091.7	1460.7	1727.2	1995.9	2394.2	963	1380.6	1681.1	1985.2	2430.7	1085.8	1457.2	1724.9	1994.6	2393.4	955.4	1375.5	1677.6	1982.4	2429.5
Mount Wellington	679.6	916	1108.1	1302.5	1590	621	900.2	1120.9	1341.2	1665	675.8	912.1	1103.9	1299.3	1587.5	616.2	896.4	1116.7	1337.5	1662.2
Porto	517	619.2	715.6	834	1015.3	481	583.3	710.5	847	1051.6	513.4	616.3	713.1	832.1	1013.8	476.9	580	708.2	845	1050.2
Rio de Janeiro	462.2	558.1	628.4	697.5	810.8	450.5	548.5	629	720.7	859.5	462.1	557.2	627.3	696.5	809.7	439	547.7	627.9	719.9	858.9

Figure 8. Energy Use Intensity (EUI) results of the case study.

The results of the regression equation, regression errors, coefficients, the main effects plot and interaction plot are fully presented within the supplementary file. The presented information in this file shows that there is no error (error = 0) in conducting the analysis of variance in the six examined cities. The computation of EUI in Figure 8 is simulated individually in Autodesk Green Building Studio cloud-based service [83]. A total of 20 sequences are displayed for each city based on the factorial design analysis as presented in Table 3.

Table 3. Experimental design outputs.

Seq.	Factorial Design			Wall	Roof	Window-to-Wall Ratio
	C_W	C_R	C_{WR}			
1	1	1	1	ICF wall, 10 thick form	CDR with Code Compliant Insulation	15%
2	1	1	2	ICF wall, 10 thick form	CDR with Code Compliant Insulation	30%
3	1	1	3	ICF wall, 10 thick form	CDR with Code Compliant Insulation	40%
4	1	1	4	ICF wall, 10 thick form	CDR with Code Compliant Insulation	50%
5	1	1	5	ICF wall, 10 thick form	CDR with Code Compliant Insulation	65%
6	1	2	1	ICF wall, 10 thick form	CDR with Super High Insulation	15%
7	1	2	2	ICF wall, 10 thick form	CDR with Super High Insulation	30%
8	1	2	3	ICF wall, 10 thick form	CDR with Super High Insulation	40%
9	1	2	4	ICF wall, 10 thick form	CDR with Super High Insulation	50%
10	1	2	5	ICF wall, 10 thick form	CDR with Super High Insulation	65%
11	2	1	1	ICF wall, 14 thick form	CDR with Code Compliant Insulation	15%
12	2	1	2	ICF wall, 14 thick form	CDR with Code Compliant Insulation	30%
13	2	1	3	ICF wall, 14 thick form	CDR with Code Compliant Insulation	40%
14	2	1	4	ICF wall, 14 thick form	CDR with Code Compliant Insulation	50%
15	2	1	5	ICF wall, 14 thick form	CDR with Code Compliant Insulation	65%
16	2	2	1	ICF wall, 14 thick form	CDR with Super High Insulation	15%
17	2	2	2	ICF wall, 14 thick form	CDR with Super High Insulation	30%
18	2	2	3	ICF wall, 14 thick form	CDR with Super High Insulation	40%
19	2	2	4	ICF wall, 14 thick form	CDR with Super High Insulation	50%
20	2	2	5	ICF wall, 14 thick form	CDR with Super High Insulation	65%

5.4. Evaluation of Results

At this level of the analysis, the plot and the interaction plot studies are conducted and analyzed in Minitab software based on the collected energy analysis results, in order to show the role of the assigned factorial designs for each city.

Analyzing the interaction plot of the factorial design for each city as presented in Figures S1–S6 in the supplementary file shows that the interaction of the factorial designs of the walls (C_W) and roofs (C_R) has a slight influence on the energy consumption in the case study building. However, the interactions between these factors, individually and the window-to-wall ratio factor; (C_W and C_{WR}) and (C_R and C_{WR}) have the highest influence on improving energy efficiency in the case study building in the examined cities. Moreover, Figure 8 evaluates the energy efficiency of the construction project by highlighting the best building components that could affect the energy consumption in the case study. The results show that constructing buildings with minor openings (low window-to-wall ratio) using different building components for walls and roofs would consume less EUI than using wide opening spaces. In other words, using super high insulation building materials and increasing the thickness of building components that have a higher window-to-wall ratio, as seen in sequences 17, 18, 19 and 20, would slightly reduce the energy consumption in buildings. At the same time, sequence 16, which uses the same properties of materials as in the previous sequences with minor opening spaces, present a significant increase in energy efficiency in the cases examined. The results confirm that the space area of the exterior openings as a major building design aspect that influences the energy consumption of the building. This point is confirmed in Figures S7–S12 in the supplementary file by illustrating the main effects plot of the assigned design factors for each city, separately. Besides, Figure 8 illustrates that sequences 6 and 16 maximize the energy efficiency of the case study building in the six examined cities whereas sequences 5, 10, 15 and 20 would consume the most energy in all cities.

The analysis of the collected results presented in Figure 8 shows that there are several performance parameters to be considered in order to improve the energy efficiency in construction projects such as insulation and thickness of the building component, a space area of the exterior openings and climate data. For example, installing the case study with opening spaces of 15% in Rio de Janeiro (Tropical Climates) disregarding any other components of walls and roofs, as shown in sequences 1, 6 and 11 and in Dubai (Dry Climates) using super high insulation for roofs, as shown in sequences 6 and 16, would consume almost the same energy. While disregarding the insulation factor for roofs, as presented in sequences 1 and 11, would consume more energy in Dubai (within values of 497.1 and 496.5 MJ/m^2/year, respectively) than in Rio de Janeiro (within values of 462.2 and 462.1 MJ/m^2/year, respectively).

Adopting a window-to-wall ratio of 15% for the case study positioned in Mount Wellington (Polar Climates), as presented in sequences 6 and 16, would consume almost the same energy when adopting a window-to-wall ratio of 30% in Dubai and Porto (Mild Temperate Climates), as presented in sequences 2, 7, 12 and 17. Besides, positioning the case study in Moscow (Continental Climates), sequences 6 and 16, would cause almost the same consumption in Dubai, sequences 10 and 20, with a window-to-wall ratio of 15% and 65%, respectively. Adopting the case study with a window-to-wall ratio of 40% in Dubai and Porto, i.e., sequences 3, 8, 13 and 18, would consume the same energy in Kuala Lumpur and Rio de Janeiro i.e., sequences 4, 9, 14 and 19, with a window-to-wall ratio of 50%, disregarding all other building components. Moreover, adopting the case study in Mount Wellington with a 40% opening space, disregarding any other components for walls and roofs, sequences 3, 8, 13 and 18, would consume almost the same energy consumption compared to the same unit positioned in Moscow and adopted with a 15% opening space, sequences 1 and 11. Analyzing and comparing these results in Figure 8 with the obtained results in Figures S7–S12 in the supplementary file illustrate that colder weather equal to more energy consumption and vice versa. Figure 8 illustrates that the results of the EUI of the case study positioned in Kuala Lumpur and Rio de Janeiro are slightly different. This proves that the sub-type climate classification plays a minor role in determining energy efficiency whereas the climate group is the main agent of manipulating the energy consumption in such types of buildings.

Constructing the case study in Dubai with opening spaces of 50% and in Kuala Lumpur with opening spaces of 65%, using CDR with Code Compliant Insulation, sequences 4 and 14 for Dubai and 5 and 15 for Kuala Lumpur and CDR with Super High Insulation for the roof, sequences 9 and 19 for Dubai and 10 and 20 for Kuala Lumpur and disregarding the thickness of the exterior walls, would result in almost the same consumption of EUI. This proves that the space area of the exterior openings is a major factor for improving energy efficiency in construction projects. This point is confirmed within the supplementary file; Figures S7–S12.

Analyzing the sequences of Figure 8; (1 to 5), (6 to 10), (11 to 15) and (16 to 20), give the opportunity to estimate the proportional impact of the exterior openings on the EUI in the case study, considering similar construction components for walls and roofs in the examined cities. Table 4 illustrates an analysis of these groups of sequences based on adopting the case study within a gradual increase of the C_{RW} between 15%, 30%, 40%, 50% and 65%, disregarding the other components of walls and roofs. The proportional impact of the C_{WR} on the EUI in the case study is then estimated by calculating the percentage increase of the EUI when adopting a building to sequential levels of the C_{WR}, as defined in Table 2, for each city, individually. Such analysis illustrates the correlation between the space area of the openings and EUI in the case study building.

Table 4. The proportional impact of the exterior openings on the EUI in the case study.

Seq.	Gradual Increase of the C_{WR}	Dubai	Kuala Lumpur	Moscow	Mount Wellington	Porto	Rio de Janeiro
1 to 5	From 15% to 30%	20.28%	14.40%	33.80%	34.78%	19.77%	20.75%
	From 30% to 40%	14.58%	9.54%	18.24%	20.97%	15.57%	12.60%
	From 40% to 50%	12.39%	8.28%	15.56%	17.54%	16.54%	10.99%
	From 50% to 65%	15.34%	12.33%	19.95%	22.07%	21.74%	16.24%
6 to 10	From 15% to 30%	24.15%	14.76%	43.36%	44.96%	21.27%	21.75%
	From 30% to 40%	17.36%	11.53%	21.76%	24.52%	21.81%	14.68%
	From 40% to 50%	14.25%	11.12%	18.09%	19.65%	19.21%	14.58%
	From 50% to 65%	17.66%	14.30%	22.44%	24.14%	24.15%	19.26%
11 to 15	From 15% to 30%	20.40%	14.52%	34.21%	34.97%	20.04%	20.58%
	From 30% to 40%	14.69%	9.55%	18.37%	21.03%	15.71%	12.58%
	From 40% to 50%	12.37%	8.26%	15.63%	17.70%	16.69%	11.03%
	From 50% to 65%	15.28%	12.32%	19.99%	22.18%	21.84%	16.25%
16 to 20	From 15% to 30%	24.53%	15.20%	43.97%	45.47%	21.62%	24.76%
	From 30% to 40%	17.31%	11.32%	21.96%	24.57%	22.10%	14.64%
	From 40% to 50%	14.22%	11.27%	18.17%	19.77%	19.32%	14.65%
	From 50% to 65%	17.65%	14.19%	22.55%	24.28%	24.28%	19.31%

The results collected in Table 4 present the following:

1. Adopting a building where the C_{RW} is 30% instead of 15%, would influence the EUI in the case study by a percentage between 20.28% and 24.53% in Dubai; 14.40% and 15.20% in Kuala Lumpur;

33.80% and 43.97% in Moscow; 34.78% and 45.47% in Mount Wellington; 19.77% and 21.62% in Porto; and 20.58% and 24.76% in Rio de Janeiro.

2. Adopting a building where the C_{RW} is 40% instead of 30%, would influence the EUI in the case study by a percentage between 14.58% and 17.36% in Dubai; 9.54% and 11.53% in Kuala Lumpur; 18.24% and 21.96% in Moscow; 20.97% and 24.57% in Mount Wellington; 15.57% and 22.10% in Porto; and 12.58% and 14.68% in Rio de Janeiro.
3. Adopting a building where the C_{RW} is 50% instead of 40%, would influence the EUI in the case study by a percentage between 12.37% and 14.25% in Dubai; 8.26% and 11.27% in Kuala Lumpur; 15.56% and 18.17% in Moscow; 17.54% and 19.77% in Mount Wellington; 16.54% and 19.32% in Porto; and 10.99% and 14.65% in Rio de Janeiro.
4. Adopting a building where the C_{RW} is 65% instead of 50%, would influence the EUI in the case study by a percentage between 15.28% and 17.66% in Dubai; 12.32% and 14.30% in Kuala Lumpur; 19.95% and 22.55% in Moscow; 22.07% and 24.28% in Mount Wellington; 21.74% and 24.28% in Porto; and 16.24% and 19.31% in Rio de Janeiro.

Furthermore, this work conducts another analysis to estimate the proportional impact of the construction components of exterior walls and roofs on the EUI in the case study, considering similar C_{WR} factors. This requires organizing the sequences of Figure 8 in groups as follows: C_{WR} of 15% (1, 6, 11 and 16), C_{WR} of 30% (2, 7, 12 and 17), C_{WR} of 40% (3, 8, 13 and 18), C_{WR} of 50% (4, 9, 14 and 19) and C_{WR} of 65% (5, 10, 15 and 20). Then, the proportional impact of the construction components of exterior walls and roofs is calculated based on the lowest and highest EUI values for each group, as shown in Table 5.

Table 5. The proportional impact of the construction components of walls and roofs on the EUI in the case study based on window-to-wall ratio.

C_{WR}	EUI (MJ/m^2/year)	Dubai	Kuala Lumpur	Moscow	Mount Wellington	Porto	Rio de Janeiro
15%	*Lowest*	471.2	489.3	955.4	616.2	476.9	439
	Highest	497.1	502.7	1091.7	679.6	517	462.2
Proportional Impact		5.50%	2.74%	14.27%	10.29%	8.41%	5.28%
30%	*Lowest*	586.5	562.1	1375.5	896.4	580	547.7
	Highest	597.9	575.7	1460.7	916	619.2	558.1
Proportional Impact		1.94%	2.42%	6.19%	2.19%	6.76%	1.90%
40%	*Lowest*	685.1	626.9	1677.6	1103.9	708.2	627.3
	Highest	688.4	630.7	1727.2	1120.9	715.6	629
Proportional Impact		0.48%	0.61%	2.97%	1.54%	1.04%	0.27%
50%	*Lowest*	770	681.4	1982.4	1299.3	832.1	696.5
	Highest	786.4	698.2	1995.9	1341.2	847	720.7
Proportional Impact		2.12%	2.47%	0.68%	3.23%	1.79%	3.47%
65%	*Lowest*	888.1	765.4	2393.4	1587.5	1013.8	809.7
	Highest	925.3	797.3	2430.7	1665	1051.6	859.5
Proportional Impact		4.19%	4.17%	1.56%	4.88%	3.73%	6.15%

The results presented in Table 5 illustrate that the proportional impacts of the construction components of exterior walls and roofs in the case study would vary as follows:

(a) 5.50% in Dubai, 2.74% in Kuala Lumpur, 14.27% in Moscow, 10.29% in Mount Wellington, 8.41% in Porto and 5.28% in Rio de Janeiro, considering a C_{WR} of 15%.

(b) 1.94% in Dubai, 2.42% in Kuala Lumpur, 6.19% in Moscow, 2.19% in Mount Wellington, 6.76% in Porto and 1.90% in Rio de Janeiro, considering a C_{WR} of 30%.

(c) 0.48% in Dubai, 0.61% in Kuala Lumpur, 2.97% in Moscow, 1.54% in Mount Wellington, 1.04% in Porto and 0.27% in Rio de Janeiro, considering a C_{WR} of 40%.

(d) 2.12% in Dubai, 2.47% in Kuala Lumpur, 0.68% in Moscow, 3.23% in Mount Wellington, 1.79% in Porto and 3.47% in Rio de Janeiro, considering a C_{WR} of 50%.

(e) 4.19% in Dubai, 4.17% in Kuala Lumpur, 1.56% in Moscow, 4.88% in Mount Wellington, 3.73% in Porto and 6.15% in Rio de Janeiro, considering a C_{WR} of 65%.

6. Insights

This study examines several building components of the exterior parts of buildings, along with different window-to-wall ratios in order to improve energy efficiency in buildings. The roles of the selected factorial designs for each city were evaluated in Minitab software based on the collected energy plot. The analysis revealed that climate data has a fundamental role in determining the energy consumption in buildings; the output results show that the energy consumption of the same building varies based on the climate data of the construction site, however, colder weather equal to more energy consumption and vice versa. For example, there would be a loss of 33–50% in energy levels when constructing the same building in continental climates and in polar climates, respectively, compared to other climate classifications such as dry climates, tropical climates and mild temperate climates. However, the results of the case study proved that the sub-type climate classifications have a minor role in influencing energy consumption in buildings. The collected results show that the building components of the exterior walls and roofs have an impact on the energy efficiency in buildings, however, the space area of openings remains a significant factor among the other building components that are highly influencing the consumption of energy in construction projects (see supplementary file). The conducted analysis of this work shows a strong relation between the openings and the EUI. In these terms, comparing the collected results in Tables 4 and 5, it can be recognized that the construction component of the walls and roof would play a minor role in influencing the energy consumption in buildings, compared to the significant role of the exterior openings in buildings. This point was confirmed in the interaction plot of the factorial design for each city as presented in the supplementary file. For example, the minimum proportional impact of the exterior openings on the EUI when adopting the case study within a gradual increase of window-to-wall ratio from 15% to 30% is 20.28%, 14.40%, 33.80%, 34.78%, 19.77% and 20.58%, in Dubai, Kuala Lumpur, Moscow, Mount Wellington, Porto and Rio de Janeiro, respectively. While, the proportional impact of the construction components of the exterior walls and roofs is 5.50% and 1.94% in Dubai, 2.74% and 2.42% in Kuala Lumpur, 14.27% and 6.19% in Moscow, 10.29% and 2.19% in Mount Wellington, 8.41% and 6.76% in Porto, 5.28% and 1.90% in Rio de Janeiro, when adopting the case study within a window-to-wall ratio of 15% and 30%, respectively. Hence, it is clear that considering the space area of exterior doors and windows at the required percentage and choosing the proper insulation and thickness of construction materials that are assembling the components of walls and roof would generate better results in terms of EUI, for all climate classifications and would improve the energy performance buildings, leading to lower-energy buildings.

The analysis of the collected results of this work indicates that there is a growing interest in using BIM to improve energy efficiency in buildings. It is considered an ideal procedure for empowering the sustainability and decision-making process in the construction sector [2,8]. The proposed framework can be easily expanded to accommodate a large number of building materials for exterior walls, roofs, window-to-wall ratio or any other component of the building envelop. The proposed framework is designed to be readily available to practitioners in the construction sector, via the use of standard procedure and software in their projects, to empower the decision-making process and sustainability of building projects through a parametric analysis of construction components. This provides an opportunity to analyze and examine several construction materials that are assembling any building components in a way to improve energy efficiency in their designs.

This work focused on exterior walls as a major component of a building that is responsible for internal thermal comfort of occupants [75], roofs as an important component of a building that receives the largest amount of solar radiation per square meter annually [76,84] and window-to-wall ratio as basic factor that could affect the thermal comfort of buildings [77]. Hence, achieving the energy efficiency of such components and ratio could aid sustainability within the built environment. BIM approach has the ability to produce adjustable smart objects and easy to modify and allow using different building components within various design parameters in order to estimate the energy performance of buildings [15,72,85]. In these terms, the experimental design appears as an optimistic course that facilitates determining the expected variables of the construction process in light of the accessible construction materials [64].

7. Conclusions

Energy performance in buildings is important to consider in order to enhance the sustainability of the built environment. In an attempt to design better energy performing buildings, the work in this study presented a methodological framework that could help to integrate the experimental design within a BIM platform in order to examine all the possible design variables that impact the energy levels of buildings. The novelty of this work is to propose a framework that makes use of different performance parameters and design factors for a parametric sustainability evaluation process of building designs. The emphasis of the developed framework is on the energy performance of buildings through making the work readily available to practitioners and experts in the construction sector using standard procedure and software. The analysis considers the materials of building components, window-to-wall ratios and the energy consumed for heating, cooling, lighting and equipment purposes. The integrated methodological framework presented was based on the experimental design for determining the impact of various performance parameters related to several design factors, improving energy efficiency based on a parametric analysis. Autodesk Revit is used as a BIM software to build the building modeling; defining the building components and climate data. Minitab was utilized as an experimental tool to conduct linear regression analysis covering all the expected variables and to define the main effects plot and the interaction plot of the assigned design factors. Autodesk Green Building Studio cloud-based service was adopted as a BIM tool to analyze and estimate energy consumption.

A case study of a single-family house with different alternatives for construction components was examined in six cities, each with a different climate classification. Cities analyzed included Dubai, Kuala Lumpur, Moscow, Mount Wellington, Port and Rio de Janeiro. The results of this work indicated that the performance parameters suggested in the proposed framework significantly influence the consumption of energy in buildings. These parameters include the type of building design (i.e., the design of the final roof and exterior walls) and the climate data. In particular, the results displayed that applying super high insulation building components would slightly impact the energy efficiency in construction projects, while the design factor of the window-to-wall ratio plays a major role in influencing the energy consumption towards low-energy buildings. This work suggests constructing buildings with minor opening spaces in order to improve energy efficiency. The sub-type climate classifications have a minor role in influencing the energy consumption in buildings, while the climate group plays a fundamental role in determining this fact in construction projects. This idea was proved by showing that the same building consumed high energy when it was constructed in continental climates and polar climates whereas this value reduced dramatically in other climate classifications such as dry climates, tropical climates and mild temperate climates. In other words, it can be recognized that more windows equal to less energy efficiency and colder weather equal to more energy consumption.

The limitations of this work can be stated as follows. First, the case example of this work examined the construction of a single-family house, without considering the impact of building classification on energy consumption (i.e., office buildings, industrial buildings and mixed-use buildings). The second limitation lies in selecting a limited range of building materials, mostly materials that are available on the dataset of the Autodesk Green Building Studio cloud-based service. The framework can, however, be easily expanded to cover additional materials subject to the availablity of sufficient data. The authors' future research avenues will focus on examining other types of buildings, considering various sub-type classifications in order to point out reliable results.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/8/1515/s1, Figure S1: Interaction Plot for Dubai, Figure S2: Interaction Plot for Kuala Lumpur, Figure S3: Interaction Plot for Moscow, Figure S4: Interaction Plot for Mount Wellington, Figure S5: Interaction Plot for Porto, Figure S6: Interaction Plot for Rio de Janeiro, Figure S7: Main Effects Plot for Dubai, Figure S8: Main Effects Plot for Kuala Lumpur, Figure S9: Main Effects Plot for Moscow, Figure S10: Main Effects Plot for Mount Wellington, Figure S11: Main Effects Plot for Porto, Figure S12: Main Effects Plot for Rio de Janeiro.

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APPENDIX 8

A Framework to Estimate Heat Energy Loss in Building Operation

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A framework to estimate heat energy loss in building operation

Mohammad K. Najjar [a], Karoline Figueiredo [a], Ahmed W.A. Hammad [b], Vivian W.Y. Tam [c,*], Ana Catarina Jorge Evangelista [c], Assed Haddad [a]

[a] Programa de Engenharia Ambiental, UFRJ, Universidade Federal Do Rio de Janeiro, Brazil
[b] Faculty of Built Environment, UNSW Sydney, Australia
[c] Western Sydney University, School of Computing, Engineering and Mathematics, Australia

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A B S T R A C T

Heat energy loss in buildings occurs by two means, namely Fabric Heat Loss and Ventilation Heat Loss. Loss occurs when energy flows out through building envelope from inner warmer air to cooler air located external to the building. The purpose of this study is to identify and estimate the proportion of Heat Energy Loss that is directly caused by construction components from the building envelope. The novelty of this research is to propose a methodological framework that characterizes the Heat Energy Loss in buildings during the operation phase, taking into consideration the local climate data in which buildings are located. Reliance is on the use of a systematic approach that makes the work readily available to practitioners and experts in the area of energy efficiency. A case example of a single-family house is examined in three different climate classifications for validating the proposed method of this work. Results reveal that Fabric Heat Loss is the main factor of the Heat Energy Loss in buildings; responsible for more than 81% of the total Heat Energy Loss in buildings. Openings and exterior walls play a significant role in curbing such energy loss; accounting for around 70% of the total Fabric Heat Loss in buildings. This work points out that the percentage of energy efficiency improvement of Fabric Heat Loss is similar and directly proportional to the percentage of reduction in U-values of building components; as U-value reduces by 6.66%, the energy efficiency of Fabric Heat Loss improves by 6.66%. Besides, the analysis conducted indicates that lower air change rate would lessen the Ventilation Heat Loss in buildings. Finally, this work illustrates that Heat Energy Loss in tropical climates and dry climates could reach a value of 16% and 8%, respectively, compared to Heat Energy Loss in moist subtropical mid-latitude climates.

