

Environmental impacts of building materials in Saudi Arabia: A life cycle assessment approach**Abobakr Al-Sakkaf^a, Ghasan Alfalah^b, Eslam Mohammed Abdelkader^{c*}, Mohammed Al-Qadeeb^d and Othman Alshamrani^d**^aDepartment of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC H3G 1M8, Canada^bDepartment of Architecture and Building Science, College of Architecture and Planning, King Saud University, Riyadh 11362, Saudi Arabia^cStructural Engineering Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt^dCollege of Architecture and Planning Building Engineering, Imam Abdulrahman Bin Faisal University, Dammam 31451, Saudi Arabia**CHRONICLE***Article history:*

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ABSTRACT

The construction industry is acknowledged as one of the major primary energy consumers and contributors to global environmental emissions. To this end, proper selection of building materials is imperative to maintain the sustainability of a built environment. This research study proposed a building information modeling-based framework for lifecycle assessment of building materials in Saudi Arabia. Both Autodesk Revit and Autodesk Quantity Takeoff were adopted to define building materials, components, and their quantities. In addition, Athena Impact Estimator and Ecotect® Analysis software were leveraged to conduct thorough environmental impact assessment and energy simulation of building materials. The conducted lifecycle impact assessment tackled project phases of site preparation, construction, use, and demolition. The environmental dimensions of energy consumption, global warming, air emissions, land emissions, and water emissions were also explored. The capabilities of the developed model were tested using a case study of a college building in Saudi Arabia. The findings from this study can assist in the selection of environmentally friendly building materials that can be employed in Saudi Arabia's construction market.

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1. Introduction

Life Cycle Assessment is a process for evaluating the environmental impacts of products or processes. It provides a systematic and practical approach to identifying and quantifying the inputs and outputs across the entire life cycle or specific stages of a product or process development (Anderson et al., 2015). LCA is valuable for identifying the sources of environmental issues linked to a specific product, comparing the environmental impacts of enhanced versions of a product, designing novel greener products, or selecting among various similar products (Lei et al., 2021). In assessing the environmental impacts of materials and products, LCA has gained its ground and also plays a key role in evaluating the long-term effects of a structure throughout its lifecycle (Seyedabadi & Eicker, 2023). The 14040 series from the International Organization for Standardization outlines the procedure for conducting a standard lifecycle assessment, where energy and carbon dioxide equivalents for all phases of a building cycle, including materials and resources used and greenhouse gas emission, are calculated (Janjua et al., 2019; Yildiz et al., 2020). These findings are valuable to architects, structural engineers, contractors, and building owners who seek to predict the environmental impacts of a structure over its life span. An in-depth knowledge of a building's lifecycle is imperative to understanding and reducing its environmental impact. Amidst numerous LCA studies, direct comparisons cannot be made due to the diverse areas of concentration in these studies (Liu & Leng, 2022; Shan et al., 2018).

The envelope and structure of a building are both relatively easy to construct. However, the main difficulty is in the choice of the most appropriate and environmentally friendly alternative from an LCA perspective (Feng et al., 2022; Larsen et al., 2022). Two methods are typically employed in the choice of building type and materials: method that is guided by personal experience or ideas and the use of an arbitrary, speculative method (Olinzock et al., 2015; Sartori et al., 2022). The overarching objective of this research study was to apply two main criteria (energy consumption and environmental impact) in the choice of the types of buildings and envelopes, ultimately to define the process of choosing building materials that

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contribute to a low environmental burden. LCA was performed for environmental impact reduction. The detailed objectives are presented below:

1. Identify and characterize the types of frames, walls, floors, and roofs for six different structure-envelope configurations.
2. Assess the environmental impact of various construction materials.
3. Reduce the environmental impact associated with construction materials.
4. Compare the environmental impacts of each option that is considered to be the most sustainable alternative.

To achieve the stated research objectives, the scope of this study includes:

1. Using factors such as energy consumption and LCA, evaluate the environmental impact of different structure and envelope types.
2. Analyze six structure-envelope options, including building materials like concrete, steel, and so on.

2. Literature Review

The planet is presently facing a range of environmental challenges, which span from local to regional and even global scales. The widespread use of unsustainable development practices, as well as rapid industrial growth, urbanization, construction booms, and technological advancements, has led to severe air and water pollution and soil contamination. These issues now impact fundamental societal needs (Chen et al., 2022; Mathur et al., 2021). Other environmental issues such as depletion of the ozone layer, air pollution, water contamination, land degradation, and global warming have escalated significantly in recent years. This growing crisis calls for an urgent intervention from both governments and societies (Chandrasekaran & Dvarionienė, 2022). The rapid growth in building construction results in the use of numerous necessary materials and resources (such as water, energy, land, and minerals) and the generation of different outputs (such as contaminants) that affect the environment throughout the entire lifespan of buildings. The inputs and outputs associated with these environmental processes give rise to serious challenges, including the degradation of the ozone layer, pollution of air and water, improper waste disposal, and the acceleration of climate change. These effects ultimately jeopardize public health, natural ecosystems, and biodiversity (Jayawardana et al., 2025; Xue et al., 2021).

Over the past decade, two primary types of environmental assessment tools have been developed and employed in the construction industry: a) relies on criteria-based scoring systems such as Leadership in Energy and Environmental Design (LEED), and b) centers around LCA methodologies to measure environmental impact. The process of examining and assessing the environmental impacts associated with a product or service throughout its entire life cycle, from creation to disposal, is known as 'Life Cycle Assessment', also referred to as 'Life Cycle Analysis', 'Eco Balance,' or 'Cradle-to-Grave Analysis' (Gaurav et al., 2021; Poveda & Lipsett, 2011).

Construction professionals today are mainly focused on environmental performance of buildings, and to assess this, LCA is mostly used (Zainine et al., 2021). LCA has been increasingly applied in the evaluation of environmental impact of building materials and the entire building throughout its total life span (Nwodo & Anumba, 2019). LCA is regarded as a valuable tool in promoting sustainable building practices. Integrating LCA into the building design process allows designers to evaluate the environmental impacts of building materials and elements, enabling them to choose the most efficient system with minimal environmental impact (Geng et al., 2017). Significant efforts have been made to develop such LCA tools (Hossain & Ng, 2018). The purpose of these systems is to evaluate buildings holistically (economic, environmental, social, and technical factors). Several tools are available to evaluate entire buildings using an LCA approach, such as ATHENA (North America), ENVIST (United Kingdom), GaBi (Germany), and SimaPro (Netherlands) (Bahramian & Yetilmezsoy, 2020; Tam et al., 2018). The International Organization for Standardization outlines, LCA consists of four key phases: outlining the goal and scope, conducting an inventory analysis, evaluating impact, and interpreting the results (Su et al., 2017). In building LCA assessments, the building itself is treated as the product being evaluated, while the functional unit is the entire building, considered either over a single stage or throughout its full life cycle. The complete life cycle of the building should encompass everything from the extraction of construction materials to its eventual demolition (Martínez-Rocamora et al., 2016).

