

Article

Evaluating Construction Projects' Alternatives Using Lean Construction and Sustainability Principles in an Information Model Framework

Pedro Saieg Faria ^{1,*}, Elisa Dominguez Sotelino ^{2,*}, Cristiano Saad Travassos do Carmo ² 
and Daniel Luiz Mattos Nascimento ³ 

¹ TecGraf, Institute of Technical-Scientific Software Development, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Rio de Janeiro 22451-900, Brazil

² Department of Civil and Environmental Engineering, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Rio de Janeiro 22451-900, Brazil; csaad@puc-rio.br

³ Business School, University of Barcelona, 08034 Barcelona, Spain

* Correspondence: pedrosf@tecgraf.puc-rio.br (P.S.F.); sotelino@puc-rio.br (E.D.S.)

Abstract: This study evaluates and validates how BIM functionalities can foster the consideration of lean construction and sustainability principles in building design. To this end, a plugin was developed and implemented in a BIM-enabled visualization environment. This system aims to help a user decide the best design between alternatives, while considering the user's perspective on what generates value in the project. To illustrate and validate the usability and importance of the system, the design of a warehouse with specific requirements was considered. Four design alternatives were modeled considering different types of superstructures, building envelopes, and materials. The system imported an external database and calculated the general costs, CO₂ emissions, and thermal comfort indicators for each model. It also incorporated user-defined weights for each indicator and graphically displayed the results indicating the best options through a multiple attribute decision method. From the obtained results, it was concluded that it is possible to integrate BIM and lean principles to support sustainable development in the construction industry. Through an experiment with warehouse alternatives, the proposed approach revealed that the best project could save nearly 50% of CO₂ emissions when compared to the worst project and that the second-best project had the best performance in terms of thermal heat flow (1.80 Megawatts). The results also indicate that the system can be a great asset in supporting the decision-making process of selecting the best design alternative and understanding the impact of design changes on cost and on the environment.

Keywords: BIM; sustainability; lean thinking; design performance; plugin



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1. Introduction

According to [1], the construction industry is the main villain of sustainable development when compared to all other sectors. However, due to the ever-increasing pressure from society and health organizations, sustainability has become an especially important concern within the AEC industry. Parallel to this, the adoption of Building Information Modeling (BIM) concepts and methodologies in this industry is growing quickly as process and technology are evolving [2]. Addressing the challenges that affect sustainability early in building design (conceptual design phase) can help with the decision-making process and produce higher-quality projects.

In this context, this study aims to identify how Building Information Modeling (BIM) and lean thinking principles of project and production, along with sustainability principles, can be integrated to generate economic and decrease environmental impact, thus enabling more optimized and competitive solutions to address current and future scenarios. To achieve this, a plugin to help the decision-making process in the early stages of a project

was implemented in a BIM environment. In this sense, the paper's goal is to investigate the integration of BIM, lean thinking, and sustainability principles in the context of the construction industry. Thus, the specific goal is to propose a plugin that aids decision-making during the early stages of a project by assessing and comparing various design alternatives for a warehouse construction project.

To illustrate and validate the usability and importance of the developed system, the design of a warehouse with specific requirements was considered. Four design alternatives were modeled considering different types of superstructures, building envelopes, and materials. These models were exported as Industry Foundation Classes (IFC) files and then imported into the BIM environment. The system then imported an external database and calculated the general costs, CO₂ emissions, and thermal comfort indicators for each model based on data contained in the models' elements and in the imported database. Finally, it incorporated user-defined weights for each indicator and graphically displayed the results indicating which of the options would be the best through a multiple attribute decision method. Implementing the indicator-based system in a BIM environment enabled process automation, since the data from the model were readily available.

1.1. Theoretical Background

Since the 1960s, 3D representations of enterprises have been growing. Today, with a wider use of the BIM methodology, these models consist of both geometrical and non-geometrical information (material, construction status, fabrication attributes, etc.). This enables the creation of a construction model that contains a lot of useful information in addition to geometry [3]. However, it is worth pointing out that BIM is not just a technology; instead, it is the synergy between processes, technology, and people, and, without any one of these, BIM does not work [4]. In fact, the international standard ISO 19650-1:2018 [5], through the definition of the term BIM, explains that it involves information management to support decision-making processes.

The BIM methodology is capable of breaking and changing traditional relations between entities, converting linear to cyclical responsibility, by using a central model with early collaboration and simultaneous tasks [3]. By doing this, better decisions are made early in the process and less Requests for Information (RFI) and reworks are produced, among other benefits. In short, it can save construction cost and time, as the classical MacLeamy's curve proves [6,7].

Nonetheless, to achieve all these benefits, it is necessary to have technology interoperability, i.e., acceptable communication should occur between software tools. According to [7], a lack of interoperability results in financial loss due to inconsistency, redundant data entry, and other negative impacts that turn the process inefficient. With this in mind, the IFC format was developed with the goal of providing a common language between BIM tools. However, IFC in its current state has not yet resolved many interoperability issues between software tools [8].

More than the connection between software tools, the universal format IFC allows the integration between analysis areas. In this work, the area of sustainability in the AEC industry is connected to project management in the decision-making process. By doing this, it is possible to integrate both areas and implement strategic decisions in green building projects.

In its widest sense, green building is about sustainability, which is defined by [9] as "the ability to provide for the needs of current generations without diminishing the capacity for future generations to do the same". According to [10], green building should consider the triple bottom line (TBL) of financial, social, and environmental performance during the process.

Green design is about finding the balance between high-quality construction and low environmental impact. A lighter footprint means a longer-lasting planet, which is a positive aspect for the builder, client, and environment. Viewing sustainable building as a process is important because green building success is not just a matter of building with green

materials, but the combination of materials and processes to maximize efficiency, durability, and savings.

There are a number of rating systems with defined metrics that encourage taking greener approaches during design and construction to generate less impact on the environment in exchange for certifications of resource efficiency. These have been gaining attention among companies, since society and the government are increasingly more concerned about environmental impacts on the planet. Amongst them, the Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ stands out [11]. It was developed by the U.S. Green Building Council and is the primary certification used to measure and designate green buildings. However, the current software's BIM solutions are not fully appropriated to incorporate LEED calculations for the certification process [12].

Related to sustainability in the construction workspace, the term lean construction (LC) is used to define the application of lean thinking principles to the construction environment. It is a conceptual approach to project and construction management and refers to the application and adaptation of the underlying concepts and principles of the Toyota Production System (TPS) to construction. As in the TPS, the focus of lean construction is on waste reduction, increase in value to the customer, and continuous improvement. While many of the principles and tools of the TPS are applicable as they are in construction, there are also principles and tools in lean construction that are different from those of the TPS [13].

According to the Lean Construction Institute, LC is a continuous process that is applied through design, procurement, manufacturing, and construction. It is an integrated process in which clients, designers, contractors, and suppliers must be committed to working together, focusing on delivering value (as seen by the ultimate customer) rather than a low cost, and striving to get it 'right first time'.

The traditional design process, based on computer-aided design, fails to minimize the effects of complexity and uncertainty to ensure that the information available to complete design tasks is sufficient and to reduce inconsistencies within construction documents. Lean design is introduced as a way of reducing waste, unnecessary uncertainty, and improving value generation as early as in the design phase [14].

In this sense, there is a potential synergy between the BIM and LC universes, supported by new technologies and tools. This work intends to analyze how the BIM methodology and LC principles can be connected mainly in the decision-making process through the development of a software extension in a BIM environment.

1.2. Related Works

Many researchers have studied the fields of Building Information Modeling, lean construction, and sustainability both individually and pairwise. However, ref. [15] showed, through a comprehensive and structured literature review, that the interplay between the three concepts has not yet been explored. In their work, they also developed an interrelationship matrix incorporating the three dimensions. They showed that there exists a strong relationship between these fields in construction-related activities. The encountered synergies were mainly in the construction stages and in the decision-making during the conceptual design phase. Furthermore, according to the literature review conducted by Saieg et al. [15], due to the lack of interest from both academia and industry in the benefits of BIM, green, and lean integration, it is critical to investigate alternative manufacturing methods or technologies. In doing so, new studies can help in reducing greenhouse gases and carbon footprints. Also, there is a need for achieving, during the entire project life cycle, a broader sustainable scope and bringing multiple benefits to more stakeholders. The proposed holistic approach in this paper can help in partially filling this scientific gap.

