Environment, Development and Sustainability
https://doi.org/10.1007/s10668-023-03701-3

Sustainable assessment of concrete structures using BIM–LCA–AHP integrated approach

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Received: 12 March 2023 / Accepted: 25 July 2023

Abstract

Recently, sustainability has become one of the most critical goals to be accomplished in the construction industry to mitigate its environmental impacts, energy consumption, waste, and cost. Therefore, this research aims to assess the sustainability of concrete structures using the Building Information Modeling and Life Cycle Assessment (BIM–LCA) approach. It can aid to rank and select the type of concrete based on sustainability criteria including CO_2 emissions, embodied energy, and cost using analytical hierarchy process (AHP) method. One-Click LCA tool has been used for the recognition of the distinctions in the LCA results by adopting different environmental product declaration databases. HBERT is used as a verification tool for One-Click LCA results. A comparative study is applied to a multi-story car park concrete structure using both traditional concrete and green concrete that includes supplementary waste materials. Three different models of concrete that have the same compressive strength are selected: traditional concrete, green concrete using 30% fly ash, and green concrete using 50% ground granulated blast-furnace slag (GGBFS). The results showed that using 50% GGBFS in the concrete mix is the most sustainable alternative in terms of CO_2 emissions and embodied energy. Finally, it is concluded that using BIM–LCA–AHP integrated approach can help engineers to design computerized models that improve the sustainability of construction by evaluation based on sustainable objectives.

Keywords Building information modeling (BIM) · Life cycle assessment (LCA) · Analytical hierarchy process (AHP) · Sustainable construction · Green concrete

1 Introduction

Sustainability including environmental, economic, and social dimensions is a broad discipline that gains worldwide concern. One of the most significant factors that affect the environment is the construction industry, which is responsible for up to 50% of climate change, 40% of energy usage, and 50% of the waste of landfills (Khahro et al., 2021). Therefore, the green building movement started in searching for eco-friendly structures aiming to save the ecosystem. In addition, the activities related to the used materials directly affect the

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Extended author information available on the last page of the article project's schedule and cost. As a result, there is a growing consensus among the organizations that target enhancing environmental performance and conducting strategies to select more sustainable construction materials. Cement manufacturing—as a main component of concrete—produces a huge amount of CO_2 emissions and other greenhouse gases, resulting in high energy consumption and thus causing damage to the environment leading to global warming (Benhelal et al., 2013; Collins & Sanjayan, 2002). Egypt is one of the 15 leading countries in cement production, and the construction materials industry has a large share of its economy, estimated at 5.9%, it produced around 81 million tons in 2018 (Debnath et al., 2017).

Green concrete can be defined as concrete that includes waste material in its components, or a production procedure that does not cause environmental damage. Green concrete is fulfilling the specifications to be environmentally friendly and makes the building more sustainable. Utilizing supplementary cementitious materials (SCM) such as fly ash or ground granulated blast-furnace slag (GGBFS) or other waste materials in concrete might diminish the environmental impacts of concrete production, economize energy, and preserve natural resources. 1% replacement of cement with fly ash—as a type of SCM—resulted in a 0.7% reduction in energy consumption related to producing cement (Jin & Chen, 2013). Consequently, replacing a portion of cement in a concrete mixture can produce concrete with lower cost, less energy consumption, and improve its durability and strength.

Building Information Modeling (BIM) is a smart model-based process that assists engineers in planning, designing, constructing, and management of construction projects in an effective manner. Moreover, BIM assists in the sustainable side of design in terms of reducing project costs, material needs, material wastes, and carbon footprint through the sustainable site and logistics management (Krygiel & Nies, 2008).

Hence, using BIM aids in the processes of evaluating the environmental impacts and the selection of sustainable alternatives (Azhar & Brown, 2009). Life cycle assessment (LCA) as an environmental evaluation tool, and analytical hierarchy process (AHP) as a decision rule method are both widely used in the assessment of negative environmental impacts and analysis of complex decisions respectively in many fields. With the recent technological advances in the construction industry, there is a growing interest in more environmentally friendly and productive design approaches using BIM which leads to the "Green BIM" by integration between BIM and LCA to achieve a sustainable design process (Antón & Díaz, 2014, Lu et al., 2017, Guignone et al., 2023).

From the literature review, it is noticed that BIM has been used in many research to help engineers in the design phase, and LCA has also been used to assess the environmental impacts of construction materials. However, there is a lack of integration between BIM, LCA, and MCDM to evaluate the structural materials based on several sustainable criteria.