1. Introduction

Improving energy efficiency is a key issue in the construction sector, which accounts for around 40% of the total global energy consumption (Lasvaux, 2010); a great part of this energy is used for indoor climate purposes such as heating, cooling, and ventilation (Jones, 2011). There is an increasing interest in developing regulations related to the operation energy efficiency in buildings (Lin et al., 2018; Najjar et al., 2017; Zhou et al., 2018). Estimating the Heat Energy Loss (HEL) is another important issue to understand energy efficiency in buildings (Giraldo-Soto et al., 2018), where a wide range of construction components that are assembling the building envelopes are considered as the major contributors to the overall HEL in buildings (Alzetto et al., 2018).

HEL is a measure of the total transfer of heat occurred in buildings (Grady et al., 2017; Kreider et al., 2009). Assessing HEL in buildings helps to design the passive and active systems that are required to sustain sufficient thermal building conditions and minimize the consumption of natural resources. According to ISO 13789:2017, HEL occurs in buildings through fabric heat loss (FHL) and ventilation heat loss (VHL) (International Organization for Standardization, 2017a); this standard provides a method to estimate the heat loss and gain in buildings based on the steady-state transmission and ventilation heat transfer coefficients of whole buildings. Fabric Heat Loss is a recommended approach for assessing energy efficiency in buildings (Gupta and Kotopouleas,

* Corresponding author.
E-mail addresses: mnajjar@poli.ufrj.br (M.K. Najjar), karolinefigueiredo@poli.ufrj.br (K. Figueiredo), a.hammad@unsw.edu.au (A.W.A. Hammad), vivianwytam@gmail.com (V.W.Y. Tam), anacatarina@poli.ufrj.br (A.C.J. Evangelista), assed@poli.ufrj.br (A. Haddad).

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A Framework to Estimate Heat Energy Loss in Building Operation

Abstract. Heat energy loss in buildings occurs by two means, namely Fabric Heat Loss and Ventilation Heat Loss. Loss occurs when energy flows out through building envelope from inner warmer air to cooler air located external to the building. The purpose of this study is to identify and estimate the proportion of Heat Energy Loss that is directly caused by construction components from the building envelope. The novelty of this research is to propose a methodological framework that characterizes the Heat Energy Loss in buildings during the operation phase, taking into consideration the local climate data in which buildings are located. Reliance is on the use of a systematic approach that makes the work readily available to practitioners and experts in the area of energy efficiency. A case example of a single-family house is examined in three different climate classifications for validating the proposed method of this work. Results reveal that Fabric Heat Loss is the main factor of the Heat Energy Loss in buildings; responsible for more than 81% of the total Heat Energy Loss in buildings. Openings and exterior walls play a significant role in curbing such energy loss; accounting for around 70% of the total Fabric Heat Loss in buildings. This work points out that the percentage of energy efficiency improvement of Fabric Heat Loss is similar and directly proportional to the percentage of reduction in U-values of building components; as U-value reduces by 6.66%, the energy efficiency of Fabric Heat Loss improves by 6.66%. Besides, the analysis conducted indicates that lower air change rate would lessen the Ventilation Heat Loss in buildings. Finally, this work illustrates that Heat Energy Loss in tropical climates and dry climates could reach a value of 16% and 8%, respectively, compared to Heat Energy Loss in moist subtropical mid-latitude climates.

Keywords. *Heat Energy Loss; Fabric heat Loss; Ventilation heat Loss; U-Value; Airflow Rate.*

1. Introduction

Improving energy efficiency is a key issue in the construction sector, which accounts for around 40% of the total global energy consumption (Lasvaux, 2010); a great part of this energy is used for indoor climate purposes such as heating, cooling, and ventilation (Jones, 2011). There is an increasing interest in developing regulations related to the operation energy efficiency in buildings (Lin et al., 2018; Najjar et al., 2017; Zhou et al., 2018). Estimating the Heat Energy Loss (HEL) is another important issue to understand energy efficiency in buildings (Giraldo-Soto et al., 2018), where a wide range of construction components that are assembling the building envelopes are considered as the major contributors to the overall HEL in buildings (Alzetto et al., 2018).

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According to ISO 13789:2017, HEL occurs in buildings through fabric heat loss (FHL) and ventilation heat loss (VHL) (International Organization for Standardization, 2017a); this standard provides a method to estimate the heat loss and gain in buildings based on the steady-state transmission and ventilation heat transfer coefficients of whole buildings. Fabric Heat Loss is a recommended approach for assessing energy efficiency in buildings (Gupta and Kotopouleas, 2018) as it represents the loss of heat in buildings. It is formally defined as the process of thermal exchange that occurs through the fabric of the building components (i.e. walls, floors, roofs, and windows), from warm areas to the colder ones (Parker et al., 2019). On the other hand, VHL accounts for the heating that is added to the building through the process of replacing indoor air by the ventilation of rooms and spaces (Weerasuriya et al., 2019).

The main factor to consider when assessing HEL is the building envelope, where heat exchange occurs from the warmer indoor environment to the cooler outer environment (Grady et al., 2017; Szodrai et al., 2016). Heat energy is transferred via four mechanisms namely conduction, convection, radiation, and phase change (Designing Buildings Wiki, 2019). Understanding the dynamic relationship between four main mechanisms is imperative when controlling HEL in buildings. The novelty of this work is on proposing a methodological framework that characterizes the HEL in buildings during the operation phase, taking into consideration the local climate data of the building site. It presents the results of analyzing HEL due to FHL and VHL. Reliance is on the use of a systematic approach that makes the work readily available to practitioners and experts in the area of energy efficiency at an early stage of designing buildings. The framework is expected to allow the examination of different alternatives of construction components that are assembling the building envelope of construction projects at various climate data, and thus improve HEL in buildings. In addition, the framework is expected to establish the proportion of construction components, which plays a fundamental impact on HEL in buildings. This would also allow the identification of opportunities that are more economically and environmentally viable for the construction of buildings.

Throughout this study, the proposed framework involves different performance parameters and design factors that impact the ability to improve energy performance in buildings. The development of this study seeks to identify opportunities for improvements to estimate the FHL, VHL, and improve energy efficiency. The systematic approach of this work could empower the decision-making of energy experts and building designers to build on a balanced principle between the heat that is lost throughout the envelope of the building to the outdoor environment and the heat generated by the heating equipment. The methodological framework accommodates various global climates, in response to the general consensus worldwide on the need for improving HEL in buildings and enhancing the sustainability of the built environment. This work focuses on the application of model identification techniques to assess the HEL in buildings. It should be noted that the novelty in this work is in the proposed framework, and any applications of the framework is merely a representation of how the framework can be applied for building that have varying shapes and sizes. Hence, this work takes into consideration that the building components and parameters (i.e. *building geometry*, *building technologies*, *building envelope*, and *temperature differences)* are the main factors when analyzing the energy performance in buildings (International Energy Agency (IEA), 2016; Mejri et al., 2011; M. Najjar et al., 2019), and can be applied to both single store or multi story buildings (Catalina et al., 2008). In these terms, the single story family house of the case study presented in this work is selected as a simplified model to facilitate the comprehension of the framework. The framework can easily be extended to cover other building types and sizes

2. Literature review

Reducing energy consumption is a vital issue in the construction sector (Simonetti et al., 2016). HEL flows out through building envelope from the warmer inside air temperature to the cooler outside air temperature. It occurs by means of two main mechanisms, namely FHL and VHL (Alzetto et al., 2018). Research in the literature has focused on evaluating the energy loss in buildings from different aspects. This section reviews the recent academic paper on building energy loss, based on the following; i) evaluation of HEL in buildings towards more energy efficiency; ii) trends to analyze the FHL and VHL in buildings; and iii) thermal comfort temperature between the inside heated space and the environment external to it.

It is well known that the large majority of the building heat loss occurs through the building envelope (Nardi et al., 2018). Different studies identified the energy behavior of building components by applying advanced mathematical modeling techniques such as Auto- Regressive with eXternal model input (ARX), Auto Regressive moving Average with eXternal model input (Armax) (Piltan et al., 2017), and Grey Box modeling (Bacher and Madsen, 2011). Other studies developed methods to estimate the HEL in buildings. For example, Uriarte et al presented an average method to estimate the reduction of heat loss coefficient of an energetically retrofitted occupied office building (Uriarte et al., 2019); the authors developed an average method of a generic in-use building that can be analyzed from the Thermodynamics Open System viewpoint. Vihola et al assessed the HEL rate of the building stock using several mathematical equations; this was illustrated at the hourly level and was based on a bottom-up engineering modeling method applied on a Finnish residential and service building stock (Vihola et al., 2015). The authors found that the physical characteristics of the building envelope, ventilation, and weather conditions play a critical role in determining the HEL rate in buildings, while disregarding the height and the number of exposed openings of heated space. Moreover, several methods to estimate the HEL rate were discussed in the work of Mangematin et al. (2012) and Palmer et al. (2011). Alzetto et al compared the HEL in buildings based on an experimental whole house method, known as QUB, and the method establishes heat loss through transmission and ventilation losses (Alzetto et al., 2018); the authors found higher levels of uncertainty with the QUB method due to shorter measurement periods.

The increasing demand to improve energy efficiency in buildings by reducing heat loss through building fabrics is highly stressed in the literature (Alam et al., 2011). It is recognized that the difference between the predicted and measured fabric performance of building components can be greater than 100% (Johnston et al., 2014). To fill this gap, a careful design needs to be considered, coupled with the implementation of appropriate quality control systems. As a result, there is a need to propose new effective technologies and building materials that have the potential to achieve excellent energy efficiency and lead to low environmental impacts (Elsarrag et al., 2012). As an example, Cuce and Riffat modeled the heat transfer inside the window using various vacuum tube diameters and low energy argon-filled double glazed window. The authors found that low U-value vacuum tubes would perform better thermal insulation than low energy argon-filled double glazed window (Cuce and Riffat, 2015). Fokaides and Kalogirou presented the overall heat transfer coefficient of building components with the use of Infrared thermography to determine the percentage absolute deviation between the notional and the measured U-Values (Fokaides and Kalogirou, 2011).

Natural ventilation in buildings helps improve the quality of indoor air, by removing the heat, circulating air and contaminants from spaces In Kosutova et al (Kosutova et al., 2019), the authors presented wind-tunnel experiments and computational fluid dynamics simulations of a cross-ventilated building equipped with louvers based on four opening positions. The best ventilation rate is obtained with louvered openings in the upper part of the façade, while the highest air exchange efficiency is achieved for a building with louvered openings in the center of the façade. Simonetti et al conducted a numerical optimization and experimental testing of a new low pressure heat exchanger for passive ventilation of buildings (Simonetti et al., 2016). While Zhao et al evaluated the effects of mechanical ventilation and natural ventilation on indoor climates in China. The authors found that operating a mechanical ventilation results in better outcomes compared to the natural ventilation in order to increase energy efficiency in buildings (Zhao et al., 2018).

HEL in buildings is highly affected by the difference of air temperature between the inside heated space and the environment external to it. The outside air temperature is usually calculated for each climate zone based on the worst-case condition, denoted as the *coldest night of the year* (Holladay, 2012). Köppen classification scheme identifies five major climate zones with the average air temperature of the cooling period (A. John Arnfield, 2019; Chen and Chen, 2013; Chmielewski, Frank-M.; Blümel et al., 2011; Koppen, 2011; M. K. Najjar et al., 2019; Rubel and Markus Kottek, 2010) as shown in **Table 1**.

Table 1: Köppen classification climates and average air temperature of cooling period

Letter symbol	Climate classification	Average air temperature of the cooling Period
A	Tropical climates	greater than 18 °C

B	Dry climates	between 20 and 35 ºC
C	Moist subtropical mid-latitude climates	between -3 and 18 ºC
D	Moist continental mid-latitude climates	less than -3 ºC
E	Polar climates	lowest temperature ever recorded is -89.2 ºC

The average inside air temperature is defined as the required range of air temperatures that people would feel comfortable with, when wearing typical indoor clothing (Morgan and Dear, 2003). It varies due to the building use (i.e. residential, retail, industrial, etc.), and building type of occupancy (i.e. model building codes, and fire code enforcement) (Owen, 2015). However, the range of values for the inside air temperature which is considered appropriate for human occupancy is typically between 15 and 25 ºC (Brauer, 2016). Human comfortable temperature can lie beyond this range of temperature based on the humidity, air circulation, and warm and cool periods. For example, a suggested typical inside air temperature during the warm period is between 23 and 25.5 ºC, whereas, during cool periods, it is between 20 and 23.5 ºC (Burroughs and Hansen, 2011). Experts recommended that the optimal temperature for working or living rooms is between 21 and 22 ºC for heating systems (Holladay, 2012); between 18 and 22 ºC depending on room function (World Health Organziation, 2007); and around 22 ºC (Wargocki et al., 2019; F. Zhang et al., 2017). Taking into consideration that the inside air temperature varies according to the air movement, humidity and outside air temperature (Jin et al., 2017; Schiavon et al., 2017; Zhai et al., 2015), this work will adopt an inside air temperature of 22ºC to conduct the case study analysis.

3. Materials and methods

Based on the reviewed literature, there is an existing gap in terms of defining the impact of each construction component on the resulting value of HEL at various climate data. This is important since the HEL can assess the total transfer of heat occurred through the construction components that are assembling the envelope of buildings. This would give the opportunity for designers and architects to select environmentally friendly building materials and design more energy efficient projects at an early stage of designing buildings. To achieve this objective, this section will present a framework to characterize the HEL at an early stage of designing buildings based on ISO 13789:2017 (International Organization for Standardization, 2017a), using a systematic approach. The proposed framework is developed in a way to make the work readily available to practitioners designing buildings to enhance their energy efficiency. The use of high-tech construction components that minimize the infiltration energy loss in buildings is considered in developing the framework. It corroborates the systematic framework for estimating the HEL and indicates the proportion of the construction components that contribute towards HEL in buildings.

The proposed framework differs from the existing methods in the following ways. First, when contrasted with the framework of (Uriarte et al., 2019), the developed framework herein accounts for the HEL estimation rather than heat loss coefficient. Second, when contrasted with the framework of (Alzetto et al., 2018), the developed framework herein accounts for identifying the construction components that are highly affecting the energy efficiency of building envelopes. Generally, the proposed framework herein can accommodate a larger building with more construction components and can be applied at any climate classification.

3.1. Decision support analysis

The proposed framework to estimate the HEL in this study is based on FHL and VHL, as presented in **Figure 1**, illustrating the performance parameters, design factors, conceptual framework, and visualization aid of the decision support analysis as follows:

3.1.1. Performance parameters and design factors

When evaluating HEL in buildings, it is necessary to build a reliable inventory database. The emphasis of the calculations made is on the operation and maintenance phase of buildings. During this phase, the ability of buildings to resist the heat flow decreases and heat is lost through the fabric of the building envelope and through the infiltration of cold air via any holes and gaps (Killip, 2005). The systematic framework proposed in this study has been developed based on identifying the performance parameters and their related design factors that cover the current activities and future needs for achieving a sustainable building design. This requires defining the boundaries, limitations, and the several variables of heat energy loss in buildings in a way to build-up a complete, comprehensive, and transparent framework (Sala et al., 2015). At this level of the analysis, several performance parameters are required to be determined and decided; this includes the *building geometry*, *building technologies*, *building envelope*, and *temperature differences* that exist between internal and external environments, as shown in **Figure 1**.

The first performance parameter considered, the *building geometry*, is associated with design factors such as the floor level, floor heated area, dimensions of the heated volume, and the respective space area of each construction component in the building (Zhang et al., 2017). Design factors associated with the second performance parameter, the *building technologies* parameter, relates to the calculation of the thermal transmittance of the utilized construction components and air change rate of the geographic location of the building. Thermal transmittance, as assessed in terms of the U-value, is a measure of the heat transmission through the applied building components. Lower values of U-value represent components with better insulation properties (Bienvenido-Huertas et al., 2019). The units of measurement for the U-value are W/m^2K. Air change rate is often referred to as Air Changes per Hour (ACH), which measures the volumetric air flow entering or leaving the building, divided by its volume (Hou et al., 2017; Macarulla et al., 2018). For this measurement, higher values correspond to better ventilation (Awbi, 2017). In terms of the third performance parameter, the *building envelope,* the associated design factors are listed to recognize all construction components in a building; defining such parameters will facilitate evaluating the U-values (Thormark, 2007). The final performance parameter, the *temperature difference*, assesses the contrast between the inside air temperature and the external air temperature associated with the local climate zone of the building.

The proposed framework can accommodate larger heated floor area and heated volumes at any climate classification within several ACH and inside and outside air temperature, along with a large number of construction components within different U-values; the database can be easily extended to cover a wide range of construction components assembling the building envelope. However, some specific components in a single-family house are used in the examined case study just to validate the proposed framework.

3.1.2. Conceptual framework and visualization aid

A holistic approach of a summation of the interactions between the different performance parameters and design factors is conducted in a way to make a better understanding of the whole system in a *multidimensional* way (Spruill et al., 2001). This requires evaluating the collected results of the different models of the performance parameters and their related design factors by contrasting the alternatives that simulate the FHL and VHL as a prior step to improve the HEL and, consequently, energy efficiency in buildings. Hence, the mathematical equations are formulated and applied to the various design factors in order to calculate the total FHL and VHL. The last step of the suggested methodological framework of this work is to appraise the collected results in order to allow the determination of the HEL and the proportion of each component within the building contributing towards FHL. This step starts by categorizing of the data sources, comparing and matching results, and proposing recommendations and new options of building design.

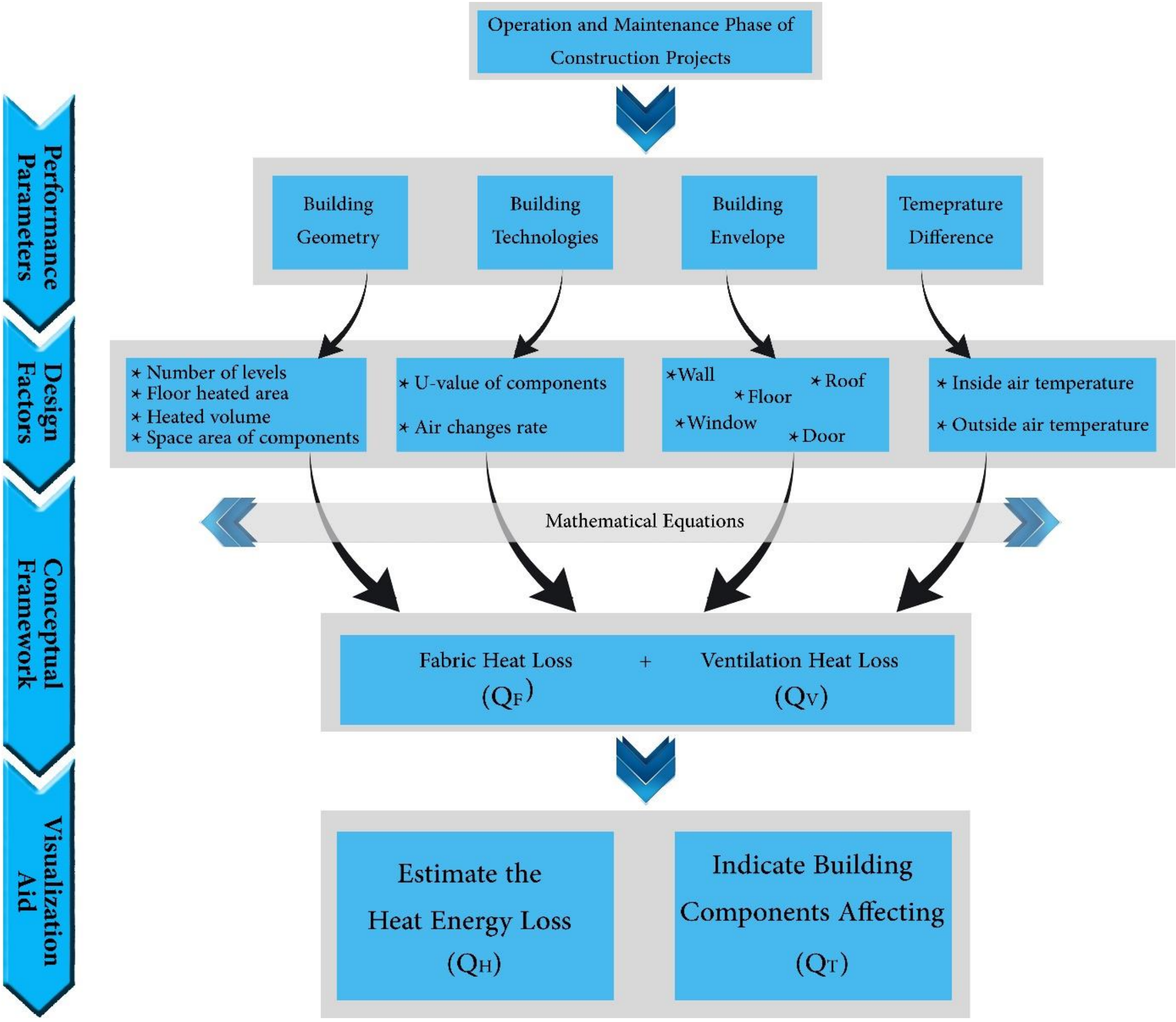

Figure 1: Methodological framework

3.2. Estimating heat energy loss in buildings (Q_H)

Since HEL in buildings is estimated via considering both FHL and VHL, the method proposed takes into consideration the factors that contribute towards FHL and VHL. This requires examining the maximum heat loss that could occur in buildings at the highest temperature difference (i.e. at the coldest night of the year). Equation (1) is formulated to calculate the HEL, as suggested by BS EN 12831-1:2017; the use of this Equation has been highlighted as an effective solution for capturing the heat transfer in buildings (BSI Standards Publications, 2017).

$$Q_H = (Q_T + Q_V).\int \Delta C \qquad (1)$$

Where Q_H denotes the Heat Energy Loss (HEL) (W); Q_T denotes the Fabric Heat Loss (FHL) (W); Q_V denotes the VHL (W); and $\int \Delta C$ denotes the Temperature Correction Factor.

In these terms, the temperature correction factor is designed as 1.0 for normal inside temperature of heated space, and 1.6 for higher inside temperature of heated space (BSI Standards Publications, 2017).

3.2.1. Estimating fabric heat loss of construction components (Q_T)

FHL depends on the U-values of the individual construction components of the building envelope, their respective areas and the difference of air temperature between the inside and outside environment. This is displayed in Equation (2) as an effective step to measure the heat loss of construction components assembling the building envelopes (BSI Standards Publications, 2017; Jack, 2015).

$$Q_T = \sum (U.S).\Delta C \qquad (2)$$

where Q_T denotes the FHL (W); U denotes the U-value of each building component (W/ m^2. K); S denotes the respective area of each building component (m^2); and ΔC denotes the difference of air temperature between the inside and outside environment (^{o}C).

The respective area of each building component requires combining the net area of each component in the construction project. For example, the respective area of exterior walls refers to the net area after subtracting all the openings (i.e. doors and windows), while the respective area of openings is composed of the total area of doors and windows, including frames. In these terms, the respective area of the roof component refers to the net area of any roof including roof lights and skylight in the roof.

The U-value of the construction components measures the rate of transfer of heat through the component (Fokaides and Kalogirou, 2011). In other words, the U-value measures the effectiveness of the material as an insulator. However, the selection of construction components of buildings changes based on climate classification, which in turn impact the U-value measure of the building envelope. The Local Authority Building Control (LABC) in the United Kingdom provides a guide to the specification of insulation components. This facilitates achieving compliance with the Building Regulations for small domestic works (LABC Hertfordshire, 2011); the guide follows the sample calculations based on BR 443 (Anderson, 2006), BS EN ISO 6946 (International Organization for Standardization, 2017b), and BS EN ISO 13370 (International Organization for Standardization, 2017c). It presents the maximum U-value achieved for various construction components as follows (LABC Hertfordshire, 2011):

I. 0.22 W/ m^2. K for ground floors such as suspended timber floor, floating floor, suspended beam and block, and ground bearing slab.
II. 0.28 W/ m^2. K for walls such as cavity wall with timber frame, timber frame wall, solid wall construction, full fill masonry cavity walls, and partial fill masonry cavity walls. While, 0.30 W/ m^2. K for dry lining existing solid walls.