These findings are the main motivation for the present research, which aims to explore the potential reduction in economic and environmental impacts through the development of a system that integrates the three concepts.

A few researchers have developed systems to investigate some of these interrelationships, but these were also limited to a consideration of at most two of the dimensions discussed earlier. These works are described in the next paragraphs.

Ref. [16] developed a design tool to evaluate environmental impacts such as solar gains and heating energy demands in buildings during neighborhoods' planning phase. However, the BIM concept is not incorporated because there is no collaboration environment with multiple players and tools, and the modeling process is based only in 3D geometrical modeling, without parametric and intelligent data attached to it.

In the work by [17], the integration between BIM and life cycle analysis (LCA) was investigated. They used a plugin named Tally to assess the green impacts caused by different building materials. Tally was the first system to connect BIM and LCA in a modeling tool, specifically Revit from Autodesk. The authors used the system in the early stages of the design of office building projects and calculated the following variables: eutrophication potential, acidification potential, ozone depletion potential, smog formation potential, primary energy demand, global warming potential, non-renewable energy, and renewable energy. They concluded that the integration of BIM and LCA in a plugin improves the decision-making process and the development of sustainable projects from the conceptual phases. However, they did not consider other metrics such as the economic impact of design decisions.

Ref. [18] used a Revit plugin, called One Click LCA, to compare distinct construction methods in building projects. He experimented with this system in two different case studies and observed problems in the data insertion process, specifically related to material definition. He concluded that the One Click LCA had satisfactory results in relation to the decision-making process, generating various scenarios related to construction techniques.

A few LCA tools exist that are not plugins implemented in a BIM environment. One such tool is SimaPro [19], which is an LCA software developed to help leaders with the decision-making process. SimaPro is capable of data collection, analysis, and monitoring sustainability indicators in projects by using an easy and systematic modeling process. This LCA tool indicates the environmental impacts throughout the entire project life cycle and highlights the hotspots present in the supply chain.

It is important to mention that there are other initiatives around the world that have similar objectives to the present study: for instance, the quantification of environmental impact and energy efficiency related to passive house wall materials [20]; the assessment of the energy impact and environmental benefits related to prefabricated components [21]; and the valuation of the environmental impact and feasibility of circular economy in the building industry through LCA [22].

2. Materials and Methods

To explore, validate, and verify some of the synergies between BIM, lean thinking, and sustainability encountered by [15], a prototype plugin was developed to implement an indicator-based system to support design decision-making through the automatic extraction of model data and conduction of sustainable assessments. The prototype was developed using the C++ language and is described next.

2.1. System Description

The system implements an indicator-based system to support design decision-making through the automatic extraction of model data and conduction of sustainable assessments. The goal is to provide a BIM-integrated system that aids the evaluation of multiple design alternatives, mainly focusing on the conceptual design stage as idealized using lean principles and required for better sustainable project development.

The developed system incorporates life cycle cost (LCC), life cycle CO₂ emission (LCCE), and thermal comfort based on heat flow indicators. However, the tool can be extended to incorporate other indicators to enable increasingly reliable and efficient decision-making support. For a better consideration of what in fact generates value to the user, the

system enables user input to vary indicators' weights (e.g., a higher weight being assigned to LCC than LCCE if the user is more concerned with costs than environmental impact).

The chosen metrics were based on the fact that CO₂ emissions are increasingly being considered by researchers in the field as a primary measure of environmental impact, since the construction industry is the main responsible party for such emissions. Despite being common knowledge that cost is always a concern not only for sustainable development but also for clients, a certain lack of concern with respect to the economic aspects could be perceived within the analyzed studies. Figure 1 presents the overall framework of the prototype.

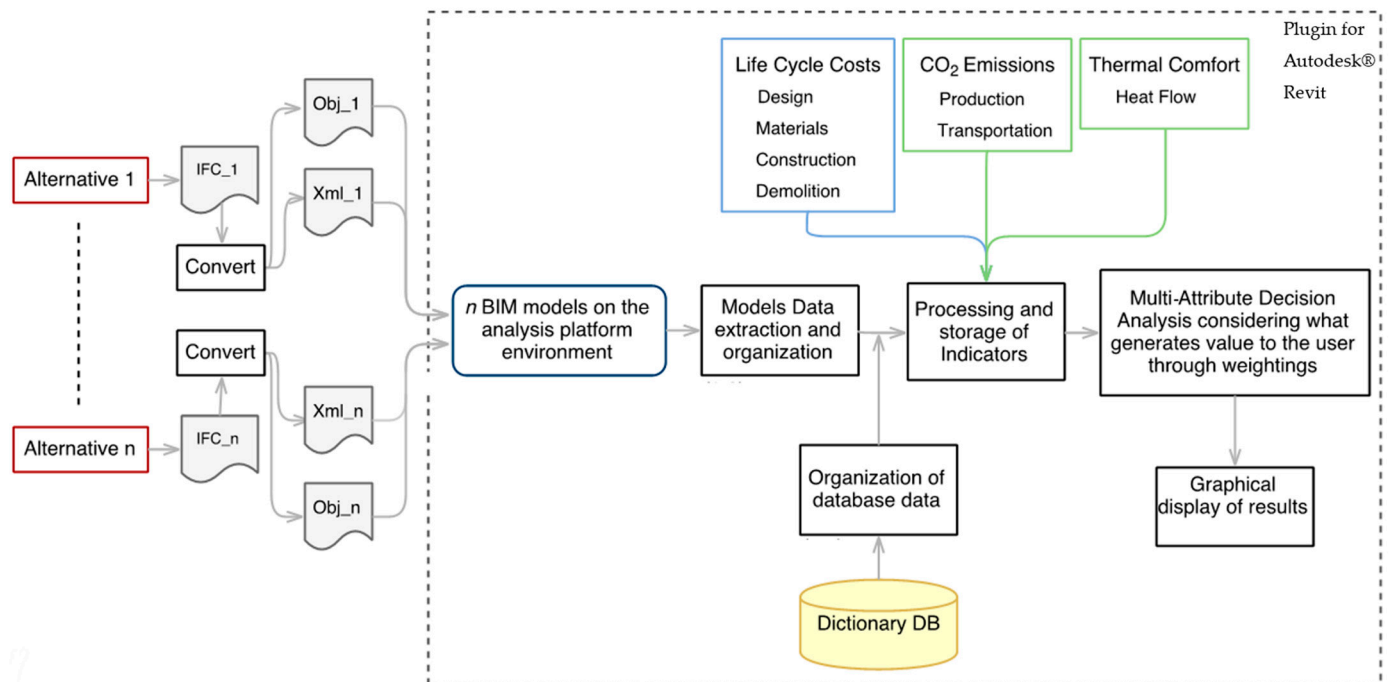


Figure 1. Flowchart of the proposed implementation.

The commercial software packages Autodesk Revit and Autodesk Navisworks were first considered for the implementation since they are capable of supporting plugins. However, it was found that, in this BIM environment, it is not possible to load multiple projects side-by-side with a clear differentiation of which element corresponds to which model, meaning that these programs could not be used. The platform adopted for this research was Environ, a 3D engineering data visualization and analysis non-commercial software developed by the Tecgraf/PUC-Rio Institute mainly to support project automation of industrial plants.

2.2. Implementation Using IFC

The model files were exported from Autodesk Revit to an IFC file developed using BuildingSMART containing geometry and object attribute data. This was performed in order to establish a single format of information flow between the systems to ease interoperability, which is one of the most prominent barriers for industry adoption of BIM, since there is no single system which is capable of doing everything.

Since the adopted platform (Environ) was not yet capable of reading an IFC file, it was necessary to first convert this IFC into an OBJ file (a geometry definition file format containing triangle mesh-based geometry) and an XML file (an attribute definition file format). The OBJ file could already be imported into the platform, while the XML could not and had to be converted. The IFC to OBJ and XML conversion was accomplished with the IfcOpenShell's IfcConvert open-source program.

With these two files in hand, it was possible to observe that each object in the XML file contained a unique tag that related to a unique object in the OBJ file with the same tag. Moreover, each object in the XML file contained a list of references that pointed to a single attribute previously defined on the XML file, as illustrated in Figure 2. Knowing this, each object and its XML file properties were associated to their respective geometry, which was already represented in the platform.