The research question is how to assess the concrete structures—in the design phase—based on sustainable criteria, and how to rank and select the more sustainable green concrete alternative. Therefore, this research aims to evaluate concrete structures on a sustainability basis using an approach that integrates BIM, LCA, and AHP tools. The Revit model is used to quantify the total amount of concrete. One-Click LCA add-in tool is used to evaluate the environmental impact of the structure. AHP is used for deciding which type of structure is more environmentally friendly. This approach can assist the decision-maker to identify the most sustainable concrete structure based on the type of concrete to achieve more sustainable structures. Three sustainable criteria are considered: CO_2 emission, embodied energy, and cost. Three types of concrete models are compared through a comparative study using the integrated approach: traditional concrete, green concrete including

30% fly ash (FA), and green concrete including 50% ground-granulated blast-furnace slag (GGBFS). These supplementary cementitious materials can be used as substitutes for Portland cement due to their impact on reducing CO_2 emissions while maintaining their structural properties. This approach can assist the decision-maker to identify the most sustainable concrete structure based on the type of concrete to achieve more sustainable structures.

The research structure can be summarized in the following items:

- Literature review that presents the previous research in green concrete using FA and GGBFS, Integration of BIM and LCA, Using of AHP method in green buildings, and Integrating MCDM and BIM.
- Materials and Methods that describe the research methodology and framework, as well as the application of the selected tools BIM, LCA, and AHP.
- Results and analysis that present and discuss the results of the applications of One-Click LCA, HBERT verification, embodied energy, cost, and AHP.
- Conclusions and recommendations that summarize the research work, findings, and limitations as well as the recommendation for future work.

2 Literature review

2.1 Green concrete using FA and GGBFS

The key variables that are utilized to recognize whether the concrete is green are the quantity of Portland cement substitution materials, manufacturing procedure and methods, performance, and life cycle sustainability impacts. The three major objectives behind the green concept in concrete are to (1) decrease greenhouse gas release especially CO_2 emission from the cement industry; (2) decrease the utilization of natural resources such as natural aggregate; and (3) utilize waste materials in concrete (Suhendro, 2014). Cost-effectiveness would be the motive drive for the industry to perform a “green” concrete concept. However, recycling and reuse of wastes need additional labor and energy input (Jin & Chen, 2013).

Portland cement is an essential ingredient used to bind concrete components together. A lot of research was conducted to find adequate alternatives to cement due to the significant amount of CO_2 released during its production, especially after the environmental organizations’ trend to develop regulations that support sustainable construction (Bakhoum et al., 2017). On the other hand, substitute reusing industrial by-products is deemed as the foremost auspicious and applicable solution to decrease the cumulation of byproducts inadvertently generated by industries. Commonly, industries deal with by-products as they squander and send them to landfills or incinerators. These by-products can be blended with raw materials and bolstered to the cement process or mixed with clinker and compose a parcel of final cement. FA and GGBFS are the most common mineral admixtures that can replace a certain cement percentage in a concrete mixture (Zhang et al., 2021). The performance properties of FA and GGBFS can enhance the durability of concrete mixture, reduce porosity, and improve the interface with the aggregate. Previous research concluded that the optimum amounts of FA and GGBFS to replace the quantity of cement in concrete are 30% and 50% respectively which are to maintain the required compressive strength. Higher percentages decrease the concrete compressive strength (Samad et al., 2017; Nath & Sarker, 2011).

FA is a byproduct often produced by the combustion of coal in power plants of electricity (Chousidis et al., 2016). Replacing a portion of cement by FA not only contributes to decreasing raw materials and energy, but also can promote concrete durability through supplanting a fraction of clinker. Previous studies have concluded that the use of FA as a supplant to cement enhances the long-term compressive strength of concrete and decreases the free chloride concentration which also has far fewer rates of steel corrosion compared to normal concrete (Chousidis et al., 2016; Chousidis et al., 2015). Regarding the setting time of fly ash concrete, the initial setting time is increased, and hence, the final setting time is delayed. In hardened concrete, the growth rate of heat and raise of temperature are decreased in situ. Moreover, the strength early gained is decreased, while it is enhanced in the long term. Also, the deformation caused by the load is diminished up to 20% at a supplant percentage of 30% (Kouloumbi & Batis, 1992).

GGBFS is a non-metallic by-product created in the manufacturing of iron and steel which is comprised of silicates, alumina-silicates, and calcium-alumina-silicates. The addition of GGBFS enhances the concrete properties and is more environmentally sustainable which contributes to saving energy, reducing CO_2 emissions, conservation of raw materials, and factors related to the fresh and hardened state of concrete (Rashad & Sadek, 2017). Moreover, experiments showed that GGBFS increased the concrete workability, and for some grades of concrete, the compressive strength, as well as split tensile strength, were increased to their maximum at a replacement ratio of 40–60% of GGBFS (Karri et al., 2015; Liew et al., 2017). In addition, usage of 50% GGBS, and 30% fly ash decreases the embodied energy use by 29%, and 14% alternatively while maintaining the compressive strength of concrete (Murthy & Iyer, 2014). Furthermore, the replacement of cement with GGBFS increases the flexural strength and decreases the effect of corrosion and acid on concrete and in cases of chloride attack. Based on the previous results of using FA and GGBFS as SCM in the concrete, they are very promising in the achievement of durable constructions even in the most aggressive environments besides the reduction of CO_2 (Kouloumbi et al., 1994; Benhelal et al., 2013; Tian et al., 2015; Liew et al., 2017; Ahmad et al., 2022; Shobeiri et al., 2023). Therefore, they are selected as alternatives to be compared with the traditional concrete comparative study in this research.

