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Interaction of Life Cycle Assessment (LCA) and BIM in a Construction Project to Reduce the Environmental Footprint

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Abstract

The construction sector is experiencing rapid growth in response to the increasing demand for new projects that address societal needs, making it one of the most significant contributors to greenhouse gas emissions. Therefore, it is essential to develop more sustainable and efficient construction processes that reduce the environmental impact in the sector. This study focuses on assessing the environmental footprint of a residential project in Colombia, based on the implementation of Building Information Modeling (BIM) with a sustainability focus. A Life Cycle Assessment (LCA) was performed using the "One Click LCA" software, where the characteristics of the building over a 50-year period were inserted and evaluated. The study determined the building's environmental impacts and direct pollutant emissions, including global warming (CO_2e), acidification (SO_2e), eutrophication (PO_4e), and ozone depletion (CFC), among others. The results were analyzed by evaluating their magnitude and criticality. One of the main findings was the emission of 1.49E+06 kg of CO_2, which directly impacts global warming significantly. This LCA-BIM approach provides a transparent methodology for construction companies in Latin America to implement projects with a lower environmental impact, promoting sustainable practices within the industry.

Keywords: BIM; Sustainable Construction; Environmental Footprint; LCA.

1. Introduction

To meet the growing needs of the population, the construction sector generates an excessive consumption of materials, encouraging the exploitation of resources on a large scale for their production [1]. This situation leads directly to the degradation of ecosystems. The construction sector is responsible for approximately 11% of the greenhouse gases in the world [2]. The construction sector is partly responsible for the climate crisis [3, 4]. It is observable that this massive industrial development in direct relation to polluting factors is the central aspect to consider when discussing the present and future of imminent climate change [5].

The most significant impacts associated with climate change have been caused by human activity, being one of the most significant contributors to carbon emissions worldwide [5, 6]. The construction sector in a country like China is responsible for 14-28% of greenhouse gas emissions [4]. The European Union also consumes approximately 40% of the energy from the construction sector [7]. Therefore, as an immediate solution, Hauashdh et al. [8] stated that buildings

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have consistently been identified as the sector with the most significant potential to reduce both energy consumption and carbon dioxide (CO_2) emissions through more sustainable and effective strategies in building maintenance [9-11].

Different solutions have been proposed to reduce the impacts associated with the construction sector; one of the most accepted worldwide is the use and implementation of Building Information Modeling [12, 13]. BIM is a methodology that is based on digital representations of assets [14], the exchange of information from a Common Data Environment (CDE) [15], and the integration of project stakeholders for execution [16] to make construction projects more efficient throughout the life cycle [17]. BIM allows the acquisition of construction models with a digital approach and the making of environmentally sustainable decisions [18-20]. Likewise, these results can be enhanced by implementing the Lean Construction philosophy that aims to improve construction processes by focusing on value and eliminating waste, reducing the environmental footprint of projects [21, 22]. However, the use of BIM for environmental impact assessment in small and medium-sized construction companies still does not reach 11% [23].

The use of materials that are harmful to the environment, the growing global consumption of non-renewable resources, and the large amount of construction and demolition waste (CDW) generated in this business sector have made this one of the main problems to be solved. Therefore, using Green-BIM methodologies, environmental management plans (PMA) focused on controlling and managing waste are proposed [24-27].

Life Cycle Assessment (LCA) is used as a methodology to assess the environmental impact of a building over its lifetime [28-30]. The life cycle analysis seeks to obtain high-performance buildings and reduce life cycle costs in the operation and construction phases. These objectives are synergistic with those obtained with BIM [31]. Based on these analyses, more sustainable practices are determined, and implementing materials with low environmental impact is encouraged [32-34].

Just as using renewable materials is emphasized, advancing towards energy-efficient buildings is equally essential for achieving sustainability [35, 36]. The energy consumption of buildings is a fundamental issue, and the operating demand is considered one of the highest among all other sectors of the economy [37]. Furthermore, it is expected that by implementing BIM and energy-efficient buildings, up to 24% of the carbon footprint could be reduced [38-41].