Four primary stages are involved in a building's lifecycle: preparation of the building site, construction, operation or utilization, and demolition. All these phases together represent the building's full life cycle. Each building segment is analyzed at the product level, with LCA conducted via a cradle-to-grave analysis for an individual product. The results of each product's LCA are then combined to determine the overall LCA of the building. "Impact assessment" refers to the process of evaluating and consolidating the quantitative outcomes of the inventory analysis into environmental impacts. Various forms of the environmental effects of buildings are illustrated in Figure 1. Temporary impacts such as the presence of dust particles and noise during construction occur, while others, like carbon dioxide emissions related to wood burning, have more lasting effects.

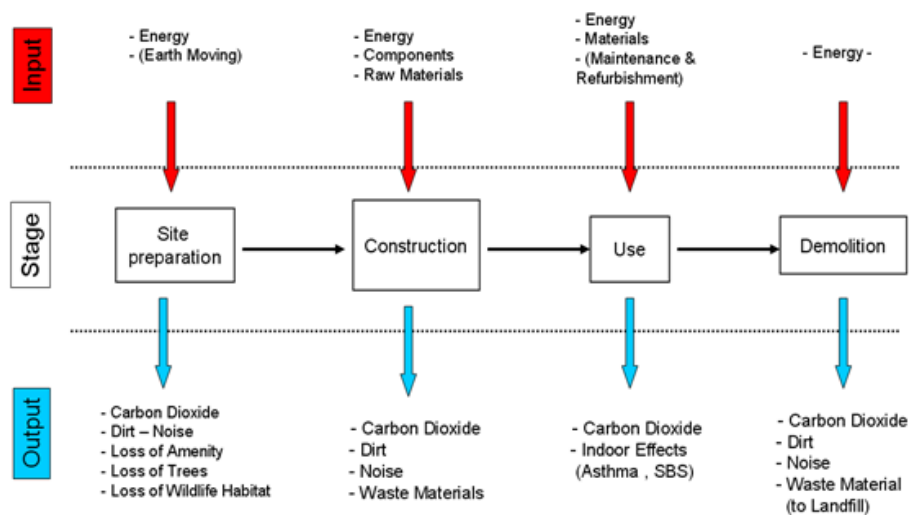


Fig. 1. Impact of a building throughout its lifetime

The Life Cycle Assessment technique offers a comprehensive evaluation of environmental impacts and is particularly beneficial in the conceptual design phase, compared to the criteria scoring system (Kaghembega et al., 2023). However, LCA tools for buildings still face limitations and challenges, as assessing a building's life cycle environmental impact is complex due to various uncertainties and changing conditions. Accurately predicting a building's full cradle-to-grave life cycle, especially over long lifespans like 50 years, remains difficult (Anand & Amor, 2017). Moreover, many LCA case studies focus primarily on the inventory analysis stage, which involves identifying energy inputs and environmental outputs such as greenhouse gas emissions. To achieve a more holistic assessment, broader building performance evaluation techniques are needed. These should consider a wider range of environmental factors and establish a universal criteria set for a more comprehensive environmental assessment (Bhyan et al., 2023; Hollberg et al., 2021).

Several studies have explored the application of Life Cycle Assessment (LCA) in evaluating building materials, sustainability performance, and environmental impact across different sectors. (Zabalza Bribián et al., 2011) compared conventional and eco-friendly building materials using LCA across three impact categories. Their findings highlighted the potential to reduce the environmental impact of construction materials by adopting eco-innovations and substituting finite natural resources with locally available waste materials. (Alshamrani, 2012) developed a sustainability performance model for non-green building alternatives using LEED categories and LCA techniques. Additionally, a life cycle cost forecasting model employing Monte Carlo simulations assessed the cost-effectiveness of 14 school building alternatives, concluding that selecting materials based on a single life cycle stage may lead to suboptimal long-term decisions.

Department of Environment and Conservation (2006) conducted an LCA of commercial composting systems in Australia, demonstrating net greenhouse benefits despite long-distance transportation of compost for agricultural use. The study provided a transparent Life Cycle Inventory (LCI), facilitating future comparative LCA research.

(Remy, 2010) analyzed wastewater management using LCA, comparing traditional drainage systems with source separation techniques. The study found that recovering energy from organic waste could reduce cumulative energy demand by 40% and GHG emissions by 46%, demonstrating the sustainability benefits of separation systems. (Hsu, 2010) examined variations in building LCAs by comparing existing studies with a new model using GaBi software. The research assessed the carbon footprint of structural steel and reinforced concrete, offering insights into standardizing LCA studies across regions. Similarly, (Khasreen et al., 2009) identified challenges in LCA application due to the lack of standardized data and methodologies, recommending future research in construction processes, impact weighting, and applications in developing countries.

(Jungbluth, 2005) evaluated the life-cycle metrics of photovoltaic (PV) systems in Switzerland, estimating CO₂ emissions (39-110 g CO₂-eq./kWh) and energy payback times (3-6 years) depending on PV system configurations. (Alsema, 2003) further assessed Si-PV modules, highlighting differences in energy consumption estimates due to varying assumptions and purification processes in silicon production. (Peuportier, 2001) applied LCA to road construction, comparing six materials from natural, demolition, and industrial waste sources. The study identified material production and transportation as the most energy-intensive phases, while also examining resource depletion and leaching behavior of secondary materials. Further, (Akadiri & Olomolaiye, 2012) reviewed LCA studies on material management, analyzing the environmental impact of recycling, incineration, and landfill disposal in the UK. Their findings highlighted the need for more detailed, quantitative studies on material replacement and waste management strategies. These studies emphasize the importance of

comprehensive LCA methodologies in building materials selection, sustainability assessments, and environmental impact reduction, underscoring the necessity for standardized and comparative research approaches.