2.2 Integration of BIM and LCA

Recently, BIM gained attention for its significance in sustainable development in construction by combining all related information such as geographic data, quantities, and geometry. In addition, a sustainable design process can be achieved by integrating BIM and LCA during the early design phase (Antón & Díaz, 2014; Mohamed, 2019; Oduyemi & Okoroh, 2016; Arenas & Shafique, 2023). BIM was explained as a green design creation and achieves sustainability by proposing an LCA-BIM approach (Jrade & Jalaei, 2013; Lu et al., 2017; Tushar et al., 2021; Abdelaal & Guo, 2022). Islam et al. proposed a framework that incorporates material passports within BIM to automate sustainability assessment (Atta et al., 2021). Lu and Wang researched BIM-enabled LCA processes to emphasize the importance of interoperability, information sources, and flows in buildings. It was found that the degree of detail was significant in the creation of the BIM life-cycle inventory. Moreover, the mapping of object/component information in the BIM model to the LCA tool is an emerging problem, as there are problems with unrivaled data formats and a lack of interoperability due to the use of various BIM tools in the model development (Lu & Wang, 2019). There are two recommended integration methods:

The first is the processing of data by IFC file formats. Automatic material de-starting and manual data entry into the LCA tool are visible characteristics of directly implemented processes according to a direct access approach. Although integration can be done to a considerable degree, there are still difficulties remaining and feasible. The lack of open standards and interoperability decreases data extraction, and process efficiency itself can be hindered by such incomputable instruments. As a drawback to this strategy, if there is any change has been made to the BIM model, the designer will require to run the LCA process. As LCA is not matured in the BIM model, at the end of each revision, extracting data from BIM model into LCA is unavoidable. However, these methods help to permit users to obtain environmental evaluations in real-time and findings that are error-free since no manual entry of data is mandatory (Antón & Díaz, 2014; Soust-Verdaguer et al., 2017).

The second indirect approach is to incorporate the construction model and the environmental properties—based on EPDs—of the BIM objects. It enables users to choose BIM objects through their environmental properties and during the design process take account of environmental evaluation as a normal part of decision-making. In this respect, the level of competence of users in the evaluation of environmental data is important and may lead to less detailed assessment arising from errors in the collection of information and objects. On the other hand, this approach makes environmental awareness a prerequisite for design decision-making. This means that environmental considerations are more integrated and normed in the design process (Antón & Díaz, 2014).

2.3 Using of AHP method in green buildings

AHP is regarded as one of the most significant tools in MCDM developed by Thomas L. Saaty (Karayalcin, 1982). Medineckiene et al. provided AHP methodology as an application of the classification of different LEED categories. It aimed to solve the challenges of multi-criteria decision-making in green building marketing and explained the ability to use the methodology of AHP in green building (Medineckiene et al., 2015). Zarchi et al. selected AHP to find priority factors among Malaysian citizens of the next generation for choosing green buildings. Eight criteria for green building were selected: energy saving, operation, and maintenance cost, water-saving, respect for society, internal quality environment (IEQ), pollution reduction, “feel good” factor, and health factors (Zarchi et al., 2012). Another study developed an automated decision support system to facilitate the sustainable evaluation of structural materials using AHP and TOPSIS methods (Bakhoum & Brown, 2015).

Debnath et al. proposed a hybrid MCDM approach by combining DANP and G-TOPSIS for the selection of green materials. The study used DANP to analyze the impact and interrelationships between each criterion and obtain final weights for each criterion. G-TOPSIS is used to get the ranking of alternatives and select the optimal alternative of green material (Debnath et al., 2017). In the same way, Govindan et al. built a hierarchical structure for material evaluation criteria including materials economy that involves initial cost, maintenance cost, and disposal cost; environmental that involves energy efficiency, raw material extraction, the possibility of recycling and reuse; social that involves operational life, esthetics, health, and safety; and technology that involves maintainability, decay resistance, and life expectancy (Govindan et al., 2016). In addition, physical properties have been applied in the selection of materials that play an important role in the process of evaluating green materials alternatives (Chatterjee et al., 2009; Tian et al., 2016).

Green materials selection can be considered as the fuzzy MCDM problem. Few studies consider environmental issues when assessing the materials alternatives, and most of these studies ignored the physical properties in the evaluation process (Chan & Tong, 2007; Zhang et al., 2017). Bhattacharya et al. combined fuzzy TOPSIS and fuzzy AHP as an approach to evaluate and select green materials, fuzzy AHP was applied to determine the significance weights of the selected criteria, and fuzzy TOPSIS was used to rank alternative materials. Six criteria for selecting green materials alternatives were chosen: initial cost, maintenance cost, disposal cost, the potential for recycling and reuse, tensile modulus, and density (Bhattacharya et al., 2008).