For example, studies in China on LCA focused on ventilation, lighting, and the use of elevators during the operation and maintenance stage [42]. Likewise, in analyzing prefabricated components, the distances from the production factory to the assembly site should be considered [43]. Other examples of its implementation for buildings manufactured in Timber, where prefabrication levels of up to 88.47% were reached [44]. In another study, the interaction for a 2-story house was analyzed by evaluating different materials from LCA [45], concluding that implementing BIM and Life Cycle Assessment in Buildings (LCA) can reduce carbon emissions by up to 43.62% [46, 47]. However, BIM-LCA implementation is still not so typical in most construction projects in both the public and private sectors due to barriers that exist for its use, such as the low availability of tools [48], few LCA experts in the industry [49], lack of transparent methodology [49], low adoption in educational spaces [50], the majority of existing literature is mainly focused on the carbon footprint, and its interaction with circular economy concepts is limited [51]. In addition, a few LCA case studies have been applied to the construction industry in Latin America.

The adaptation of the industry to the implementation of new buildings based on more environmentally friendly materials and evaluated in detail with life cycle assessment (LCA) and BIM programs is a balanced solution to solve the environmental problems of the sector through the interaction of technologies, comparison of materials, and optimizing the levels of development (LOD) of construction projects [52-54]. For this reason, this article aims to analyze the environmental footprint caused by a residential building in Colombia, focusing on understanding how life cycle assessments (LCAs) can be optimized to reduce the associated environmental impact for companies in the construction sector through a transparent methodology, taking into account the construction procedures inherent to the Latin American context.

2. Research Methodology

The proposed research method suggests determining and analyzing the environmental impact generated by constructing a residential building in a case study. Life Cycle Assessment (LCA) evaluates products and services by showing the similarities and differences in assessing the midpoint and endpoint impact categories [35]. Figure 1 shows a flowchart that describes the processes and steps necessary to investigate the interaction of building modeling by applying BIM methodology and Life Cycle Assessment (LCA) through One Click LCA software. This research has three main phases:

1) Technical specifications of the project: In this phase, the specifications were proposed collaboratively with the designers. In this way, the technical specifications of the different building systems were obtained.

2) BIM modeling: In this phase, which is carried out in parallel with the definition of the project specifications, the results are obtained from the quantities of work (3D), the project schedule (4D), and the budget (5D), taking into account the uses defined by the project client (EIR).

3) LCA: Finally, based on the quantities obtained from each of the primary materials of the project, a life cycle analysis is carried out where variables such as acidification, eutrophication, global warming, damage to the ozone layer, photochemical potential, and primary energy were taken into account.