III. 0.18 W/ m^2. K for roofs such as vented cold deck pitched roof (insulation between rafters), and warm deck pitched roof. While, 0.16 W/ m^2. K for vented cold deck pitched roof (insulation between & over ceiling joists)

IV. 1.6 W/ m^2. K for double-glazing windows and 1.8 W/ m^2. K for double-glazing doors. While, 1.0 W/ m^2. K for triple glazing within 12mm argon cavity and 0.8 W/ m^2. K for triple glazing within 16mm argon cavity.

The case example of this work considers all the variables contributing to the U-values of construction components, as specified in the guide of LABC. The use of such standards allows the identification of the contribution of the U-value of construction components on the level of FHL that results during the operation phase of buildings.

3.2.2.Estimating ventilation heat loss in buildings (Q_V)

VHL is the process of exchanging the air in any space and enhance the quality of indoor air. It occurs mainly through the building envelope (i.e. walls, floors, roof, and openings) (Chahwane et al., 2018), as shown in **Figure 2**.

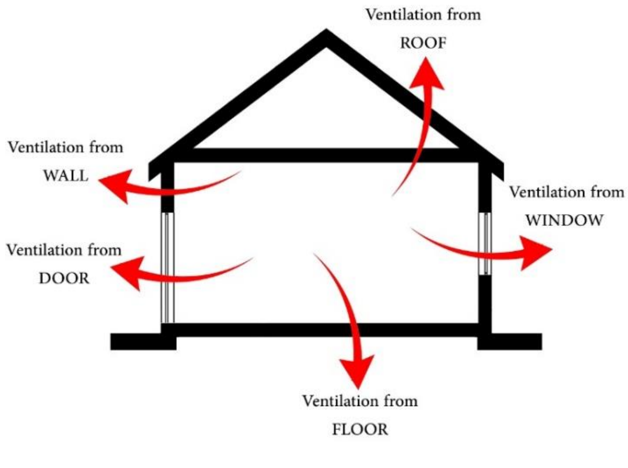

Figure 2: Ventilation in buildings

Equation (3) is formulated to illustrate the calculation process of VHL in buildings (BSI Standards Publications, 2017). It is an effective solution to measure the total infiltration heat loss in buildings. Equation (3) is a factor of the minimum air flow rate, the difference of temperature between the inside and outside of the heated space, and the specific heat of air adopted as 0.34 (W/ m^2. K) (Jack, 2015).

$$Q_V = 0,34.V_{maf}.\Delta C \tag{3}$$

where Q_V denotes the VHL (W); $0{,}34$ denotes the Specific heat of the air (W/ m^2. K); V_{maf} denotes the minimum airflow rate (m^3/h); and ΔC denotes the temperature difference between the inside and outside (^{o}C).

The minimum air flow rate V_{maf} is as seen in Equation (4). It is the result of multiplying the factor of the ACH, the volume of the heated space, the shielding coefficient factor, and the height correction factor (BSI Standards Publications, 2017); it has been highlighted in the literature as an effective method to capture the air flow rate in buildings.

$$V_{maf} = N.V.S.H \tag{4}$$

where N : denotes the Air Exchange Rate - ACH (1/h); V denotes the internal respective volume of the heated space (m^3); S denotes the Shielding Coefficient; and H denotes the Height Correction Factor.

ACH refers to the amount of air that enters and exits a room from the HVAC system, in a single hour (Oxycom Fresh Air BV, 2017). In literature, Eskola et al (Eskola et al., 2008) measured 172 detached houses in Helsinki in Finland between 2002 and 2007. The average ACH was assessed to be between 0.38 and 0.42 1/h. Wallace et al (Wallace et al., 2002) measured the ACH in an occupied house over a single year. The authors considered the effect of temperature, wind, fans, and windows and outlined that the monthly average ACH varies between 0.44 and 1.30 1/h. The case example of this study considers the ACH as a design variable between 0.40 and 1.00 1/h, with a 0.05 1/h increment.

On the other hand, the Shielding Coefficient (S) and Height Correction Factor (H) are outlined in BS EN 12831-1:2017 (BSI Standards Publications, 2017). Considering a heated space with more than one exposed opening; S=0.2 for heavy shielding; S=0.3 for moderate shielding; and S=0.5 for no shielding. While the default values for the height correction factor are assumed based on the height of heated space above ground-level; if the height is up to 10m, H=1.0; if the height is between 10m and 30m, H=1.2; if the height is more than 30m, H=1.5.

4. Linking framework components

Figure 3 is produced to illustrate how the HEL is computed, and to determine the proportions of construction components that result in energy loss in buildings. Once the type of project is determined (i.e. single-family house, multi-story building, etc.). the next step is to apply the methodological framework presented in Section **3.1**. The inventory of database is built through several performance parameters and their representative design factors. The procedure also recognizes three different climate classifications to locate the examined house.

Estimating the FHL requires defining the alternative construction components that are assembling the building envelope of the building. This work applies the components as mentioned in LABC. At this level of the analysis, there is a need to assess the U-value for each component within the representative area and define the difference of air temperature between the heated space and external environment. The U-value of the construction components making up the project directly impacts the different FHL values. This is because U-value assesses the rate of losing and gaining of heat energy through the construction of materials (Jack, 2015). The next step is to apply Equation (2), as shown in **Figure 3**.

Estimating the VHL in Equation (3) requires deciding the minimum airflow rate V_{maf} as shown in Equation (4), which necessitates expecting the internal volume of the heated space, shielding coefficient, height correction factor, and the air exchange rate. Applying the case study in three different climate classifications permits the examination of several values of air exchange rate and the evaluation of different VHL values. The next step is to apply Equation (3), as shown in **Figure 3**.

Then, Equation (1) is applied in order to evaluate the total HEL of the case example. The output results are used to indicate the proportion of building components affecting the fabric heat loss. Such indication permits the designer to comprehend the individual impact of each building component, as well as the portion of VHL making up the HEL in buildings.

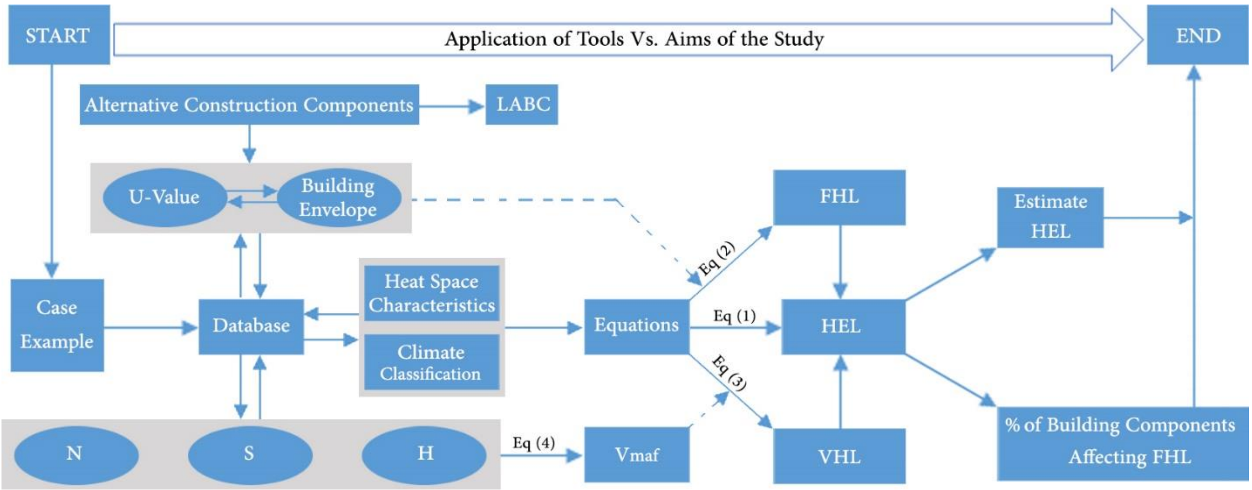

Figure 3: Application of tools vs. aims of the study

5. Case study - Validating the methodological framework

5.1. Size of the case study

To maintain the brevity of the discussion, the framework is applied on a single-family house case example to facilitate the comprehension and validation of this framework. The framework can however be applied on bigger house sizes including multi-story buildings with very minor modifications required in the performance parameters and design factors of the proposed framework. The case example of this work is a typical one floor single-family house composed of a living room, kitchen, and two en-suite bedrooms. **Figure 4** presents the dimensions of the four facades of the building considered in the case study. The building envelope of the considered house is composed of several alternative construction components as mentioned in LABC. These are floors (i.e. suspended timber floor, floating floor, suspended beam and block, and ground bearing slab); walls (i.e. cavity wall with timber frame, timber frame wall, solid wall construction, full fill masonry cavity walls, and partial fill masonry cavity walls, and dry lining existing solid walls); roofs (i.e. vented cold deck pitched roof insulation between rafters, warm deck pitched roof, and vented cold deck pitched roof insulation between and over ceiling joists); and openings (i.e. double-glazing windows, double-glazing doors, triple glazing within 12mm argon cavity and triple glazing within 16mm argon cavity).

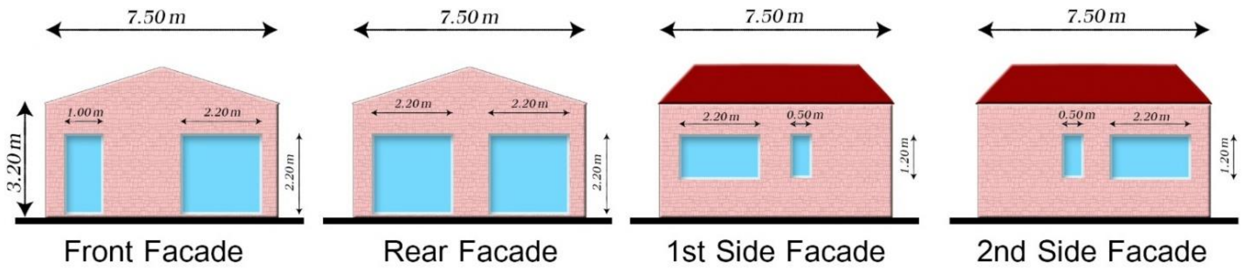

Figure 4: Prospect modeling of the case example

This work focuses on three basic climates: tropical climates, dry climates, and moist subtropical mid-latitude climates. These climates cover more than 60% of the global surface area, including large regions of Europe, Africa, Asia, Australia, America, and South America (Big Ladder Software, n.d.). The recognized outside air temperature of each climate classification is the one that can achieve the maximum HEL; this is 18°C in tropical climates, 20°C in dry climates, and -3°C in moist subtropical mid-latitude climates. Furthermore, this work proposes an indoor temperature of 22°C.

5.2. Data Inventory

Equation (1) is applied to assess the HEL of the case study, considering a normal internal design temperature of heated space is recognized, giving a value of the Temperature Correction Factor ($\int \Delta C$ =1.0). The difference in air temperature between the inside and outside environment is estimated according to the recognized indoor temperature and outside air temperature of each climate classification. This means that the temperature difference is 4°C {22-(18)°C} in tropical climates, 2°C {22-(20)°C} in dry climates, and 25°C {22-(-3)°C} in moist subtropical mid-latitude climates.

Equations (2) is applied to assess the FHL of the case study. This requires considering the representative U-value of the several alternatives of building components as mentioned in LABC; the respective area of each building component based on the case study, as shown in **Table 2**; and the difference of air temperature between the inside and outside environment.

Equations (3) is applied to assess the VHL of the case study. This requires considering the minimum airflow rate and the difference in air temperature between the inside and outside environment. In these terms, assessing the minimum airflow rate requires applying Equations (4). This work considers a range of ACH between 0.40 and 1.00 1/h, incremented at 0.05 1/h; the internal respective volume of the heated space of the case study, as shown in **Table 2**; a moderate shielding coefficients, which means buildings in the country with trees or other buildings around them, giving a value S=0.3; and the Height Correction Factor, giving a value H=1.0.

The main and fixed characteristics of the building involved in the simulation are shown in **Table 2**.

Table 2: Fixed characteristics of the analyzed case example

Building Geometry	Characterization
Number of levels	1
Height of building	3.20 m
Floor heated area	7.50 X 7.50 m^2
Dimensions of the heated space	7.50 X 7.50 X 3.20 m
Space area of the roof	7.50 X 7.50 m^2
Space area of walls	52.04 m^2
Space area of openings (windows)	6.48 m^2
Space area of openings (doors)	16.72 m^2

5.3. Assessment of FHL and VHL

This step considers the input data in **Table 2** in order to estimate FHL and VHL for the case study examined. **Table 3** illustrates the calculated FHL. At this level of the analysis, the results are collected based on Equation (2), where the U-values of the building components making up the building envelope of the case study are obtained from LABC (LABC Hertfordshire, 2011). The respective space area of each building components is obtained from **Table 2**, and the difference of air temperature between the inside and outside environment is estimated as discussed in the previous section.

Table 3: Estimating the **FHL** of the case study

Building Component	**Construction Component**	**U-Value (W/ m^2. K)**	**Space Area (m^2)**	**ΔC (°C)**	**FHL per Component based on Climate Classifications (W)**		
					A	**B**	**C**
Floor	Suspended timber floor	0.22	56.25	A = 4 B = 2 C = 25	49.50	24.75	309.38
	Floating floor	0.22					
	Suspended beam and block	0.22					
	Ground bearing slab	0.22					
Exterior Walls	Cavity wall with timber frame	0.28	52.04		58.28	29.14	364.28
	Timber frame wall	0.28					
	Solid wall construction	0.28					
	Full fill masonry cavity walls	0.28					
	Partial fill masonry cavity walls	0.28					
	Dry lining existing solid walls	0.30			62.45	31.22	390.30
Roof	Vented cold deck pitched roof (insulation between rafters)	0.18	56.25		40.50	20.25	253.13
	Warm deck pitched roof	0.18					
	Vented cold deck pitched roof (insulation between and over ceiling joists)	0.16			36.00	18.00	225.00
Openings (windows)	Double-glazing windows	1.6	6.48		41.47	20.74	259.20
	Triple glazing within 12mm argon cavity	1.0			25.92	12.96	162.00
	Triple glazing within 16mm argon cavity	0.8			20.74	10.37	129.60
Openings (doors)	Double-glazing doors	1.8	16.72		120.38	60.19	752.40

Table 4 presents the evaluation of the minimum airflow rate (V_{maf}) of the case study for the case study, based on Equation (4), as discussed in the previous section.

Table 4: Estimating the V_{maf} of the case study

Respective ACH (1/h)	**Volume of the heated space (m^3)**	**Shielding coefficient (S)**	**Height correction factor (H)**	V_{maf} **(m^3/h)**
0.40	7.50 X 7.50 X 3.20 m = 180.00 m^3	S=0.3	H=1.0	21.60
0.45				24.30
0.50				27.00
0.55				29.70
0.60				32.40
0.65				35.10
0.70				37.80
0.75				40.50
0.80				43.20
0.85				45.90
0.90				48.60
0.95				51.30
1.00				54.00

Table 5 illustrates the calculated VHL. At this level of the analysis, the results are collected based on Equation (3), where the values of the (V_{maf}) are obtained from **Table 4**, and the difference of air temperature between the inside and outside environment is estimated as discussed in the previous Section.

Table 5: Estimating the **VHL** of the case study

Specific heat of air (W/ m^2. K)	V_{maf} **(m^3/h)**	ΔC **(ºC)**	**VHL based on Climate Classifications (W)**		
			A	**B**	**C**
0,34	21.60	A = 4 B = 2 C = 25	29.38	14.69	183.60
	24.30		33.05	16.52	206.55
	27.00		36.72	18.36	229.50
	29.70		40.39	20.20	252.45

	32.40		44.06	22.03	275.40
	35.10		47.74	23.87	298.35
	37.80		51.41	25.70	321.30
	40.50		55.08	27.54	344.25
	43.20		58.75	29.38	367.20
	45.90		62.42	31.21	390.15
	48.60		66.10	33.05	413.10
	51.30		69.77	34.88	436.05
	54.00		73.44	36.72	459.00

5.4. Evaluation of results

The calculations of FHL, **Figure 5** and **Figure 6**, and VHL, **Figure 7**, are carried out for each of the three climates considered. The values of heat loss in **Figure 5** show that the FHL is considerably higher in moist subtropical mid-latitude climates compared to the tropical and dry climates. In other words, FHL of building components in tropical climates and dry climates could reach a value of 16% and 8%, respectively, compared to moist subtropical mid-latitude climates. The maximum and minimum FHL considered for the case study, based on the higher and lower U-values applied, as shown in **Figure 6**. It shows that the minimum FHL accounts for 284.90 W, 142.45 W, and 1780.66 W, while the maximum FHL accounts for 314.30 W, 157.15 W, and 1964.41 W in tropical climates, dry climates, and moist subtropical mid-latitude climates, respectively. Yet, **Table 3** shows that the use of construction components with a lower U-value (i.e. 0.28 W/ m^2. K) for exterior walls would reduce the FHL, compared to components with a higher U-value (i.e. 0.30 W/ m^2. K). This example shows that reducing the U-value of exterior walls from (0.30 W/ m^2. K) to (0.28 W/ m^2. K) would improve the energy efficiency of FHL by 4.17 W in tropical climates, 2.08 W in dry climates, and 26.02 W in moist subtropical mid-latitude climates. In other words, achieving a reduction in U-values for 6.66% would improve the energy efficiency of FHL by around 6.66% at any climate classification. The same issue can be realized for the roof and opening components. This proves that the percentage of energy efficiency improvement of FHL is similar and directly proportional to the percentage of reduction in U-values of building components.

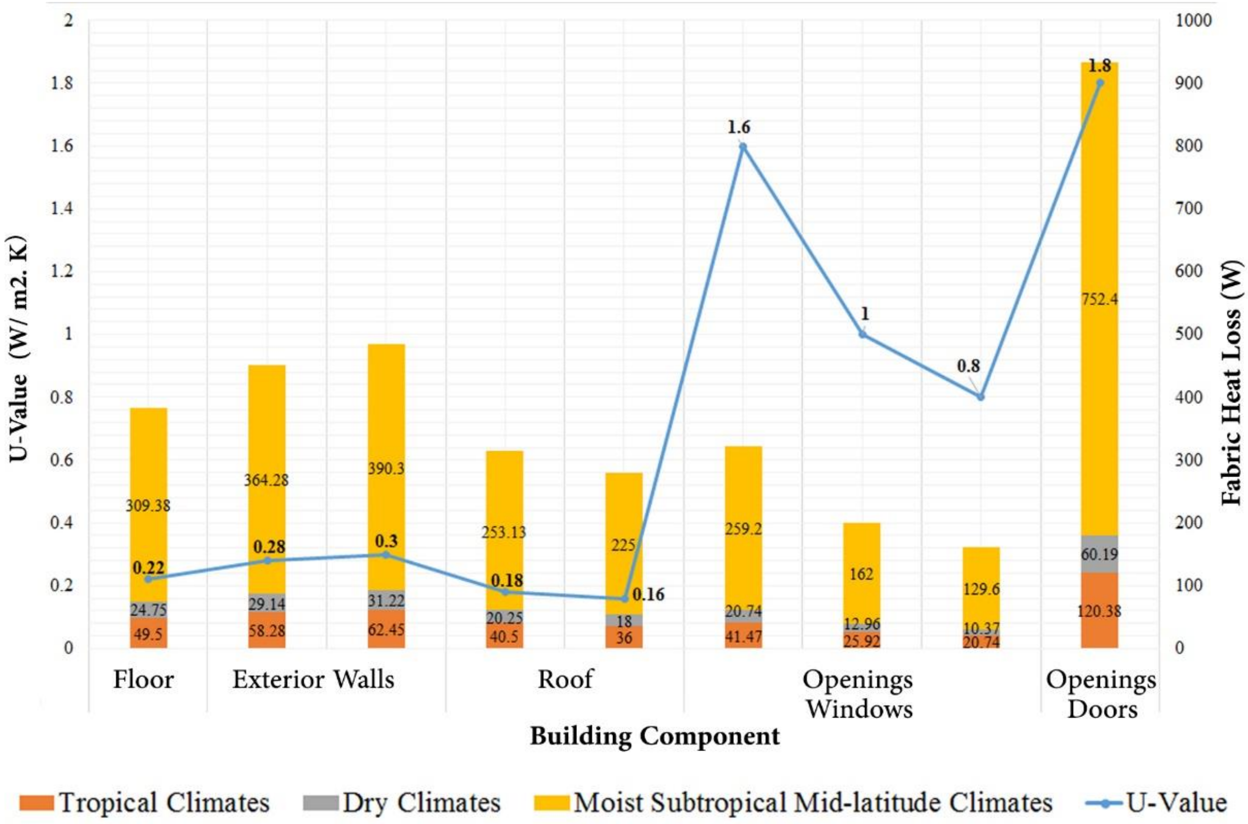

Figure 5: FHL at various climates for the case example

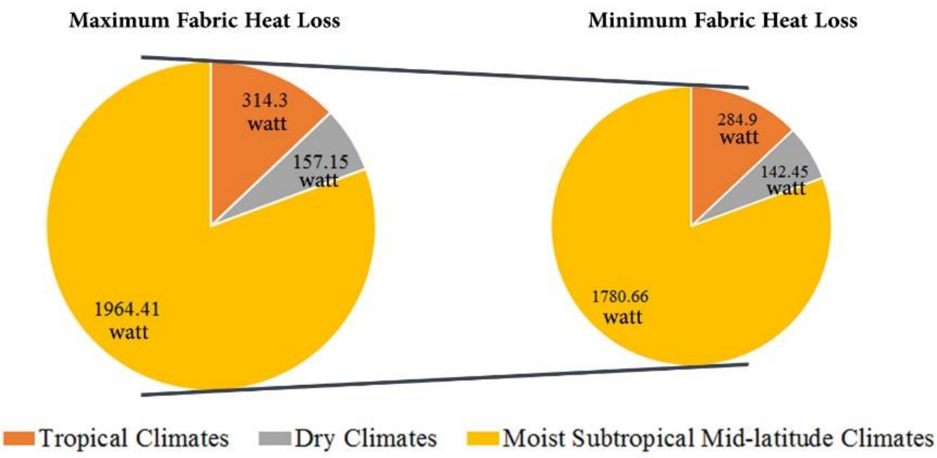

Figure 6: Maximum and minimum FHL in the case examined

The results of VHL in the case example, presented in **Figure 7**, varies based on the minimum air flow rate (V_{maf}) and accordingly based to the ACH itself. The presented values show that the VHL in tropical climates and dry climates could reach a value of 16% and 8%, respectively, compared to moist subtropical mid-latitude climates. As a result, it can be noticed that using lower values of ACH would reduce the VHL in the case example, and vice versa. For instance, reducing the ACH to 0.4 instead of 1.0 could reduce the VHL by about 60% in any climate classification. This could help designers control the ACH, taking into consideration the requirements of the owners and the difference of air temperature between the heated space and the external environment, in a way to reduce the value of VHL in their projects.

