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# Integrated Framework for Optimizing Environmental Impact of Construction Activities in Cairo: A BIM, and LCA Approach

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## ABSTRACT

The global movement towards sustainability and eco-conscious practices is driving efforts to address issues such as carbon emissions, landfill overflow, and resource depletion. With the construction sector being a significant contributor to greenhouse gas (GHG) emissions, particularly in developing nations, there's an urgent need to quantify and mitigate these emissions. This study introduces an innovative framework that integrates advanced methodologies, including building information modeling (BIM), life-cycle assessment (LCA), and the quantification of embodied emissions. The aim is to optimize various aspects of construction processes, such as design, material selection, operations, maintenance, and waste management. To demonstrate the effectiveness of this approach, a real-world case study is conducted in Cairo, Egypt. Firstly, a BIM model is created to represent the building, capturing its physical and functional attributes. Subsequently, a comprehensive LCA is performed to evaluate the environmental impacts across the building's life cycle stages. Using mathematical analyses, embodied emissions associated with waste handling and transportation to disposal sites are calculated. Furthermore, targeted mitigation strategies are proposed and implemented. The case study results indicate significant reductions in GHG emissions across different phases of the building life cycle, with a 30% reduction during the materialization stage, 15% during the operational stage, and 14% during the end-of-life phase. This underscores the importance of proactively assessing and addressing environmental impacts associated with construction activities, offering opportunities for sustainable development in Cairo and beyond.

## 1. Introduction

The construction industry stands as a significant contributor to environmental degradation, with its activities generating substantial carbon emissions and waste production. In Cairo, Egypt, where construction projects are prevalent, there's a pressing need to adopt sustainable practices to mitigate these environmental impacts. Globally, the construction sector generates 38% of green-house gas emissions, consumes 40–50% of all raw materials and 30–40% of energy. (Seyis, 2020). In Cairo, the annual production of construction materials is considerable, worsening the issue of waste generation. Additionally, extensive construction activities in Egypt, particularly in Cairo, have a significant impact on the country's natural resources.

To address these challenges, there is an increasing emphasis on adopting approaches that promote circular economy and reduce energy consumption, greenhouse gas emissions, and waste production. Sustainable and environmentally friendly practices are increasingly being promoted to tackle issues such as GHG emissions, Energy consumption and resource reduction. In this context, integrating innovative construction materials, advanced mitigation strategies, modern designs, and digital technologies becomes an obligation to repair the environment.

The literature offers various approaches to mitigate the environmental impacts of construction activities in the building sector. Life-cycle assessment (LCA) has emerged as a valuable tool for evaluating the environmental impact of projects. Studies have utilized LCA to identify and analyze phases of the building life cycle with the highest environmental impact and assess the energy use and GHG emissions of different buildings typologies. Additionally, the integration of building information modeling (BIM) with Life Cycle Assessment LCA has shown promise in enhancing sustainability practices assessments by updating data management and analytical processes.

Recent research has explored the integration of BIM and LCA to overcome the limitations of traditional LCA methods, such as over-time consumption and manual data entry requirements reducing the expected error percentages. Mathematical analyses have also been utilized to quantify GHG emissions intertwined with construction activities, offering insights into mitigation strategies for reducing environmental damage.

This paper proposes an innovative approach to integrate BIM, LCA, and mathematical analyses for GHG emission quantification to develop an efficient estimation and evaluation framework covering all phases of the construction life cycle. Through a real-world case study in Cairo, Egypt, mitigation strategies such as optimized design and sustainable material selection are implemented to validate the approach's efficiency. The re-evaluation of all phases with improved materials and processes promotes the potential for sustainable and eco-friendly construction practices in Cairo and similar contexts. This integrated approach empowers designers and construction managers to assess and mitigate environmental impacts, paving the way for the construction of more sustainable structures in Cairo and beyond.

## 2. Research Questions

- Research Question 1: What are the main methodological aspects for the application of Life-cycle Assessment (LCA) to buildings?
- Research Question 2: How can Life-Cycle Assessment (LCA) techniques integrate with Building Information Modelling (BIM) tools?
- Research Question 3: How can we produce an efficient framework for design decision making using BIM- LCA integration?

## 3. Research Objective

The primary objective of this research is identifying the principal tools used for the integration of BIM-LCA to produce an efficient framework that promotes sustainable mitigation strategies in the early design stages.

## 4. Literature Review

### 4.1. Life-cycle assessment (LCA)

Life-cycle assessment (LCA) is a valuable methodology primarily focused on assessing social and environmental impacts, commonly utilized across various sectors including automotive design, equipment production, and consumer goods manufacturing. (Tam et al., 2022)In the construction industry, LCA has been employed since the 1980s and underwent standardization in the 1990s through workshops and publications.(Zubair et al., 2024) It is typically used to evaluate the environmental effects of buildings throughout their lifecycle, containing stages such as raw material extraction, production, construction, maintenance, and demolition as shown in figure 1. Architects and designers leverage LCA to compare the environmental impact of different design choices and make informed decisions, such as selecting for sustainable materials with lower carbon footprints.(Rezaei et al., 2019) While LCA databases are specific to areas of study, they provide valuable insights for decision-making in construction projects, contributing to the growing adoption of LCA in the sector.

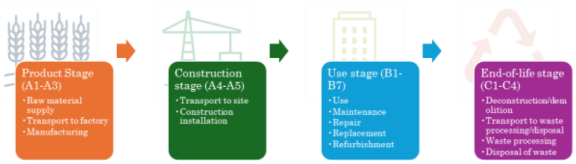


**Figure 1 Life cycle stages for building products by Author.**

### 4.2 Greenhouse Gas (GHG) Emissions

The greenhouse gas (GHG) emissions of buildings can be categorized into embodied and operating emissions.(Cavalliere et al., 2019).Embodied emissions arise from activities like raw material extraction, production, transportation, construction, demolition, and landfill emissions, while operating emissions stem from daily energy consumption for heating, lighting, air conditioning, and water supply and have increased by 19%. (IPCC, 2014) Historically, evaluations of building GHG emissions focused primarily on operational energy consumption, overlooking embodied emissions.(Zubair et al., 2024). However, there is a growing recognition of the importance of considering both aspects to comprehensively address GHG emissions in the construction sector.