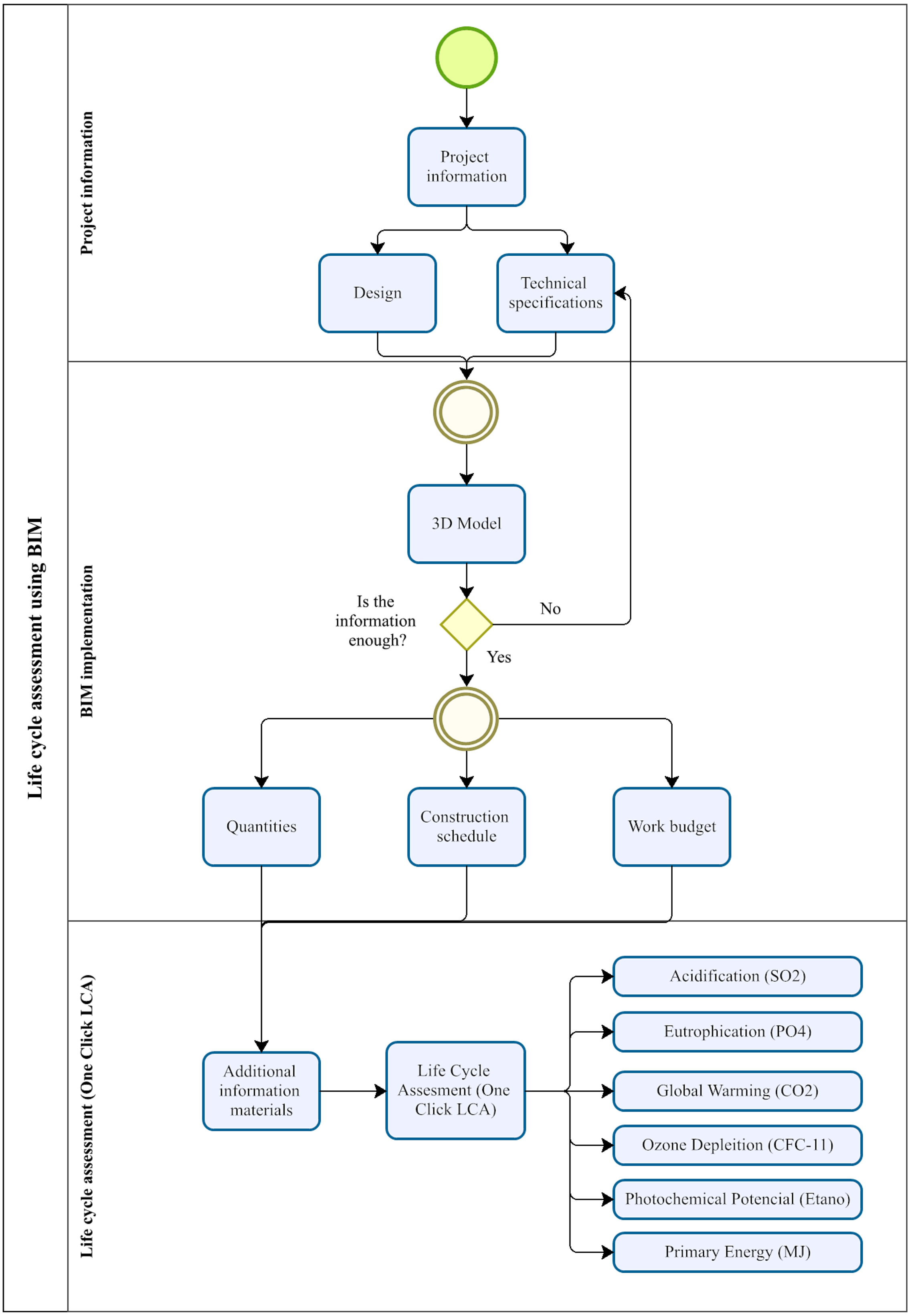

Figure 1. Research Method LCA-BIM

2.1. Technical Specifications

Following this, previous research was carried out on the use and implementation of the One Click LCA tool, specifically focused on determining, according to the life cycle of a building, the induced impacts generated to the environment, bearing in mind that buildings interfere in a given environment throughout their life cycle. The energy consumption of a building is linked to the process of extracting the materials for the construction phase of the building without neglecting the operational energy that the building requires for its operation. With this in mind, collecting project information on variables such as location, transportation, displacements, raw material, and final disposal is necessary to understand the project's environmental impact and what changes could be implemented to reduce it during design.

2.2. BIM Modeling

In parallel with the technical design, the quantities of materials used in the project in each of the most relevant and substantial construction processes were determined. In this way, it was identified that, according to the structural system of the building, caissons, floor slabs, reinforced masonry, and the structural system in general were the main activities. In addition, the paint used and the glass installed in the structure were also considered as materials. The information was collected using the BIM model, and the additional data was obtained directly from the construction company and corroborated in the field visits. The level of development (LOD) used in this model was 400 in a large part of the model. Moreover, the federation and the CDE were used as a design collaboration strategy. In addition, the recommendations of the ISO19650 for exchanging information and project roles established in the BIM Execution Plan (BEP) were taken into account.

2.3. Life Cycle Assessment (LCA)

Finally, based on the data obtained in the BIM modeling, the case study was analyzed under the LCA methodology, determining, according to the quantities and construction processes, the most polluting materials, the criticality of certain activities, the generation of CO_2 equivalent, and primary energy expenditure (MJ). This information made it possible to conclude on technical decisions that were made in the project and provide a scheme for possible future optimizations to reduce the environmental footprint of construction projects.