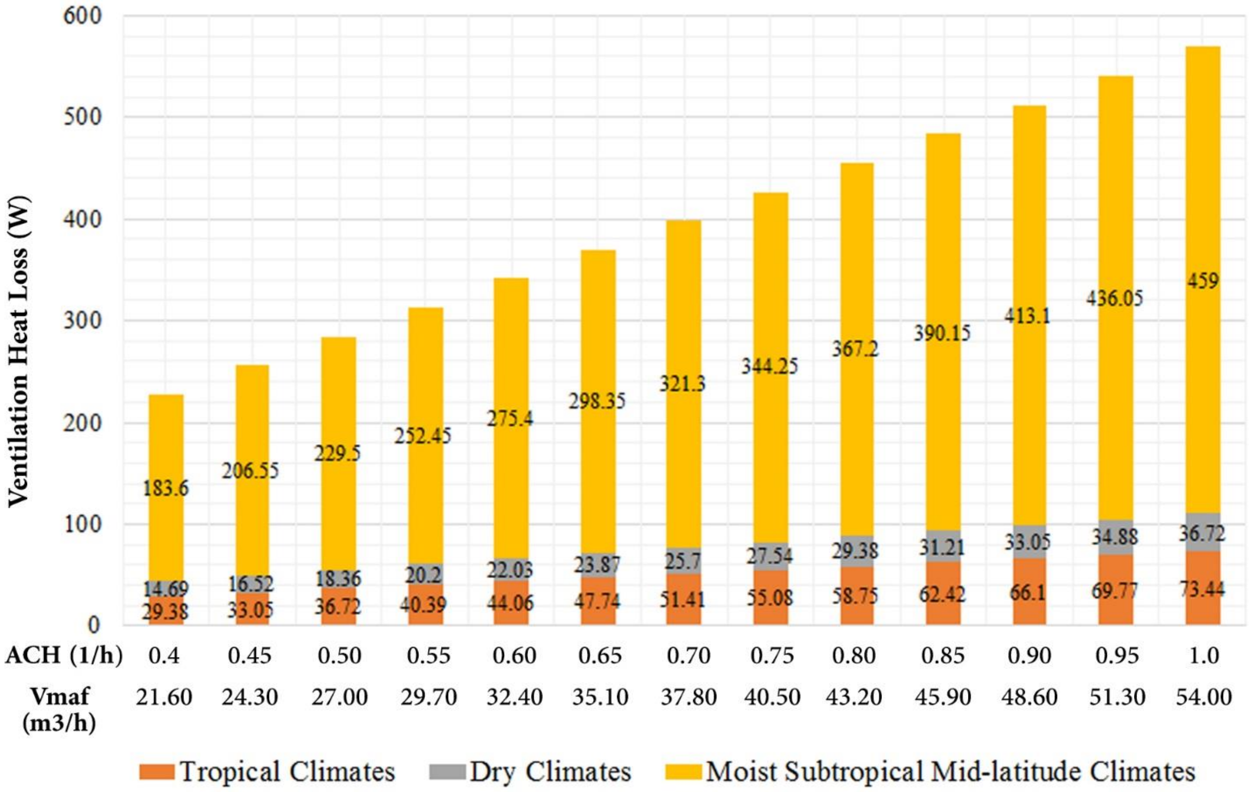

Figure 7: VHL at various climates for the case example

Collecting the maximum and minimum values of the FHL in the case example, as shown in **Figure 6**, would result in different values of the total HEL, considering a normal internal design temperature of heated space ($\int \Delta C$ =1.0). Thus, this work considers the maximum and minimum HEL of the case example based on each climate classification, as shown in **Figure 8**. For instance, the minimum and maximum of the HEL is 314.28 W and 387.74 W respectively, in tropical climates; 157.14 W and 193.87 W, respectively, in dry climates; 1964.26 W and 2423.41 W respectively, in moist subtropical mid-latitude climates. Additionally, it shows that HEL in tropical climates and dry climates could reach a value of 16% and 8%, respectively, compared to moist subtropical mid-latitude climates.

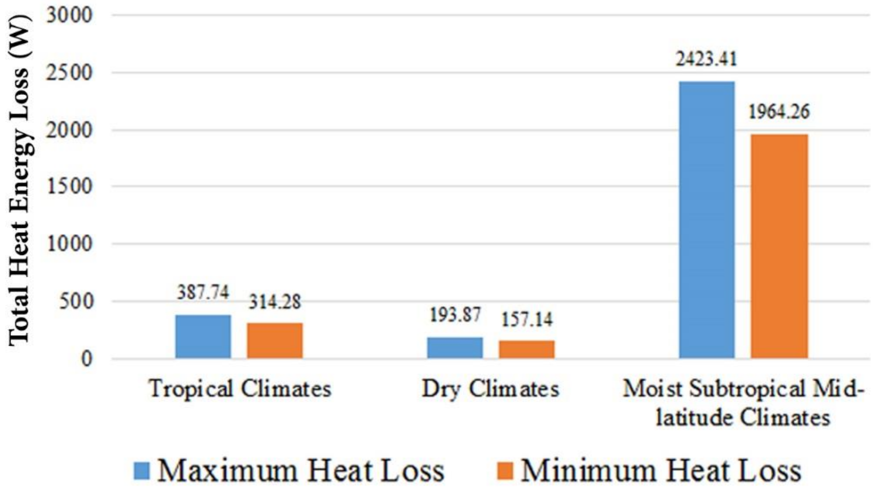

Figure 8: Maximum and minimum total heat loss of the case example

Dividing the values of VHL, presented in **Figure 7**, to the collected results in **Figure 8** shows that VHL could account between 7.73% and 18.94% of the total HEL of the case study, at any climate classification, while the rest of the HEL comes back to the FHL of construction components; account for more than 81% of the total HEL. In other words, FHL of construction components plays an important role in reducing the HEL in buildings. Hence, **Figure 9** presents the percentage breakdown of the FHL of construction components that are assembling the envelope of the building based on the three examined climate classifications. It can be seen that the openings (doors + windows) account for 51.50 % of the total FHL in such types of buildings whereas floors, exterior walls, and roof account for 15.75%, 19.87%, and 12.88%, respectively. Openings are the major construction components that could influence the heat loss in buildings, while exterior walls are the second major construction component influencing the energy loss in buildings, constituting up to 19.87 % of the total FHL.

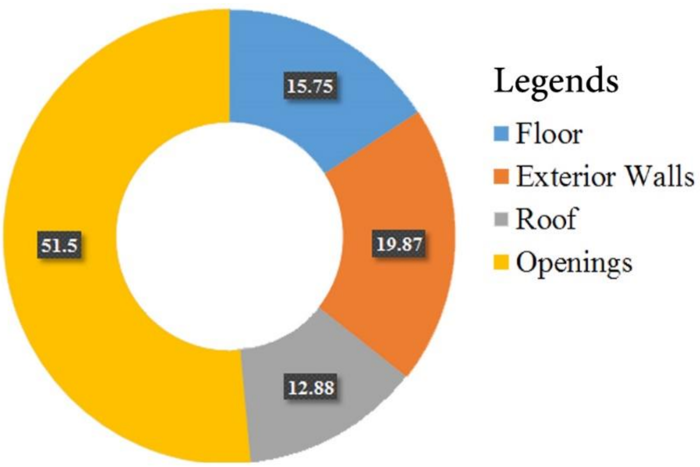

Figure 9: The percentage breakdown of the FHL of construction components

6. Discussions

The analysis of the case study shows that the total HEL of buildings in tropical climates and dry climates could reach a value of 16% and 8%, respectively, compared to moist subtropical mid-latitude climates. Furthermore, it clarifies that the FHL of construction components is the main agent of the total HEL in buildings; the majority of impacts is due to construction materials assembling the openings (doors and windows) and exterior walls, within a percentage of 51.50% and 19.87%, respectively. The analysis makes clear that the VHL has a recognized impact on the HEL in buildings, within a range between 7.73% and 18.94% of the total HEL in the case study.

Evaluating the presented results above shows that the impact of VHL in terms of improving the HEL in buildings is less than 19%, whereas the major impact is due to the FHL, which accounts for more than 81% of the total HEL in buildings. At this level of the analysis, the VHL could be maximized based on the ACH in buildings; lower ACH would lessen the VHL and vice versa. This is because the volume of the building, or the heated space, is defined by the owner requirements whereas the difference of air temperature between the inside and outside is set by the climate data. Providing the minimum amount of ACH delivers better indoor air quality (Goicoechea and López, 2012; Oxycom Fresh Air BV, 2017). Hence, it is imperative to consider the volume of the heated space, along with the difference in air temperature between indoor and outdoor, height of buildings, and shielding coefficient, when designing buildings as these factors play a significant role in evaluating the minimum airflow rate in buildings. On the other hand, it can be notified that the FHL could be maximized when choosing construction materials with higher U-values and vice versa; reducing the U-value of construction components would improve the energy efficiency of FHL. This could reduce the HEL in buildings and, consequently, increase energy efficiency and protect the built environment by lessening the dependence on fossil fuels to heat the required spaces. Furthermore, it can be seen that all construction components are influencing the FHL in buildings, however, openings and exterior walls account for more than two-third of such energy consumption. Hence, it is imperative to take the U-values and respective space area of these two components into consideration, as well as the difference of air temperature between the inside and outside environment when designing buildings in order to increase energy efficiency.

The proposed method of this work characterizes the HEL in buildings during the operation phase, due to FHL and VHL. The systematic approach of this work makes it readily available to practitioners and experts in the area of energy efficiency in a way to empower the decision-making of building designs as stated by (Wong et al., 2019), as well as building a balancing principle by compensating the heat that is lost through the building envelope using heating equipment as stated by (Shi, 2017). The proposed framewrok is designed to involve different performance parameters and design factors that help to assess the HEL in buildings and to identify opportunities for improvements to estimating the FHL and VHL. The framework can be applied for various cases as long the database can be easily extended to cover a wide range of construction components, hence, Equation (2) can account for larger buildings. Furthermore, the framework can accommodate various climate classifications within various ACH, hence, Equation (3) can account for more locations at several climate databases.

7. Conclusion

The impact of heat loss on total energy consumed by buildings during the operation phase is of high significance. A need exists to present a method that estimates the values of HEL in buildings and determine the construction components that are highly influencing such energy loss. In this paper, a novel methodological framework was adopted to characterize the HEL in buildings during the operation and maintenance phase due to FHL and VHL, based on various performance parameters and design factors that accommodate several global climates and provide opportunities to empower the sustainability of the built environment. Reliance is on the use of a systematic approach that makes the work readily available to practitioners and experts in the area of energy efficiency.

The proposed framework accommodates various global climates, within various ACH, to improve HEL in buildings and enhance the sustainability of the built environment. It accommodates different heated floor area and heated volumes at any climate classification within several ACH and inside and outside air temperature, along with a large number of construction components within different U-values. Some specific components were adopted in the examined case study just to illustrate the versatility of the proposed framework. HEL in the case study was estimated considering the modifications of different options of construction materials based on three different climate classifications. These modifications included the main components that are forming the building envelopes such as floors, exterior walls, roofs, and openings. Several mathematical equations were adopted to estimate the FHL and VHL in order to improve the HEL in buildings and identify the construction components that are highly affecting the energy efficiency of building envelopes.

The proposed framework aids designers to estimate the HEL in their projects at an early designing phase. At this level of the analysis, the application of this framework appears as a distinctive way to collect the minimum and maximum values of the FHL of construction components, which could help to determine the components that are influencing the HEL in buildings. In addition, it helps to set and to assess the best building conditions that could deliver proper values of ACH and, consequently, minimizing the estimated values of VHL in buildings. A typical one floor single-family house in three various climate classifications is applied to validate the proposed framework. The chosen climates are tropical climates, dry climates, and moist subtropical mid-latitude climates; these three climates cover large regions of Europe, Africa, Asia, Australia, America, and South America. The application of the proposed framework aid designers to determine the FHL of construction components that are influencing the HEL in buildings. As a result, it permits assessing building conditions that could deliver proper values of ACH that in turn impact the estimation of VHL in buildings. The results indicate that the major impacts on the HEL are due to the FHL of construction components. Higher U-values would maximize the values of FHL, hence the selection of construction components within low U-values could increase energy efficiency in buildings; this work proves that the percentage of energy efficiency improvement of FHL is similar and directly proportional to the percentage of reduction in U-values of building components. Additionally, the results display that controlling the ACH in buildings, using the lowest values, could reduce significantly the VHL in buildings. Finally, this work illustrates that HEL in tropical climates and dry climates reaches a proportion of 16% and 8%, respectively, compared to HEL in moist subtropical mid-latitude climates.

The limitations of this work can be stated as follows. The selection of construction components that are assembling the building envelope of buildings varies depending on climate classification. Hence, this work applied standard materials in general rather than the specific materials adopted in each climate zone. Besides, the case study of this work assumed a range of values for the ACH. This comes back to examine the case study in three different climate classifications, which are covering more than 60% of the global surface area. Future works by the authors will focus on addressing these limitations.

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APPENDIX 9

Framework for a Systematic Parametric Analysis to Maximize Energy Output of PV Modules Using an Experimental Design

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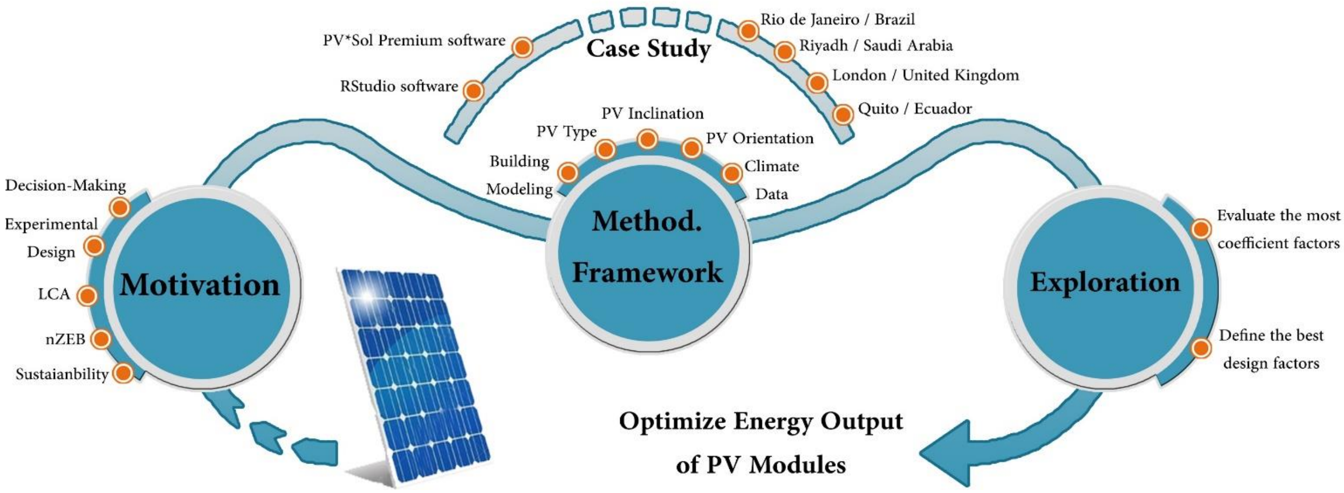
Graphical Abstract:



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Article

Framework for a Systematic Parametric Analysis to Maximize Energy Output of PV Modules Using an Experimental Design

Mohammad K. Najjar [1,*], Eduardo Linhares Qualharini [1], Ahmed W. A. Hammad [2], Dieter Boer [3] and Assed Haddad [1,*]

[1] Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-901, Brasil; linhares@poli.ufrj.br

[2] Faculty of Built Environment, University of New South Wales, Sydney, NSW 2052, Australia; a.hammad@unsw.edu.au

[3] Department of Mechanical Engineering, Universitat Rovira i Virgili, 43003 Tarragona, Spain; dieter.boer@urv.cat

* Correspondence: mnajjar@poli.ufrj.br (M.K.N.); assed@poli.ufrj.br (A.H.)

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Abstract: Use of photovoltaic modules in buildings has been reported to be an effective tool in managing energy consumption. The novelty in the research herein is in a framework that integrates different performance parameters through the use of an experimental design to expect all variables via linear regression analysis. An emphasis is placed on making the method readily available to practitioners and experts in the area of renewable energy, using standard procedure and easily accessible software. This work empowers the decision-making process and sustainability through a parametric analysis of the installation of photovoltaic modules to increase their energy output towards nearly zero energy buildings. A case study of a group of photovoltaic modules is examined in four cities with different locations and climate data to validate the proposed framework. Results demonstrate that the installation of photovoltaic modules on the mounted roof is better than elevations, and the vertical installation of modules is the worst possible inclination to maximize the yielded energy. The impact of inclination is higher than orientation in influencing the energy productivity of photovoltaic modules. This work specifies integrating such modules mounted on roofs and elevations towards the equator line, by a proportion of inclination/latitude equal to 85 ± 3%, to maximize the energy output.

Keywords: photovoltaic modules; building integrated photovoltaic system; energy consumption; experimental design; nearly zero energy buildings

1. Introduction

The construction sector is renowned for its high consumption of energy and natural resources [1]. It is reported to be responsible for almost 30% of annual greenhouse gas (GHG) emissions and 34×10^6 Gigawatt-hours of total energy consumption worldwide, making it one of the top contributors to pollution [2], and causing several environmental impacts, such as global warming [3]. Soaring rates of urbanization will also exacerbate the issue even further, leading to an increase in energy consumption and GHG emissions [4]. Worldwide access to electricity has increased from around 73% in 1990 to 85% in 2014 [5]. The identification of sustainable energy solutions is a crucial need to enhance the effectiveness of energy consumption within the built environment [6], hence, it is highly important to understand the concept and the structure of future energy utilization [7].

The global desire for renewable energy systems witnessed an unprecedented upsurge in its uptake since 2014 [8], due to the augmentation of the global debate on energy costs and consumption rates [9]. Renewable energy systems provide a range of options for meeting the mounting demand for energy, particularly in a sustainable context that considers social and environmental aspects when planning the consumption of energy [10]. Specifically, solar energy is considered to be one of the most important renewable energy sources [11]; it can be converted into a useful form of energy using photovoltaic (PV) modules [12]. The focus of this study is hence on incorporating the installation of PV modules in a complete Building Integrated Photovoltaic (BIPV) system to increase energy efficiency in buildings and aid their transformation towards nearly zero energy buildings (nZEBs).

Although several aspects regarding the performance and design of PV modules have been examined in the literature, a systematic procedure for the assessment of critical performance and design parameters for installation of PV modules that can be easily accessed by practitioners is required, particularly, the orientation and inclination parameters [13]. In an attempt to address this, factorial design analysis, along with a visualization aid, for designing solar energy systems for buildings are adopted in order to assess and choose the best installation of PV modules at various inclinations and orientations on roofs and elevations of buildings. Enhancing the energy output (EO) of PV modules is conducted through a simulation and parametric analysis approach. Initially, an experimental design, which involves a systematic collection of data, is utilized to focus on the planning of the installation process itself rather than defining the coefficients of the design factors, based on a linear regression analysis. Such method helps to model all expected technical variables that maximize the performance of PV modules [14].

The novelty of this paper is to establish a framework that captures different performance parameters and design factors that determine the design energy efficiency of PV modules in a complete BIPV system. A reliance is on the use of standard procedure and software that make the work readily available to practitioners and experts in the area of renewable energy. PV*Sol software validates the extracted results and facilitates the selection process of the desired PV module by relying on the MeteoSyn climate database that contains thousands of global climate datasets and the use of an online component database that involves thousands of modules and inverters [15]. A case study of a group of PV modules is examined in different cities with varying irradiations, latitudes, and climate data to validate the developed methodological framework; the energy efficiency of PV modules in a complete BIPV system is examined, taking into consideration the energy produced, the installed capacity, and the potential of optimizing the EO of PV modules.

2. Background

In this section, a description of the components of a complete BIPV system is given. Moreover, a related literature review to the recent publications in the same field of the study is presented.

2.1. Components of a BIPV System

The built environment allows several forms of PV modules to be integrated into different parts of the structure of buildings, such as roofs, windows and semitransparent facades, facades, skylights, and shading systems [16]. The successful installation of BIPV systems necessitates the cooperation of both the functional and aesthetic issues within the financial constraints [17]. BIPV systems provide weather and sun protection, thermal insulation, noise protection, electromagnetic shielding, aesthetic quality, visual cover, and safety for construction projects. This comes back to the fact that the conventional building materials that are covering the final roof or façades of the building are being replaced by PV modules [18].

PV modules are classified into three generations based on the basic material used and the level of commercial maturity. The first-generation systems are the wafer-based crystalline silicon (c-Si), the most used material in the PV industry [19,20]. In 2013, c-Si wafers presented 91% of the total share in the global market of PV systems [21], and within the European Union, they accounted for around 85% of all new PV systems installed [22]. C-Si modules are basically manufactured using two common materials: Poly-crystalline (p-Si) and mono-crystalline (mono-Si); mono-Si occupies less space and has the ability to produce higher energy output compared to p-Si; mono-Si is less affected by high temperatures compared to p-Si, which has a shorter lifespan. The choice between these two types depends mainly on the climate data of the installed region; the efficiency rate of mono-Si is higher than p-Si—20% and 15%, respectively—however, p-Si is cheaper than mono-Si. [23]. The second-generation systems use thin-film technology, such as cadmium telluride solar cell (CdTe) [24]. This generation is the most efficient among all other generations if they face the sun at a perfect angle [25]. The third-generation systems use other technologies such as thin-film solar cells (TFSC) [25]. The advantage of this generation is that the modules are less affected by high temperatures and allow opportunities for better alternative installation, however, they occupy more space and have a shorter lifespan compared to the first generation [24].

The basic components of a BIPV system are presented in Figure 1, including the PV modules, a charge controller, a power storage system, a power conversion equipment, a backup power supply, and appropriate supports, such as mounting hardware, wiring, and safety disconnects [19,20], in addition to a fan and air duct, which are optional components that help reduce the heating load in winter by drawing the heated air into the space [18]. The characteristic parameters of PV modules are measured under standard test conditions that require defining the solar irradiance, module temperature, and wind speed [26]. The PV modules can be first, second, or third generation [19], while a power storage system can refer to the utility grid itself or the number of batteries [27]. The charge controller can provide and reduce the pure flow of power energy to the utility grid [28]. The charge controller regulates the power into and out of the power storage. The power conversion equipment, such as an inverter, converts the output direct current (D.C) energy of PV modules to output alternating current (A.C) energy that is used for household appliances. The inverter is a piece of very important equipment that operates the power energy in the utility grid and delivers the maximum power to the electric power grid [29]. The backup power supply is optional equipment, such as a diesel generator, used for providing the necessary power when the input power source fails [20]. However, ensuring the safety of the instalment of PV modules and the reliability of the utility grid are two major technical requirements that need to be satisfied when installing a complete BIPV system [18].

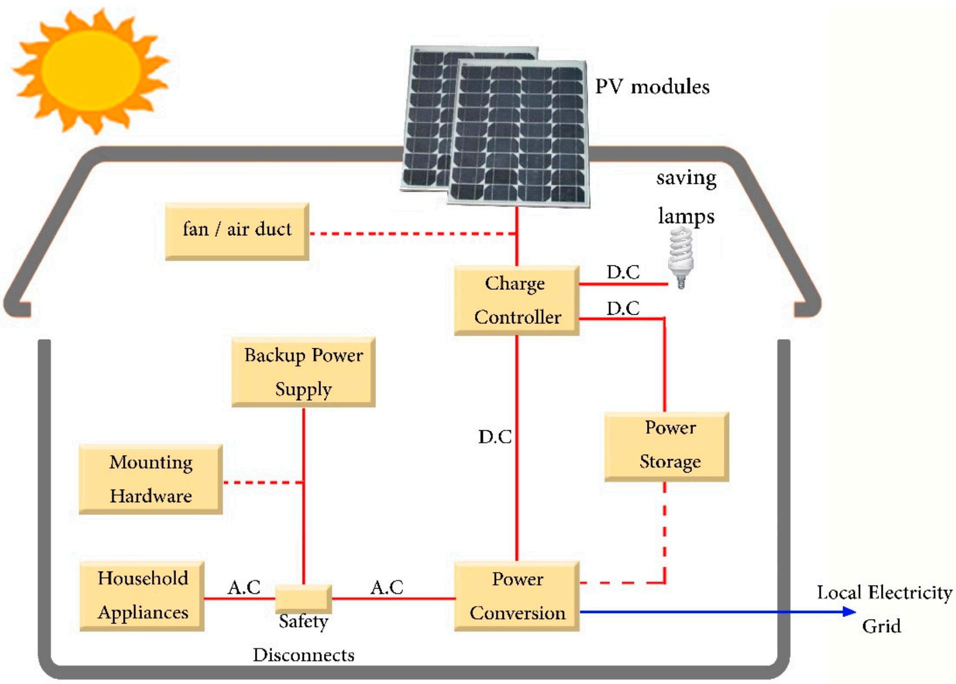

Figure 1. The basic components of a complete Building Integrated Photovoltaic system.