(Fischer et al., 2023) analyzed construction methods of multi-storey residential buildings based on their embodied environmental impacts. The first method was a load-bearing wooden structure that encompassed exterior walls of timber frames and mineral wool insulation alongside interior walls and flooring of cross-laminated timber. The second method is a reinforced concrete structure with expanded polystyrene foam insulation. Results manifested that the operational stage accounted for the highest contribution of environmental impact in both construction methods while the transportation phase maintained the least influence on the environment. In the same vein, (Desai & Bheemrao, 2022) compared the environmental footprint of bamboo and concrete in a two-storey residential building. They studied the potentials of global warming, smog, acidification, and eutrophication besides primary energy consumption. It was derived that reinforced concrete consumed more significant amounts of carbon footprint and primary energy than bamboo, mostly in the production stage.

(Rinne et al., 2022) estimated the environmental performance of three construction solutions in a five-storey apartment buildings which were hybrid, concrete and timber. It was concluded that timber apartments had the least carbon footprint over the production stage, and they consumed notable lesser carbon footprint during the transportation stage. (Abouhamad & Abu-Hamd, 2021) compared the ecological footprint of three building construction systems, namely light steel, hot-rolled steel and reinforced concrete. They conducted life cycle inventory analysis and appraised these building systems based on embodied greenhouse gases and energy. It was underlined that light steel construction sustained the least life-cycle energy, moreover, the manufacturing phase consumed the highest embodied environmental impact over the life cycle of building materials.

(Illankoon et al., 2023) assessed the embodied carbon of three construction systems in Australian residential buildings. They varied in relation with the material types of substructure, building frame and interior walls. It was shown that aluminum windows constituted the largest contributor of embodied carbon while foundations made of concrete waffle pod came in the second place. (Sravani et al., 2022) conducted a comparative LCA analysis of passive cooling materials an Indian residential building. They urged for the use of sustainable materials such as autoclaved aerated concrete blocks as wall tiles and the likes of terrazzo tiles, cool tiles and clay tiles as roof insulation. (Risha et al., 2025) conducted a life-cycle carbon assessment of functionally equivalent three- and six-storey commercial office buildings using reinforced concrete (RC), structural steel (SS), and mass timber (MT) in Vancouver, Montreal, and Toronto, Canada, considering regional seismicity and the 2020 National Building Code of Canada. Using the Athena Impact Estimator for Buildings, the authors evaluate global warming potential (GWP) across phases A–C (product, construction, use, end-of-life) and phase D (beyond end-of-life). Excluding biogenic carbon, MT reduces GWP by 33–36% (three-storey) and 27–32% (six-storey) compared to RC, and by 14–19% and 5–14% compared to SS. On the same note, (Allan & Phillips, 2021) presented a cradle-to-grave life cycle assessment comparing MT and SS buildings of five and twelve stories in Seattle, Washington, using the Athena Impact Estimator for Buildings (IE4B) and following TRACI methodology. The results show that MT buildings have a 31–41% lower GWP than steel buildings when excluding biogenic carbon, with normalized values of approximately 161–165 kg CO_{2e}/m² for MT versus 211–233 kg CO_{2e}/m² for steel. MT also outperforms steel in eutrophication potential and human health particulate matter. However, steel buildings have lower impacts in smog potential, acidification potential, and ozone depletion potential (45–55% lower than MT).

(Kumar et al., 2024) scrutinized the environmental impacts of MT, SS, and reinforced concrete (RC) buildings (8, 12, and 18 stories) designed under the 2021 international building code. It was corroborated that MT buildings could reduce GWP by 39–51% compared to RC and 28–34% compared to SS when excluding biogenic carbon, and by 81–94% and 76–91%, respectively. In another attempt, (Zahabi et al., 2025) pointed out that the full mass timber design has the lowest GWP, 16% lower than concrete, while the hybrid design achieves a 14% reduction, with both timber-based systems using about 30% less non-renewable energy. However, mass timber and hybrid systems have higher impacts in acidification, eutrophication, ozone depletion, and smog formation, largely due to long-distance transport of timber from Austria and end-of-life wood decomposition in landfills. In the light of previous research endeavors, it is observed that there is a dearth of study in the Middle East and in the Kingdom of Saudi Arabia specifically for this will be searching for assessing the life cycle of the institutional Buildings in Saudi Arabia. Additionally, it is noted that few studies that addressed embodied energy and emissions in educational buildings.

3. Research Methodology

This section outlines the methodology used for data collection, the analysis process, and the various techniques and tools employed to evaluate different alternatives in pursuit of the study's main objectives. Fig. 2 elucidates the various inputs, processes and outputs in the current study. The input consists of structure and envelope options. For each option, energy and life cycle assessment simulations are conducted as part of the process to measure the environmental impact. The output is the selection of the option with the minimum environmental impact. Figure 3 illustrates the step-by-step procedure in the adopted research methodology. The process begins with building modeling using Revit, where building parameters are defined. Energy simulation of alternatives is then conducted, and the architectural and structural elements are determined by Autodesk Revit. Next, life cycle assessment LCA simulation is performed using Athena software to find the proportion of CO₂ in each of the alternatives. Finally, the building materials that have low environmental impact are selected. The

baselines of building specifications are given in Table 1. The project under study is the College of Science building, a six-story structure with a total floor area of 53,985 m² and a height of 27.5 m (4.5 m per floor). It accommodates 925 users, comprising 800 students and 125 staff members, with a glass-to-wall ratio of 33% (See Table 2). Regarding structural envelope alternatives, various structures and envelope types can be utilized for constructing the college building in Saudi Arabia. The selection of each structure type is influenced by various factors, including location, material and resource availability, weather conditions, material and labor costs, and lifespan. Figs. (4)–(9) present detailed sections of the different alternatives examined.

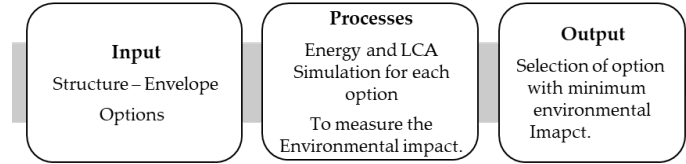


Fig. 2. Input, process and output of the adopted research methodology

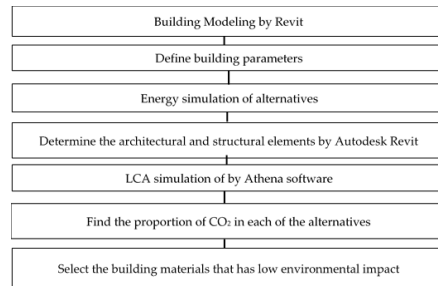


Fig. 3. Steps of the adopted research methodology

Table 1
Building specifications of college case study

| Roof type | Floor type | Wall type | Frame type |
|---------------------|---------------------|------------------------|--------------------|
| Hollow core slab | Hollow core slab | Precast concrete panel | Precast concrete |
| Solid concrete slab | Solid concrete slab | Block | Reinforce concrete |
| Metal deck | Solid concrete slab | Block | Steel frame |
| Metal deck | Solid concrete slab | Aluminum cladding | Steel frame |
| Metal deck | Solid concrete slab | glazing | Steel frame |
| Solid concrete slab | Solid concrete slab | Block +glazing | Reinforce concrete |