3. Results and Discussion

The case study is about a 14-story residential apartment building located in Colombia. The building has eight floors with a structural system of reinforced hollow walls (apartment area) and six floors in reinforced concrete porticoes (parking area); prefabricated wood is used for the façade and an essential part of the exterior finishes. Additionally, each apartment has an approximate area of 66 m^2; the building information was collected based on the three-dimensional model in Revit. Figure 2 presents the building's general characteristics, floor distribution, and accesses.

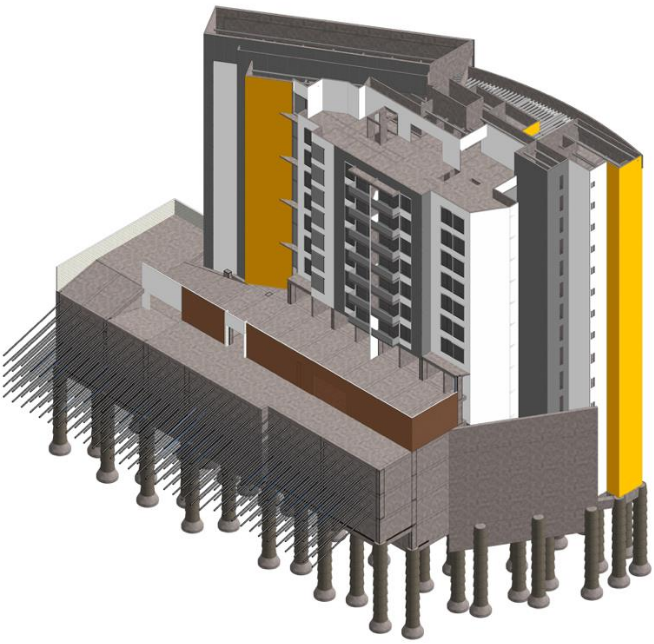

Figure 2. 3D Model View

3.1. BIM Modeling

The BIM model was designed to meet the company's requirements, embodied in the Employer's Information Requirements (EIR). The BIM model has critical structural elements, such as the caissons, exterior columns, and passive anchors, that complete the structural system of the project (Figure 3). However, the model incorporated a constructive perspective on the processes to generate added value during construction. For instance, the trenches had an approximate length of 4.7 meters, and the construction process for the retaining walls and anchors began in the intermediate sections. The trenches were numbered and followed a logical sequence to ensure optimal flow during the excavation process. Three drilling machines were recommended to be used, which reduced the excavation time by approximately 35% per level. Also, it was found that with the budget made from 5D BIM, there was an error in the initial budget of approximately 22% in the reinforcing steel of the project’s structure, which would have meant high-cost overruns for its financial viability.

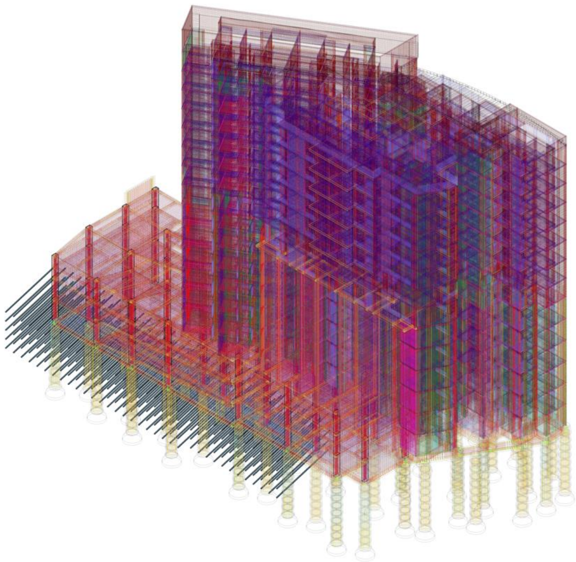

Figure 3. Structural (Reinforcing steel) Model 3D

To achieve the planned objectives, information was extracted from the BIM model, where each of the materials used and their type of use according to the designs were characterized. Subsequently, materials were calculated and filtered by aspects such as the name of the material, the type of element, level, use, area, and volume. Additionally, 4D (times) and 5D (costs) were implemented in BIM. Additionally, the 4D simulation allowed to identify a bottleneck in the excavation process since a top-down system had to be made to avoid the collapse of the adjacent lot. The BIM process allowed the identification of construction errors during the design and construction phases. Furthermore, in addition to being able to balance costs, this information influenced the logistics to improve the duration of the project and its environmental performance (Figure 4).