The grid-interconnection of PV modules in a BIPV system can be designed in three main circumstances [28]: (i) Grid-connected without storage; (ii) grid-connected with storage; and (iii) off-grid with storage. The EO of PV modules in any of these circumstances can be influenced by several factors, such as the characteristics of the components of the PV modules, their geographical location, and the installation variables, as well as the local solar radiation [29]. The successful installation of such modules facilitates the achievement of ambitious energy targets [30], where the generated energy can be stored in the power storage as a D.C energy or can be converted by the power conversion to A.C energy. At this level, the A.C energy is ready to be consumed directly or fed into the local energy grid if it accepts such an interconnection agreement [31], as illustrated in the blue line in Figure 1, where the excess renewable energy generated can be transferred to the local electricity grid; it is rated by a policy mechanism called "feed-in tariffs" [32]. This mechanism is considered the most effective policy that stimulates the rapid development of renewable energy sources and has been implemented in several regions worldwide [33].

2.2. Related Literature

Renewable energy systems appear as sustainable and alternative energy forms; they are extensively utilized in nearly Zero Energy Buildings (nZEBs) to reduce the consumption of energy and, consequently, reduce the environmental impacts associated with climate change [34]. Several publications in the literature have been dedicated to evaluating the performance of PV modules from different aspects. This section reviews the recent academic papers of PV performance evaluation based on three axes of literature: (i) The application of PV modules towards sustainability; (ii) the factors that are influencing the performance of PV modules; and (iii) the recent trends to optimize the application of PV modules.

First, several publications observed the use of PV modules towards more sustainable built environment, such as D'Adamo [35], who analysed the profitability of residential PV systems as the main resource towards the clean global economy of the future. This work stimulated a new diffusion of PV plants, considering the output energy over 20 years. The author found that PV modules are important alternatives to improve environmental impacts and reduce the dependence on fossil fuels. Similarly, Ferreira et al. [36] conducted an economic overview of the application and production of PV modules in Brazil and observed that the energy generation of PV modules is a convenient alternative to the diversification of the energy matrix in the country. Khan and Arsalan [37] reviewed the technologies of solar PV modules towards sustainable electricity generation, taking into consideration their types, efficiency, cost factors, and mechanism. The authors indicated that the mature technology of PV modules is well-suited for all scale applications, and is more commercially developed in addition to the fact that PV modules are a major source of clean energy as they have the potential to supply the global increasing requirements of electricity. In addition to this, Stropnik and Stritih [38] studied methods for increasing the electrical efficiency and power output of PV panels using phase change materials (PCM). The authors focused on the experimental setup and simulation heat extraction from PV panels to evaluate the PV-PCM integration in a Canadian city and found that the annual energy efficiency could increase by more than 7% in the city. Traverso et al. [39] evaluated the sustainability assessment performance of the assembly production of p-Si PV modules in order to compare their life cycle sustainability assessment (LCSA). The authors indicated that LCSA methodology empowers the decision-making process of the different stakeholders towards the more sustainable performance of PV modules.

Second, some authors highlighted several factors that are influencing the application and, consequently, the EO of PV modules. For instance, the geographical location of the application site, where the longer sunshine hours of high-latitude regions result in better EO of PV modules than shorter sunshine hours of low-latitude regions [40]. You et al. [3] compared the environmental efficiency of four PV plants in China, including a mountain plant, desert plant, rooftop plant, and complementary plant. Taking into consideration several input variables (i.e., insolation, covering area, and annual sunshine duration) and output variables (i.e., annual electricity generation, the installed capacity, coal saving, and CO_2 emission reduction), the authors found that there is a difference in the performance of PV plants. However, serious aerosol pollution and the high urbanization rate are the main agents of the inefficiencies of the output energy of these plants. Carstens and Cunha [41] identified the challenges and opportunities of PV use in Brazil, considering two main approaches: The multilevel perspective and the functions of the innovation system. The authors found that the vast territory and the high solar irradiance play a basic role in improving the EO of PV modules, while the lack of new technology development, the shortage of skilled professionals, and insufficient knowledge transfer are the main challenges of implementing PV modules.

Third, some authors proposed a new model for the optimum tilt angle of a soiled PV module. They found that the cell temperature of a PV panel and the tilt angle are key factors to evaluate the power output of PV modules [42]. Another study investigated the PV panels' optimum tilt angles for various cities in the Kingdom of Saudi Arabia. The authors used MATLAB software to optimize the tilt angle by maximizing solar radiation, considering the experimental work to validate the theoretical requirement for negative tilt angles during summer. The authors concluded that adjusting tilt angles six times per year harvests 99.5% of the solar radiation that could be achieved with daily PV panel adjustment [43]. Yu et al. [13] established a database to optimize the PV applications in Japan. The authors focused on the orientations and inclinations of installing PV modules as two major factors to achieve the aim of their study, while Han and Kim [44] developed an optimization-based framework to design renewable energy systems for the residential sector in Korea.

Furthermore, Gunerhan and Hepbasli [45], and Benghanem [46] in their studies indicated that the yearly optimum inclination of PV modules is nearly equal to the latitude of the installation site. Landau [47] examined the optimum inclination of PV modules in various cities around the world as shown in Table 1. The author suggested several formulae to find the best inclination at which the panel should be tilted. This work used a proportion of the best inclination compared to the latitude. At this level of the analysis, the results presented in Table 1 are collected from the proportion of dividing the optimum inclination of PV modules, suggested by Landau, for each city by the representative latitude, individually, ((inclination/latitude) × 100).

Table 1. The optimum inclination of photovoltaic modules in various cities [47], and the proportion of the best inclination compared to the latitude (adapted by the authors).

City	Optimum PV Module Inclination	Proportion of the Best Inclination Compared to the Latitude	City	Optimum PV Module Inclination	Proportion of the Best Inclination Compared to the Latitude
Winnipeg	41.1	82%	Houston	25.9	86%
Prague	41.1	82%	Cairo	25.9	86%
Minneapolis	37.3	83%	Dakar	13.1	87%
Milano	37.3	83%	Caracas	8.7	87%
Madrid	33.5	84%	Mérida	17.4	87%
Denver	33.5	84%	Bogotá	4.4	88%
Albuquerque	29.7	85%	Key West	22.1	88%
Tokyo	29.7	85%	Taipei	22.1	88%

Accordingly, it is apparent that an emphasis is placed in the literature on the optimization of certain design factors associated with the installation of PV modules, such as the orientation and inclination. Nevertheless, there is little focus on the development of a methodological framework that could integrate such installation in buildings using the experimental design on the one hand, and optimizing the EO of PV modules in a complete BIPV system by indicating the best geographic orientation and inclination, on the other hand. In the next section, the proposed framework to cover this apparent gap in the literature is presented.

Furthermore, several studies in the literature have evaluated the energy performance of renewable energy systems based on the use of yearly data. Researchers that implemented this common practice include Bellos and Tzivanidis [48], Hasan et al. [49], Pillai et al. [50], Kim and Lim [51], and Han et al. [52].

Additionally, Autodesk reviewed the energy analysis and summarized the amount of electricity that a building site could produce using solar panels and wind turbines based on the use of yearly data [53,54]. Thus, the proposed framework in this work will be demonstrated on yearly data, but the same concept can still be extended for other temporal data as well.

3. Materials and Methods

A novel framework is proposed and highlighted in Figure 2, where the link between performance parameters and design factors is outlined. The installation of PV modules in a BIPV system requires the identification of various performance parameters and their associated design factors. Performance parameters refer to the characteristics that are defining and classifying a particular system in the model, while design factors are features and variables that define the performance parameters, and these are displayed in Figure 2, including building modelling, climate data, and PV module installation. Evaluating the parameters of PV module installation that are influencing their EO is the concern of this study. However, the next subsections highlight the main components of the proposed framework.

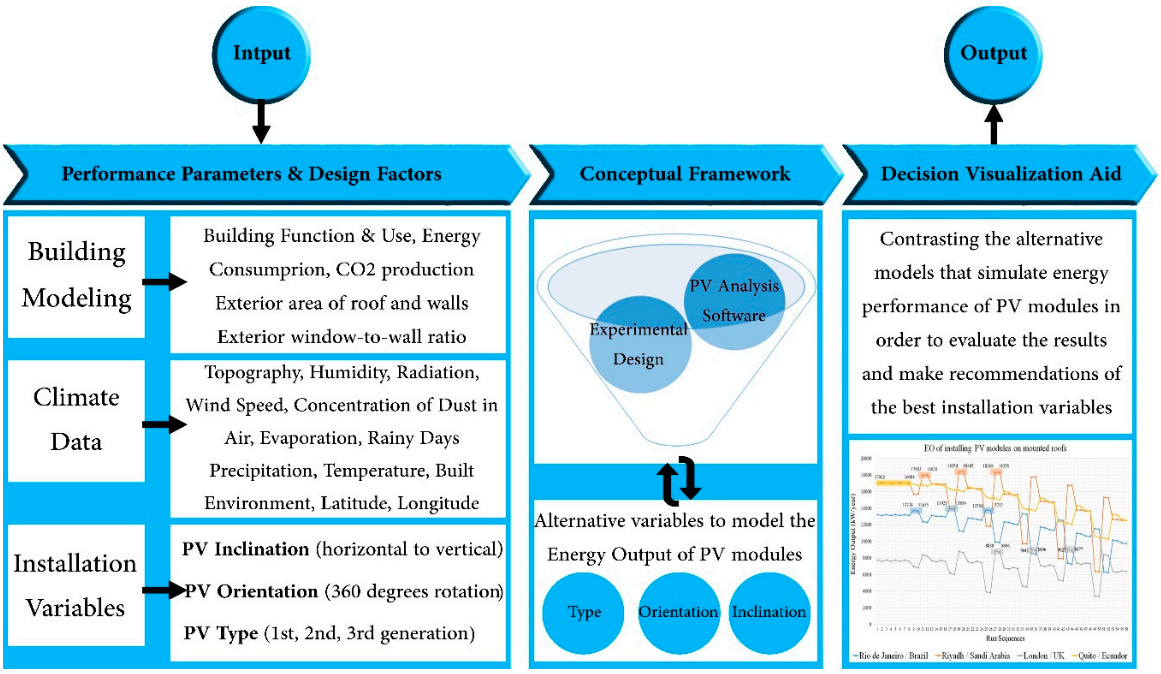

Figure 2. A methodological framework for installing PV modules in a BIPV system.

3.1. Performance Parameters and Design Factors

The initial step in the proposed approach is the integration of a number of performance parameters that impact the operation phase EO of PV modules. In these terms, the building modelling parameter means recognizing the type of building design (the design of the final roof and elevations) [32]. The design factors relevant to this parameter include: (i) The identification of the function and use of the building; (ii) type of energy use and consumption; (iii) CO_2 production; (iv) exterior area of roof and walls; and (v) the exterior window-to-wall ratio associated with the building [55–57]. Examples of the associated design features of the climate data parameter include the topography, humidity level, solar radiation, wind speed, the concentration of dust in the air, evaporation, rainy days, precipitation, temperature, built environment, latitude, and longitude of the exact location where the PV modules are to be installed [58–60]. The third performance parameter of the proposed framework of this study is PV module installation, which means defining the model of the installed panels, quantity, and installation variables (i.e., PV type, PV inclination, and PV orientation) [29].

The geographic orientation and inclination are two vital installation variables playing a fundamental role in the installation of PV modules in a successful BIPV system [61]. Determining the PV orientation involves analysing the wind, rain, and site conditions in order to define the best geographic orientation for the PV modules [62,63]. The PV inclination refers to the analysis of the sun movement and latitude in order to identify the preferable inclination of the PV modules [64,65]. It is reported that the performance of PV modules is affected by the orientation and inclination, which are the main factors influencing the amount of solar energy incident upon the surface of the PV module [66]. Thus, this work will focus on these two installation variables. In addition, the PV type is another parameter to be considered to validate the impact on the energy yielded from the installed module [20]. The proposed methodological framework of this analysis can accommodate a large number of PV inclinations (i.e., from horizontal to vertical inclination) and PV orientations (i.e., 360 degrees rotation) as well as the available PV types on the local market. However, some specific PV types, PV inclination, and PV orientation are chosen in the case study, shown in Section 5, to validate the proposed framework.

3.2. Evaluation Method

This step starts by evaluating the collected database of energy consumption and output emissions using indicators of sustainability, which can lead to better decisions and more actions that are effective. This is achieved by simplifying, clarifying, and making aggregated information available to policy makers. Hence, sustainability indicators are used to calibrate the progress toward sustainable development goals by communicating the thoughts and values of the collected results [67]. The methodology of this study makes use of an experimental design procedure to indicate the best geographic orientation and inclination of PV modules in buildings. The experimental design work, which was applied via linear regression, is based on a parametric analysis that examines different values for several design factors related to the PV type, PV orientation, and PV inclination. Such a process provides maximum information at minimum experimental cost [68]. This work examines the performance of PV modules at various types, inclinations, and orientations to support policy makers in planning the features required to be targeted when installing such energy sources. Hence, the expected variables generated via the experimental design were accommodated individually and evaluated using PV*Sol software to integrate the installation process of PV modules and estimate the EO of PV modules installed in a complete BIPV system [15]. This software allows the simulation of PV systems and facilitates the process of design and analysis of grid connected PV systems [69]. In the literature, PV*Sol software has been applied as a PV analysis software to validate such results and design and model the performance of PV systems and low-energy solar buildings [70,71].

3.3. Decision Visualization Aid

The last step of the methodological framework of this study is to evaluate the collected results by contrasting the alternative models that simulate the energy performance of PV modules to define the best installation variables that could improve their energy efficiency. This process starts by clarifying and classifying sources of data, comparing results, and suggesting recommendations and new design options. Changes to the variables in experimental design were evaluated using software, such as Minitab. This software was used for determining all the expected variables of the experimental design work and to define the coefficients of the design factors through a linear regression analysis [72].

4. Linking Framework Components

In terms of the required analysis, the first step is to identify the size of the case study, which means identifying the amount, weight, and quality of the specific product investigated (i.e., building), as shown in Figure 3.

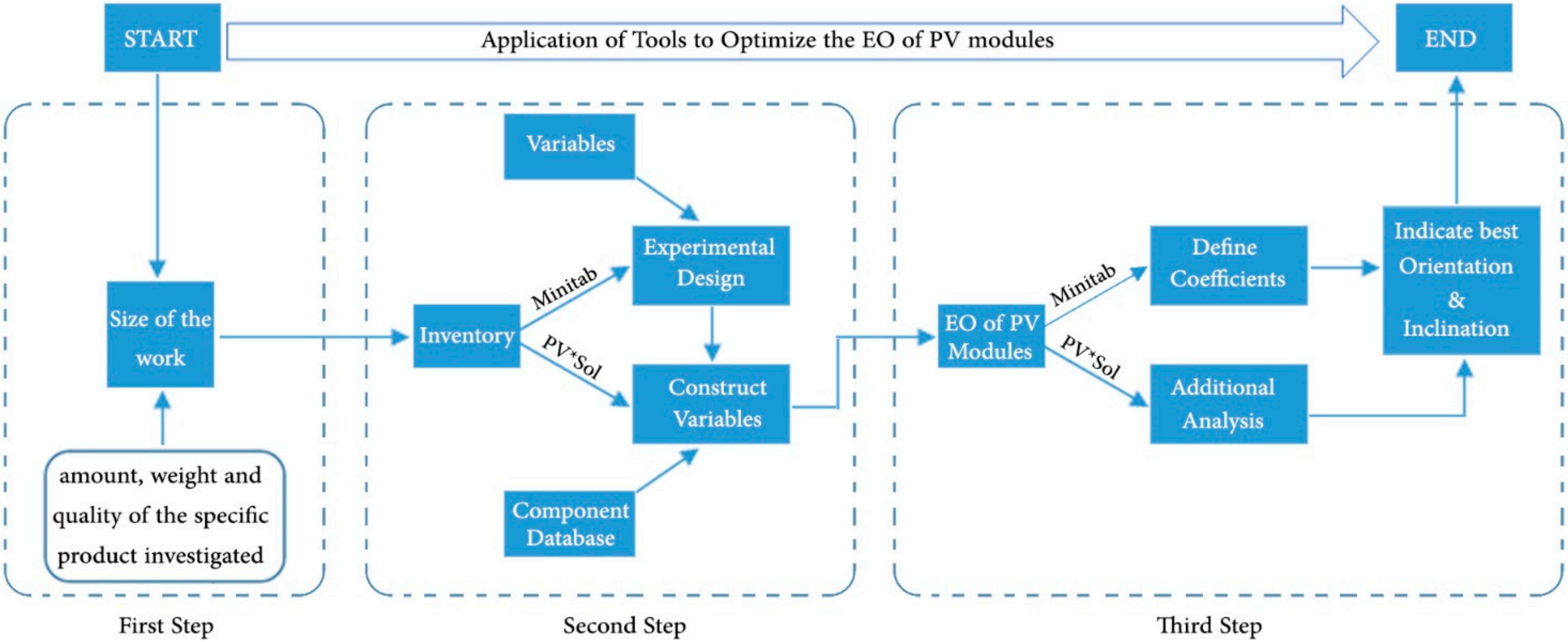

Figure 3. Linking framework components.

The second step is to build the inventory of database. The proposed framework applies an experimental design to estimate all the expected variables using a parametric analysis based on linear regression. At this level of the analysis, the interaction effects are found by the use of statistical factorial design technique [73]. This involves running a full complement of all possible factor combinations and estimating all the interaction effects, through knowing the number of factors (κ) and the number of levels for each factor. A factorial design model is presented in Equation (1) that allows the estimation of all coefficients ($\beta_0, \ldots, \beta_\kappa$) [14,74]:

$$\Upsilon = \beta_0 + \beta_1.\chi_1 + \beta_2.\chi_2 + \ldots + \beta_\kappa.\chi_\kappa + \epsilon. \tag{1}$$

Though Equation (1) calculates all the actual responses and interactions of the expected variables [74], in the experimental design, errors are inevitable [75]. Minitab is used to estimate all the expected variables and reduce regression errors and uncertainty [72]. The variables of the experiment are then examined using PV analysis software. This work utilized PV*Sol software to construct the determined variables, individually, and estimate the EO of PV modules [76]. PV*Sol software relies on the MeteoSyn climate database, which contains thousands of global climate datasets. In addition, an online component database that contains thousands of modules and inverters used [15] in order to sort out files and, accordingly, facilitate the selection process of the desired module or inverter type [77]. Collecting a reliable dataset requires assessing the following parameters:

i. System, climate data, and grid: For system, this involves recognizing the type of building design (basically the design of the final roof and elevations); for climate, this is related to obtaining the climate data associated with each region analysed, and identifying the exact location where the PV modules are to be installed, in order to determine the latitude, longitude, annual sum of global irradiation, and annual average temperature; and for grid, this involves determining the usage voltages and phase system of electricity.
ii. PV modules: This refers to defining the model of the examined PV module, the number of PV modules, installation type, inclination, orientation, shading, and degradation of the module.
iii. Inverters: This refers to selecting the configurations, determining the values of the configuration module, and the number of inverters.
iv. Cables: This is associated with calculating the loss of energy in cables, based on their length and thickness, through consideration of the distances between the various components of the BIPV system.

The third step is to evaluate the collected database in order to calculate the EO of PV modules. At this level of the analysis, the collected results of the PV analysis software are evaluated in two phases. First, the results are transferred to the experimental design software to define the coefficients of the assigned design factors through linear regression analysis [72]. Second, analysis of additional PV modules mounted on the roof is conducted to define the specific inclinations that would maximize the EO of the PV modules. This stage requires running another analysis in the *PV*Sol* software to specify the best inclinations. Conducting such an analysis demands a parametric analysis involving gradual increments of inclinations.

5. Case Example: Installation of PV Modules in a Complete BIPV System

The applied case study aims to validate the proposed framework used to model the decisions involved in installing PV modules in a complete BIPV system. In order to showcase the versatility of the proposed framework, the proposed analysis of the installation of PV modules was conducted in four different cities with differing climate data, latitude, longitude, annual average temperatures, and global annual irradiation. The chosen cities include Rio de Janeiro in Brazil, Riyadh in Saudi Arabia, London in the United Kingdom, and Quito in Ecuador. The choice of these cities was made to ensure comprehensive consideration of various climatic conditions. Rio de Janeiro is located down the equator to the west side of the Greenwich, at a latitude of 22° and longitude of 43°. Riyadh is located up the equator to the east side of the Greenwich, at a latitude of 24° and longitude of 46°. London is located on the north side of the equator on the Greenwich, while Quito is located to the west side of the Greenwich directly on the equator.

It is important to note that Rio de Janeiro and Riyadh are almost located on a symmetric location with respect to the Greenwich and equator. Rio de Janeiro has a tropical climate, while the climate of Riyadh is characterized as dry [78,79]. London and Quito have moist subtropical climates [78–80]. In particular, the choice of including Riyadh and London in the study is to analyse the impact of differing climate conditions between the cities, where other performance parameters are near identical, on the total sum of EO of PV modules.

5.1. Size of the Case Study

The case study of this work examines the installation of 100 PV modules, considering two types of 100 W PV modules of the first generation systems, namely poly-crystalline (p-Si) and mono-crystalline (mono-Si), that are commonly adopted worldwide. The parametric analysis considers a range of different inclinations of PV modules mounted on roofs and elevations, which is subsequently incremented by 10° (0, 10, 20, 30, 40, 50, and 60°) based on the four cardinal directions (i.e., North, South, East, and West). An option of integrating PV modules on the exterior walls of elevations at a vertical inclination (90°) was also examined.

5.2. Inventory of Database

The inventory of the database focuses on the operation phase of the case study and was constructed through three main steps based on the guidelines provided in Section 4.

First, the assigned design factors that were determined in the case study, Table 2, were integrated into a linear statistical regression using Minitab software to cover all the expected variables of the experimental design, using three factors within different levels. This is known as a mixed-level design or general full factorial design [14]. The first factor is the PV type (PV_T), consisting of two levels which consider the most known types of PV modules of the first generation system (p-Si and mono-Si). The second factor is the PV orientation (PV_O), which consists of four levels, associated with the four cardinal directions. The third factor is the PV inclination (PV_I), which is considered via two scenarios, namely scenario A and scenario B. Scenario A is associated with seven levels while scenario B is comprised of eight levels; both scenarios consider the various inclinations between the horizontal and vertical positioning of the installation of PV modules within an increment of 10°, as displayed in Table 2. However, this step considers the same distances between the PV modules, disregarding the shading impacts.

The model for such an experiment analysis is presented in Equation (2). The number of sequences for each experiment based on a single iteration will be the result of multiplying the number of levels associated with each factorial design considered within a single analysis together [81]. As an example, the number of sequences that are required to cover all the expected variables on roof mounting installations is 56 (2 × 4 × 7) whereas at elevation, it is 64 (2 × 4 × 8). Applying Equation (2) in the case study example of this work results in the following:

$$EO = \beta_0 + \beta_1.PV_T + \beta_2.PV_O + \beta_3.PV_I + \beta_{12}.PV_T \times PV_O + \beta_{13}.PV_T \times PV_I + \beta_{23}.PV_O \times PV_I + \beta_{123}.PV_T \times PV_O \times PV_I + \epsilon. \quad (2)$$

An interaction between the assigned factors that are defining the functional unit is achieved to simulate all expected variables. The effects of such interaction are found only by the use of a statistical factorial design technique, as described in the work of Fegade et al. [73]. The EO response based on the main effects of PV_T, PV_O, and PV_I is captured, in terms of ($PV_T \times PV_O$), ($PV_T \times PV_I$), ($PV_O \times PV_I$), and ($PV_T \times PV_O \times PV_I$); these terms were included to consider all possible interactions between the main variables. The constant, β_0, is the response of EO when all main effects are equal to 0, while β_1, β_2,

β_3, β_{12}, β_{13}, β_{23}, and β_{123} denote the unknown parameters to be estimated. The variable, ϵ, refers to the experimental error.