Table 2
Characteristics of college case Study

| Parameter | Characteristic |
|--------------------|----------------|
| Total gross area | 53985 m2 |
| Number of floors | 6 |
| Floor height | 27.5 m |
| Number of students | 800 |
| Number of staff | 125 |
| Window area | 33% |

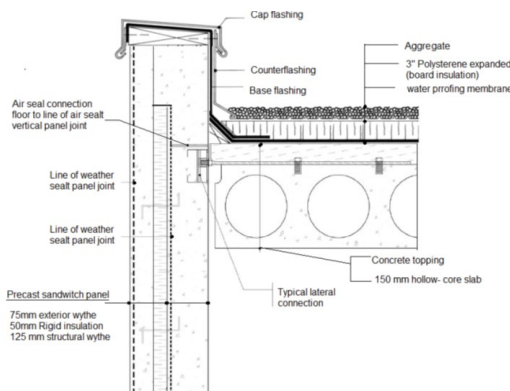


Fig. 4. First option: structure and envelope precast concrete

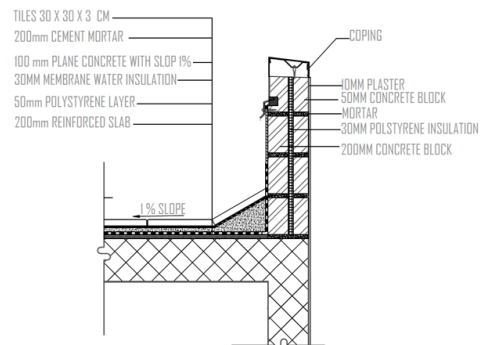


Fig. 5. Second option: structure and envelope reinforce concrete

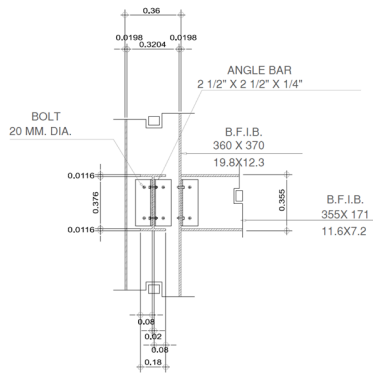


Fig. 6. Third option: steel frame aluminum cladding

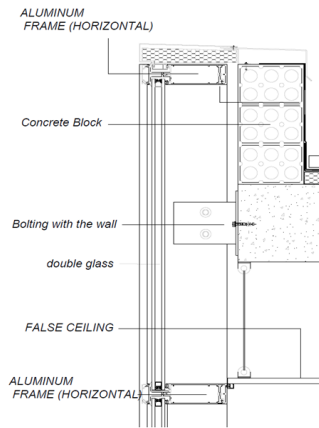


Fig. 7. Fourth option steel frame and glazing

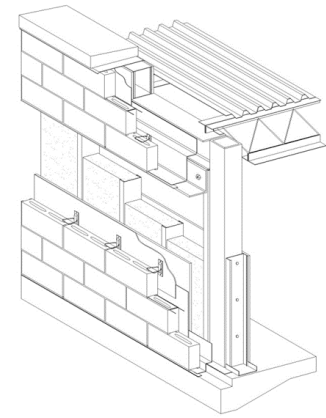


Fig. 8. Fifth option: steel frame and glazing

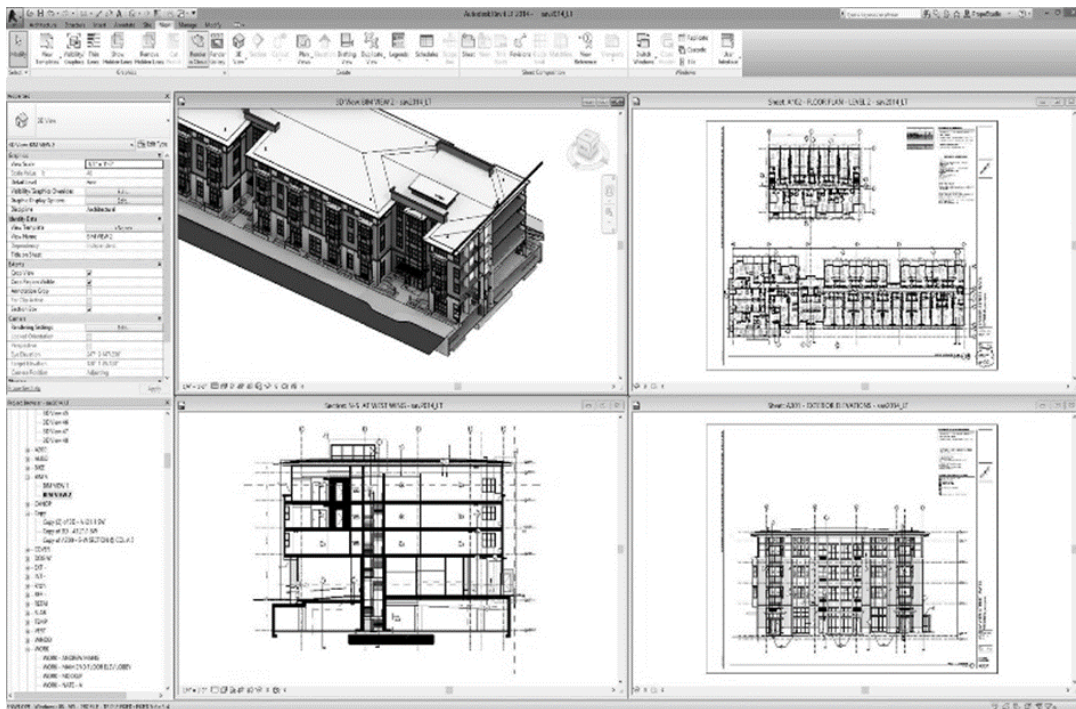


Fig. 9. Visualization of the developed Autodesk Revit model

The various software programs used in this study are presented as follows:

1. Autodesk Revit (for modeling)
2. Autodesk Quantity takeoff (for inventory)
3. Autodesk Ecotect® Analysis (for energy simulation)
4. Athena software (for energy simulation)

Autodesk Revit is a Building Information Modeling (BIM) software designed for architects, structural engineers, MEP engineers, designers, and contractors. It enables users to create 3D building models, annotate designs with 2D drafting elements, and access a comprehensive building information database (see Figure 10). Revit facilitates a coordinated and consistent model-based approach, supporting the entire design and construction process from concept to completion. It integrates architectural design, structural engineering, and MEP systems within a single platform. Additionally, Revit MEP allows users to incorporate geometry, images, and data from other tools, automate or manually measure areas, count building components, and export data to Microsoft® Excel®, or DWF format.