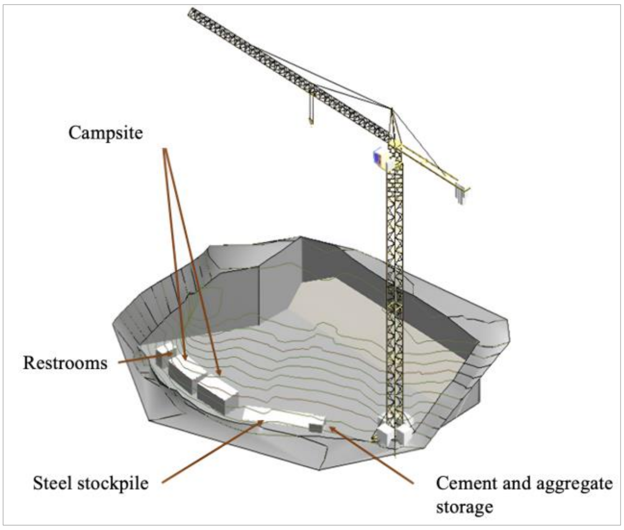

Figure 4. Logistics and Camp Planning

3.2. Life Cycle Assessment (One Click LCA)

The case study used the One Click LCA software, which has the most integrations with standards and certifications, such as ISO, LEED, and BREEAM [55]. This way, it was decided to consider the most used materials with the highest volumes for the analysis. Other factors to be evaluated were the life span of the structure (50 years), the time of operation to carry out the activities, and the displacement of suppliers. The transport distance of the most relevant materials, such as ready-mix concrete and steel, was from cargo trucks, and the distance was approximately 10 km. Also, the distances from the different camps to the execution site were calculated using the BIM model to make it more optimal. Regarding the development of the project and the satisfaction of future needs in the building, two utilities of maximum value were considered related to the generation of polluting factors and the deducted life period, energy expenditure, and water consumption.

Table 1 shows the results obtained through the LCA simulation of the case study carried out in the One Click LCA software; six categories of environmental impacts (acidification, depletion of the ozone layer, global warming, energy consumption, eutrophication, and photochemical ozone creation potential) are defined in direct relation to polluting factors. The magnitude of the impact can be quantitatively observed in terms of each category and its corresponding unit of measurement. One of the most significant impacts is energy consumption, which in turn impacts global warming due to the emission of greenhouse gases. A high acidification value also has a high impact by releasing nitrogen oxides (NOx) and sulfur dioxide (SO_2), which can negatively affect ecosystems and water quality when combined with atmospheric water vapor.

Table 1. Environmental Impacts Generated by Building – Categories.

Impact	Impact Category	Results	Units
Environmental	Acidification	4.69E+03	Kg SO_2 - Eq
	Depletion of the Ozone Layer	6.00E-02	Kg CFC-11 - Eq
	Global Warming	1.49E+06	Kg CO_2 - Eq
	Energy Consumption	1.15E+07	MJ
	Eutrophication	7.60E+02	Kg PO_4 - Eq
	Photochemical Ozone Creation Potential	1.87E+02	Kg C_2H_4 -Eq

Figure 5 illustrates the CO2e emissions generated by each of the key construction processes, which are identified as the primary contributors to pollution during the various life cycle stages of the building. The concrete structural walls contribute 462710.39 kg CO_2e in total, considered the analysis's most significant and outstanding impact. Furthermore, the basements and foundations are the second most relevant, with 371050.4 kg CO_2e. Likewise, the remaining elements represent a smaller proportion of the total building volume because the material used in the other activities was comparatively minor. The columns, in this case, had a low value since the primary structural system of the building consisted of structural concrete walls.