### 4.3 Building Information Modelling (BIM)

Building information modeling (BIM) is a comprehensive digital framework that preserves project data and design information throughout the building's lifecycle.(Cavalliere et al., 2019). BIM enables precise environmental performance assessments and sustainability improvements by integrating multidisciplinary information within a single model.(N & Padala, 2024). The concept of "green BIM" has gained traction in the industry, referring to the use of BIM tools to achieve sustainability objectives. Despite the potential of BIM for enhancing environmental sustainability, its adoption in green construction projects remains limited, highlighting opportunities for further exploration and utilization.(Zubair et al., 2024).

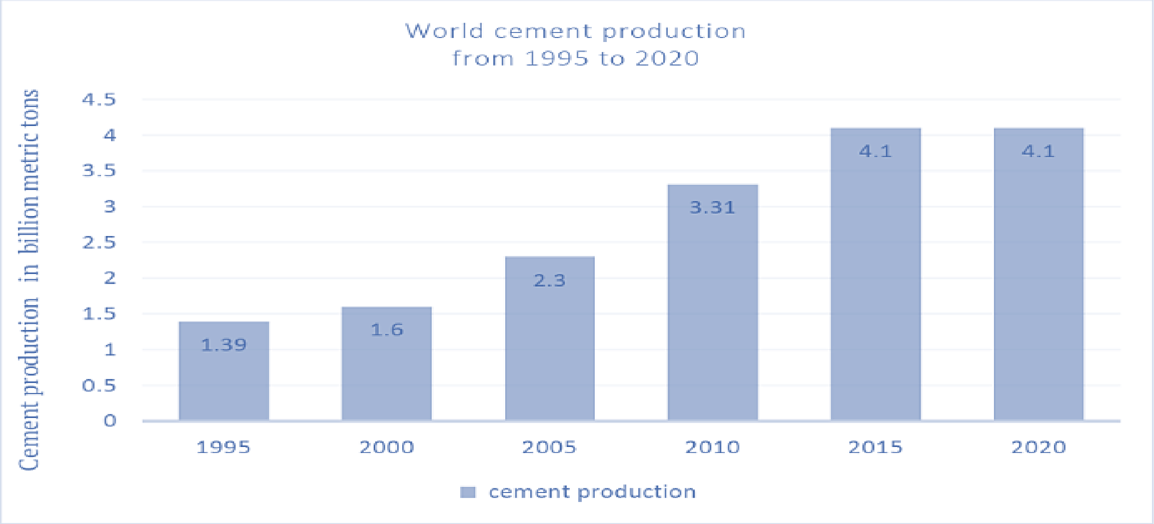
### 4.4 BIM-LCA Integration

BIM facilitates the implementation of comprehensive LCA for various types of buildings.(Seyis, 2020). Researchers have developed methodologies using BIM to assess embodied energy and optimize building systems to reduce life-cycle costs.(Zheng et al., 2023). There is significant potential for BIM and LCA integration to overcome the limitations facing sustainable design decision making specifically in the early stages of design.(Rezaei et al., 2019). BIM- LCA integration helped produce mitigation strategies that promotes sustainable practices Such as: creating buildings that minimize environmental impact while pushing economic and social development (Anton and Diaz, 2014). Several case studies of BIM and LCA integration in the building industry demonstrate that, through this approach, it is possible to obtain quick and reliable results about the environmental impact of a building, even at an early design.(Rezaei et al., 2019). BIM-LCA integration can be classified into five principles. These are data extraction, data exchange, data flow, automation degree and application. (Zheng et al., 2023). BIM-enabled LCA accelerates the collection of life-cycle inventory data and enhances simulation accuracy, yet there is a need for continued improvement and harmonization of BIM and LCA technologies.

## 5 Material Selection

### 5.2 Green Concrete.

CO2 emissions are associated with the consumption rate of construction materials in the building sector worldwide. The high consumption of concrete represents a challenge since cement production contributes around 8% of the carbon emissions globally.(Chen et al., 2023).



This is directly reflected in the rate of cement production which increased from 1.39 billion tons in the year 1995 to 4.1 billion tons in the year 2020.(Marey et al., 2022).

**Figure 2 Global cement production from 1995 to 2020, in billion metric tons. By Marey et al., 2022.**

As a result, by 2010, cement accounted for 36% of the 7.7 Gt CO2 emissions from the construction industry.(Marey et al., 2022). Therefor substituting the regular concrete to green concrete is expected to result in reduction of embodied carbon emissions leading towards an effective mitigation strategy for carbon neutrality.(Chen et al., 2023). Recently, the use of alternatives to cement, including solid wastes from the construction industry such as marble and granite waste, has rapidly increased.(Nasr et al., 2020). These waste materials are preferred because of their abundance, low energy consumption, zero cost, and required binding properties, which fulfil the characteristic of suitable construction materials.(Sivakrishna et al., 2020).

### 5.2 Neopor GPS Insulation.

As new constructions are characterized by reduction in carbon footprint and energy consumptions, more attention should be given to the embodied components such as the Embodied Carbon in building materials construction industry. (Izaola et al., 2023). Insulation materials have an effective role in the reduction of carbon emissions in buildings and improve their environmental profile. (Juanicó & González, 2017). Expandable polystyrene (EPS) is a common insulating material but due its high density and embodied carbon kgco2/kg it has increases the carbon footprint in the building sector. A new insulating material named Neopor Graphite Polystyrene which is composed of additional micro-sized graphite leads to a better insulation property. It reduces the Density of EPS sheets by 20% .(Juanicó, 2020).

### 5.3 Rubber Sheets (Damp-proof Membrane.

Rubber Sheets has good resistance properties to hydrolytic and acids, it is not degraded by microorganisms and has low gas permeability. Additionally, its relatively low density and embodied carbon compared to bitumen felt/sheets, which is commonly used, presents it as the best alternative eco-friendly material.(F D Z & D, 2015).

### 5.4 Cork Tiles.

Traditional ceramic tiles are the base products which can be applied anywhere, but due to their high embodied carbon their impact on carbon footprint is high. On the other hand, new cork tiles are produced by addition of porcelain which has better acoustic and thermal properties than ceramic tiles. Furthermore, it has lower embodied carbon and lower density. (Izaola et al., 2023).