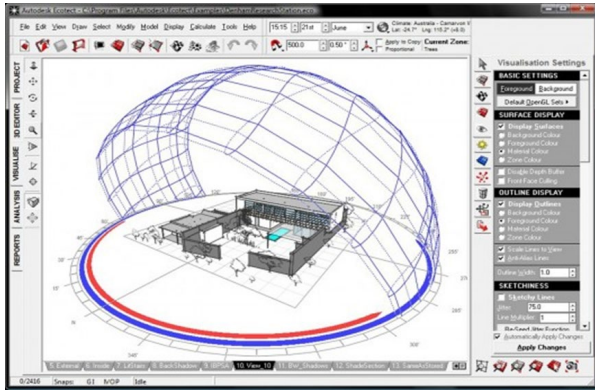


Fig. 10. Perspective view of college case study

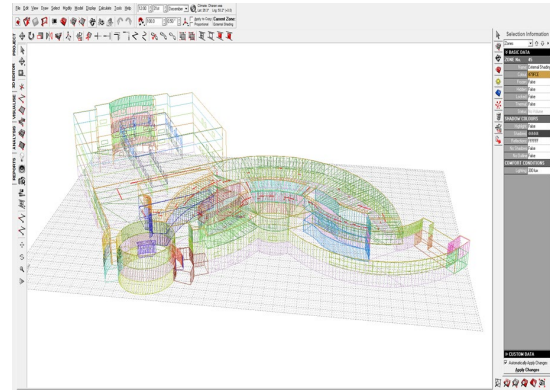


Fig. 11. Visualization of the developed Ecolect analysis model

Autodesk Ecotect® Analysis is a sustainable design software used for energy consumption analysis. Compared to other sustainable building design tools, it provides a broad range of simulation and energy analysis capabilities, with potential for further enhancement. Assessment of the Performance of existing buildings and their new designs, is quintessential for upgrading sustainability measures. Online tools for analyzing energy, water usage, and carbon emissions can be integrated with visualization and simulation tools to assess a building's performance within its environmental context. A comprehensive building energy analysis includes calculating the total energy consumption and carbon emissions based on an annual, monthly, daily, and hourly basis, using a global database of weather information. In addition, the thermal performance analysis involves calculating heating and cooling loads, as well as assessing the impacts of occupancy, internal gains, infiltration, and equipment.

The ATHENA Impact Estimator is a building impact assessment tool based on life cycle assessment, developed by the Athena Institute in Canada, a non-profit organization focused on improving building sustainability through the application of LCA methods (Athena Sustainable Materials Institute, 2025). It is the only software in North America that evaluates entire buildings and assemblies using LCA methodology. This tool is designed to assess building assemblies, such as floors, walls, roofs, or entire building systems and components. It allows architects to evaluate and compare the environmental impacts of designs in advance, whether for new constructions or major renovations. The software incorporates ATHENA's databases, which cover a wide range of building exposure systems and structural types typically used in both commercial and residential buildings. ATHENA helps users define their building design and provides LCA-based environmental comparisons of alternative designs and materials. The Impact Estimator is specifically created for use at the conceptual design stage and offers a summary of key environmental impacts without weighting, including global warming potential, embodied energy usage, water pollutants, solid waste emissions, air pollutants, and natural resource usage. The tool also features an evaluation and comparison function, allowing users to compare multiple design alternatives side by side. Ultimately, the ATHENA Impact Estimator delivers region-specific design results from cradle to grave.

4. Analysis and Discussion

Autodesk Ecotect® Analysis is a comprehensive sustainable design tool that supports concept-to-detail building analysis, offering a wide range of simulations and energy performance assessments. After drawing the building in Autodesk Revit program, it is exported into Autodesk Ecotect® Analysis program to be ready for the calculation of energy simulation (see Fig. 11). Input data of the different building components (walls–floors–roofs–doors–windows–insulation) are plotted in Figs. (12-14). After specifying all the needed input data, monthly energy simulation is carried out (see Fig. 15).

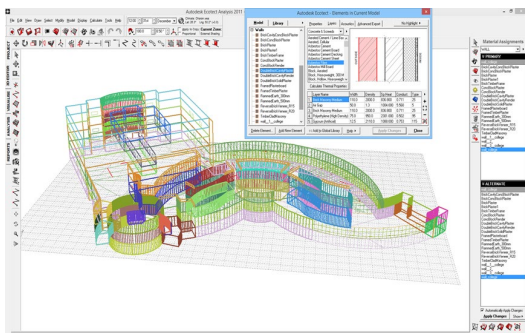


Fig. 12. Definition of wall specifications in the developed Ecolect analysis model

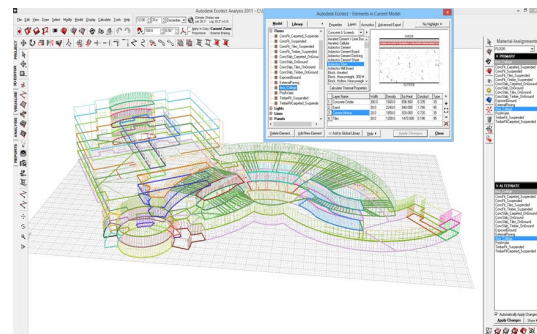


Fig. 13. Definition of floor specifications in the developed Ecolect analysis model

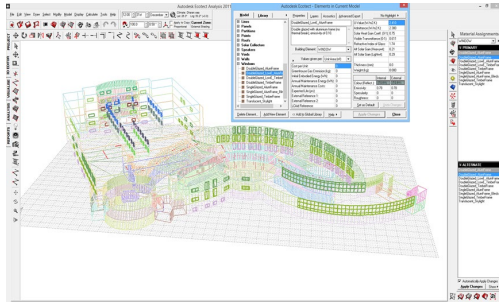


Fig. 14. Definition of window specifications in the developed Ecolect analysis model

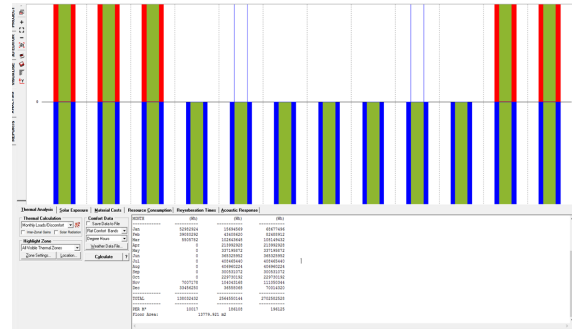


Fig. 15. Monthly energy simulation results

Athena impact estimator for building is the software tool used in this study to evaluate building structures, and Envelope based on LCA methodology. The step by step procedure in the energy simulation by Athena is elaborated as follows: The first step is opening the program and inserting the public information about the location and type of building and the default age and height and the total area in addition to a brief description of the main building shown in Figure 16. This software features an extensive database used to assess the environmental impact of different structural and envelope types, as shown in Figure 17. Additionally, operational data, including electricity and gas consumption, is incorporated through energy simulations to conduct an LCA from the manufacturing phase to demolition.