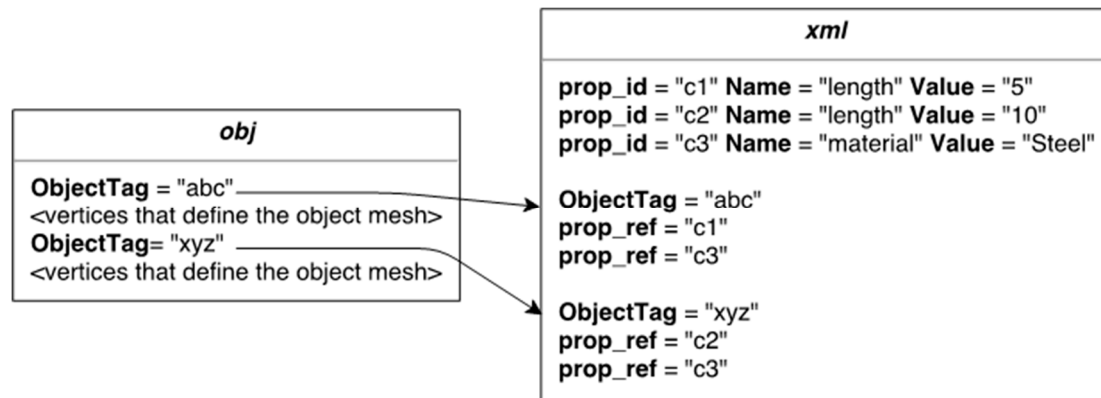


Figure 2. OBJ and XML files connection.

2.3. Adopted Indicators

To test the proposed method, life cycle costing (LCC) and CO₂ emissions were implemented as the main indicators to evaluate the example models. This is because they represent economic and environmental aspects of sustainability, and, according to the [23], whole life cost and carbon performance were identified as the key variables that can significantly influence building sustainability performance. Thermal comfort based on heat flow was also incorporated in order to emphasize further the environmental side of sustainability. Each indicator is discussed in more detail next.

2.3.1. Life Cycle Costing (LCC)

To determine the overall life cycle costs of each hypothetical enterprise model assessed in this study, the following stages were considered: design development, material acquisition, construction activities, and demolition. Calculations were made on an element-by-element basis and incremented until all the elements had been considered. This enabled the consideration of cases for which there were multiple types of materials within elements of a single category.

Costs regarding design development are usually defined as a fraction of the project costs and decrease as the volume or weight increases. Therefore, for each material within that category, the total volume (or weight, depending on material) of elements was calculated to determine the applicable range, thus enabling design cost calculations. Equations (1) and (2) apply to columns, beams, and slabs, and, for roofs and walls, only dependent on the total area of each category, the cost is calculated with Equation (3). The total design costs of each model were then calculated as the summation of the design costs per category.

$$V = \sum V_e \quad (1)$$

$$DE_C = \sum \left(MA_C \times RA_P \times \frac{V_e}{V} \right) \quad (2)$$

$$DE_C = \sum (MT_C \times A_e) \quad (3)$$

where the terms are as follows:

V = total volume of the category in m³ (may be W in kg, depending on the material);

V_e = volume of the element in m^3 (may be W_e in kg, depending on the material);
 DE_C = design cost of the category in Brazilian currency (BRL);
 MA_C = material cost of the category in BRL;
 RA_P = cost of the design in percentage, dependent on the range it falls into;
 MT_C = cost of the material design in BRL/ m^2 ;
 A_e = area of the element in m^2 .

Material costs were calculated based on volume, weight, and/or area of each element, depending on the type of material and its category, as presented in Equations (4)–(7). The calculations also considered the average factor of material loss on site, found in the literature for each type of construction material.

$$MA_C = \sum \left(V_e \times MT_{cv} \times \{1 + SL_f\} \right) \quad (4)$$

$$MA_C = \sum \left(V_e \times MT_d \times MT_{cw} \times \{1 + SL_f\} \right) \quad (5)$$

$$MA_C = \sum \left(A_e \times MT_{ca} \times \{1 + SL_f\} \right) \quad (6)$$

$$MA_C = \sum \left(A_e \times MT_{cu} \times MT_q \times \{1 + SL_f\} \right) \quad (7)$$

where the terms are as follows:

MT_{cv} = material cost in BRL/ m^3 ;

SL_f = average factor of material loss on site as a percentage;

MT_d = density of the material in kg/ m^3 ;

MT_{cw} = material cost in BRL/kg;

MT_{ca} = material cost in BRL/ m^2 ;

MT_{cu} = material cost in BRL/units;

MT_q = material quantity in units/ m^2 .

Based on the material and the element's category, it was possible to gather from the database inserted by the user the necessary input to assemble or build a particular element (e.g., a steel column requires a certain number of work hours of an assembler, as well as a laborer and a welder, each of which has a related cost value per hour). Equations (8) and (9) present the calculation procedure for the construction-activity-related costs.

$$CA_C = \sum \left(V_e \times \sum \{NR_{iuv} \times IP_{cv}\} \times \{1 + SL_f\} \right) \quad (8)$$

$$CA_C = \sum \left(V_e \times MT_d \times \sum \{NR_{iuv} \times IP_{cw}\} \times \{1 + SL_f\} \right) \quad (9)$$

where the terms are as follows:

CA_C = construction activities' cost in Brazilian currency (BRL);

NR_{iuv} = number of input units required for the activity in hour/ m^3 , m^3/m^3 , hour/ m^2 , or m^3/m^2 ;

IP_{cv} = cost of the input unit in BRL/hour/ m^3 or BRL/ m^3/m^3 ;

NR_{iuv} = number of input units required for the activity in hour/kg, hour/ m^2 , m^3/kg , or m^3/m^2 ;

IP_{cw} = cost of the input unit in BRL/hour/kg or BRL/ m^3/kg .

Following the same line of thinking, the demolition costs were calculated based on the element volumes and/or weights one by one, incrementally, until all the elements were analyzed, as shown in Equations (10) and (11).

$$DM_c = \sum(V_e \times DE_{cv}) \quad (10)$$

$$DM_c = \sum(V_e \times MT_d \times DE_{cw}) \quad (11)$$

where the terms are as follows:

DM_c = demolition cost in Brazilian currency (BRL);

DE_{cv} = demolition cost in BRL/m³;

DE_{cw} = demolition cost in BRL/kg.

2.3.2. CO₂ Emissions

CO₂ emissions during production comprises the processes of extracting and processing the raw material to obtain the desired final product. It also includes the chemical-reactions-related emissions and was calculated here as presented in Equation (12).

$$EP_{CO_2} = \sum \left(V_e \times \frac{MT_d}{1000} \times \{EF_m \times EF_r\} \times \{1 + SL_f\} \right) \quad (12)$$

where the terms are as follows:

EP_{CO_2} = emission of CO₂ gases during the production process;

EF_m = emission factor of manufacturing in tonCO₂/ton;

EF_r = emission factor of chemical reactions in tonCO₂/ton.

The CO₂ emission generated from the transportation of materials is also an important indicator. It goes beyond just considering material-related emissions, and it takes into consideration the distance between the supplier and the construction site. Equation (13) presents the calculation procedure used for this indicator.

$$ET_{CO_2} = \sum \left(V_e \times \frac{MT_d}{1000} \times TM_c \times FU_e \times DI_s \times \{1 + SL_f\} \right) \quad (13)$$

where the terms are as follows:

ET_{CO_2} = emission of CO₂ gases during the production process;

TM_c = transport modal consumption in L/t/km;

FU_e = fuel emission in tonCO₂/L;

DI_s = distance from the supplier to the site in km, accounted twice to consider the round-trip.

2.3.3. Thermal Comfort

The concept of thermal comfort refers to the condition in which one is satisfied with the environment's temperature and is assessed using a subjective evaluation [24]. To provide a comfortable environment, engineers and designers need to consider the thermal balance of the building, which, according to [25], is a principle in which the whole building is considered as an entity with a number of energy sources and sinks (where energy goes to). The energy efficiency of a building is defined through its thermal balance.