## 6. Methodology

To mitigate and assess the environmental impact of buildings across their lifecycle stages, this research proposes a comprehensive framework integrating different tools and methods, including Life Cycle Assessment (LCA), Building Information Modeling (BIM), and quantification of greenhouse gas (GHG) emissions. The efficiency of this framework is analyzed through a real-world case study aimed at reducing GHG emissions in the construction sector. By combining various tools and methods, the framework facilitates efficient evaluation and timely adoption of sustainable strategies. The proposed model framework is illustrated in Figure 1.

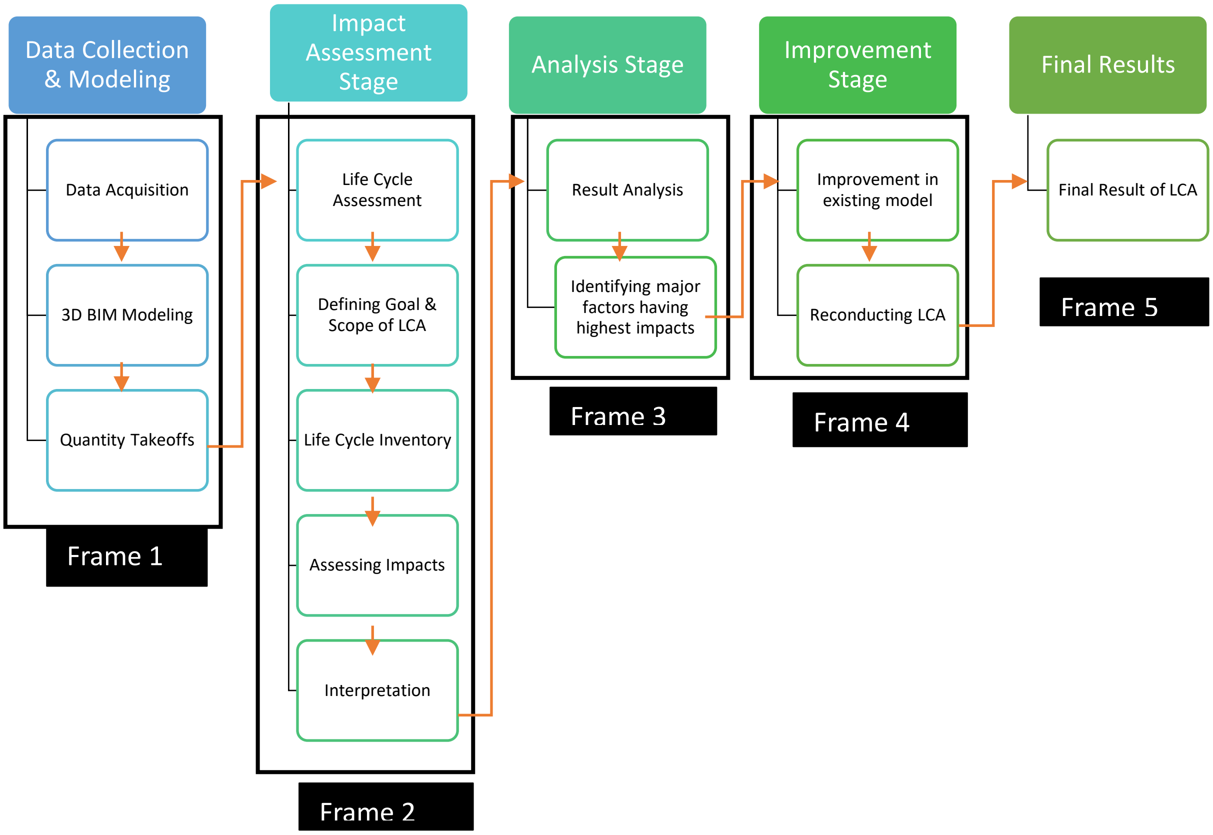


*Figure 3. Proposed framework by Author.*

Creating a detailed 3D BIM model of the building with functional and physical features is essential for assessing its overall efficiency performance. In the proposed framework, the first step involves gathering data to develop an accurate BIM model. This BIM model, along with related information, forms the foundation for the impact assessment, analysis, and improvement stages of the framework. Although various modeling software capable of BIM integration are available, Autodesk Revit-2023 is chosen for this research due to its built-in features for developing an efficient estimating model and resolving interface issues. Additionally, Revit platform facilitates this requirement by incorporating comprehensive building data, including walls, floors, roofs, structures, windows, doors, etc., and offering various customization options through 3D objects known as "families." The procedure is illustrated in Figure 2.

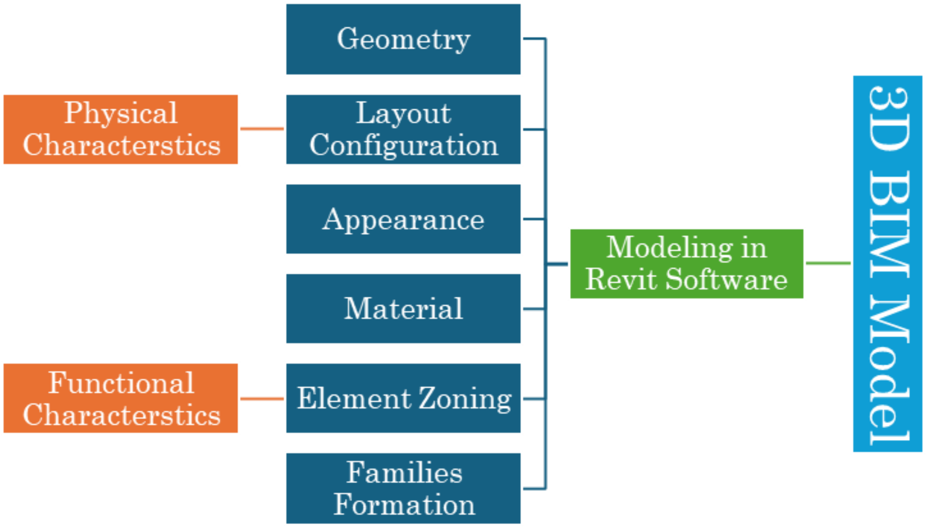


*Figure 2 Procedure for developing 3D BIM model in Revit by Author.*

Consistent modeling using standard naming practices in the material database is crucial for reliable LCA findings. Incorporating all life-cycle stages, from the creation of materials to the end-of-life phase of a building's lifespan, the LCA aims to comprehensively analyze its environmental impact. During the design process, particular attention should be given to reducing embodied impacts, which include structural, architectural, mechanical, and electrical components. The stages integrated into the LCA process are illustrated in Figure 3 below.