2.4 Integrating MCDM and BIM

Tan et al. analyzed the workflow to define BIM functions and methods of synergies between MCDM and BIM. Five strategies were applied for successfully integrating MCDM and BIM: (1) establish multiple reasonable criteria for the target problem; (2) fulfill BIM functions in the process of MCDM; (3) BIM and MCDM collaboration for the target problem; (4) define MCDM tools and data collection methods based on the characteristics of the building; and (5) improving information richness in BIM be suitable for MCDM techniques (Tan et al., 2021).

Ahmad and Thaheem integrated BIM with the MCDM model using an application programming interface (API) (Ahmad & Thaheem, 2018). Marzouk and Daour added toolbars, functionality, and custom connectivity to an external application, and it is concluded that it is expected that extending BIM functionality to the MCDM process can enhance the integration and interaction of these two approaches (Marzouk & Al Daour, 2018).

Haruna et al. tried to solve the building energy efficiency problem with ANP as an MCDM tool considering BIM mitigating factors. ANP performed the pairwise comparison of alternatives from the response that is obtained concerning the BIM application to achieve sustainable building. MCDM methods have proven to be very suitable to support the selection of the most effective decisions. The application of BIM is suggested as a reliable source of energy efficiency techniques to support decision-making (Haruna et al., 2021).

3 Materials and methods

3.1 Methodology

The research methodology can be summarized in the following steps:

- Step 1 (Green concrete): Identifying the concrete mixture models that were used and collecting the environmental and cost data related to their components.
- Step 2 (BIM): Structure modeling (a multi-story car park concrete structure).
- Step 3 (LCA): Integrating One-Click LCA databases with Revit and using the HBERT database to verify the results.
- Step 4 (Sustainable criteria): Obtaining and analysis of results related to sustainability impacts (embodied CO_2, embodied energy, and cost).
- Step 5 (AHP): Use the AHP method to rank the alternatives and get the most sustainable model.

The research compared three types of concrete: traditional concrete that uses OPC, green concrete including 30% FA, and green concrete including 50% GGBFS. Figure 1 illustrates the framework of the developed approach. Data input related to embodied CO_2 emissions and embodied energy is gathered from the literature and used as input for BIM. Cost data related to the alternatives is collected from the market.

3.2 Building Information Modeling (BIM)

BIM is one of the effective ways to visualize buildings and models before real-life implementation. It refers to cooperation and interoperability that contribute to better project efficiency across the project life cycle from design to demolition (Ghaffarianhoseini et al., 2017). Building is the world's main greenhouse gas contributor; cement alone makes up 5% of global human-made CO_2 emissions (Heemskerk et al., 2002). As a result, industry designers (BIM) and owners are increasingly aware of the value of their sector in reducing greenhouse gas emissions, which must take more action to realize the industry's emissions-saving potential. Since the model offers valuable pricing data by environmental performance parameters, iterative BIM design may assist in the identification of the best environmental return on investments (Succar, 2009). To optimize a sustainable project, it is necessary to collect all Environmental Project Declaration (EPDs) and other environmental properties in a single BIM model to create a model with the required details to generate EPD and to certify the entire project using that model (Grilo & Jardim-Goncalves, 2010).

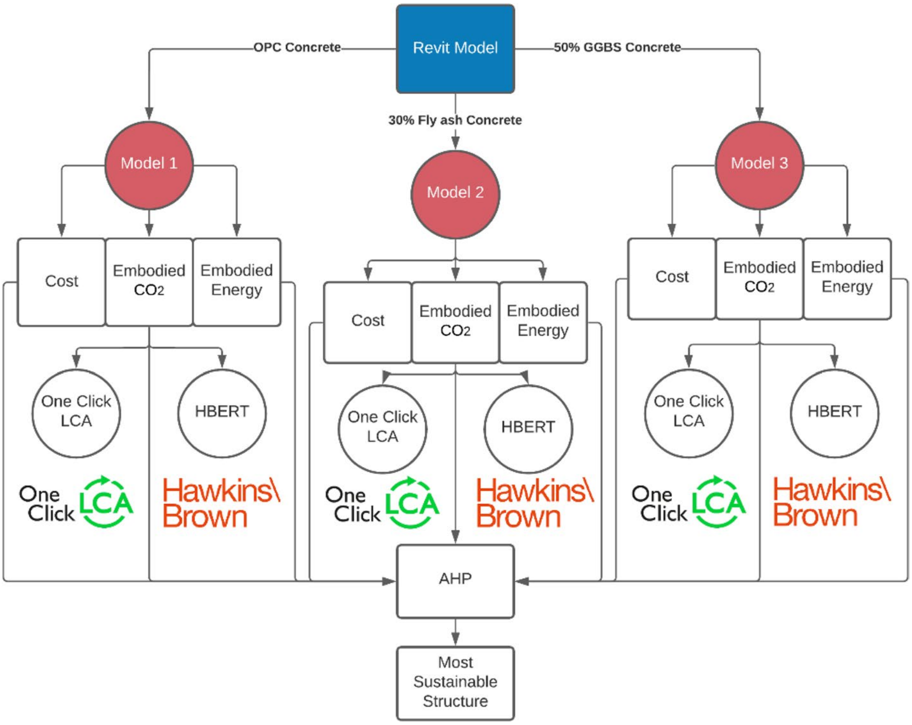


Fig. 1 Framework of the developed approach

To achieve an automated workflow process, the research integrated BIM and environmental sustainability software tools.