When comparing building options, heat flow can be used, among others, as an indicator to expose which alternative would need more energy in order to achieve thermal balance. This indicator only considers the external envelope of a building, i.e., the walls and the roofs, which was appropriate for the type of application being considered in this work (other indicators can be easily incorporated in the system). According to [25], this indicator can be calculated as expressed in Equation (14) for the walls and in Equation (15) for the roofs.

$$HF_W = \sum (TT_e \times A_e \times \{T_{ext} + AC_e \times SR_{eo} \times ER_e - T_{int}\}) \quad (14)$$

$$HF_R = \sum (TT_e \times A_e \times \{T_{ext} + AC_e \times SR_{eo} \times ER_e - Fac_r - T_{int}\}) \quad (15)$$

where the terms are as follows:

HF_W = heat flow on the walls in Watts;

TT_e = thermal transmittance of the element (based on its material) in $W/(m^2K)$;

T_{ext} = exterior temperature in $^{\circ}K$ (considered as $303,15^{\circ}K$);

AC_e = absorptance of the element (based on its material) as a percentage;

SR_{eo} = solar radiation based on the element's cardinal orientation in W/m^2 ;

ER_e = external resistance of the element (based on its material) in m^2K/W ;

T_{int} = interior temperature in $^{\circ}K$ (considered as $298,15^{\circ}K$);

HF_R = heat flow on the roofs in Watts;

Fac_r = factor applied to the roofs representing the fact that higher atmosphere layers present low temperatures, forcing horizontal (roof) plans to permanently lose energy through radiation, in $^{\circ}K$ (considered as $^{\circ}K$ according to the standard, based on experimental data).

2.4. Decision Making

According to [23], multiple attribute decision making (MADM) deals with the problem of choosing one alternative from a set of alternatives. In order to calculate the choice criteria in the application of most MADM methods, it is necessary to make the attribute values comparable on a common scale. Therefore, the values of each attribute are normalized separately. Normalization is the mapping of attributes to the scale $[0, 1]$. Afterwards, different procedures are applied in order to evaluate each alternative using a single value and choose the best according to the set criterion.

In the developed system, besides presenting the overall absolute calculation results for each model, options are compared based on the principle of the multiple criteria decision method. It essentially combines criteria with different units by assigning performance weights to calculate the relative score of different options. The results present both a macro performance result considering the total costs, CO_2 emissions, and heat flow and a micro performance result, in which a weight is designated to each sub-indicator as well.

The system computes the relative scores for the various design options being compared based on specified weights and identifies the best performance option by the magnitude of their scores. It employs MADM, which is a more suitable option for the multi-criteria decision analysis carried out in this work. This is because the method has the advantage of allowing the comparison of attributes with different units of measurement by means of weighting factors.

Also, the number of conceptual design options to be compared will be finite, and decisions will be based on information that is not yet finalized or complete. In addition, the method allows trade-offs among attributes as it is envisaged that no single alternative will exhibit the preferred value for all the attributes. The normalization methodology adopted here is that of [26], which is shown in Table 1.

Table 1. Normalization procedure options (adapted from [26]).

Type of Normalization	Type of Attribute	
	Benefit attribute, X_j^+ (r_{ij}^+)	Negative attribute, X_j^- (r_{ij}^-)
Simple (SN)	$r_{ij}^S = \frac{x_{ij}}{x_j^*}$	$r_{ij}^S = \frac{x_j^-}{x_{ij}}, x_{ij} > 0$
Njikamp's (NN)	$r_{ij}^N = 1 - \frac{x_j^* - x_{ij}}{x_j^* - x_j^-}$	$r_{ij}^N = 1 - \frac{x_{ij} - x_j^-}{x_j^* - x_j^-}$

The desirability score for each option is given by Equation (16), where the sum of weights must be equal to 1. It gives the summation of the contribution of each attribute with respect to the cardinal numerical score for each alternative conceptual design solution. The most favorable option will be the solution with the highest desirability score.

$$D_j = \sum_{i=1}^n w_i \times r_{ij} \quad (16)$$

where the terms are as follows:

D_j = desirability score for a particular alternative (max = 1);

n = number of attributes associated with the alternatives;

w_i = weight of the attribute or criteria.

2.5. System Flowchart

To understand how this system works, a flowchart was developed, and it is shown in Figure 3. As can be seen, it starts with the indicators' input; then, the model is read, and the elements (e.g., column, beam, etc.) are identified and stored. After that, a database file is imported by the user, and the calculations are performed, relating the elements to the properties in the database. The calculation process is incremental, meaning that, for each category, the total value of a certain metric is incremented element by element, allowing elements to have different materials in the same category, as exemplified in Equation (17).

$$EP_{CT} = EP_{CT} + EP_{CE} \quad (17)$$

where the terms are as follows:

EP_{CT} = total material production emissions of columns in tons of CO₂;

EP_{CE} = material production of a single column element in tons of CO₂.

The user interface of the developed plugin is presented in Figure 4. When the "Indicators" button is pressed, the "Decision Support" window is opened. The first button in the "Decision Support" box is responsible for going through each element of a model, reading the element's "Family" attribute to identify to which family group it belongs. The second button calls a function that opens a dialog for the user to select the XLS (Microsoft Excel format) database file to be imported. The third button does all the calculations presented previously, and the fourth button opens a dialog with default values for the weights, as presented in Figure 5. It should be noted that these weights can be modified by the user. Finally, when the user presses the "OK" button, the plugin verifies if the summation of both micro and macro weights is equal to 1, and, if so, it displays graphics to ease user understanding of which alternative is the best option along with the reasons why it is so.

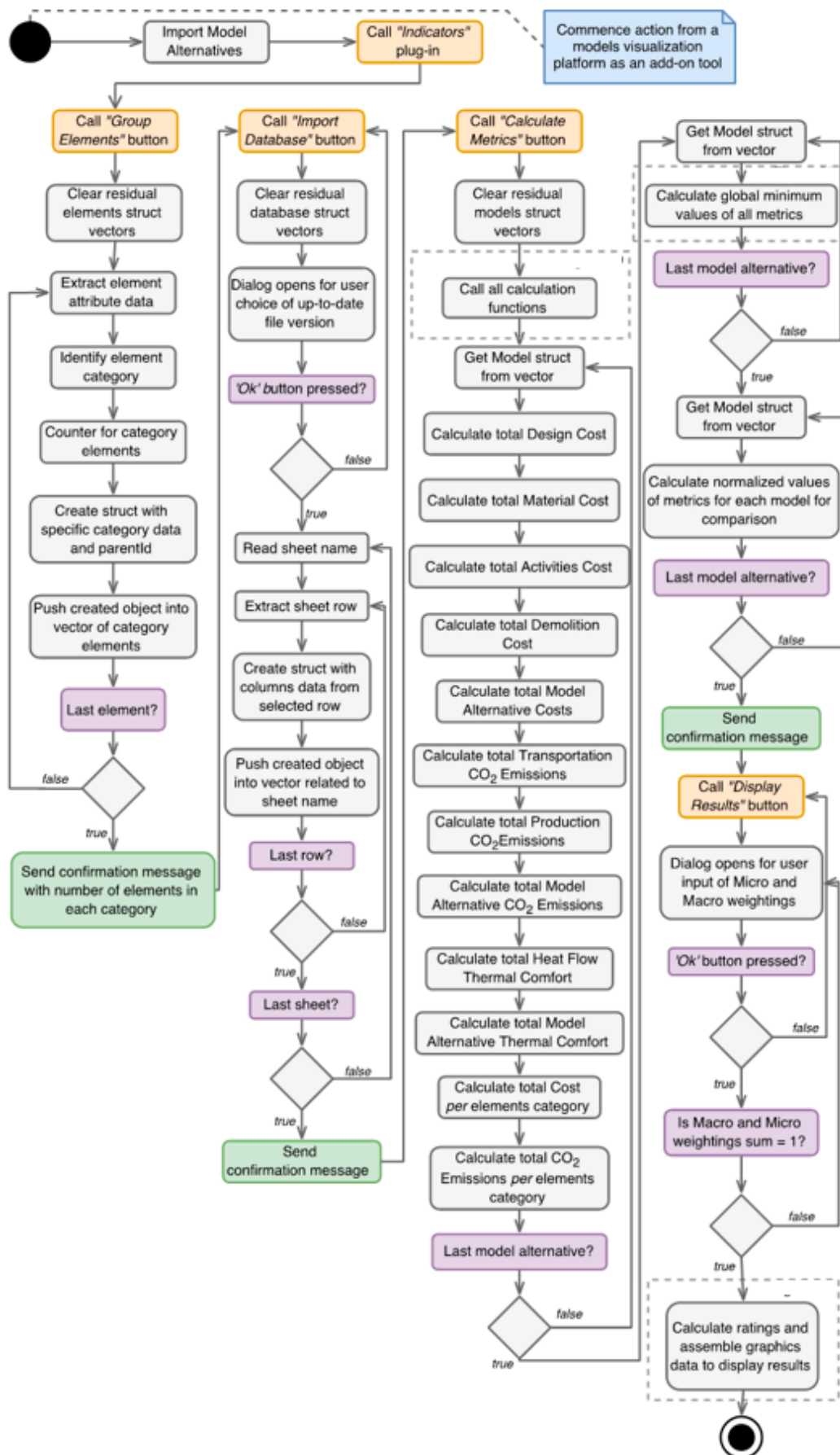


Figure 3. Overall algorithm flow of the developed system.