Frame 2

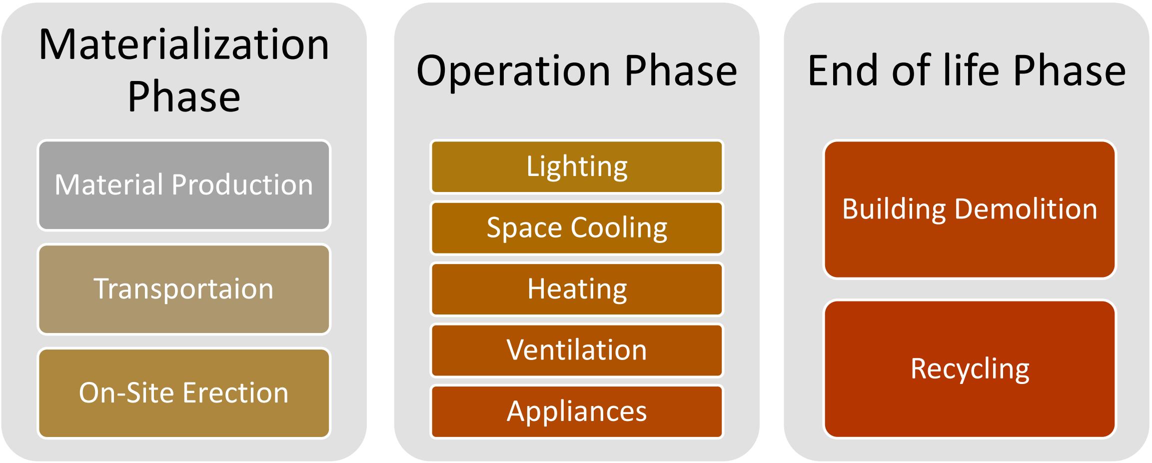


*Figure 3 Stages included in life-cycle assessments by Author.*

In the 3D BIM model of a building, the building components are categorized and ranked according to suggested levels. Figure 2 provides insights into data integration and processing within the BIM environment. Furthermore, during the impact-assessment stage of the proposed framework, environmental effects are evaluated, considering all construction phases and materials, with a specific focus on carbon emissions. The four fundamental phases of the LCA technique aim and scope, inventory, impact assessment, and interpretation—are incorporated to assess the environmental impacts comprehensivelyAnalyzing the resulting Greenhouse Gas (GHG) emissions generated from the building is a crucial part in assessing the mitigation strategy for enhancing the environmental impact. Therefore, Insight Tech- Revit program is chosen for its ability to integrate with Revit providing a quantified data of embodied carbon emissions. The role of Insight Tech is illustrated in Fig. 4

*Figure 4 Stages of modelling and simulation by Author.*

During the aim and scope phase, the purpose, audiences, and system limits are identified. The inventory phase involves gathering information on all pertinent energy and mass flow inputs and outputs, as well as emissions, for each stage of operation. The life-cycle impact-assessment (LCIA) method included in the Eco-invent database, based on various sustainability-assessment methodologies, is employed to assess possible environmental effects. In this study, carbon emissions are assessed in terms of tonsCO2, considering all materials and phases throughout the building's lifespan. The interpretation phase includes scenarios and input-data variability to improve construction performance and provides clear findings aligned with the study objectives.

To quantify CDW emissions, mathematical formulae based on several factors are utilized. In the analysis stage, factors with the highest environmental impact are identified, and emission-reduction strategies are incorporated in the amelioration stage. Finally, a re-evaluation of environmental impact is conducted considering all phases of a building's lifespan.

## 7. Case-Study

Villa project in Cairo, Egypt of area 200m2 is selected as a case study for the performance of Greenhouse Gas (GHG) emissions simulation. The project is selected as a case study as it represents building sector in Egypt as the construction of villas has increased in the past few years in Egypt specifically in the new urban development projects.

## 8. Simulation BIM-LCA Integration

### 8.1 Revit Implementation

Detailed modeling of the selected case-study was executed using Revit program to produce a detailed set of drawings and specifications applied that have an impact in the design decision making.

Ground floor plan modelling is illustrated in different sets of drawings shown in figures 5

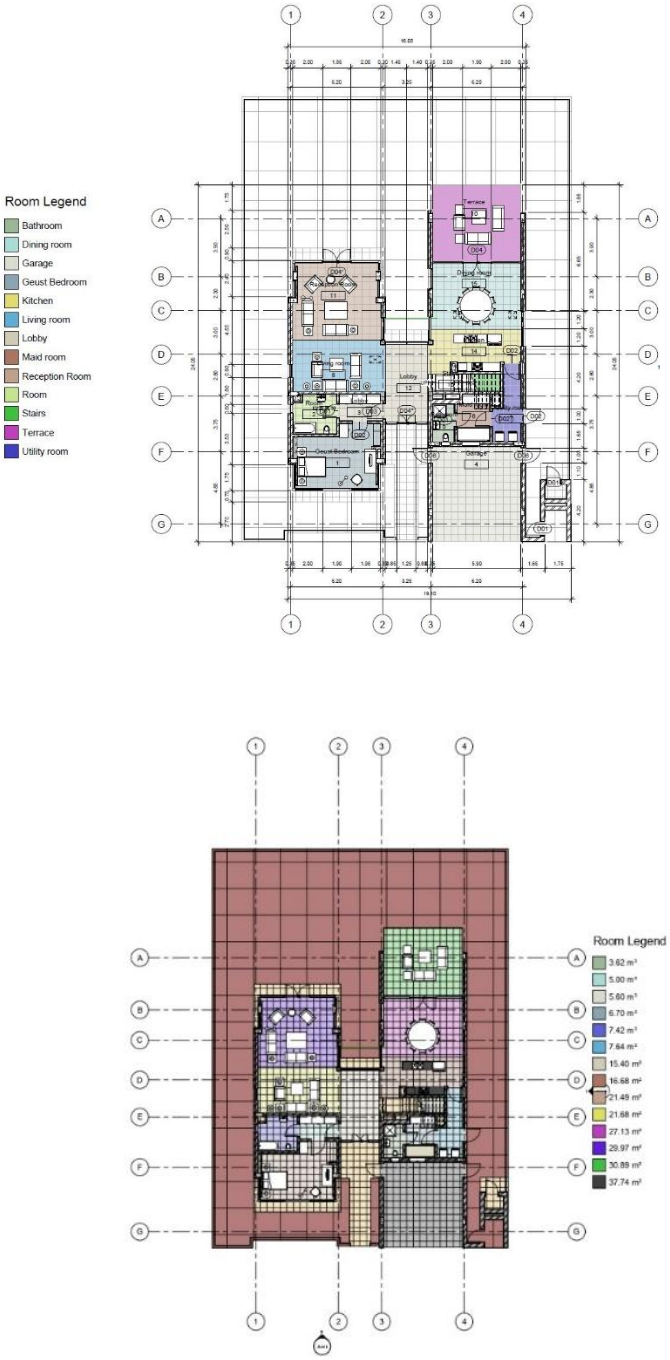


*Figure 5 Ground floor plan by Author.*

First and roof floor plan modelling is illustrated in different set of drawings shown in figures 7&8.