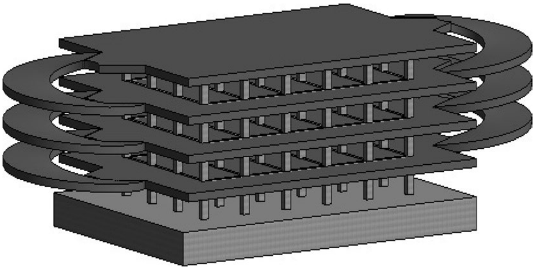
In this research, Autodesk® Revit® has been selected to design, simulate, and visualize a three-dimensional virtual model of a multi-story car park. Accordingly, three models were created on Revit using three types of concrete: traditional concrete (OPC concrete), concrete with FA, and concrete with GGBFS. Then, the developed approach is applied to it and the results of the considered criteria are generated. Revit was selected as it allows the creation of models and drawings focusing on the core tenets of BIM as well as its compatibility to work with LCA software. Only the structural system is considered to get and analyze the impact of concrete without taking the influence of finishing works as the main target is to get the effect of changing the type of concrete mixture. As shown in Fig. 2, the model consists of a foundation slab, three floors, and two ramps. Each floor consists of 48 columns and 28 beams. The two ramps are connected outside the garage. The area of the garage is 917.52 m^2, and the height is 8 m.

3.3 Life cycle assessment (LCA)

Life cycle assessment is specified in Iso 144,044 (ISO, 2006) as a method of analyzing environmental impacts and aspects of materials manufactured and used widely throughout their life lives or in a specific amount of time (Standardization, 2006). LCA is used for multiple purposes including multicriteria decision-making process, materials usability, and production enhancement (ISO, 2006). LCA can improve the decision-making in buildings by allowing the designers to have better design solutions for the environment and optimize the design to include all stages of the building's life including extraction of raw materials, manufacturing of materials, building use phase, and end of life (Soust-Verdaguer et al., 2017; Abd Rashid & Yusoff, 2015; Sartori et al., 2021). LCA has been regarded as an accredited tool for sustainability evaluation and for enhancing the construction sector in general (Ortiz et al., 2009).

In this research, two LCA software were used: One-Click LCA and HBERT as verification. One-Click is an LCA (Life cycle assessment) and LCC (life-cycle costing) software that complies with EN 15,978 standards and aims to reduce costs including environmental impacts. Accordingly, it enables users to design greener buildings and to create Environmental Product Declarations (EPD) to earn valuable certifications credits like LEED and BREEAM. EDP is a verified representation of any product's environmental profile based on life cycle assessments according to the EU countries' standards ISO 14,044, ISO 14,040, and EN 15,804. This software is selected due to its features to develop building LCA analysis with the link to a BIM environment as well as its quickness and user-friendly