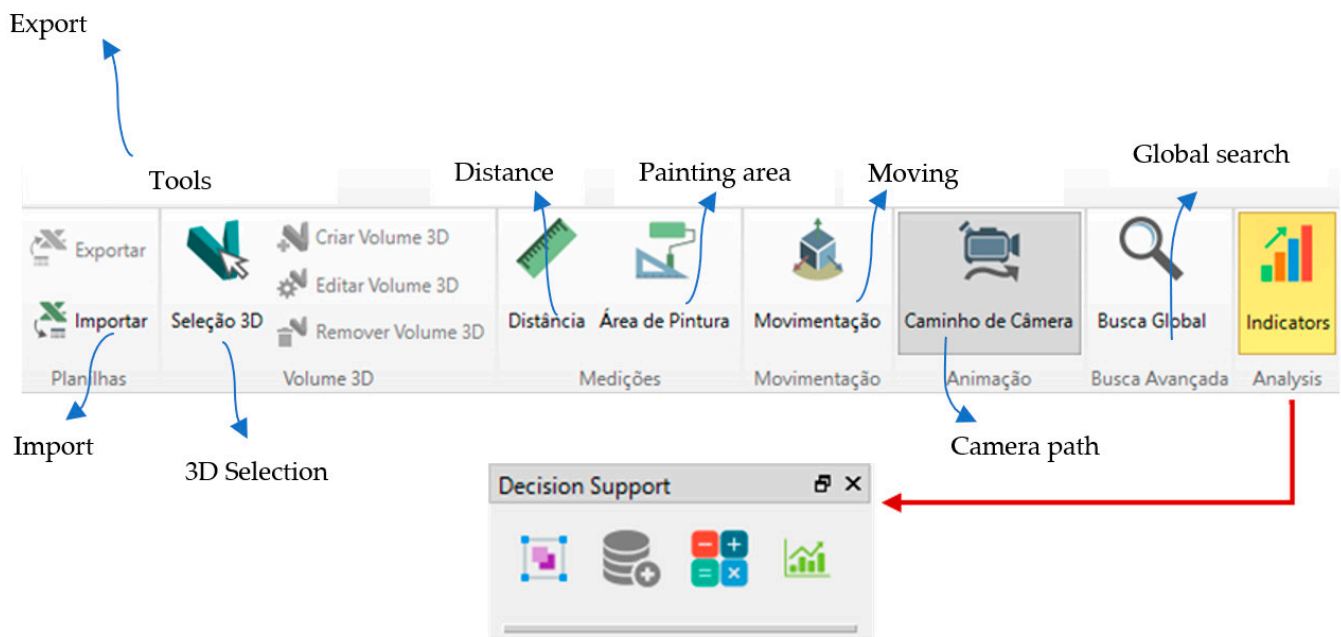


Figure 4. Buttons responsible for initiating the system and its functions.

Macro Level Weightings	
LCC	0.4
CO2 Emissions	0.4
Thermal Comfort	0.2
Micro Level Weightings	
Design Cost	0.1
Material Cost	0.2
Activities Cost	0.1
Demolition Cost	0.1
Production CO2 Emissions	0.1
Transportation CO2 Emissions	0.2
Heat Flow Thermal Comfort	0.2

Figure 5. User weightings input window and default values.

3. Case Study

To illustrate the usability and effectiveness of the proposed methodology, four hypothetical warehouse models were developed, seeking to mainly comprise different structural framing typology possibilities, while also considering varied types of roofs, walls, slabs, and dimensions. For the four examples, three different types of structural solutions were considered: steel truss-based solution (Figure 6a—Model 1; Figure 6d—Model 4); solid steel beams and columns (Figure 6b—Model 2); and a solution based on pre-cast concrete elements (Figure 6c—Model 3). The developed models are shown in Figure 6.

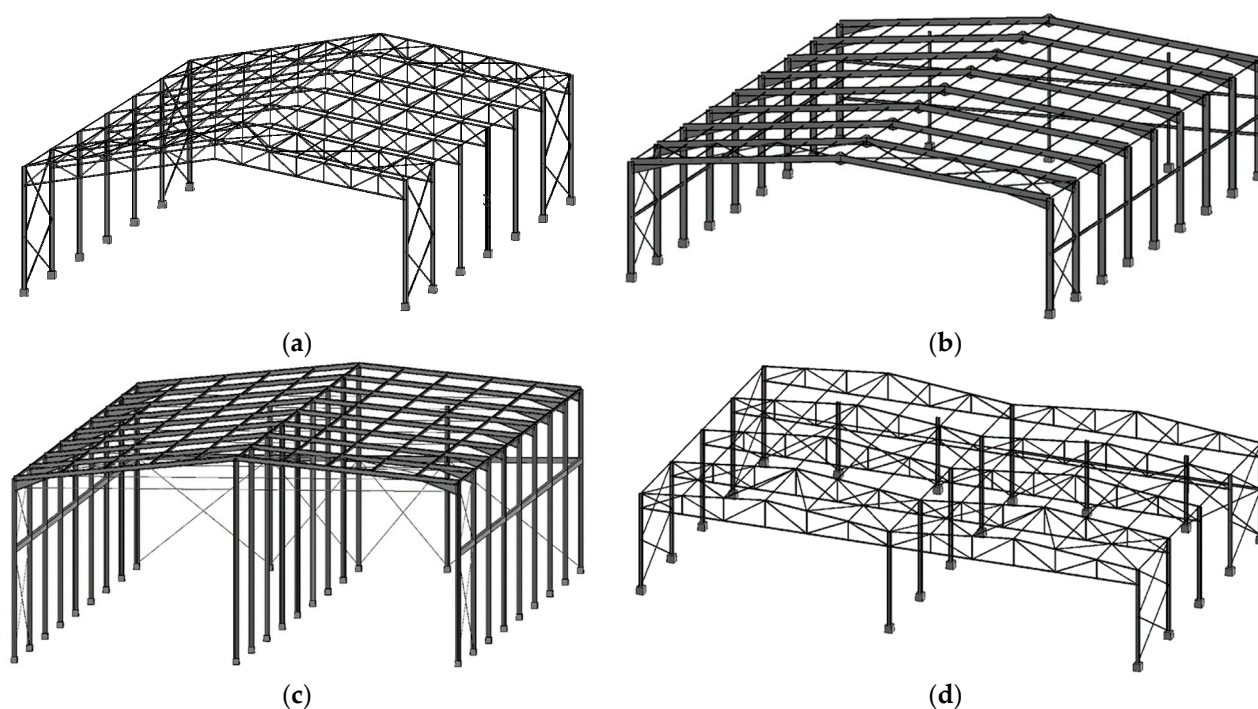


Figure 6. Project solutions used as examples in this case study. They are as follows: (a) steel truss-based solution type A; (b) solid steel beams and columns; and (c) a solution based on pre-cast concrete elements; (d) steel truss-based solution type B.

The structural designs of all these models were thoroughly verified using the software Autodesk Robot Structural Analysis and then exported to the software Autodesk Revit 2018, where the plugin was implemented. In the Revit environment, the architectural components were chosen and added to the model.

It is important to report that problems were detected during the exchange process between the two software packages. They were as follows: the connections and reinforcements modeled in Autodesk Robot were not recognized when imported into Autodesk Revit, and double L-shaped sections modeled in Autodesk Robot caused Autodesk Revit to crash. Finally, some sections available on the Autodesk Robot database could not be verified when dimensioning calculations were undertaken.