*Figure 1 First floor plan by Author.*

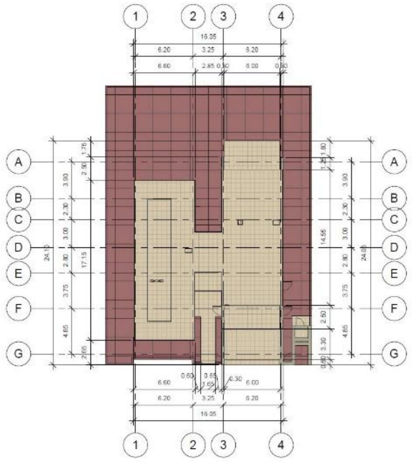
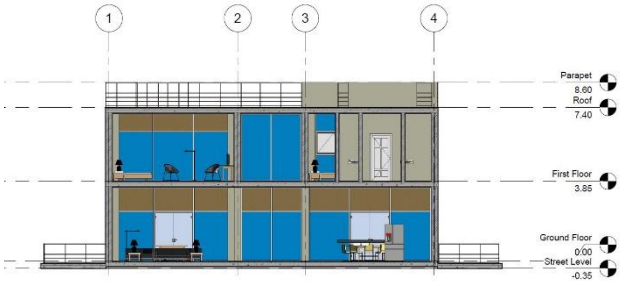


*Figure 2 Roof plan by Author.*

Further modeling details of the selected case-study are illustrated in the following drawings of figures 11,12,13 & 14



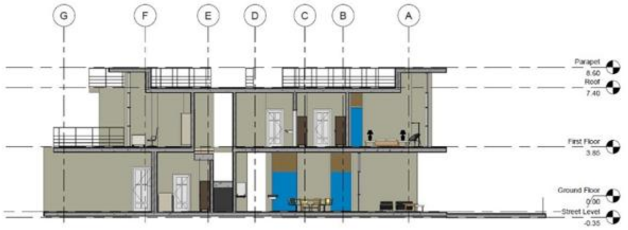


*Figure 3 Sections by Author.*

*Figure 4 North & South elevations by Author.*

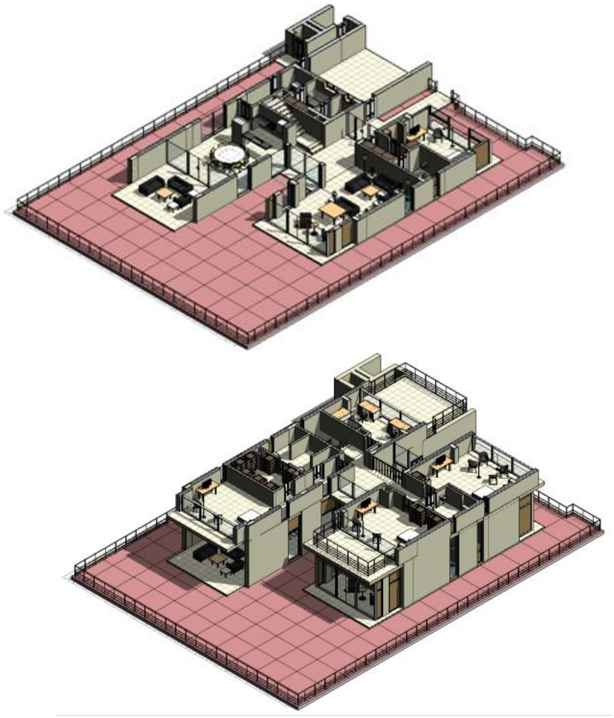


*Figure 5 3D views by Author.*

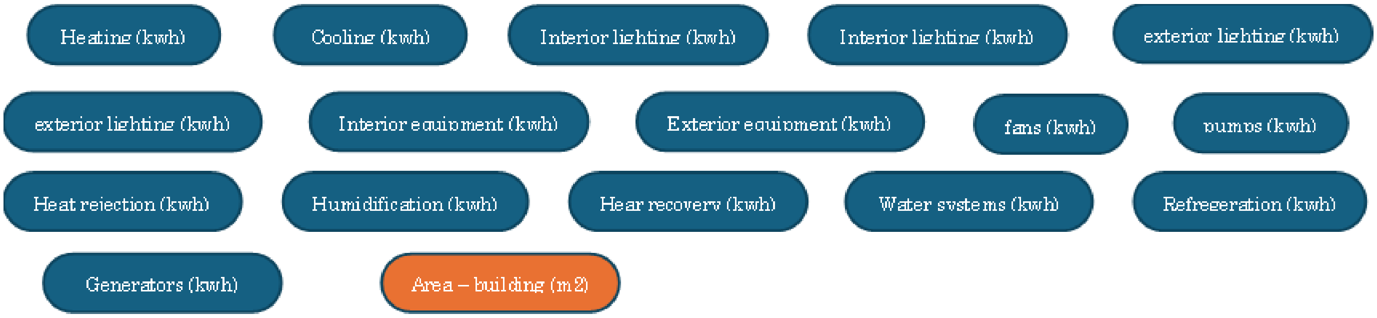
### 8.2 Insight- Tech. Implementation

Insight Tech. program is integrated with the Autodesk Revit modeling file of the case study to perform an environmental simulation through the specified data provided such as: Materials specifications, Location, Weather data file and Building orientation.

Insight Tech. program analyzes this data and incorporates it into the following equation to calculate the Greenhouse Gas (GHG) emissions.