Second, PV*Sol software was applied to estimate the EO of PV modules based on the running sequences that were previously built in the regression model. At this step, the database for each sequence was constructed individually. This means that a total of 120 (56 (for roof − mounted installements) + 64(for elevation installment)) separate analyses were performed in this software.

Third, the collected results in the PV*Sol software were integrated into Minitab software in order to evaluate the collected data and estimate the coefficients of the various effects of design factors, based on the EO of PV modules in the chosen cities. Furthermore, an additional and more specific examination of the EO of PV modules mounted on roofs was conducted based on the best geographic orientation of PV modules and the range of optimum inclinations in the chosen cities. This additional examination applied the same PV types as mentioned in Table 2, while it only considered the PV orientations that would optimize the EO of PV modules for each city, individually, taking into consideration a 1° increment to the inclination angle in order to quantify the best choice for positioning the PV modules.

Table 2. The assigned factors defining the functional unit.

PV_T	PV_O	PV_{IA}	PV_{IB}
p-Si 100 W (1)	North (1)	0° (1)	0° (1)
mono-Si 100 W (2)	South (2)	10° (2)	10° (2)
	East (3)	20° (3)	20° (3)
	West (4)	30° (4)	30° (4)
		40° (5)	40° (5)
		50° (6)	50° (6)
		60° (7)	60° (7)
			90° (8)

5.3. *Assessment of Design Factors*

The experimental design was applied at this level of the analysis to clarify the various effects of the assigned design factors. Tables 3 and 4 present the estimated values of the EO of PV modules in a complete BIPV system mounted on roofs and elevations, respectively.

The results of the regression equation, regression errors, and coefficients are fully presented in the supplementary file. Moreover, the supplementary file illustrates the main effects plot of installing PV modules on mounted roofs (Figures S1–S4) and elevations (Figures S5–S8). The presented information in this file shows that there is no error (error = 0) in building up the analysis of variance in the four examined cities. The estimated coefficients of the assigned factorial designs, which are shown in Figure 4, were analysed in Minitab software based on the collected EO results in the four cities. Figure 4 indicates the factors that have the most influence on the energy efficiency of the PV modules, where PV_{IA} and PV_{IB} refer to the factorial impact of the PV inclination based on scenarios A and B, respectively; PV_O refers to the factorial impact of the PV orientation; PV_T refers to the factorial impact of the PV type; PV_O:PV_{IA} and PV_O:PV_{IB} refer to the factorial impact of the interaction between the PV orientation and PV inclination based on scenarios A and B, respectively; PV_T:PV_{IA} and PV_T:PV_{IB} refer to the factorial impact of the interaction between the PV type and PV inclination based on scenarios A and B, respectively; PV_T:PV_O refers to the factorial impact of the interaction between the PV type and PV orientation; and PV_T:PV_T:PV_{IA} and PV_T:PV_T:PV_{IB} refer to the factorial impact of the interaction between the PV type, PV orientation, and PV inclination based on scenarios A and B, respectively. As can be noticed from Figure 4, PV_{IA} and PV_{IB} have the highest influence regarding the generation of EO for roof mounted instalment and elevations, respectively, while PV_O is the second factor that could affect the EO in such models. The third factor that could affect the EO of PV modules is the interaction between the orientation and inclination, while the lowest one is the interaction between the type and the inclination. Yet, the type of PV modules comes as the fourth factor that could influence the EO of PV modules.

Table 3. Energy output of PV modules mounted on roofs based on the assigned design factors.

Run Sequence	Factorial Designs			EO (kWh/Year)			
	PV_T	PV_O	PV_{IA}	Rio de Janeiro/Brazil	Riyadh/Saudi Arabia	London/United Kingdom	Quito/Ecuador
1	1	1	1	13,221	17,060	7758	17,062
2	2	1	1	13,129	17,102	7601	16,904
3	1	2	1	13,221	17,060	7758	17,062
4	2	2	1	13,129	17,102	7601	16,904
5	1	3	1	13,221	17,060	7758	17,062
6	2	3	1	13,129	17,102	7601	16,904
7	1	4	1	13,221	17,060	7758	17,062
8	2	4	1	13,129	17,102	7601	16,904
9	1	1	2	13,734	15,699	6973	16,891
10	2	1	2	13,655	15,702	6825	16,733
11	1	2	2	12,386	17,953	8381	16,817
12	2	2	2	12,280	18,028	8223	16,640
13	1	3	2	13,126	16,881	7690	16,963
14	2	3	2	13,036	16,919	7535	16,802
15	1	4	2	13,034	16,847	7716	16,806
16	2	4	2	12,944	16,894	7564	16,651
17	1	1	3	13,921	13,931	6163	16,324
18	2	1	3	13,850	13,901	6027	16,151
19	1	2	3	11,282	18,354	8801	16,180
20	2	2	3	11,164	18,447	8647	15,983
21	1	3	3	12,824	16,400	7551	16,585
22	2	3	3	12,737	16,435	7403	16,424
23	1	4	3	12,644	16,329	7594	16,299
24	2	4	3	12,556	16,381	7449	16,147
25	1	1	4	13,784	11,841	3896	15,371
26	2	1	4	13,712	11,794	3822	15,188
27	1	2	4	9949	18,268	8838	15,180
28	2	2	4	9830	18,358	8696	14,979
29	1	3	4	12,357	15,696	6781	16,030
30	2	3	4	12,273	15,724	6658	15,862
31	1	4	4	12,091	15,605	6846	15,562
32	2	4	4	12,005	15,656	6730	15,421
33	1	1	5	13,339	9731	4592	14,067
34	2	1	5	13,256	9681	4492	13,867
35	1	2	5	8544	17,730	9041	13,846
36	2	2	5	8433	17,795	8896	13,646
37	1	3	5	11,734	14,821	7107	15,252
38	2	3	5	11,650	14,835	6974	15,098
39	1	4	5	11,411	14,691	7165	14,715
40	2	4	5	11,327	14,734	7040	14,581
41	1	1	6	12,587	7952	5351	12,454
42	2	1	6	12,489	7895	5231	12,242
43	1	2	6	7365	16,731	9027	12,215
44	2	2	6	7260	16,754	8877	12,014
45	1	3	6	10,997	13,783	7359	14,318
46	2	3	6	10,910	13,778	7219	14,177
47	1	4	6	10,653	13,652	7411	13,740
48	2	4	6	10,567	13,680	7276	13,612
49	1	1	7	11,554	6378	3398	10,659
50	2	1	7	11,440	6324	3345	10,445
51	1	2	7	6310	15,283	8432	10,414
52	2	2	7	6213	15,258	8291	10,215
53	1	3	7	10,160	12,656	6389	13,292
54	2	3	7	10,068	12,627	6273	13,162
55	1	4	7	9799	12,535	6453	12,646
56	2	4	7	9711	12,543	6346	12,525

Table 4. Energy output of PV modules on elevations based on the assigned design factors.

Run Sequence	Factorial Designs			EO (kWh/Year)			
	PV_T	PV_O	PV_{IB}	Rio de Janeiro/Brazil	Riyadh/Saudi Arabia	London/United Kingdom	Quito/Ecuador
1	1	1	1	13,186	16,684	7744	16,709
2	2	1	1	13,099	16,717	7590	16,563
3	1	2	1	13,186	16,684	7744	16,709
4	2	2	1	13,099	16,717	7590	16,563
5	1	3	1	13,186	16,684	7744	16,709
6	2	3	1	13,099	16,717	7590	16,563
7	1	4	1	13,186	16,684	7744	16,709
8	2	4	1	13,099	16,717	7590	16,563
9	1	1	2	13,696	15,352	6961	16,538
10	2	1	2	13,623	15,348	6816	16,390
11	1	2	2	12,355	17,558	8364	16,468
12	2	2	2	12,254	17,621	8209	16,309
13	1	3	2	13,091	16,509	7675	16,616
14	2	3	2	13,006	16,538	7524	16,473
15	1	4	2	13,000	16,475	7702	16,455
16	2	4	2	12,915	16,513	7552	16,313
17	1	1	3	13,882	13,622	6154	15,979
18	2	1	3	13,817	13,589	6019	15,820
19	1	2	3	11,256	17,951	8782	15,845
20	2	2	3	11,142	18,031	8632	15,668
21	1	3	3	12,790	16,038	7537	16,250
22	2	3	3	12,709	16,064	7392	16,106
23	1	4	3	12,611	15,968	7580	15,957
24	2	4	3	12,528	16,011	7438	15,817
25	1	1	4	13,746	11,810	3893	15,329
26	2	1	4	13,679	11,768	3820	15,154
27	1	2	4	9928	18,205	8818	15,140
28	2	2	4	9813	18,303	8680	14,948
29	1	3	4	12,325	15,646	6769	15,988
30	2	3	4	12,246	15,680	6648	15,830
31	1	4	4	12,060	15,555	6833	15,518
32	2	4	4	11,979	15,612	6719	15,386
33	1	1	5	13,303	9513	4587	13,761
34	2	1	5	13,226	9463	4489	13,563
35	1	2	5	8527	17,340	9020	13,549
36	2	2	5	8419	17,394	8879	13,355
37	1	3	5	11,704	14,493	7093	14,946
38	2	3	5	11,625	14,500	6964	14,800
39	1	4	5	11,383	14,365	7152	14,400
40	2	4	5	11,302	14,401	7029	14,273
41	1	1	6	12,554	7772	5344	12,180
42	2	1	6	12,461	7717	5225	11,970
43	1	2	6	7353	16,362	9007	11,946
44	2	2	6	7250	16,377	8861	11,749
45	1	3	6	10,970	13,477	7345	14,025
46	2	3	6	10,887	13,467	7207	13,891
47	1	4	6	10,627	13,348	7397	13,445
48	2	4	6	10,545	13,372	7265	13,323
49	1	1	7	11,527	6369	3395	10,637
50	2	1	7	11,417	6316	3343	10,427
51	1	2	7	6301	15,238	8414	10,392
52	2	2	7	6206	15,219	8277	10,197
53	1	3	7	10,137	12,620	6377	13,257
54	2	3	7	10,048	12,597	6264	13,134
55	1	4	7	9777	12,499	6441	12,612
56	2	4	7	9693	12,512	6337	12,497
57	1	1	8	7411	3515	2572	6134
58	2	1	8	7297	3509	2556	5975
59	1	2	8	3972	9269	6178	5994
60	2	2	8	3933	9160	6052	5844
61	1	3	8	7241	8880	4812	9544
62	2	3	8	7145	8792	4725	9398
63	1	4	8	7030	8843	4881	9182
64	2	4	8	6944	8789	4804	9045

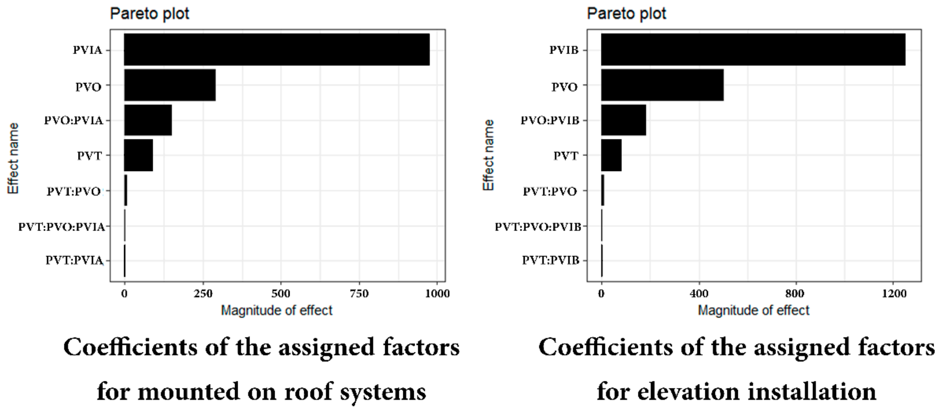

Figure 4. Coefficients of the assigned factorial designs.

5.4. Evaluation of Results

After classifying and evaluating the results collected in the previous section, the aim is to highlight the best geographic orientation and inclination of PV modules that would increase the EO of the functional unit. Tables 3 and 4 display the results of the EO of PV modules that were installed in a complete BIPV system in the four examined cities. However, Figures 5 and 6 illustrate the same results in a way to facilitate the comparison of EO of PV modules between these cities. The two figures show that the installation of PV modules mounted on the roof would generate more EO than the installation of modules on elevations. Besides, they illustrate that the sequence number (9, 10, 17, 18, 25, and 26) maximizes the EO of PV modules in Rio de Janeiro. The sequence number (11, 12, 19, 20, 27, and 28) maximizes the EO of PV modules in Riyadh. The sequence number (27, 28, 35, 36, 43, and 44) maximizes the EO of PV modules in London. The sequence number (1, 2, 3, 4, 5, 6, 7, and 8) maximizes the EO of PV modules in Quito.

The analysis of the collected results presented in Figures 5 and 6 and the main effects plot for each city presented in the supplementary file (Figures S1–S8) are shown in Table 5, which identifies the basic conclusions yielded from the collected results in the case study. Several performance parameters are required to be considered in order to install PV modules in a complete BIPV system such as latitude, climate data, and building modelling. For example, the EO of PV modules increases in higher global annual irradiation sites and vice versa [82,83]. Table 5 illustrates that the vertical installation of PV modules on elevations is the worst inclination to maximize the EO. Moreover, it shows the best and worst geographic orientation for PV modules on roof mounting systems, and the preferable elevation of the building to install these modules in each city as follows:

In Rio de Janeiro, positioning PV modules towards the North orientation within a range of inclinations between 10° and 30° for mounted roof systems and elevations would maximize the EO of PV modules, while the South geographic orientation is the worst for the same installation. The Northern façade is the best orientation for installing PV modules, while the Eastern and Western façades are the second and third preferable orientations, respectively.

In Riyadh, positioning the PV modules at the Southern orientation within a range of inclinations between 10° and 30° for mounted roof systems and elevations would maximize the EO of PV modules, while the North geographic orientation is the worst for the same installation. The Southern façade is the best orientation to install PV modules, while the Eastern and Western façades are the second and third preferable ones, respectively.

In London, positioning the PV modules at the Southern orientation within a range of inclinations between 30° and 50° for mounted roof systems and elevations would maximize the EO of PV modules, while the North geographic orientation is the worst for the same installation. The Southern façade is the best orientation for installing PV modules, while the Western and Eastern façades are the second and third preferable elevations, respectively. It is estimated that the EO of PV modules installed on any of these facades is equal.

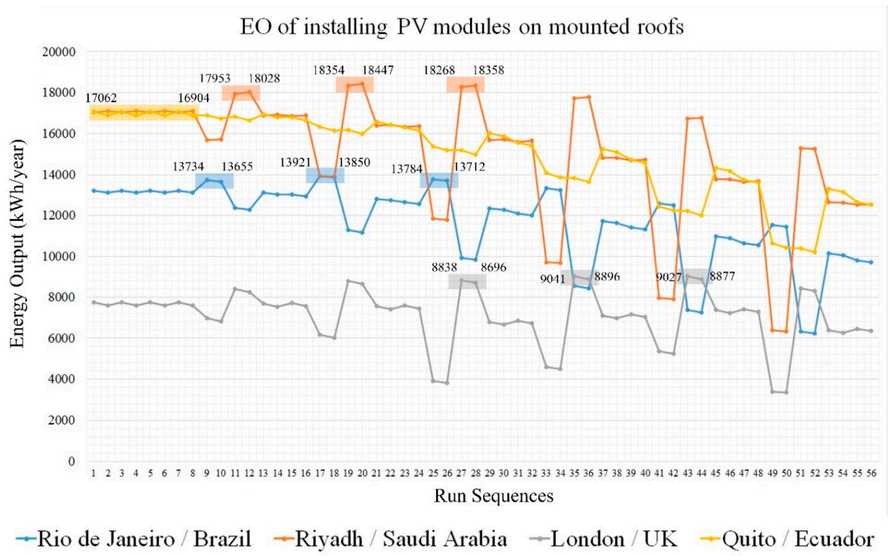

Figure 5. EO of installing PV modules mounted on roofs.

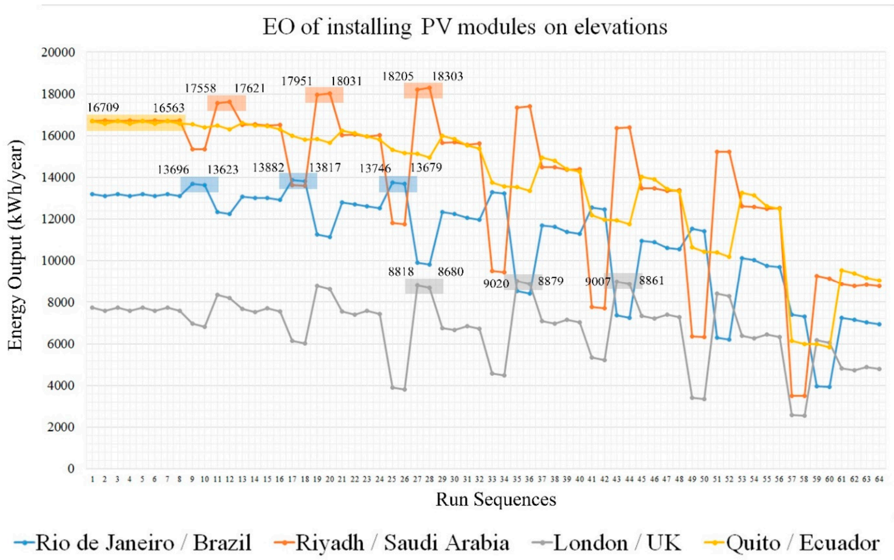

Figure 6. EO of installing PV modules on elevations.

In Quito, positioning PV modules to the East and West geographic orientation for roofs and elevations would maximize the EO of PV modules, while the North and South geographic orientation are the worst orientations at which to install PV modules. However, the horizontal positioning of PV modules installed on roofs and elevations would maximize the EO of these modules. East and West façades are preferable for the installation of PV modules rather than other elevations. It must be noted that the EO of PV modules based on various geographic orientations is significantly smaller than in the other cities analysed in the case study.

On the other hand, Figure 4 illustrates the results of the regression analysis, which evaluated the coefficients of the assigned design factors of the functional unit of this work. It shows that the impact of PV inclination is the main factor that highly affects energy generation in a BIPV system, whether it be mounted on roofs or elevations. This means that the choice of a proper inclination will increase the energy efficiency in PV modules. The impact of the PV orientation is the second main factor that affects the energy generation in a BIPV system, while the third important factor is the interaction between both the inclination and geographic orientation of PV modules. The impact of the PV type is the fourth important factor that influences energy generation in PV modules. However, the impacts of other interactions between PV types, PV orientation, and PV inclination are the lowest coefficient factors that would stimulate the EO of PV modules and can be neglected. This point was confirmed by analysing the figures presented in the supplementary file (Figures S1–S8). It must be noted that p-Si and mono-Si have a slight impact on influencing energy generation compared to the PV orientation. Yet, PV inclination is the main factor that could significantly influence energy generation.

Table 5. Summary of results of the case study.

Basic Notifications	Rio de Janeiro/Brazil	Riyadh/Saudi Arabia	London/United Kingdom	Quito/Ecuador
The best geographic orientation of PV modules mounted on roof	North	South	South	East and West
The worst geographic orientation of PV modules mounted on roof	South	North	North	North and South
Range of preferable inclination of PV module	10°–30°	10°–30°	30°–50°	0°
The worst inclination of PV modules on elevations	90°	90°	90°	90°
Best elevation to install PV modules	North	South	South	East and West
Second/Third preferable elevation to install PV modules	East/West	East/West	West/East	North/South
Worst elevation to install PV modules	South	North	North	N/A

5.5. *Additional Roof Mounted Analysis*

An additional specific examination of the EO of PV modules mounted on roofs was conducted based on the best geographic orientation of PV modules and the range of preferable inclinations in the examined cities. The need for this analysis is due to the aim of defining the specific inclinations that would maximize the EO of PV modules. The city of Quito was excluded from this analysis as Table 5 shows that the horizontal installation of PV modules is the best geographic orientation associated with the city.

The examination was conducted for the other three cities using a subsequent increment of 1° in order to quantify the best angle for positioning PV modules, as shown in Figure 7. The analysis of Rio de Janeiro (a) and Riyadh (b) included 21 frequent inclinations between 10° and 30° within the Northern and Southern geographic orientations, respectively, while the analysis of the city of London (c) included 21 frequent inclinations between 30° and 50° within a Southern geographic orientation. According to this additional analysis, Figure 7 illustrates the best inclination that would optimize the annual EO of PV modules and the proportion of (inclination/latitude), which is evaluated as previously outlined in Section 2.2, as follows:

(a) In Rio de Janeiro, the best inclination is 19°. The EO equals 13,929 kWh/year and 13,858 kWh/year for poly-crystalline and mono-crystalline, respectively, with a proportion of around 86%. The installation of PV modules within 10° or 30° will cause an annual energy waste of 195 and 145 kWh, respectively, using poly-crystalline modules, and 203 and 146 kWh, respectively, using mono-crystalline modules.

(b) In Riyadh, the best inclination is 21°. The EO equals 18,395 kWh/year and 18,488 kWh/year for poly-crystalline and mono-crystalline, respectively, with a proportion of 87%. The installation of PV modules within 10° or 30° will cause an annual energy waste of 442 and 127 kWh, respectively, using poly-crystalline modules, and 460 and 130 kWh, respectively, using mono-crystalline modules.

(c) In London, the best inclination is 43°. The EO equals 9066 kWh/year and 8920 kWh/year for poly-crystalline and mono-crystalline, respectively, with a proportion of 84%. The installation of PV modules within 30° or 50° will cause an annual energy waste of 228 and 634 kWh, respectively, using poly-crystalline modules, and 224 and 629 kWh, respectively, using mono-crystalline modules.