Since the commercial software packages used in this research, namely Autodesk Revit and Autodesk Navisworks, cannot load multiple projects into the same environment side-by-side with a clear differentiation of which element corresponds to which model, they could not be used for the visualization step. The chosen platform adopted in this research was Environ, a 3D engineering data visualization and analysis non-commercial software developed by the Tecgraf/PUC-Rio Institute mainly to support project automation of industrial plants.

However, since this platform could not read an IFC file, it was necessary to first convert this IFC into an OBJ file (a geometry definition file format containing triangle mesh-based geometry) and an XML file (an attribute definition file format). This IFC to OBJ and XML conversion was accomplished with the IfcOpenShell's IfcConvert open-source program. With these two files in hand, it was possible to relate each object and its XML file properties with their respective geometry, already represented in the platform.

After the association was properly conducted, all four models could be simultaneously loaded onto the Environ platform, as illustrated in Figure 7. Whenever an object is selected, its attributes and associated values retrieved from the IFC file are shown on the right-hand side window. After loading the models in the environment and running the required steps, the results are displayed graphically on separate windows, as will be described in the next section.

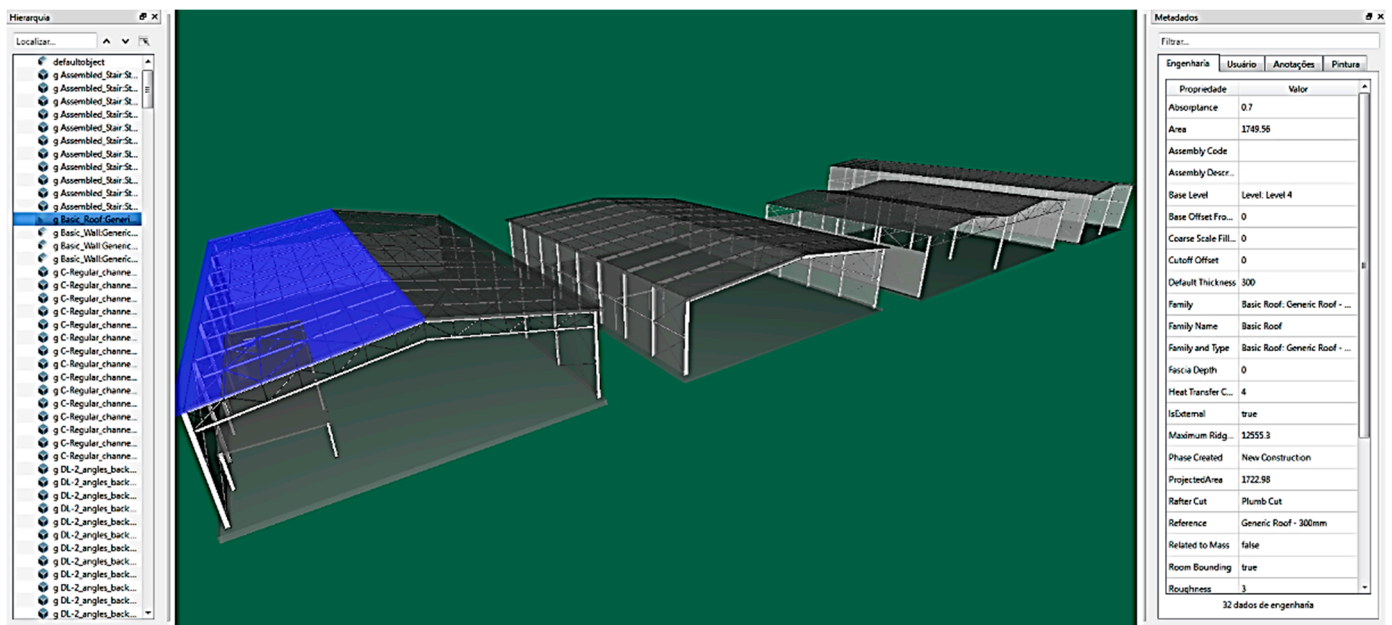


Figure 7. View of the models and object properties on the platform.

4. Results and Discussion

In this section, the results from the analysis of the four warehouse designs considered in this research are presented. The charts shown in Figure 8 display the expected costs of each design alternative (in thousands of BRL), with the first chart displaying the results for each stage of the project’s life cycle and the second for each examined category of the elements.

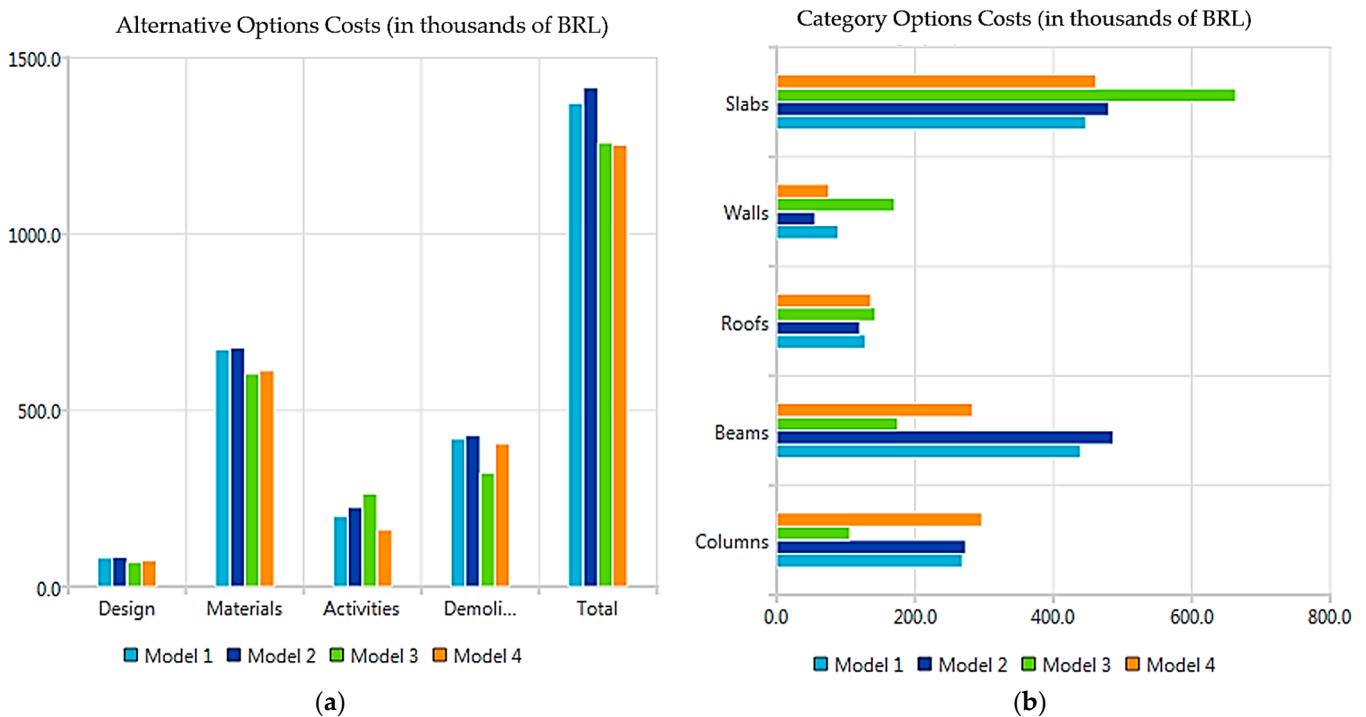


Figure 8. Expected costs of each model, organized as follows: (a) per project stage; (b) per element category.

For this example, as can be seen in Figure 8, alternatives 3 and 4 presented lower total costs even though, when analyzed per category of elements, model 3 displays considerably

higher costs for the slabs and walls. It is interesting to mention that these two design alternatives have considerably lower beam/column costs, which directly influenced the results. This is because both of them have columns in the middle of the span, a point which was considered within the hypothetical client design scope as a possibility.

The charts in Figure 9 show the environmental impact in terms of CO₂ emissions into the atmosphere expected for each of the loaded design alternatives (in tons of CO₂). The first of the two charts displays the overall model emissions due to the materials' production and transportation to the building site, and the second chart breaks down the contributions for each category examined. As can be seen in this figure, alternative design option 3 presented the highest total level of CO₂ emissions, while models 1 and 4 showed considerably lower overall emissions. This result can be explained because of the significant differences between the walls and roofs categories when compared to the other models, and it becomes clear in Figure 9b. These results also indicate that, at least for the analyzed scenario, the CO₂ emissions due to the transportation of the materials to the site are basically the same for all the alternatives.