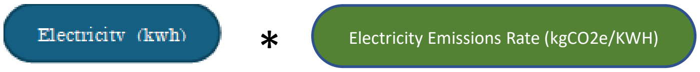
### 8.3 Insight- Calculations

**Energy use intensity (EUI)** is an indicator of the energy efficiency of a building's design and/or operations. It represents the amount of total energy used in one year divided by the building area.



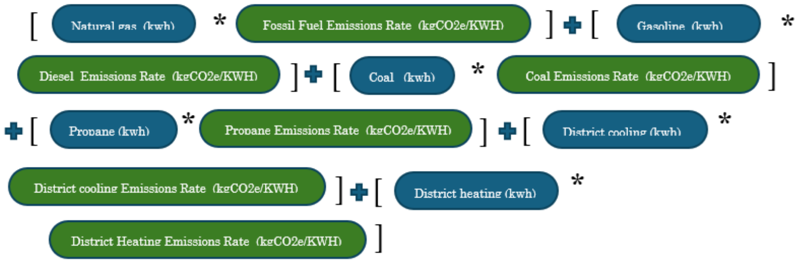
*Equation 1 Energy use intensity (EUI)*

Operational Carbon - electricity represents the yearly carbon emissions linked to the use of electricity necessary for operating building systems.



*Equation 1 Operational Carbon - electricity.*

**Operational Carbon - fossil fuel** represents the yearly carbon emissions linked to the use of fossil fuels necessary for operating building systems.



*Equation 3 Operational Carbon - fossil fuel*

**Operational Energy** - fossil fuels represent the annual energy needed to run building systems. The calculation of Operational Energy can be determined by categorizing fossil fuel tunes considering.

Natural gas (kwh) + gasoline (kwh) + diesel (kwh) + coal (kwh) + Propane (kwh) + District Cooling (kwh) + District Heating (kwh)

*Equation 4 Operational Energy - fossil fuels represent.*

**Embodied Carbon** - Global warming potential of emissions associated with the manufacturing stages (A1-A3) of building materials.

EC - Exterior Openings (kgCO2e) + EC- Underground Walls Openings (kgCO2e) + EC – Freestanding Columns (kgCO2e) + EC – Interior Openings (kgCO2e) + EC – Embodied Column (kgCO2e) + EC – Slabs On Grade (kgCO2e) + EC – Interior Floors (kgCO2e) + EC – Interior Walls (kgCO2e) + EC – Exposed Floors (kgCO2e) + EC – Underground Ceilings (kgCO2e) + EC – Raised Floors (kgCO2e) + EC – Underground Slabs (kgCO2e) + EC – Roofs (kgCO2e) + EC – Shades (kgCO2e) + EC – Ceilings (kgCO2e) + EC – Exterior Walls (kgCO2e)

*Equation 5 Embodied Carbon*

**Operational Carbon** represents the total carbon emissions equivalent produced by fossil fuels and electricity used in operating building systems

[ Annual Operational Carbon - Electricity (kgCO2e) + Annual Operational Carbon – Fossil Fuel (kgCO2e) ] * Building Lifespan (years)

*Equation 6 Operational Carbon*

**Operational Energy** represents the total energy required to operate building systems, determined through analysis of fossil fuel types and electricity data

[ Electricity (kwh) + Annual Operational Energy – Fossil Fuel (kWh) ] * Building Lifespan (years)

*Equation 7 Operational Carbon*

The total carbon emissions associated with the manufacturing of the building materials and emissions that occur during the operation (use) of the building.

Operational Carbon (kgCO2e) + Embodied Carbon (kgCO2e)

*Equation 8 The total carbon*

## 9. Results and Discussion

### 9.1. Simulation results

Insight Tech. program calculates the embodied carbon of each component in the building and quantifies the data to calculate the total carbon footprint of the building.

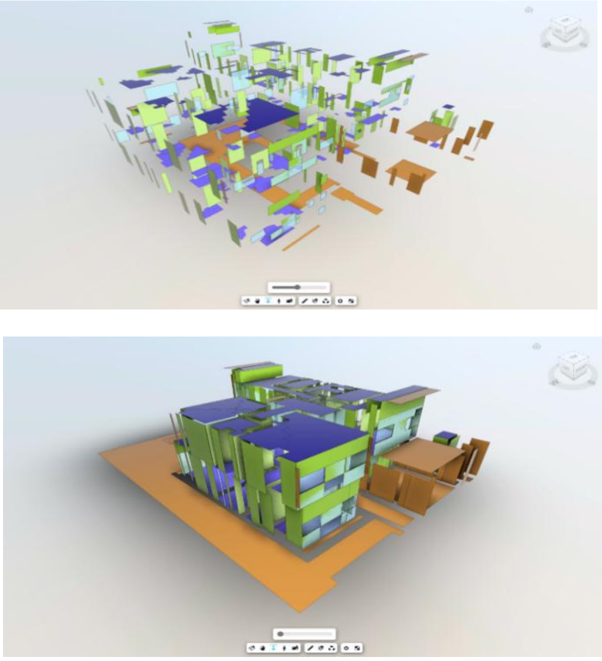
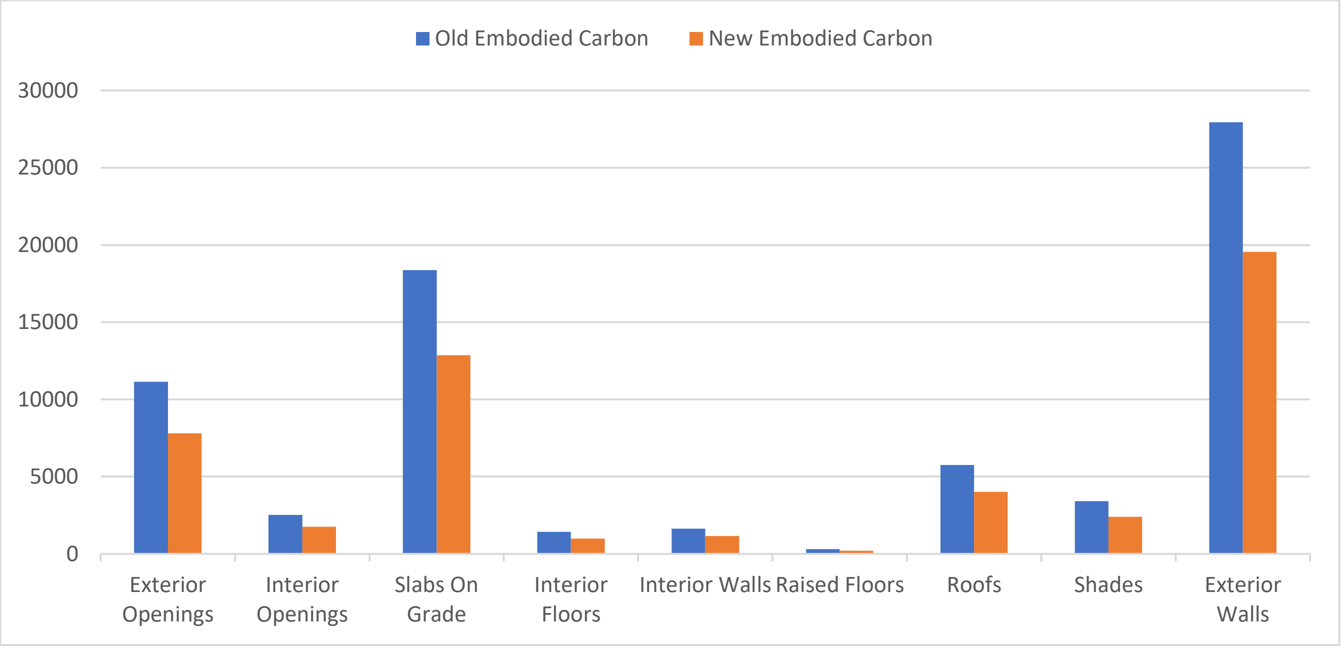