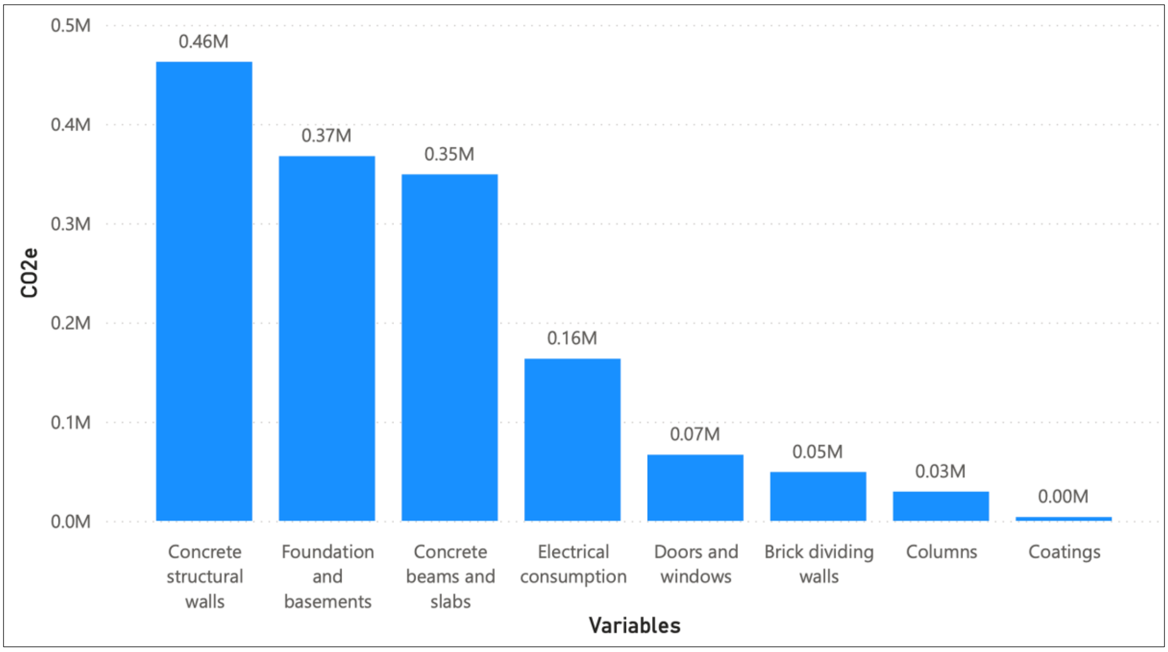

Figure 5. Global Warming kg CO_2e - Classifications

Figure 6 depicts the effects produced (kg) by each of the leading environmental impacts evaluated in the life cycle analysis of the structure. The analysis shows that the most significant environmental impact produced is associated with the generation of carbon dioxide (CO_2), but acidification (SO_2) and eutrophication (PO_4) are also relevant. The data reveals that among the impacts generated, the highest of these categories is the production of SO_2 (acidification), causing up to 1231.11 kg in the activity of structural walls, which is a crucial part of the structural system. Correspondingly, electricity consumption during construction also significantly impacts acidification and eutrophication, contributing (932.29 and 189.92 kg, respectively). Finally, brick dividing walls have a lower proportional impact due to the quantities. However, despite the fact that bricks are manufactured at high temperatures, recycled raw materials from other sub-processes can be used, reducing their environmental impact.