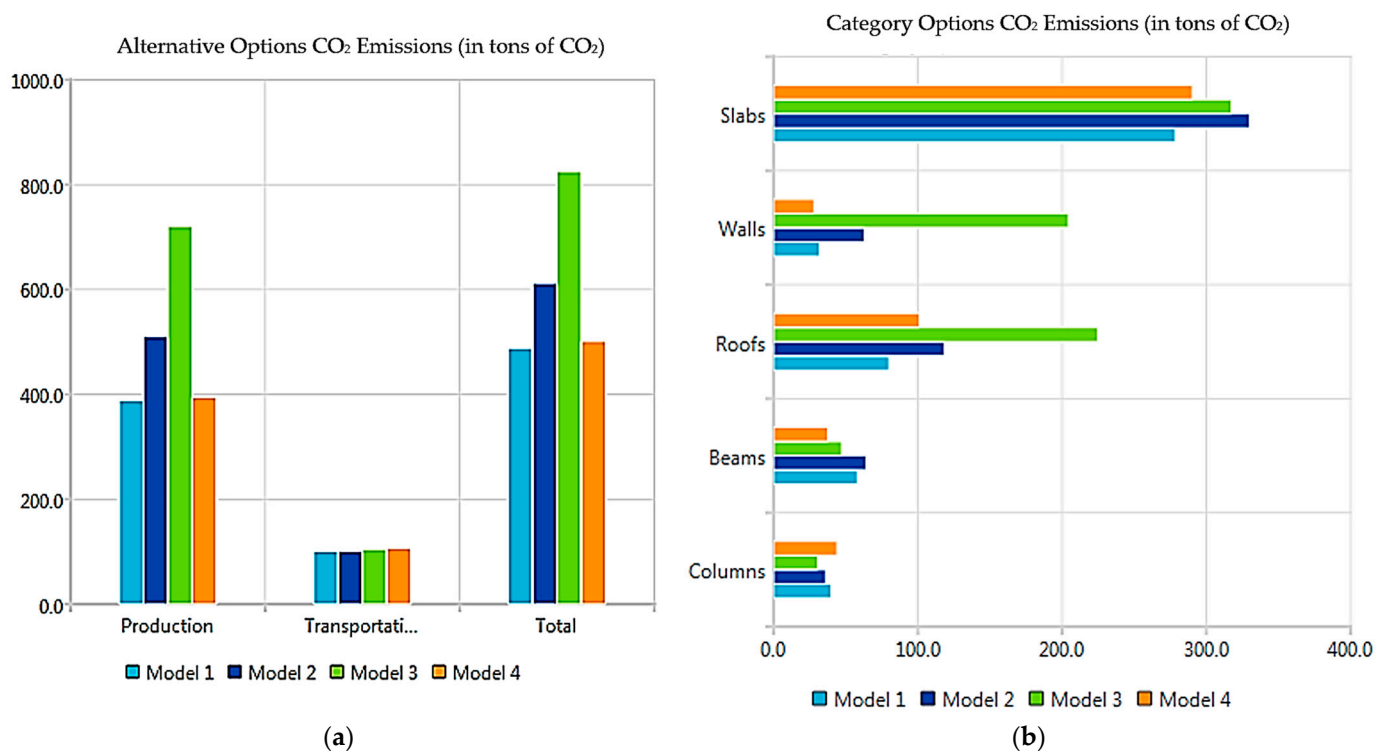


Figure 9. Simulated CO₂ emissions of each model organized as follows: (a) per project stage; (b) per element category.

Figure 10 shows the charts that compare the thermal heat flow (in Megawatts) simulated for each design option and break it down for each category. Only the walls and the roofs were considered in the simulation, since only the envelope of a building influences these results.

As can be seen in this figure, the results for model 2 have a large discrepancy in terms of the heat flow that goes into the building when compared to the other models. This could be explained by the choice of material used for the roof, which was aluminum, which is a greater thermal conductor than the other materials selected for the other three options. As can be seen, the roof on model 3 presented the best performance, which confirms the importance of using thermoacoustic tiles. However, model 3 did not present the overall best heat flow performance because its walls are partly made of metallic materials.

The two final charts shown in Figure 11 display the overall performance of each model based on the considered indicators and weights input by users using the multiple attribute

decision method. The charts present the normalized performance values of each macro indicator and the overall alternatives' performance considering default micro and macro weights.

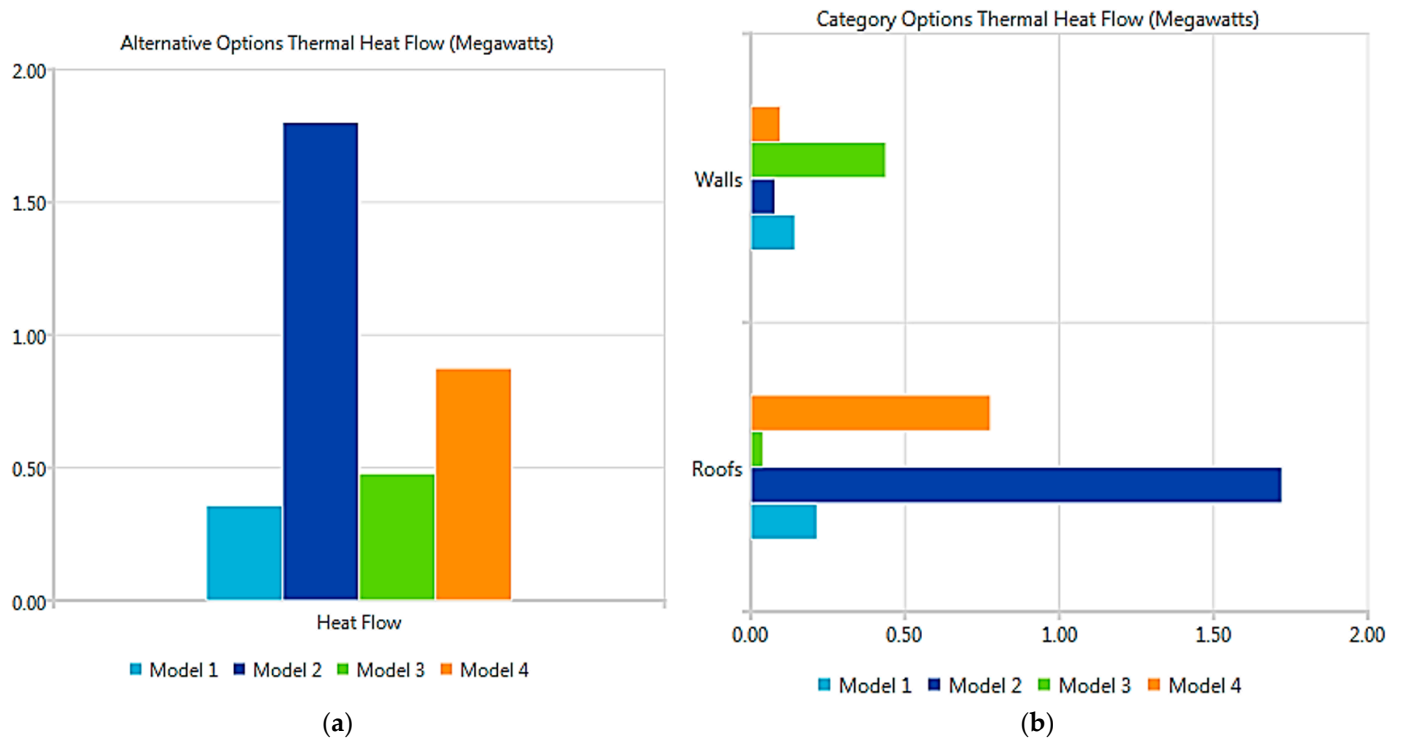


Figure 10. Simulated heat flow on each alternative model organized as follows: (a) overall; (b) per element category.