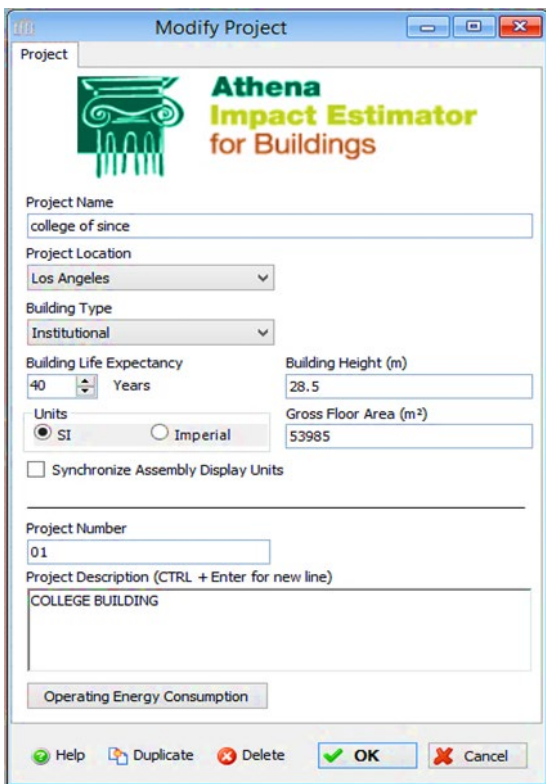


Fig. 16. Definition of general information in Athena impact estimator

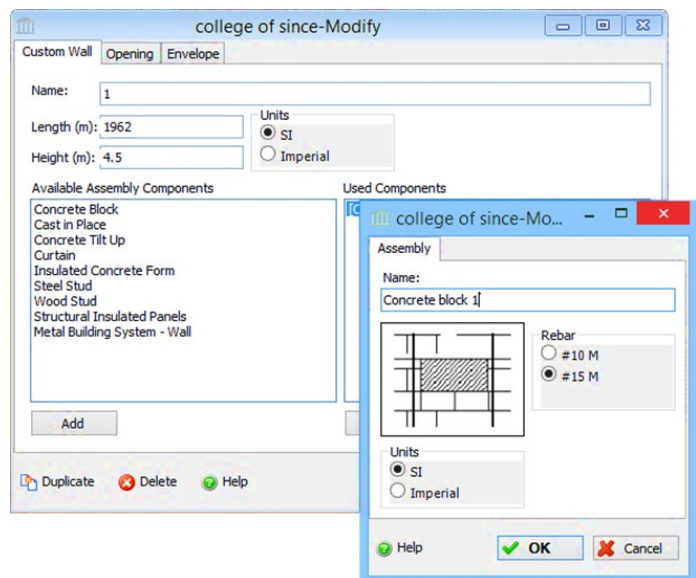


Fig. 17. Definition of wall specifications in Athena Impact Estimator

The second step is to define inventory quantities, dimensions and types of columns and beam (concrete, steel, precast...) as shown in Fig. 18. The third step is to identify quantities, dimensions and types of floors (concrete, steel, precast...) as seen in Fig. 19. The fourth step comprises specifying quantities, dimensions and types of roofs (concrete, steel, precast...) as seen in Fig. 20. As for the fifth step, it includes identifying quantities, dimensions and types of foundation (footing or raft) as depicted in Fig. 21. The sixth step is to determine quantities, dimensions and types of openings as seen in Fig. 22. Fig. 23 elucidates the annual energy consumption of six alternative case studies. After the completion of the energy simulation comparison between the six options, it is shown that case study four has the least annual energy consumption followed by the fifth alternative case study while the second alternative case study is accompanied by the highest energy consumption.