Fig. 2 Revit 3D model



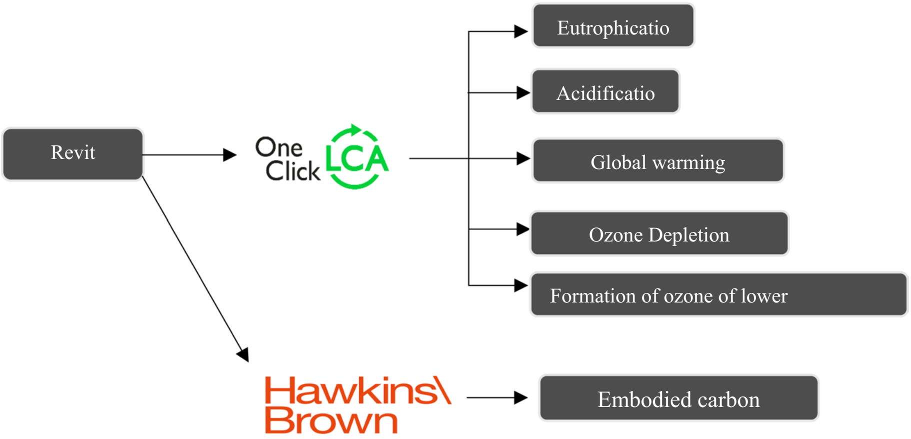


Fig. 3 Inputs and outputs of One-Click LCA and HBERT

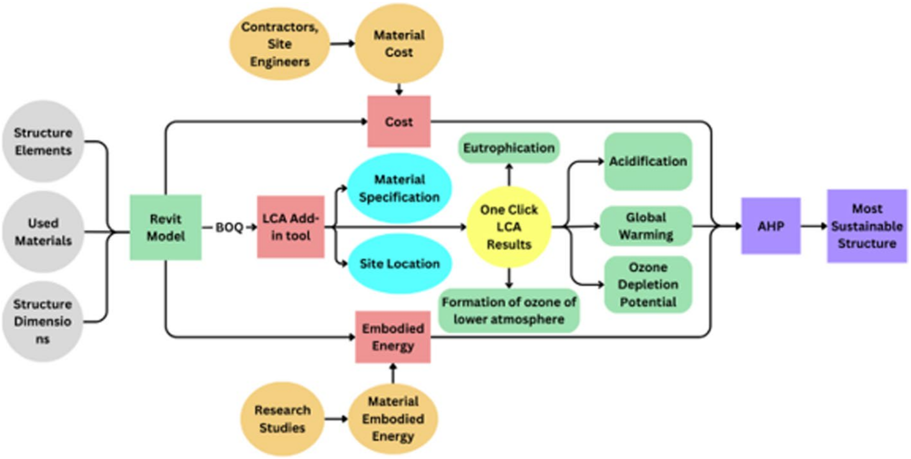


Fig. 4 One-Click framework structure

interface, as LCA usually requires a lot of time and effort during the process. The software works as a plugin by importing data from the Revit model. The software can compare the alternatives in terms of global warming, acidification, eutrophication, ozone depletion potential, and the formation of ozone in the lower atmosphere. Figure 3 illustrates the workflow of One-Click LCA and HBERT.

One-Click LCA can be used to perform the assessment process for the complete Cradle-to-Grave LCA study, which includes stages from A1 to D. So, Fig. 4 shows the breakdown structure of using One-Click LCA. According to the aim of this project, the result that will take more attention regarding the environmental impact is Global warming (embodied CO_2 emissions), which is resulted from different categories of life cycle assessment. One-Click LCA can quantify the environmental impact values with a minimized need for manual information entry. The EPD database that One-click LCA uses is enormous, it gives the user the flexibility to add geographical conditions and preferences to the LCA study. The

One-Click LCA EPD database used in this study was the Egyptian database, the selected database was according to the design, and location of the designed model.

On the other hand, Hawkins Brown emission reduction tool (HBERT) is an easy-to-use open-source Revit-based platform that allows construction teams to easily evaluate and visualize the carbon emissions of multiple building materials at any period during the design process. HEBERT's working discipline is calculating the volume of all products selected in the Revit model. It then adds the embodied carbon data to the material, broken down into the life cycle stages. HBERT conforms to the latest Guidelines for RICS and RIBA and currently uses the ICE database of the University of Bath V3 (2019). However, the software enables the user to use an external database wherever available but with limitations. HBERT makes a quick yet rigorous comparison of basic design choices and provides the basis for a full carbon footprint study of the life cycle. The method interfaces with Revit and allows the designer to rapidly test embedded carbon emissions of various material alternatives during the design process (Bowles et al., 2021). HBERT assesses the building's environmental impacts according to British standards, databases, and geographical conditions. HBERT gets the information from the Revit model as an automated function, the margin of error is lower than getting information from ongoing site work, or manual entry of material in the web interface database. HBERT lacks the option of comparing different models' results, as it is an Excel sheet-based add-in tool in Revit, not a web interface. HBERT has more flexibility in adding or changing the material specification database.

3.4 Analytical hierarchy process (AHP)

This study uses AHP to assess the three alternatives based on sustainability criteria. AHP is the measurement theory by pairwise comparison based on the judgments of experts to set priority scales. AHP is considered one of the most popular and widely used MCDM and decision support techniques that is applied to solve complex decision problems (Fu, 2019). The AHP approach is determined to be practical since it combines environmental performance, technical, social, and economic performance in one value that can be easily interpreted (Penadés-Plà et al., 2016). The hierarchical structure used in this tool is divided into goals, criteria, and alternatives as presented in Fig. 5. AHP ranks decision alternatives and when the decision-maker has multiple criteria, it helps in making the best decision. The AHP can be used successfully to quantitatively analyze qualitative data (Zhao et al., 2009).