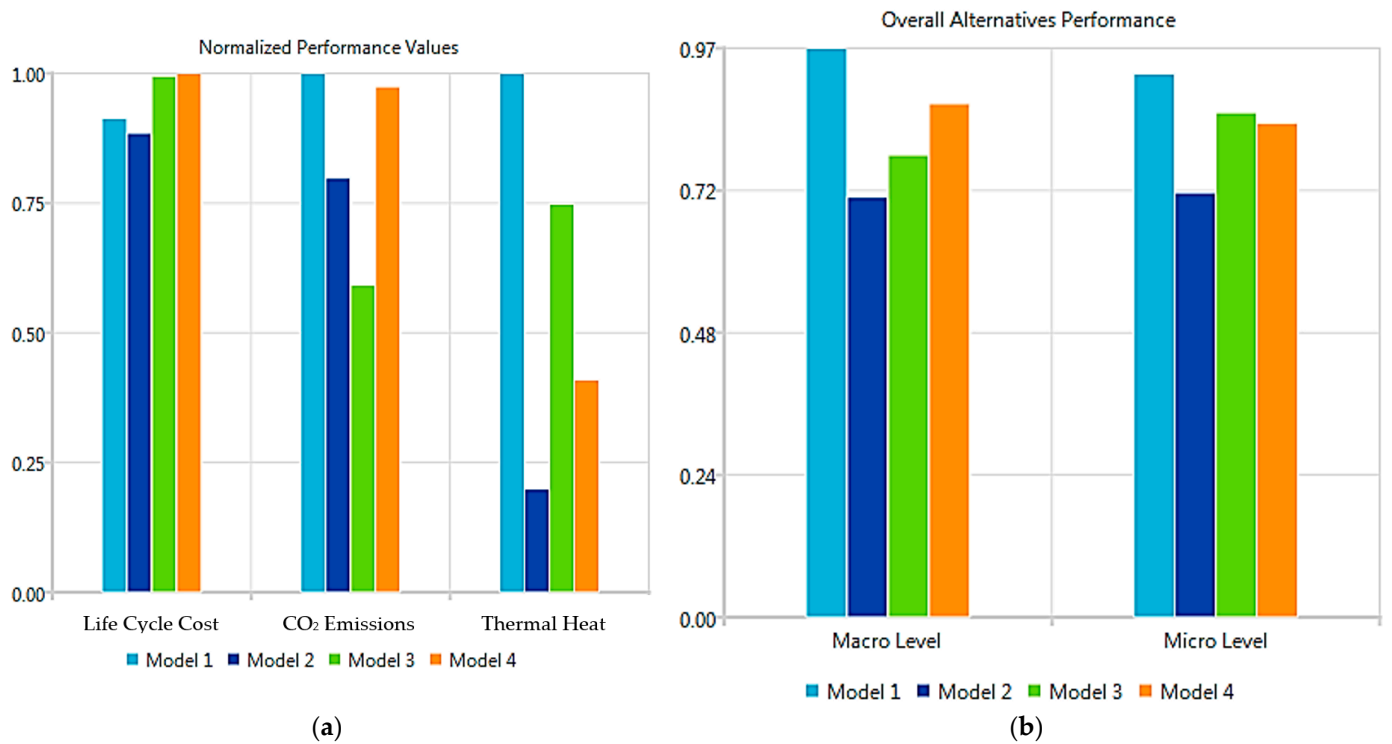


Figure 11. Calculated performances, as follows: (a) with normalized performance values; (b) overall alternatives' performance considering default weightings.

As can be seen in Figure 12, the larger performance differences among the models are related to the CO₂ emissions and the thermal heat flow, while the costs of the design options are less discrepant. An overall analysis of the results obtained from the conducted analysis points to model 1 as the overall best design option within the hypothetical scenario.

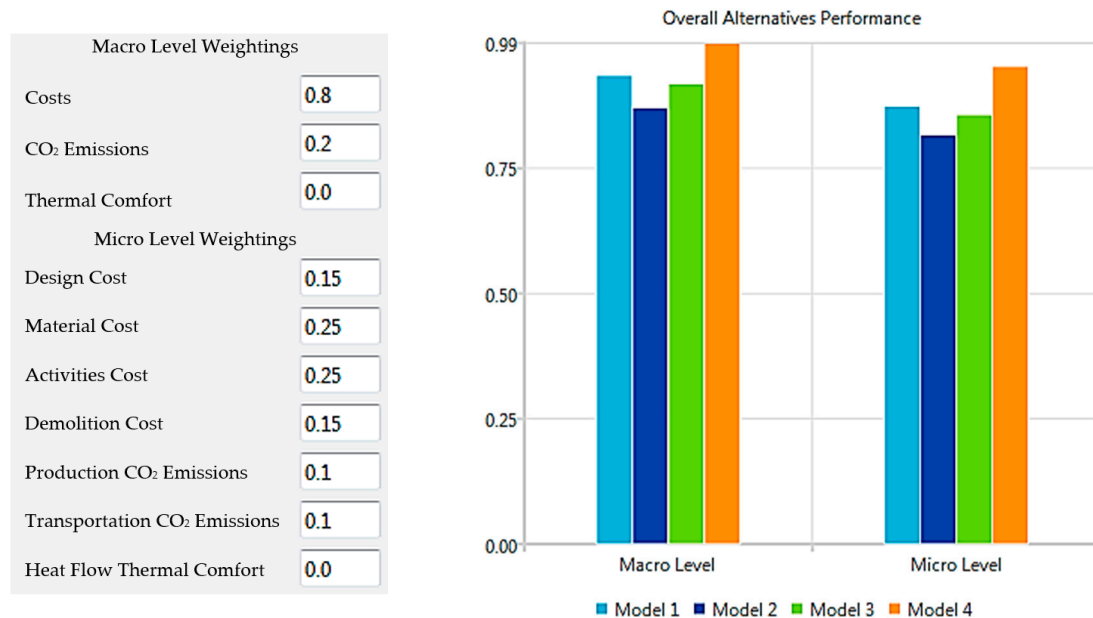


Figure 12. Simulation of different user inputs of weightings and the shift in the best design solution.

It is interesting to observe that the final result is greatly influenced by the user's perspective of value generation. If, for instance, a user was to define other indicator weights, the overall best performance design option may change, as illustrated in Figure 9, in which the best option shifts to model 4.

As can be seen from this case study, the developed system enables an automated process to analyze design alternatives early on during the design process, which is a very important line of research and development for the construction industry. From this research, it also becomes clear, as previously reported in the literature, that IFC interoperable file formats are viable but still lack information to support better and more automated sustainability assessments.

Finally, it is important to mention that the proposed system is scalable since it can include other features. As the industry shifts to a BIM-based process of project development, the system can be augmented to support innumerable indicators and different categories of elements. It is important to notice that automation of the analysis process becomes increasingly necessary as more features are considered.

5. Conclusions

The present work evaluates and validates how BIM functionalities can foster the consideration of lean construction and sustainability principles and help the decision-making process in the conceptual building design phase. To achieve this, an indicator-based (e.g., life cycle cost, life cycle CO₂ emissions, etc.) BIM system was developed and tested. The developed system automatically extracts model data to analyze multiple design alternatives. Furthermore, the system is extendable to accommodate the incremental addition of indicators. It supports a user's input of weight factors and determines normalized performance ratings. It displays the results graphically to support decision-making according to what the user values most. The prototype BIM system was implemented and tested on hypothetical models considering aspects that could be observed from BIM–lean–green principles interactions.

It was found that implementing the indicator-based system in a BIM environment enabled process automation, since the data from the model were readily available. From the results obtained in the case study, it can be concluded that an integration of BIM and lean principles to support sustainable development in the construction industry is not only possible but also facilitates the process. Finally, the results from the case study indicate that the developed system can be a great asset in supporting the decision-making process of design alternatives and that it can be used to understand the impact of design changes.

As for future research work, the developed framework could be further validated using practical evidence. Also, additional indicators could be implemented to make the system even more robust, and more complex calculation methods could be adopted, mainly related to the thermal comfort indicator. Also, it would be useful to integrate the system with GPS systems to automate the use of geographical coordinates-dependent indicators. Finally, policy recommendations for long-term growth in the construction sector include clear government-defined standards for both the public and private sectors. This includes implementing a carbon standard calculation for prefabricated buildings to reduce waste and environmental impact, promoting the use of BIM—which is already widely used in many countries (e.g., the United Kingdom and Italy)—to reduce CO₂ emissions during the operational phase of building and instituting environmental taxes. Furthermore, emphasizing eco-efficient practices in environmental logistics as well as incorporating Sustainability Literacy Results (SLR) to guide governmental investment and management strategies are critical to achieving long-term performance across the industry.

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