*Figure 11 Exploded components of the building.*

*Table 1 Embodied carbon for old & new materials.*

| ***Component*** | ***Current Material*** | ***Embodied Carbon*** | ***New Material*** | ***Embodied Carbon*** |
|---|---|---|---|---|
| *Exterior Openings* | Ceramic Tiles | 15.64 | Cork Tiles | 2.01 |
| *Interior Openings* | Ceramic Tiles | 15.64 | Cork Tiles | 2.01 |
| *Slabs On Grade* | Standard Reinforced Concrete | 186.00 | Green Reinforced Concrete | 139.5 |
| *Interior Floors* | Standard Mortar | 10.64 | Green Mortar | 4.16 |
| *Interior Walls* | Standard Mortar | 10.64 | Green Mortar | 4.16 |
| *Raised Floors* | XPS-Extruded Polystyrene | 5.04 | Neopor GPS | 0.6 |
| *Roofs* | Bitumen Felt/Sheet | 7.48 | Rubber Sheet | 2.77 |
| *Shades* | Standard Mortar | 10.64 | Green Mortar | 4.16 |
| *Exterior Walls* | Standard Mortar | 10.64 | Green Mortar | 4.16 |



| ***Building Component*** | ***Old Embodied Carbon (kgCO2)*** | ***New Embodied Carbon (kgCO2)*** |
|---|---|---|
| *Exterior Openings* | 11145.04 | 7,801.99 |
| *Interior Openings* | 2515.86 | 1,760.5 |
| *Slabs On Grade* | 18382.02 | 12,867.4 |
| *Interior Floors* | 1426.44 | 998.2 |
| *Interior Walls* | 1641.20 | 1,148.7 |
| *Raised Floors* | 301.78 | 210 |
| *Roofs* | 5747.82 | 4,022.9 |
| *Shades* | 3424.31 | 2396.8 |
| *Exterior Walls* | 27940.01 | 19,558.007 |
| *Total Embodied Carbon* | 72524.53 | 50,764.50 |

*Table 2 Old & New Values of embodied carbon*

Comparison between old carbon emissions values and new carbon emissions value shows a significant decrease int the carbon foot print of the building. Additionally, the integrated BIM-LCA approach provides a Building component breakdown for the embodied carbon values. Therefore, This integrated approach facilitates targeting specific components and materials selection during the early design stagesSimulation results are represented in the following charts that provide quantified data of embodied carbon emissions, Total carbon footprint and operational carbon. Illustrated in figures 17,18&19.