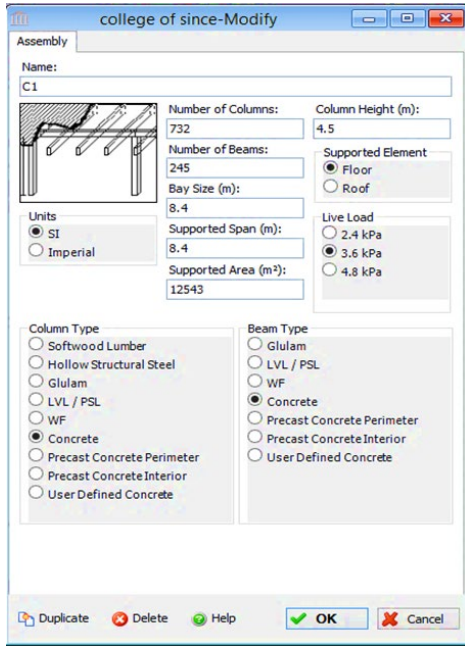


Fig. 18. Definition of beam and column specifications in Athena Impact Estimator

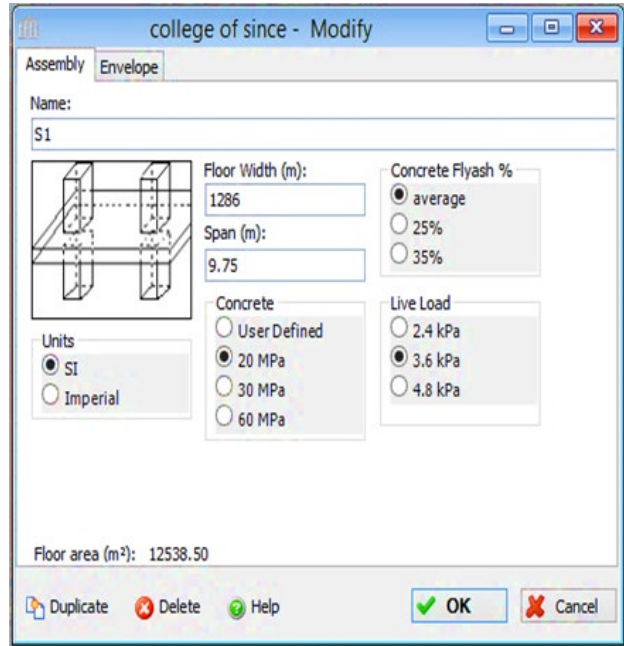


Fig. 19. Definition of floor specifications in Athena Impact Estimator

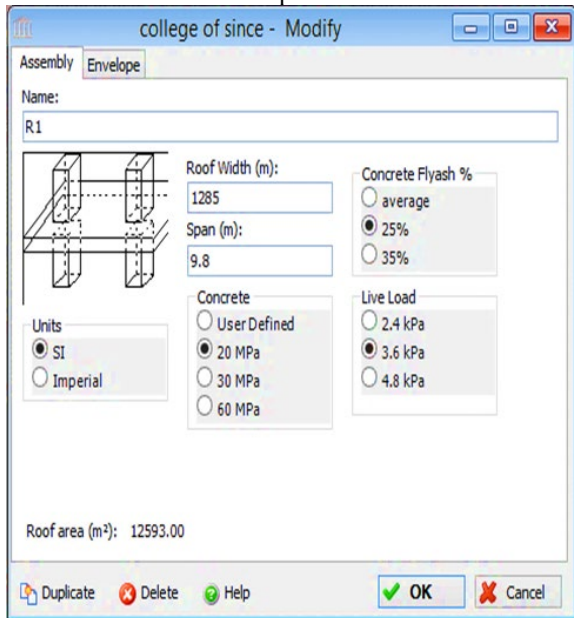


Fig. 20. Definition of roof specifications in Athena Impact Estimator

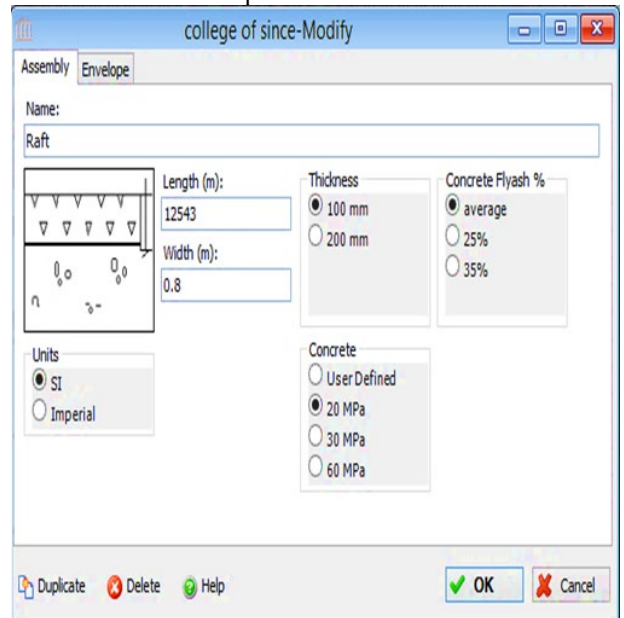


Fig. 21. Definition of foundation specifications in Athena Impact Estimator

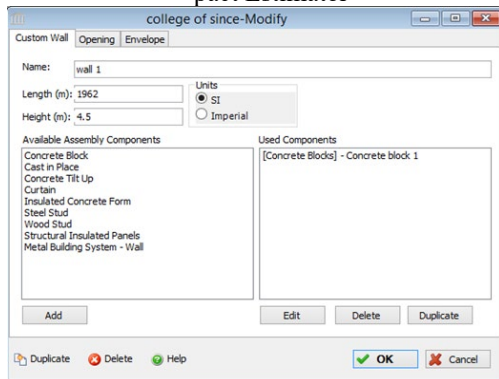


Fig. 22. Definition of opening specifications in Athena Impact Estimator

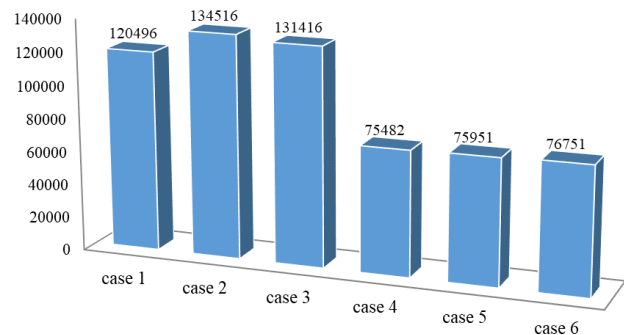


Fig. 23. Energy Simulations of six alternative case studies

Life cycle assessment is integrated into the assessment model to evaluate the impact of conventional college buildings over a 40-year operational period. The LCA results for each structure and envelope type at each stage are presented below. The Global Warming Potential (GWP) metric is used to quantify the change in the greenhouse effect caused by human-induced emissions and absorptions. Table 3 gives global warming potential values of main building components in six alternative case studies. It can be noticed that extra basic materials are the dominant component of all case studies except in the second case study where beam and columns account for the highest contribution of greenhouse gases. On the other hand, foundation accounted for the least amounts of greenhouse gases in all alternative case studies. Figures (24)-(26) demonstrate breakdown of ozone depletion potential in first, second and fifth alternative case studies, respectively. It is found that floors significantly outweigh the remainder of building components in the first case study. As for the second case study, it is manifested that walls, roofs, floors and beams and columns almost share the same contribution in ozone depletion potential. With regards to fifth case study, the highest amounts of ozone depletion potential are generated from roofs. Table 4 summarizes land emissions of first alternative case study. It is observed that Solid waste to landfill (3.34E+07) and concrete solid waste (1.63E+06) are the main sources of land emissions. Other notable waste streams include other solid waste (600,000 kg) and bark or wood waste (52,600 kg), while blast furnace dust contributes 42,500 kg. In contrast, steel waste is negligible at only 8.52 kg, suggesting efficient steel management or recycling. Overall, the table highlights that landfill disposal of concrete and general solid waste dominates the project's land emissions profile.