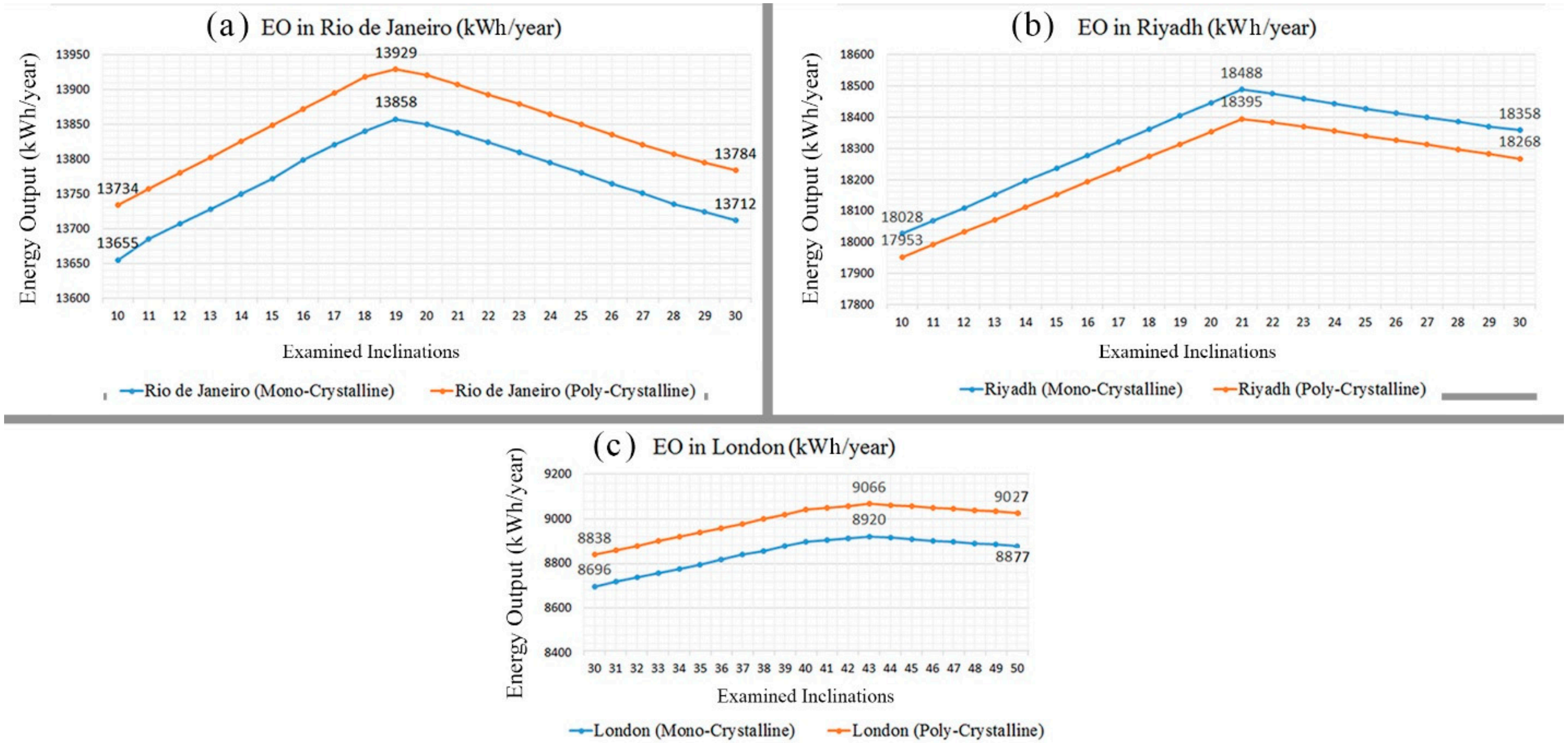

Figure 7. EO of installing PV modules mounted on roofs within a frequency of (1°).

6. Discussion

Analysis of the results of this work illustrate that the performance parameters (building modelling, climate data, and the installation variables) and their related design factors in the proposed framework using the experimental design can significantly evaluate the EO of PV modules. Additionally, this work clarifies that the impact of the PV type is the lowest coefficient factor that could influence energy generation. However, the impact of the PV inclination is the main coefficient factor that influences the process of producing energy in PV modules, while the impact of the PV orientation is considered the second main coefficient factor that simulates energy generation; Figures S1–S8 in the supplementary file have proven this point.

This work indicates that the geographic orientation of PV modules towards the Southern orientation is ideal for cities located North of the Equator while positioning PV modules at a Northern orientation is ideal for cities located South of the Equator. As expected, this means that PV modules should be oriented towards the equator line, however, the installation of PV modules on the East and West elevations of buildings would maximize the EO of PV modules in lower latitude regions close to the equator. In terms of PV inclination, the integration of PV modules on the exterior walls of buildings within a vertical inclination would produce the minimum EO in the four cities. The case study example confirms this point, as shown in Figure 8. It is clear that there would be a loss of one-third to almost one-half of the EO when PV modules are integrated on the exterior walls of buildings within a vertical inclination compared to the preferable inclinations of PV modules for each city: 46.61% in Rio de Janeiro, 49.36% in Riyadh, 31.51% in London, and 42.88% in Quito. This proves that the vertical installation of PV modules on elevations is the worst inclination compared to the preferable inclination for each region, in terms of maximizing the EO of these modules.

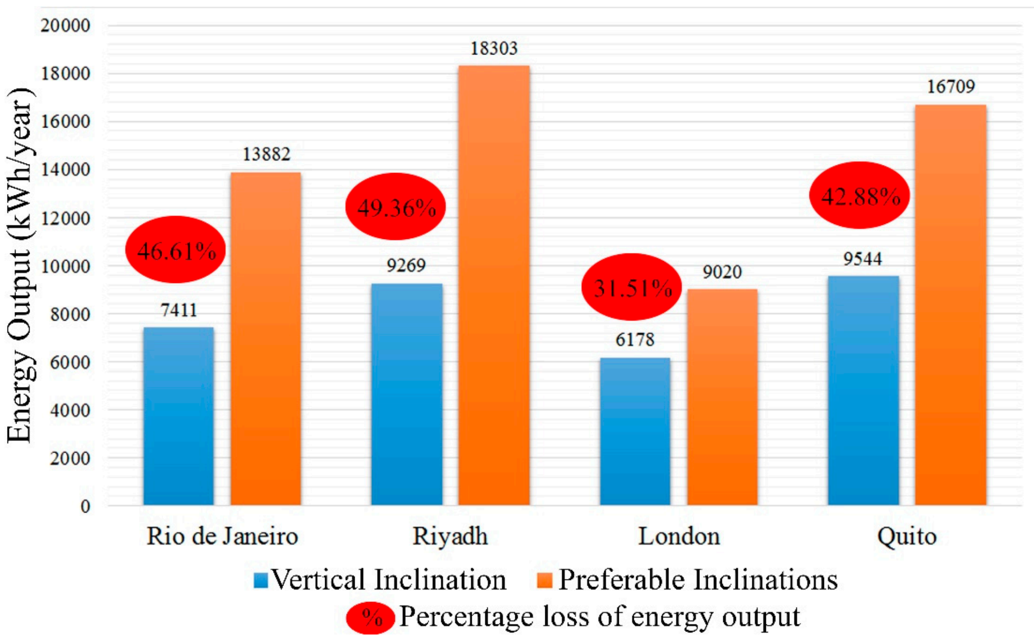

Figure 8. EO loss between the vertical inclination and preferable inclination of PV modules on elevations.

It must be noted that the installation of PV modules mounted on the roof is better than the elevation to maximize the EO of these modules. The results associated with the installation of PV modules in buildings located in Rio de Janeiro and Riyadh, which are situated at almost symmetric latitudes, show that the best inclination that increases the EO of PV modules is between 10° and 30°. This inclination increases to be between 30° and 50° in the city of London, while the horizontal inclination is suggested as the best position of PV modules for the city of Quito, which is located directly on the equator. Specifically, the installation of PV modules at inclinations of 0, 19, 21, and 43° would maximise the EO of PV modules in Quito, Rio de Janeiro, Riyadh, and London, respectively. As a result, this work considers that the closer we get towards the equator, the lower the preferred inclination angles for the installation of PV modules. Consequently, comparing the collected results at this level of the analysis with the work of Gunerhan and Hepbasli [45], Benghanem [46], and Landau [47], presented in the literature review, reveals that PV modules should be oriented towards the equator line at inclinations almost equal to the latitude of the site, in the range of {(0.85 × Latitde_of_the_site) ∓ 3%}.

7. Conclusions

It is important to consider the energy performance of PV modules in order to enhance the sustainability of the built environment towards nZEBs. In an attempt to design better energy performing PV modules, the work in this study presented a methodological framework that could help to integrate the experimental design within the installation variable of PV modules in order to examine all possible design variables that influence the energy levels of these modules. The novelty of this work is in the establishment of a framework that captures performance parameters and design factors that determine the design energy efficiency of PV modules in a complete BIPV system. An emphasis was placed on the use of a standard procedure and software, making the work readily available to practitioners and experts in the area of renewable energy. An integrated methodological framework, which considers various performance parameters and related design factors, based on the experimental design was presented in order to empower the decision-making process of PV module installation. This work considers that improvements of the EO efficiency of PV modules as a major source of renewable energy in buildings has the potential to satisfy the increasing requirements of electricity and, consequently, reduce the dependence on fossil fuels, thus achieving sustainability and protection of the built environment.

A case study of 100 PV modules was examined in four cities, each with a different climate, through the use of an experimental design. The cities analysed included Rio de Janeiro, Riyadh, London, and Quito. First generation PV modules were studied, namely mono-crystalline and poly-crystalline modules. These modules were integrated into a complete BIPV system at different inclinations and geographic orientations. PV*Sol software was adopted as an analysis and planning tool in order to estimate the output energy of PV modules. Minitab software was utilized to build up the experimental design, estimate all the expected variables, and to conduct a linear regression analysis to define the coefficients of the assigned design factors.

It is envisaged that the proposed method will empower the decision-making process and sustainability of the installation of PV modules in a complete BIPV system. The results indicate that the performance parameters suggested in the framework significantly impact the maximization of the EO of PV modules. These parameters include the type of building design (i.e., the design of the final roof and elevations), the climate data, in addition to installation variables, such as the PV type, PV orientation, and PV inclination. Among the applied installation variables of this work, it must be noted that the impact of PV inclination was the major coefficient factor influencing energy generation; the impact of PV orientation was the second coefficient factor influencing energy generation; while the impact of PV type was the lowest coefficient factor influencing the energy generation of PV modules. Yet, it was found that the installation of PV modules on roofs would generate more EO compared to the elevation installation, however, the integration of PV modules on the exterior walls of buildings at a vertical inclination produces the minimum EO compared to other configurations in all cities; between 30% and 50% of the EO of PV modules would not be efficient if PV modules were integrated on the exterior walls compared to the mounted roofs of buildings. The results also display that the global positioning of PV modules in buildings should be towards the equator line. The installation of PV modules on the East and West elevations of buildings are preferable in locations close to the equator. However, it is preferable that PV modules are installed at lower inclinations, in cities close to the equator line. Maximizing the EO of PV modules requires positioning PV modules at inclinations almost equal to the latitude of the site, in the range of {(0.85 × Latitde_of_the_site) ∓ 3%}.

This work has three major limitations. First, the case example examined the first generation of PV modules, mounted on roofs and elevations of buildings, thus neglecting the important role of building modelling, in particular, the design of the elevations and roof, in determining the amount of the installed PV modules. Second, it disregarded the possible shadows on the functional unit; shadows have a negative impact on solar systems. Hence, multi-criteria decision analysis (MCDA) can be a viable direction for future works as a way to assess the other generations of PV modules and explicitly evaluate the conflicting criteria of the elevations and roof design. The third limitation is that building up the sequences of the experimental design in the PV*Sol software required that the same data and variables were entered for every sequence, which means plenty of time was consumed building up the case study. Hence, a future recommendation is the use of different software that facilitates entering the input data and saves time.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/10/2992/s1, Figure S1. Main effects plot of installing PV modules on mounted roofs for Rio de Janeiro, Figure S2. Main effects plot of installing PV modules on mounted roofs for Riyadh, Figure S3. Main effects plot of installing PV modules on mounted roofs for London, Figure S4. Main effects plot of installing PV modules on mounted roofs for Quito, Figure S5. Main effects plot of installing PV modules on elevations for Rio de Janeiro, Figure S6. Main effects plot of installing PV modules on elevations for Riyadh, Figure S7. Main effects plot of installing PV modules on elevations for London, Figure S8. Main effects plot of installing PV modules on elevations for Quito

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APPENDIX 10

Towards a Literature Review of Sustainable Energy Life Cycle Assessment in Buildings

(A conference paper in 14th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, 2019)

The Organizing Committee of
The 14th SDEWES Conference
FMENA, University of Zagreb
Ivana Lučića 5
HR-10000 Zagreb
CROATIA

To:
Mr. MOHAMMAD NAJJAR
Universidade Federal do Rio de Janeiro,
RIO DE JANEIRO,
Brazil

This letter confirms that ***Mr. MOHAMMAD NAJJAR*** has the following submissions reviewed by the editors and accepted for presentation and publication on digital proceedings of the 14th SDEWES Conference on Sustainable Development of Energy, Water and Environment Systems to be held from October 1 - 6, 2019 in Dubrovnik, Croatia:

Oral presentation(s)
SDEWES2019-0680 **Towards a Comprehensive Review of Sustainable Buildings Life Cycle in Water, Energy and Materials**
by Assed Haddad, Ahmed Hammad, Ali Akbarnezhad, Karoline Figueiredo, Mohammad Najjar*

The oral presentations will be conducted in the 15 minutes presentation plus 5 minutes discussion fashion.

This letter **DOES NOT** serve for getting entry visa to Croatia!

For any communication please use the following e-mail address: sdewes2019@sdewes.org

Sincerely yours,

Prof. Neven Duić
Chairman of Local Organizing Committee

Towards a Literature Review of Sustainable Energy Life Cycle Assessment in Buildings

Mohammad Najjar
Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil
e–mail: mnajjar@poli.ufrj.br

Karoline Figueiredo, Assed Haddad*
Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil
e–mail: karolinefigueiredo@poli.ufrj.br, assed@poli.ufrj.br

Ahmed Hammad
UNSW, Sydney, Australia
e–mail: a.hammad@unsw.edu.au

Ali Akbarnezhad
The University of Sydney, Sydney, Australia
e–mail: ali.nezhad@sydney.edu.au

ABSTRACT

This work conducts a literature review with the presentation of clusters for the determination of the most influential key patterns for the system. The novelty herein is to identify the close relationship between the Life Cycle Assessment (LCA) and sustainable energy in buildings through a bibliometric and bibliographic analysis. A flowchart analysis towards a comprehensive model of sustainable energy life cycle assessment in buildings requirements, interrelations between LCA, sustainable development, and most related issues is proposed. The reviewed literature covers the major aspects of a sustainable building (i.e. energy efficiency, environmental impacts, and materials selection). The bibliometric analysis illustrates several clusters that make the refinements of further searches and classify the documents and the primary sources. The bibliographic analysis shows that the assessed methodologies and approaches facilitate the process towards sustainable energy life cycle assessment in buildings; giving the opportunity to evaluate the environmental impacts and improve energy efficiency in buildings.

KEYWORDS

Sustainable Energy, Life Cycle Assessment, Sustainable Development, Energy Efficiency, Environmental Impacts, Materials Selection.

INTRODUCTION

Sustainability success depends mainly on the combination of three interactive pillars: environment, economy, and society [1], which are highly influenced by the construction sector [2]. Since 1962 up to date, several publications, working groups, conferences, and initiatives have been held showing the growing concern about sustainable development [3].

* Corresponding author

The United Nations Environmental Programme highlighted the crucial need to consider the traditional focus on manufacturing processes and production sites at the environmental, economic, and social levels over the entire lifespan of a product, taking into consideration the energy consumption level [4]. Environmental impacts account for around 40% of the global impacts of materials and energy use in the construction sector [5–8]. The environmental performance of products has gained an increasing awareness of the development of the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies [9]. it should match the requirements of users along with their personal comfort needs [10].

Applying the methodology of LCA towards sustainability results in more extensive and complex studies, as well as more uncertainties will arise based on the diversity of stakeholders [11]. In these terms, several approaches can be integrated with LCA to empower the decision-making process in the construction sector such as the mathematical optimization [12,13], Building Information Modeling (BIM) [14], Multi-Criteria Decision Making analysis (MCDM) [15], and Life Cycle Thinking (LCT) tools [16]. The pattern of energy consumption in the construction sector is being influenced by several factors such as the building type, climate zone, economic development level, and the different properties of construction materials [17]. Hence, determining the components of the building envelopes, which are influencing the energy consumption over the entire lifespan of a building [18] to improve the energy efficiency in the construction sector, is a priority in energy strategies [19]. Such assumption could affect the embodied energy and the operational energy of the buildings; where the embodied energy accounts between 10% and 20% of the total energy consumption lifecycle [20] whereas the rest of energy consumption occurred during the using phase of a building [21].

The novelty of this work is to identify the close relationship between the LCA methodology and sustainable energy in buildings through a bibliometric and bibliographic analysis. A flowchart analysis towards a comprehensive model of sustainable energy life cycle assessment in buildings requirements, interrelations between LCA, sustainable development, and most related issues over the entire lifespan of buildings is proposed. This could facilitate achieving the objectives of this work by conducting a literature review with the presentation of clusters for the determination of the most influential key patterns for the system. This study reviews recent publications related to the sustainable energy life cycle assessment in buildings. The reviewed publications are contributed to the development of several applications and practices, and resulting in different streams related to the utilization of different methodologies (i.e. LCA, LCC, and LCT) and approaches (i.e. BIM and MCDM) in a way to cover the major aspects of a sustainable building, and validate and justify the main conclusions.

MATERIALS AND METHODS

There are several methods to be applied when conducting a literature review. Utilizing these methods at the same time might results in uncertainty outcomes [22], hence, it is important to choose the appropriate method for each analysis. This section illustrates the applied methods for this work, as presented in the flowchart analysis in **Figure 1**, where the input data starts in the Scopus Elsevier Database as the largest worldwide citation database [23,24].

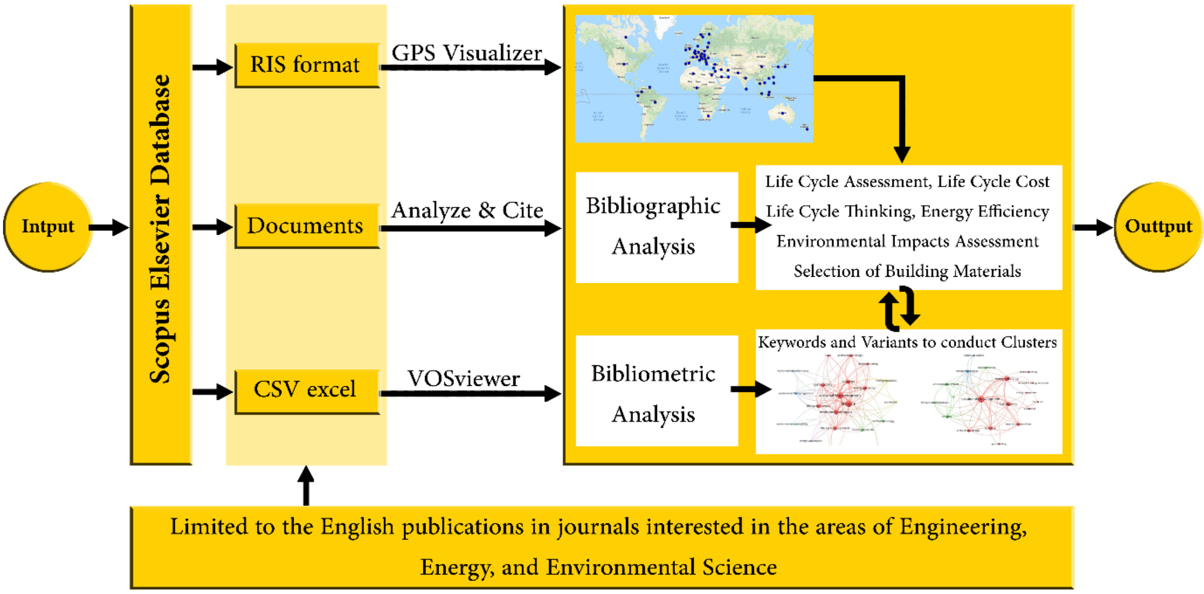

Figure 1. Flowchart analysis of this work.

Life cycle analysis

Environmental Life Cycle Assessment is applied in the construction sector to evaluate the environmental impacts of construction materials over their entire lifecycle [25,26]. In literature, several publications proposed methods to improve the understanding and practical application of this concept in the construction sector. As an example, some publications discussed the role of environmental sustainability to empower decision-making process in the construction sector [27,28], while others presented the understanding of assessment methods and data quality in buildings [29,30]. In these terms, there is a crucial need to use the Life Cycle Thinking (LCT) tools to consider the three pillars of sustainability and empower the decision-making process [16]. LCT permits integrating the sustainable development approach in the decision-making process by following a narrow traditional focus and considering the environmental, economic and social impacts of buildings over their entire lifespan. It is a holistic approach that works on reducing the negative environmental impacts and enhance the socioeconomic performance of buildings [31]. However, meeting the objectives of sustainability requires integrating the LCT methodology within the environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) [32].

LCA methodology is an integrated way that combines the frameworks, environmental impacts assessment and data quality [33], as well as the energy efficiency [34]. It aims to achieve sustainable building practices based on the worldwide recognition for obtaining environmental-related product information by LCA. Applying such methodology in the construction sector is considered as a crucial and distinctive working zone because of the following factors [21]:

- The difficulty of predicting the whole life cycle of a building from cradle-to-grave in the light of the long lifetimes of buildings, often more than 50 years.
- The possible changes to the building form and function during its lifespan make uncertain opportunities to evaluate the environmental impacts.
- The critical role of proper design and material selection in minimizing the environmental impacts, particularly, many of the environmental impacts occur in the using phase.

The shortage of choices of standardization for the whole building design in the light of increasing numbers of stakeholders in the construction industry and the exceptional conditions for each building with its design and specific situation.

Selection of publications

The topic of “sustainable building energy life cycle” includes different research communities and requires reviewing of large bodies of information. For this, the Scopus Elsevier Database is selected as the primary platform for the identification and counting of existing publication of articles in the same field. This platform is the worldwide largest citation database of peer-reviewed literature (i.e., scientific journals, conferences, and books) with more than 22,000 titles from more than 5000 international publishers [35].

The novelty of this work is to identify the close relationship between the LCA methodology and sustainable energy in buildings through a bibliometric and bibliographic analysis. Achieving this goal requires conducting separate research for each matter, as well as conjunction research. Research in the Scopus Elsevier Database sorts out more than 26 thousand documents related to the LCA studies published since 1961. While conducting the same analysis for sustainable building energy shows more than 14 thousand documents published since 1981. To conduct a practical approach that could support the publication of bibliographic and bibliometric specialist authors [36], a further approach including the sustainable building energy life cycle, following the same steps, sorts out around 1.6 thousand documents published since 1996.

The next step is to utilize VOSviewer as a bibliometric software that has a smooth integration with the Scopus Elsevier Database [37]. At this level of the analysis, the downloaded documents in the Scopus Elsevier Database are transferred to VOSviewer software in a comma separated format; the details of the results are limited to the Engineering, Environmental Science, and Energy subject areas, and followed different steps as follows:

i. Using “Life Cycle Assessment” as keywords to conduct a search in the Title and Abstract field retrieved 29,430 documents published since 1964. At this level of the analysis, conducting the same previous search in the Source Title field limited to English language and journal publications only retrieved 19,453 documents.
ii. Using “Sustainable Development” and “Building” as keywords to conduct a search in the Title and Abstract field retrieved 19,816 documents published since 1981. At this level of the analysis, conducting the same previous search in the Source Title field limited to English language and journal publications only retrieved 7,811 documents.
iii. Using “Sustainable Development” and “Life Cycle Assessment” as keywords to conduct a search in the Title and Abstract field retrieved 5,009 documents published since 1989. At this level of the analysis, conducting the same previous search in the Source Title field limited to English language and journal publications only retrieved 3,236 documents.
iv. Using “Energy” as a keyword to conduct a search in the Title and Abstract field retrieved 1,767,646 documents published since 1864.
v. Using “Sustainable development” and “Energy” as keywords to conduct a search in the Title and Abstract field retrieved 42,428 documents published since 1975. At this level of the analysis, conducting the same previous search in the Source Title field limited to English language and journal publications only retrieved 20,772 documents.
vi. Using “Energy” and “Life Cycle Assessment” as keywords to conduct a search in the Title and Abstract field retrieved 11,934 documents published since 1974. At this level

of the analysis, conducting the same previous search in the Source Title field limited to English language and journal publications only retrieved 8,717 documents.

vii. Using "Sustainable", "Energy", "Life Cycle Assessment", and "Building" as keywords to conduct a search in the Title and Abstract field retrieved 774 documents published since 1996. At this level of the analysis, conducting the same previous search in the Source Title field limited to English language and journal publications only retrieved 462 documents; the number of publications per year is presented in **Figure 2**.