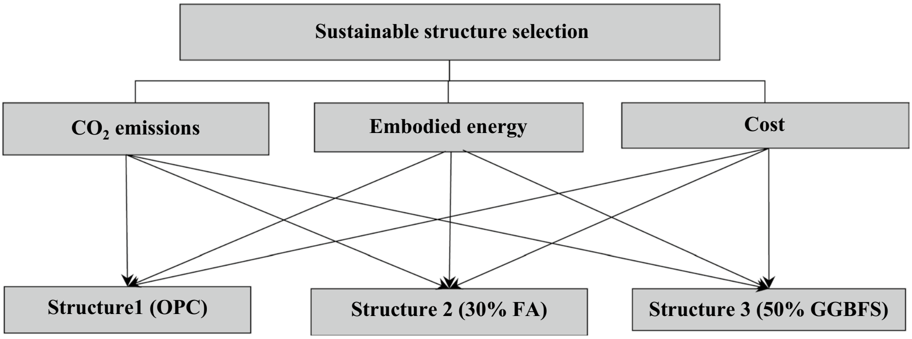


Fig. 5 AHP structure

In this research, the AHP approach is applied to compare three types of structures with three different types of concrete mixes, to select the best sustainable structure. AHP involves three main steps: hierarchy framework, priority analysis, and consistency verification. At the top level is defining the main goal of the study is the selection of the best sustainable structure. The second level set the main criteria. The three criteria used in this to meet the goal are CO_2 emissions, embodied energy, and cost. The last level is a set of alternatives that are three types of the concrete mixture. The first structure contains 100% OPC from the concrete mixture, the second structure contains 30% fly ash from the concrete mixture as a cement substitute, and the third structure contains 50% GGBFS from the concrete mixture as a cement substitute.

4 Results and analysis

4.1 One-Click LCA results

The investigation through One-Click LCA begins with importing the BIM model data—families and amounts to the One-Click LCA web interface, accordingly, characterizing the particulars and impediments of the LCA study that can be carried on over the selection and mapping of the material. Thus, the results of the three used models are presented in Table 1. In addition, Fig. 6a, b, and c show the LCA results for the three alternatives in percentages.

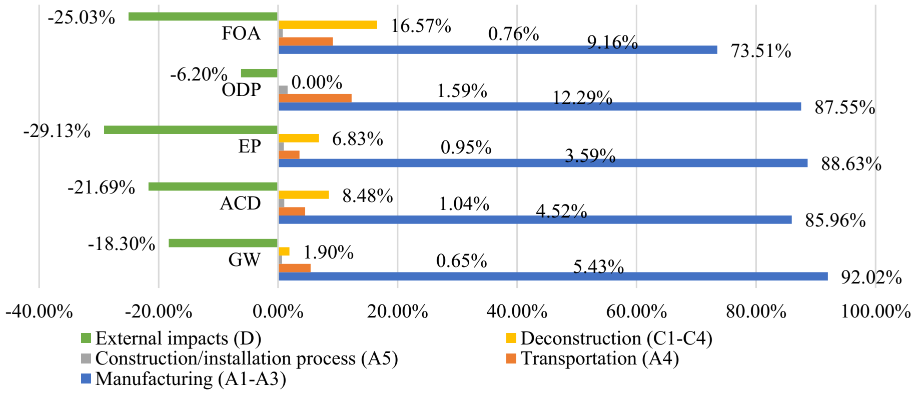
From the generated results, it can be noticed that:

- Global Warming has the highest environmental impact of the three alternatives. Therefore, it is the most critical environmental criterion that should be considered.
- The total embodied CO_2 emissions of OPC are equal to 1440 tons, which presents that global warming has the highest environmental impact among other environmental impacts in the life cycle of multi-story car parking. It is an expected result, and that is why we move to green concrete using FA or GGBFS.
- Construction material (Manufacturing module) (A1-A3) is the most generating emissions for the three alternatives through all environmental impact categories. Therefore, it is recommended to minimize the emissions during that phase by using byproducts such as FA or GGBFS.
- The manufacturing module (A1-A3) is the most generating of CO_2 emissions with 1324.7, 1016, and 843 tons for OPC, FA, and GGBFS alternatives, respectively. On the other hand, it can be noticed that the GGBFS alternative has the lowest CO_2 emissions.
- The second-highest category of generating CO_2e is the transportation LCA module with 78.2 tons for the three alternatives because transportation is similar for them.
- The construction material module has the highest ratio in the GWP impact category by 92%, 90%, and 88% of the total for OPC, FA, and GGBFS alternatives, respectively. External impacts (D) come next with an 18.3%, 23.5%, and 27.48% recovery of embodied CO_2 emissions for OPC, FA, and GGBFS alternatives, respectively.
- For OPC, the transportation module (A4), the deconstruction module (C1-C4), and the construction process module (A5) come after with 5.43%, 1.9%, and 0.65%, respectively. The same order for both FA and GGBFS alternatives, with 7%, 2.44%, and 1% for FA and 8.16%, 2.85%, and 1% for GGBFS, respectively.