Table 3
Global warming potential of main building components in six alternative case studies

| Building component | Case study 1 | Case study 2 | Case study 3 | Case study 4 | Case study 5 | Case study 6 |
|-----------------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Beams and Columns | 7.19E+05 | 2.54E+06 | 1.75E+05 | 3.12E+04 | 3.12E+04 | 3.70E+06 |
| Extra basic materials | 1.30E+06 | 1.30E+06 | 1.30E+06 | 1.30E+06 | 1.30E+06 | 1.30E+06 |
| Floors | 9.62E+05 | 1.62E+06 | 1.62E+06 | 1.62E+06 | 1.62E+06 | 1.62E+06 |
| Foundation | 3.21E+05 | 3.21E+05 | 3.21E+05 | 3.21E+05 | 3.21E+05 | 3.21E+05 |
| Roofs | 2.90E+06 | 1.62E+06 | 6.08E+06 | 6.08E+06 | 7.70E+06 | 2.53E+06 |
| Walls | 1.01E+06 | 2.56E+06 | 1.58E+06 | 4.56E+05 | 1.58E+06 | 1.58E+06 |

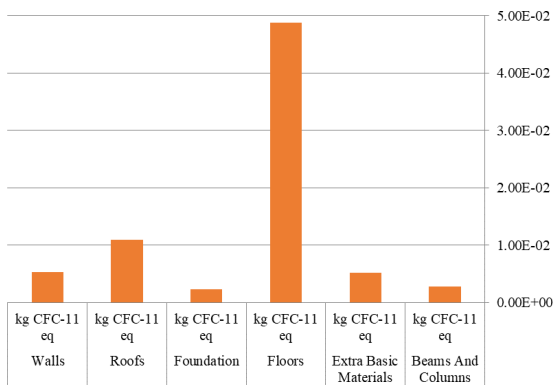


Fig. 24. Breakdown of ozone depletion potential in the first case study

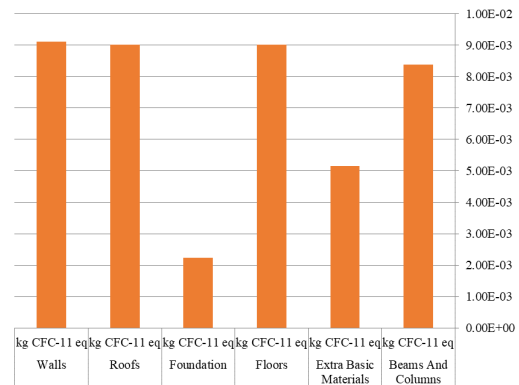


Fig. 25. Breakdown of ozone depletion potential in the second case study

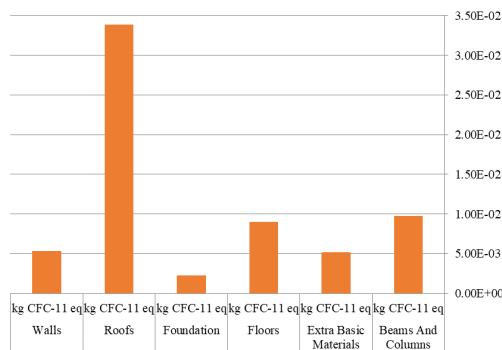


Fig. 26. Breakdown of ozone depletion potential in the fifth case study

Table 4
Land emissions of first case study

| Source | Unit | Total kg |
|-------------------------|------|----------|
| Bark/Wood Waste | kg | 5.26E+04 |
| Concrete Solid Waste | kg | 1.63E+06 |
| Blast Furnace Slag | kg | 1.95E+02 |
| Blast Furnace Dust | kg | 4.25E+04 |
| Steel Waste | kg | 8.52E+00 |
| Other Solid Waste | kg | 6.00E+05 |
| Solid Waste to Landfill | kg | 3.34E+07 |

Table 5 renders a holistic comparison between alternative case studies according to generated energy consumption and environmental emissions over their life cycle. Precast (7.21E+06) and Concrete buildings (9.00E+06) produce the lowest overall global warming potential impact, while reinforced concrete frames with block and glazing walls (1.25E+07) contribute the highest, compared to the other systems under this study. Likewise, precast (1.71E+08) and concrete (1.75E+08) buildings contribute the lowest overall air emissions while reinforced concrete frames with block and glazing walls (3.11E+08) contribute the highest. In addition, Precast buildings (1.81E+07) account for the lowest overall land emissions while reinforced concrete buildings with block walls (2.09E+07) are the dominant contributors. Steel buildings with glazing (4.58E+11) contribute the lowest overall water emissions (4.58E+11) while reinforced concrete frames with block and glazing walls (6.49E+11) produce the highest amount. In the grand scheme of things, precast concrete buildings produce the lowest life cycle assessment of environmental impact, while reinforced concrete buildings with block and glazing walls contribute the highest, compared to the other systems herein.

Table 5
Breakdown of energy consumption and environmental emissions of all alternatives

| Alternative | Energy consumption | Global warming | Air emissions | Land emissions | Water emissions |
|-------------|--------------------|----------------|---------------|----------------|-----------------|
| PC | 120496,7 | 7.21E+06 | 1.71E+08 | 1.81E+07 | 5.13E+11 |
| RC | 134516,2 | 9.00E+06 | 1.75E+08 | 2.09E+07 | 4.86E+11 |
| SS | 131416,2 | 1.11E+07 | 1.89E+08 | 2.02E+07 | 4.97E+11 |
| SG | 75482,4 | 9.80E+06 | 1.83E+08 | 1.84E+07 | 4.58E+11 |
| CG | 75951,7 | 1.25E+07 | 3.11E+08 | 1.90E+07 | 6.49E+11 |
| SC | 76751,7 | 1.10E+07 | 2.80E+08 | 1.92E+07 | 5.83E+11 |

5. Conclusions

This study has focused on the environmental impact of structure – envelope on life cycle assessment such as energy consumption, Global Warming, Air Emissions, land Emissions, and water Emissions, of college building. The college model was modeled by using Rivet software, and simulation the energy consumption by Ecotect® program with different cases of structure – envelope, after that do simulation the life cycle assessment by using Athena software, and simulation the six different cases of structure – envelope, Global Warming, Air Emissions, land Emissions, and water Emissions. Then the above properties were compared to select the best envelope for the college building. The following conclusions are worth noting:

1. Floor and roof have significant effect on the LCA performance of college building. Among the six tested cases, the precast concrete building is the most sustainable design alternative.
2. The environmental impact damage to the rules is the lowest among the structural elements.

It is recommended to collect additional data points for key life cycle components, such as initial costs of conventional colleges, energy costs, and operating and maintenance expenses. Incorporating different probability distribution functions could also enhance the accuracy and comprehensiveness of the analysis. Additionally, future research should explore the application of this study's findings in regions like Saudi Arabia, where limited support programs exist for such initiatives in the Middle East. Expanding the research to this context could provide valuable insights into the region's unique challenges and opportunities.

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