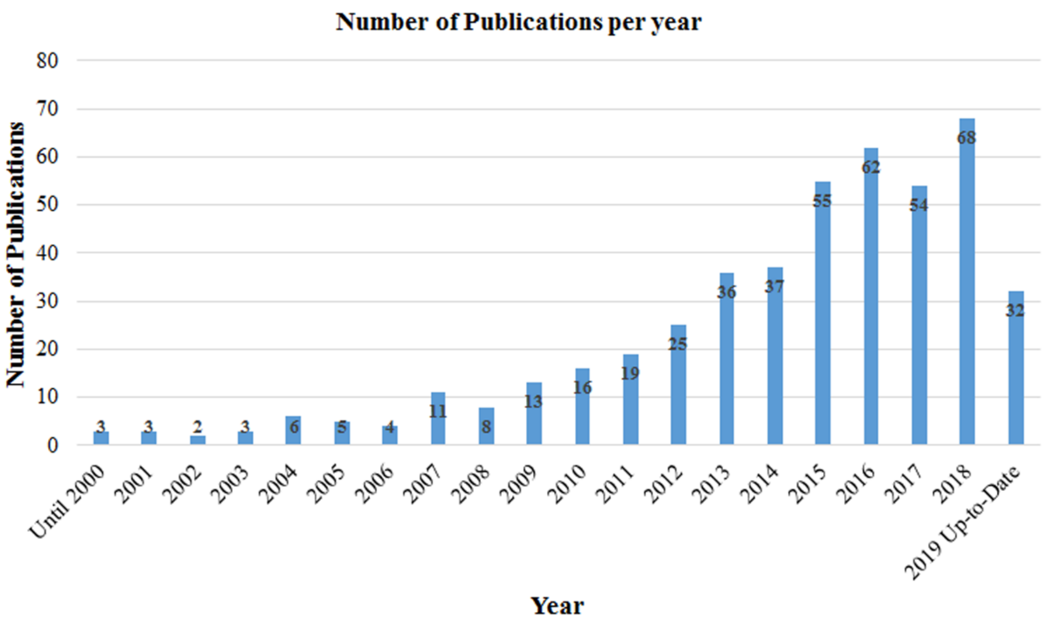

Figure 2. The number of publications per year according to the Scopus Elsevier Database.

An overview extracted from the Scopus Elsevier Database illustrates that Journal of Cleaner Production is the main source of these publications (55), while Journal of Energy and Buildings and Building and Environment come next within (49) and (40) publications, respectively. Furthermore, this analysis highlights that institutions with most of the publications are from United States (80). While the next countries in a number of publications are Italy (52), the United Kingdom (45), Spain (44), and China (41). Canada (23), Australia (21), Portugal (21), Sweden (21), and Germany (20) come next. However, this work uses the GPS Visualizer (Global Positioning System) for the plotting of the Geo-location of publications and the countries of affiliation of the authors [38]. It utilizes the extraction of data (i.e. country name) from the Scopus Elsevier Database and bibliometric software in the GPS Visualizer, as presented in **Figure 3**.

Figure 3. Plotting of the Geo-location of publications related to the sustainable energy life cycle in building extracted from the Scopus Elsevier Database.

RESULTS AND DISCUSSION

This section is conducted in two main streams; bibliometric analysis and bibliographic analysis, as described in **Figure 1**.

Bibliometric analysis

In the first searches using the keys "Life Cycle Assessment or LCA" and most common variants; Life Cycle Analysis, Life Cycle, and Whole Life Cycle Assessment, a set of 19,453 documents are retrieved. At this level of the analysis, this work conducts a cluster analysis for these documents in order to make the refinements of further searches. However, the initial results are presented in **Figure 4**, where the first cluster sorts out that the main concerns related to the LCA, named environmental impacts, life cycle analysis, sustainable development, environmental management, sustainability, and decision making. Followed by energy efficiency, environmental performance, energy utilization, costs, recycling, and waste management. In the second cluster, the basic environmental impacts that can be inferred to conduct the refinement of the searches are global warming, greenhouse gases, gas emissions, global warming, carbon dioxide, eutrophication, carbon footprint, and the greenhouse effect. The high occurrence of the environmental impacts, presented in **Figure 4**, allows concluding a strong relationship between the closely related issues in the LCA studies.

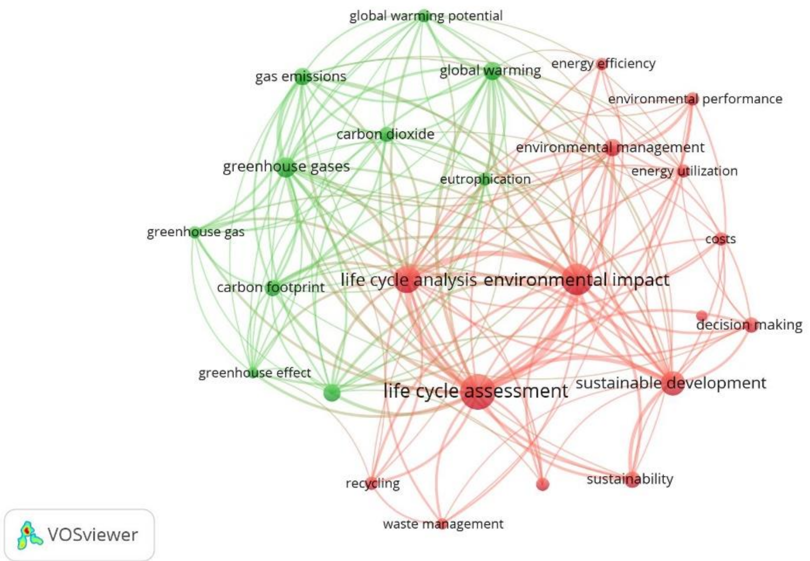

Figure 4. Life Cycle Assessment and most related issues.

In the second searches using the keys "Sustainable Development", "Building" and most common variants, a set of 7,811 documents is retrieved. At this level of the analysis, this work conducts a cluster analysis for these documents in order to make the refinements of further searches. However, the initial results presented in **Figure 5**, illustrate that the first cluster has a close relationship between sustainable development, energy efficiency, sustainability, and buildings. Followed by energy conservation, architectural design, decision-making, and intelligent buildings. In the second cluster, the LCA methodology and the environmental impacts can be inferred to conduct the refinement of the searches.

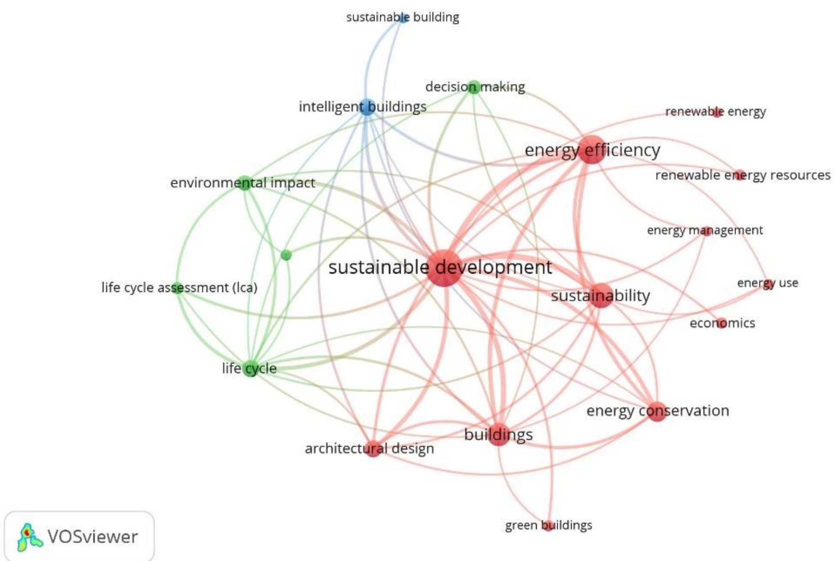

Figure 5. Sustainable development, energy efficiency, buildings, and most related issues.

In the last searches using the keys "Sustainable", "Energy", "Life Cycle Assessment", and "Building" and most common variants, a set of 462 documents are retrieved. At this level of the analysis, this work conducts a cluster analysis for these documents in order to make the refinements of further searches. However, the initial results presented in **Figure 6**, illustrate that the first clusters have a close relationship between sustainable development, life cycle, environmental impact, energy efficiency, and buildings. Followed by sustainability, life cycle analysis, life cycle assessment, decision-making, architectural design, and costs. In the second cluster, several variants can be inferred to conduct the refinement of the searches such as intelligent buildings, sustainable buildings, energy consumption, recycling, environmental performance, environmental management, environmental sustainability, as well as sustainable construction, building materials, and embodied energy.

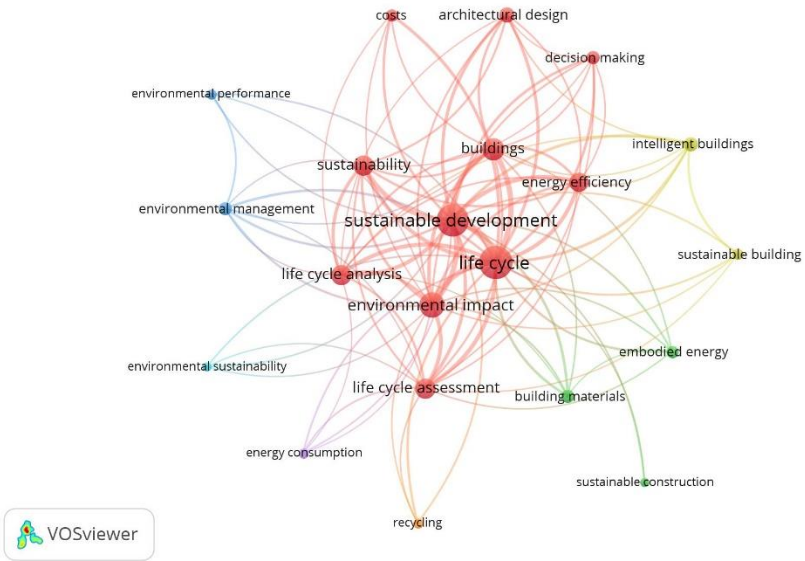

Figure 6. Life cycle, sustainable development, and most related issues.

Bibliographic analysis

Reviewing the most recent studies in the literature shows that the development of sustainable energy life cycle assessment in buildings has been adopted in different mainstreams related to the first and second clusters illustrated using the keys "Sustainable", "Energy", "Life Cycle Assessment", and "Building" and most common variants. At this level of the analysis, LCA appears as a successful methodology to increase energy efficiency in buildings [39]. In the literature, several studies examined and analyzed the energy efficiency as the main part towards sustainability over the entire lifespan of construction projects such as Moslehi and Reddy [40], Li and Liu [41], and Corcelli et al. [42]. However, **Table 1** presents the most recent studies, in the literature, that used sustainable development, LCA, and energy efficiency as first clusters.

Table 1. Studies used sustainable development, LCA, and energy efficiency as first clusters

Source	Description
[43]	Presented various solutions for office buildings in Norway to move from zero-energy to zero-emission.
[44]	Conducted cost and eco-costs analysis and the rebound effects of energy savings towards better controlling the temperature of domestic heating in buildings.
[45]	Examined the LCA methodology of double-skin façade system with fiber-reinforced concrete towards achieving more sustainable and energy-efficient

	buildings.
[46]	Analyzed several methodological choices to estimate the embodied and GHG emissions in buildings.
[47]	Highlighted the link between mitigation measurement of energy consumption in the cities and the built environment towards resilient cities, utilizing the proposed Integrated Design Approach inside the real context of Bolognina neighborhood.
[48]	Developed a new framework proposal to assess the environmental impacts and consumption of freshwater beyond the water footprint.
[49]	Developed a tool to evaluate the entire lifecycle of CO_2 emissions of construction projects in Sri Lanka.
[50]	Assessed a thermodynamic method based on the economic indicator in order to facilitate estimating energy and exergy consumption and CO2 emission of construction materials.
[51]	Developed a representative economic sustainability framework incorporated with BIM implications to improve the energy efficiency in residential buildings.
[52]	Presented a recycling proposal for recycling the unused stockpiles of treated wastewater sludge in fired-clay bricks.
[53]	Assessed the embodied energy impacts of rammed earth facades over the production and construction phases.
[54]	Showed that equal LEED ratings do not result in equal ecological performance, as well as it can be attributed to widely divergent ecological performers, presenting comparative results for two building; a new research laboratory and the other an extensively remodeled classroom building.
[55]	Assessed the LCA methodology over the embodied and operational energy of a passive housing block in Austria.
[56]	Estimated the embodied energy impacts of several building materials applied in Northern Cyprus.
[57]	Appraised the role of LCA in assessing the energy and water consumption, as well as the carbon footprint of educational buildings in hot climate conditions.
[58]	Presented a holistic BIM framework towards sustainable low carbon design of high-rise buildings.
[59]	Presented a BIM-based tool framework to assess the embodied energy over the entire lifespan of buildings.
[60]	Incorporated the whole Life Cycle Energy Assessment into BIM for refurbishment projects in order to increase energy efficiency in buildings.

Besides, LCA appears as a successful methodology to evaluate the environmental impacts in buildings [61–63]. In the literature, several studies, which used sustainable development, LCA, and environmental impacts as first clusters, examined and analyzed the environmental impacts as a main part towards sustainability over the entire lifespan of construction projects, as presented in **Table 2**.

Table 2. Studies used sustainable development, LCA, and environmental impacts as first clusters

Source	Description
[64]	Presented the role of LCA in evaluating the environmental impacts of water recycling solutions in buildings.
[65]	Devoted efforts to evaluate the environmental impacts of buildings, especially in terms of energy consumption and carbon emissions, using LCA and

	methodological framework development.
[66]	Evaluated the environmental impacts of construction components that are assembling the envelope of low-rise buildings.
[67]	Evaluated the LCA of greenhouse-gas emissions in an Australian commercial building.
[68]	Highlighted the challenging issue of managing a large amount of wood waste generated from construction activities, particularly, wood waste as a fundamental renewable resource that can be recycled and used to produce green products and renewable energy. To achieve this, the authors developed a comparative LCA of wood waste management strategies generated from construction activities in buildings.
[69]	Analyzed the application of advanced life cycle integrated exergoeconomic in building heating systems.
[70]	Developed an LCA methodology to evaluate the environmental impacts of a detached house designed following two different approaches (i.e. cold-formed steel with sheathing and insulating panels, and a more conventional reinforced concrete with brick walls).
[71]	Presented the role of a novel design for deconstruction structural systems in steel buildings towards evaluating the Life Cycle Energy Assessment and environmental impacts.

In the literature, plenty of publications have evaluated the environmental impacts in building using the environmental impacts, LCA, and decision-making process as first clusters towards sustainable development, as presented in **Table 3**.

Table 3. Studies used environmental impacts, LCA, and decision-making as first clusters

Source	Description
[72]	Assessed the influence of structural systems on the environmental performance of tall buildings through calculating the embodied energy and CO_2 emissions of construction materials in order to compare their environmental behavior and account for their differences on the amount of the applied construction materials.
[73]	Proposed a proposal to integrate the LCA benchmarks based on the existing databases in Germany at an early designing phase in order to evaluate the environmental impacts and protect the natural resources.
[74]	Highlighted the main challenges in evaluating strategies to reduce the environmental impacts of buildings.
[75]	Evaluated the environmental performance of a refurbishment building.
[76]	Identified the factors that are significantly influencing the environmental impacts at an early designing phase of buildings utilizing the data center lifecycle in order to minimize the environmental impacts.
[77]	Evaluated the environmental impacts of hybrid rainwater-greywater systems in residential buildings.
[78]	Developed strategies to evaluate the environmental impacts for glazing systems at an early designing phase.
[79]	Compared the energy consumption, greenhouse gas emissions, and environmental damages of a retaining wall backfilled with sand, and a retaining wall backfilled with shredded tires, taking into consideration the extraction and production of the applied materials, transport to the site, and installation, in order to evaluate their environmental impacts.

[80]	Provided an integrated assessment framework to compare three different types of exterior wall systems (wood frame, insulated concrete forms, and pre-cast insulated concrete panel), focusing on the performance of building envelope, cost efficiency, and environmental impacts of these three components.
[81]	Evaluated the structural performance and embodied carbon footprint of a recycled aggregate concrete high-rise buildings.
[82]	Examined the operating phase of concrete overlays made of gray and white cement and incorporated with titanium dioxide in order to evaluate the environmental impacts on vehicular pollutant removal, urban heat island, and energy consumption in buildings.
[83]	Developed sustainable and resilience strategies to select construction materials.
[84]	Presented the important role of utilizing wood, as a sustainable building material, in constructing houses in Macedonia.
[85]	Developed engineering perspectives and environmental LCA optimization towards enhancing aggregate mining in Vietnam.
[86]	Conducted an energy and carbon footprint assessment using hemp-lime concrete and Recycled-PolyEthylene Terephthalate façades in office buildings in France and Italy.
[87]	Evaluated the environmental impacts of bio-based wood flooring coatings as an alternative to fossil-based building blocks in order to achieve cleaner production and sustainability goals.
[88]	Developed strategies using MCDM towards more sustainable buildings.
[89]	Assessed the application of LCA methodology in Indonesia.
[90]	Appraised the application of LCA methodology for future sustainable construction.

Other studies applied the life cycle analysis to empower both the decision-making process and sustainability in construction projects using sustainability, life cycle analysis, decision-making and costs as first clusters, as presented in **Table 4**.

Table 4. Studies used sustainability, life cycle analysis, decision-making and costs as first clusters

Source	Description
[91]	Conducted a quantified assessment of the financial benefits and environmental impacts of introducing circular design alternatives for seven internal wall assemblies over a period of 60 years. Moreover, the authors reviewed the methodological implications of a consequential LCA and LCC, using multi-model set-up assumptions and service life models.
[92]	Evaluated the environmental and economic performance of traditional strategies and innovative strategies, using LCA to define a benchmark for the environmental impact, and LCC to assess the economic impact.
[93]	Evaluated the environmental impacts of an educational building through an LCC perspective.
[94]	Conducted a literature review to explore the environmental and economic costs and benefits of a circular economy approach over the construction and demolition phases of buildings.
[95]	Evaluated the LCA and LCC of an educational building in China.
[96]	Described the LCA and LCC of two wall schemes towards reducing the environmental impacts, basically, the climate change impact.

[32]	Presented the role of LCT in assessing the sustainability of heat pump technology. The authors highlighted LCT as a promising opportunity for energy-efficient and low-carbon buildings.
[97]	confirmed that LCT is an important approach towards sustainable development policy-making in buildings.
[98]	Illustrated the important role of LCT in selecting construction components that are assembling the facades of the buildings.
[99]	Presented the role of LCT towards achieving more sustainable buildings via investigating the application of LCA methodology to assess the energy efficiency and environmental impacts of buildings.

Eventually, some studies in the literature elevated the role of life cycle analysis in terms of selecting the construction materials and improving the architectural design and decision-making over the entire lifespan of buildings using life cycle analysis, sustainability, decision-making, and architectural design as first clusters, as presented in **Table 5**.

Table 5. Studies used life cycle analysis, sustainability, decision-making, and architectural design as first clusters

Source	Description
[100]	Optimized traditional and non-traditional concrete mixes from various perspectives; technical performance, cost, and environmental life cycle perspective.
[101]	Developed a disassembly and deconstruction analytics system to provide the end-of-life performance assessment of buildings at an early designing stage in order to guarantee efficient materials recovery.
[102]	Presented the role of LCA in evaluating the lifespan of geopolymer concrete.
[103]	Studied the eco-efficiency and building optimization potential of prefabricated structures in a way be used in new buildings, considering the dry precast structural connections.
[104]	Presented that using additively manufactured components in buildings are more energy efficient and environmentally sustainable than using conventionally manufactured.
[105]	Presented a sustainability innovation approach to evaluate the quality of wood in green business.
[106]	Developed sustainable and resilience strategies to select the components of building design.
[107]	Highlighted that a significant potential for material efficiency and GHG emissions mitigation is required to increase the efficiency of construction design and the application of construction materials.
[108]	Presented the role of LCA and multi-criteria analysis towards evaluating the sustainability of retrofit solutions for rural buildings.
[109]	Developed a new performance indicator of LCA methodology in order to evaluate the potential of thermal and ventilation processes in buildings.
[110]	Constructed an LCA model of the urban innovation ecosystem under the background of new urbanization in China and selected the multi-objective classification matrix method of fuzzy decisions towards the urban innovative ecological system.
[111]	Applied the LCA methodology to compare different building roof construction systems.

[112]	Appraised the role of LCA towards new modular greening systems.
[113]	Presented the role of LCA towards achieving more solutions that are sustainable and constructive.
[114]	Evaluated the LCA methodology of magnesium oxide structural insulated panels in Vancouver.
[115]	Evaluated the LCA methodology of emergent masonry blocks.

CONCLUSIONS

This study reviews the sustainable energy publications over the entire lifespan of buildings. The novelty of this work is to identify the close relationship between the LCA methodology and sustainable energy in buildings through a bibliometric and bibliographic analysis. The objective of this work is to conduct a literature review with the presentation of clusters for the determination of the most influential key patterns for the system, to present the framework for the sustainable energy life cycle assessment in buildings. Reviewing the recent publications related to the sustainable energy life cycle assessment in buildings encompasses two major aspects of a sustainable building (i.e. energy efficiency, environmental impacts, and materials selection).

A flowchart analysis towards a comprehensive model of sustainable energy life cycle assessment in buildings requirements, interrelations between Life Cycle Assessment, sustainable development, and most related issues over the entire lifespan of buildings is proposed. The applied flowchart can be considered as an appropriate method. This comes back to the fact that 462 documents related to the sustainable energy life cycle in buildings published since 1996 are retrieved. While the publications reviewed in this work covered the most recent studies in this area of interest; they were analyzed in more details in a way to validate and justify the main conclusions. The analyzed papers in this work show a crescent interest in evaluating sustainable energy over the entire lifespan of buildings. Around 462 English journal publications in the literature, up-to-date, contributed to the development of such applications and practices, resulting in different streams related to the utilization of different methodologies and approaches.

Integrating the retrieved and downloaded documents in the Scopus Elsevier Database within the Bibliometric Software VOSviewer facilitates analyzing thousands of keywords and terms from Titles and Abstracts at the same time, and classifying them based on their relevance. However, the bibliometric analysis presented in this work illustrated several clusters that make the refinements of further searches. These clusters aimed to classify the documents and the primary sources, as well as pinpoint the related issues. For this work, the first clusters concluded show that the main concerns related to the Life Cycle Assessment methodology are environmental impacts, life cycle analysis, sustainable development, environmental management, sustainability and decision-making, energy efficiency, environmental performance, energy utilization, costs, recycling, and waste management. Besides, this work shows that the environmental impacts (i.e. global warming, greenhouse gases, gas emissions, global warming, carbon dioxide, eutrophication, carbon footprint, and greenhouse effect) are the major second clusters related to the Life Cycle Assessment methodology. On the other hand, the first clusters concluded for the “Sustainable Development” and “Building” keywords illustrate a close relationship between sustainable development, energy efficiency, sustainability, and buildings, as well as energy conservation, architectural design, decision-making, and intelligent buildings. Furthermore, the first clusters related to the sustainable energy life cycle assessment in building present the relative connections between sustainable development, life cycle, environmental impact, energy efficiency, and buildings, as well as sustainability, life cycle analysis, life cycle assessment, decision-making, architectural design, and costs.

Accordingly, the bibliographic analysis presented in this work results in some conclusions about the evolution of the LCA methodology and its relation to the environmental impacts and energy consumption in buildings. The literature review shows that several methodologies have been applied, as promising opportunities, in the environmental science, engineering, and energy studies such as Life Cycle Assessment, Life Cycle Costing, and Life Cycle Thinking, as well as different approaches such as BIM and MCDM. Such methodologies and approaches facilitate the process towards sustainable energy life cycle assessment in buildings, giving the opportunity to evaluate the environmental impacts and improve energy efficiency in buildings. At this level of the analysis, the assessed studies are evaluated and classified in five tables (**Table 1** to **Table 5**) in order to confirm the close connections between the first clusters presented in the bibliometric analysis in **Figure 6**.

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