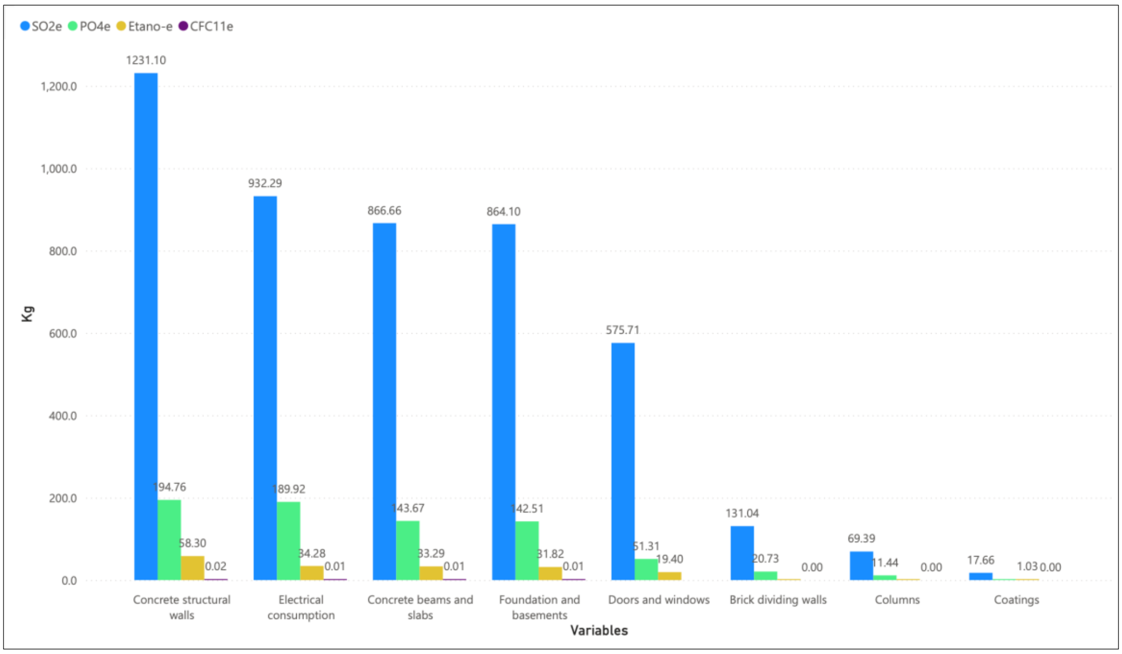

Figure 6. Global Warning kg CO_2e - Classifications

Figure 7 illustrates the energy expenditure of the building's construction and operational phases over 50 years, expressed in Mega Joules (MJ). The highest consumption produced occurs in the elaboration of floor slabs and beams, causing expenses of up to 2440808.75 MJ and being the main contributor associated with the generation of CO_2. Finally, it is evident that in the four main activities (beams and slabs, foundations, structural walls, walls, and windows), there was a consumption of more than 7.38 million MJ in all activities, which indicates a high energy consumption during the execution of the project.