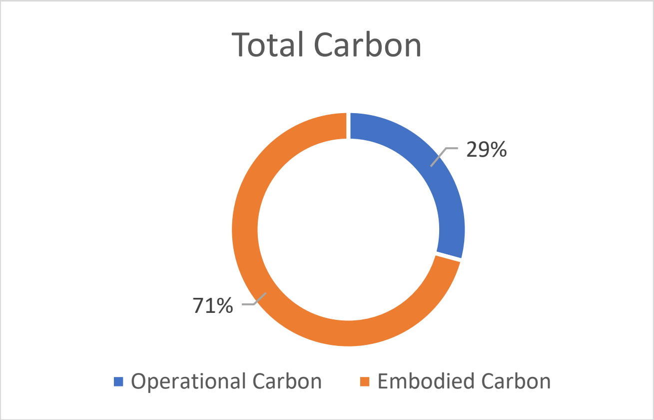


*Figure 13 Percentage of operational & embodied carbon.*

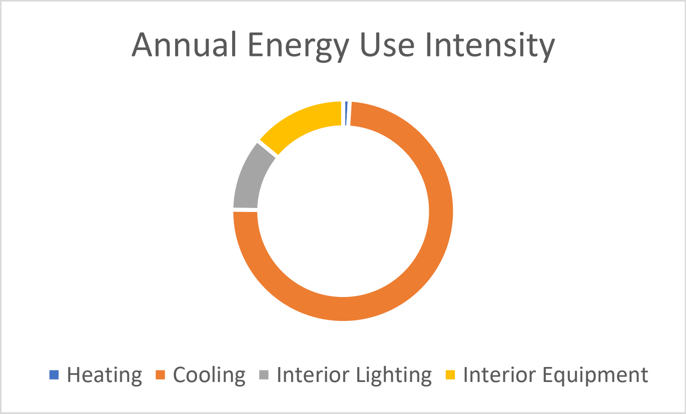


*Figure 15 Percentage annual energy use intensity.*

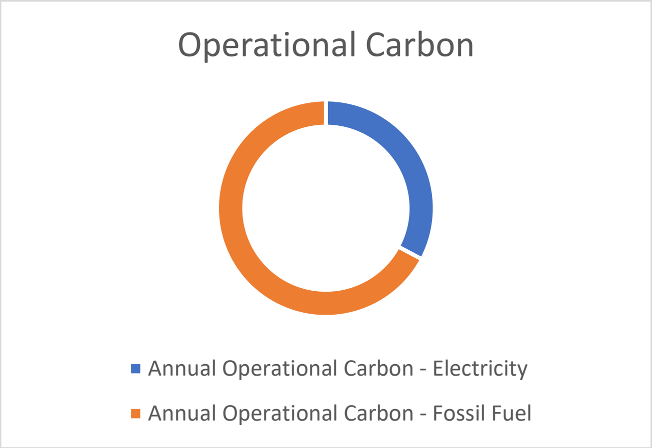


*Figure 16 Percentage Operational Carbon*

The simulation results represent a significant efficiency regarding the proposed methodology of framework. Eco-friendly materials have resulted in the decrease of carbon foot-print by 30% in the represented case-study that was analyzed by the integration of BIM-LCA assessment done through Autodesk Revit and In-sight programs. The results indicate that the plug-in-based approach outperforms the conventional approach in developing and calculation time, while the conventional approach could derive the most accuracy in BOQ extraction. Despite this, the BIM-LCA integration-based approach produces outcomes with approximately 1% error, proving its validity.

### 9.2. Proposed Framework

The integrated BIM -LCA approach proved it efficiency and applicability therefore a framework is proposed to enhance the sustainability of building regarding GHG emissions in the early design stages. The proposed framework is applied through the assist of Autodesk Revit and Insight programs.

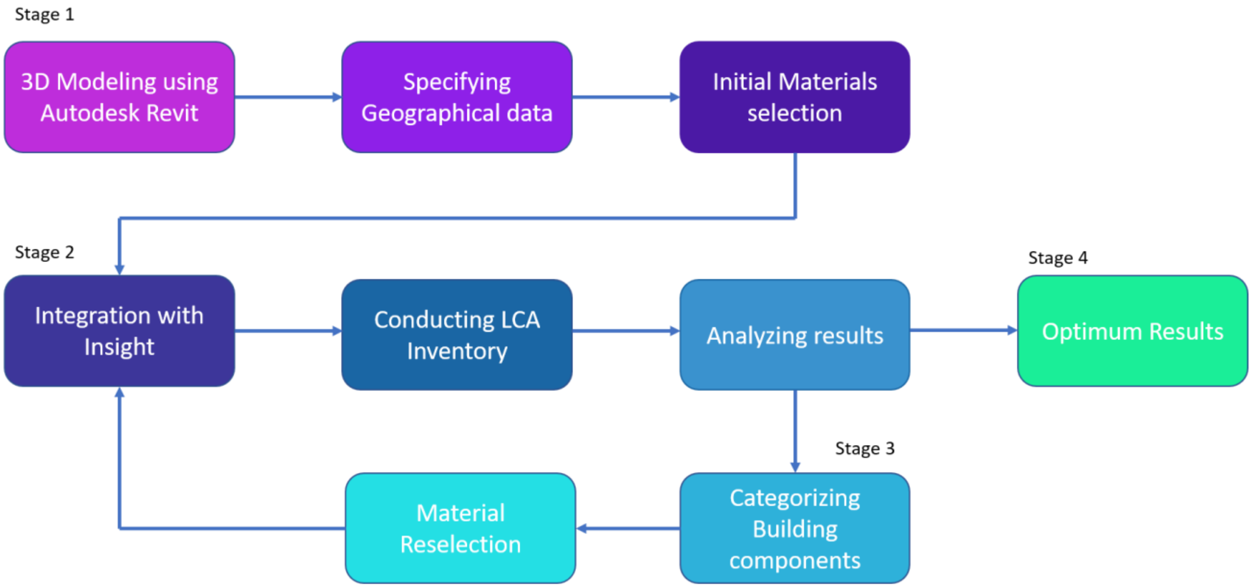


*Figure 17 Proposed Framework, By Author.*

### 9.3. Mitigation Strategies

According to the proposed framework a series of mitigation strategies is suggested to ensure the efficiency of the BIM-LCA based framework.

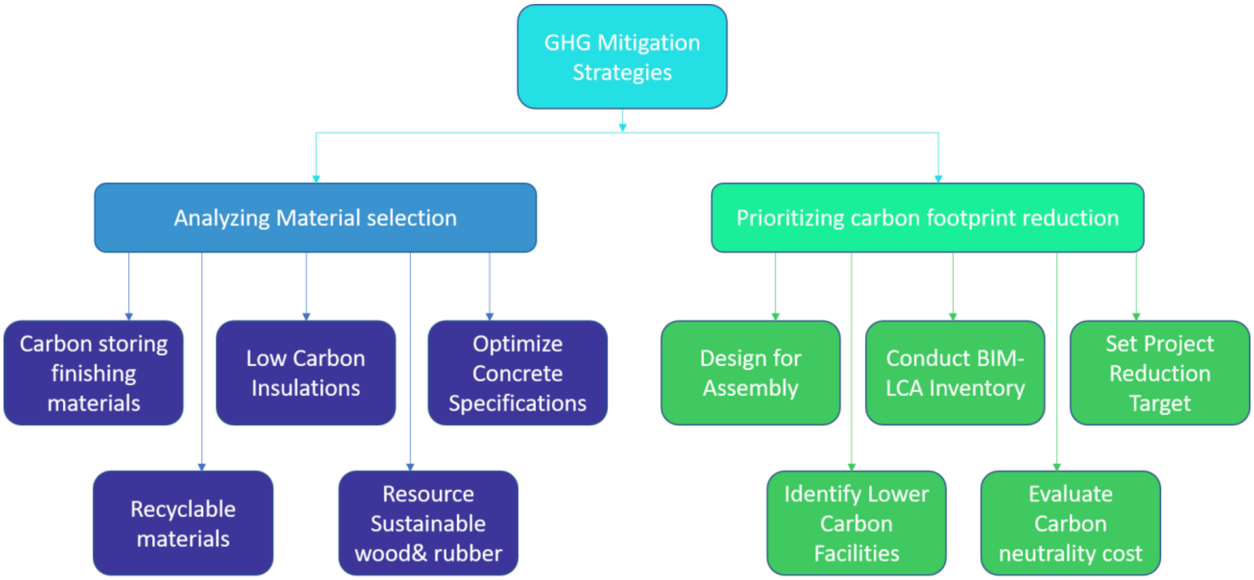


*Figure 18 Mitigation Strategies, By Author.*

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