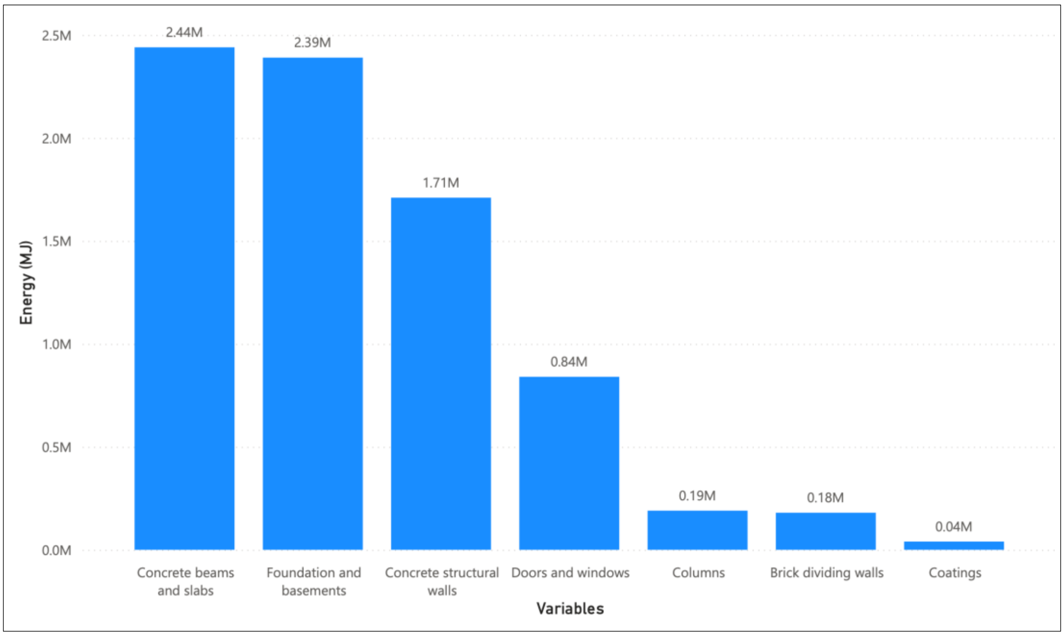

Figure 7. Total Primary Energy Utilization Mega Joules (MJ) - Under Construction

4. Conclusion

The construction industry worldwide has contributed significantly to the degradation of ecosystems and the emission of greenhouse gases, generating problems not only associated with the recognized global warming or the affectation of the ozone layer but also with the potential development of diseases caused by atmospheric pollution or the affectation of the trophic chain. Based on the nature of this problem, the construction sector must take advantage of the new methodologies and techniques available to reduce the environmental impact significantly. Because of this, multiple studies address strategies such as implementing BIM and Lean as a joint strategy to reduce the environmental footprint of projects. In addition, LCA also appears as a way to reduce impacts and make better decisions in construction projects.

Likewise, the transport stage is one of the main influences in the production of pollution linked to industry, resulting in the production of 8178.5 kg CO_2e derived from this implication in some cases [56]. Considering these effects, environmental impacts such as acidification and the global warming potential produced by construction and its implications can be reduced by more than 30%. In this way, the aim is to optimize not only the construction processes but also the commissioning of the buildings during the operation and maintenance phases.

This study determined that the excessive use of partition walls, in conjunction with their materials, can become highly invasive in the environment, a primary factor in pollution due to the enormous waste generated in this construction process. Consequently, it is recommended that future projects minimize the use of these techniques and replace them with different materials that fulfill the same function of distributing the architectural spaces of a building. It is essential to remember that each project is different in construction. Therefore, a thorough and unique study must be carried out every time the proposed BIM-LCA methodology, taking into account the type of structure, materials to be used, location, and time required to carry out the project. Similarly, a transparent methodology for the joint use of BIM-LCA is suggested from the "OneClick LCA" software, which would allow companies in the construction sector in Latin America to carry out their own analysis of construction projects to make decisions from the design stages to make their projects more efficient and environmentally sustainable. In addition, it can also serve as a guide to strengthen the teaching of LCA in educational spaces and minimize knowledge barriers for new professionals in the construction industry.

This study also had some limitations; the information on the associated costs could be more extensive, but construction companies are reluctant to present detailed financial data. Also, manually capturing information on-site can be a logistical challenge, primarily due to the investment in personnel. Finally, investment in LCA software can be high for small and medium-sized companies when the end customer is unaware of the benefits of living in construction projects with a lower environmental footprint. Likewise, raising awareness of the entire value chain to improve the environmental performance of projects is still a challenge.

As future research, it is proposed that the research that emerges from this study should focus on the comparison of results using different materials and scenarios with the use of the tool implemented in this building (One Click LCA) since this combination could reach an environmental/economic optimal point to make it viable from the finances of the project to its sustainability. Furthermore, strengthening the relationship between the private and public sectors is necessary to encourage sustainable projects [48], from financing with green bonds, reducing interest rates, and incentivizing clients to acquire sustainable projects. Finally, ensuring more sustainable practices in the construction value chain, not only in construction processes but also in administrative activities, is necessary to reduce the environmental impact caused by the sector.

5. Declarations

5.1. Author Contributions

Conceptualization, C.C.O.G. and A.A.B.; methodology, C.C.O.G., A.A.B., and C.C.A.L.; software, C.C.O.G.; validation, A.A.B., D.A.T., and E.A.M.; formal analysis, C.C.O.G.; investigation, C.C.O.G.; resources, C.C.A.L.; data curation, E.A.M.; writing—original draft preparation, C.C.O.G.; writing—review and editing, A.A.B.; visualization, D.A.T.; supervision, C.C.O.G.; project administration, E.A.M.; funding acquisition, D.A.T. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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