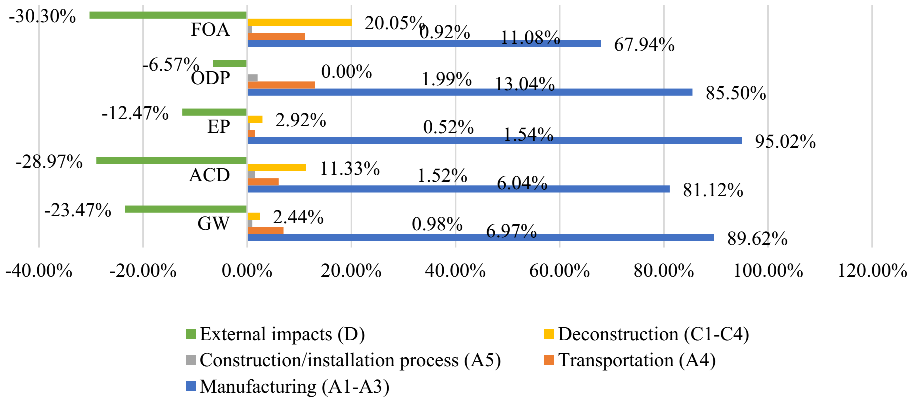
Table 1 One-Click LCA results

Result Category		Global warming kg CO_2e			Acidification kg SO_2e		
		OPC	FA	GGBFS	OPC	FA	GGBFS
A1-A3	Construction materials	1,32E6	1.01E+06	8.43E+05	2.17E+03	1.54E+03	1.77E+03
A4	Transportation to site	7.82E+04	7.82E+04	7.82E+04	1.14E+02	1.14E+02	1.14E+02
A5	Construction/installation process	9.35E+03	1.10E+04	9.77E+03	2.62E+01	2.88E+01	2.74E+01
C1-C4	deconstruction	2.74E+04	2.74E+04	2.74E+04	2.14E+02	2.14E+02	2.14E+02
D	External impacts (not included in totals)	-2.63E+05	-2.63E+05	-2.63E+05	-5.49E+02	-5.49E+02	-5.49E+02
	Total	**1.44E+06**	**1.12E+06**	**9.59E+05**	**2.53E+03**	**1.89E+03**	**2.13E+03**

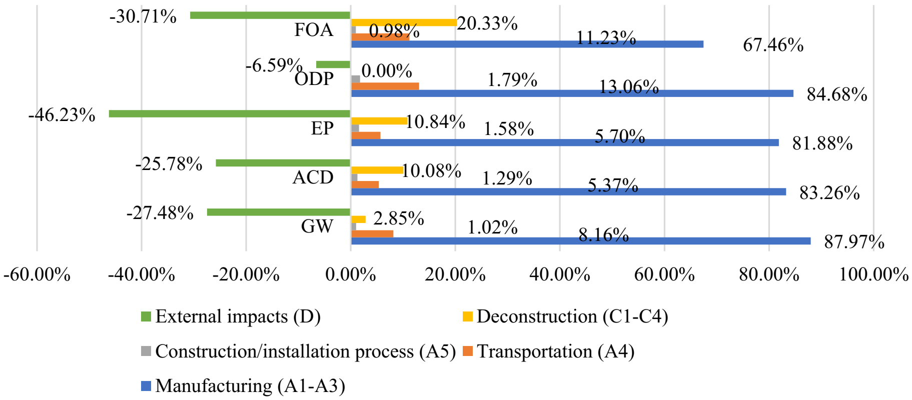
Result Category		Eutrophication kg PO_4e			Ozone depletion potential kg CFC11e			Formation of ozone of lower atmosphere kg Ethenee		
		OPC	FA	GGBFS	OPC	FA	GGBFS	OPC	FA	GGBFS
A1-A3	Construction materials	5.77E+02	1.44E+03	3.36E+02	9.32E-02	8.56E-06	8.51E-02	9.41E+01	7.19E+01	7.04E+01
A4	Transportation to site	2.33E+01	2.33E+01	2.33E+01	1.32E-02	1.32E-02	1.32E-02	1.17E+01	1.17E+01	1.17E+01
A5	Construction/installation process	6.19E+00	7.91E+00	6.47E+00	1.70E-03	1.98E-03	1.78E-03	9.73E-01	9.73E-01	1.02E+00
C1-C4	deconstruction	4.44E+01	4.44E+01	4.44E+01	2.19E-08	2.19E-08	2.19E-08	2.12E+01	2.12E+01	2.12E+01
D	External impacts (not included in totals)	-1.89E+02	-1.89E+02	-1.89E+02	-6.58E+03	-6.58E-03	-6.58E-03	-3.20E+01	-3.20E+01	-3.20E+01
	Total	**6.51E+02**	**1.52E+03**	**4.10E+02**	**1.08E-01**	**1.01E-01**	**1.00E-01**	**1.28E+02**	**1.06E+02**	**1.04E+02**



(a) LCA modules results (in %) for OPC alternative



(b) LCA modules results (in %)for FA alternative



(c) LCA modules results (in %) for GGBFS alternative

Fig. 6 **a**: LCA modules results (in %) for OPC alternative. **b**. LCA modules results (in %) for FA alternative. **c**. LCA modules results (in %) for GGBFS alternative

- The manufacturing module (A1-A3) is dominating environmental impact in all categories by over 70%, 65%, and 65% for the OPC, FA, and GGBFS alternatives, respectively.
- Acidification has the second highest environmental impact of the three alternatives. The total embodied SO_2 emissions of OPC are equal to 2.53 tons as the highest emissions among the three alternatives. It is another reason to use green concrete with FA or GGBFS. In addition, FA has the lowest SO_2 emissions with 1.89 tons. It can be noticed that the quantities of CO_2 emissions are bigger than SO_2 emissions and other emissions. Therefore, it is selected as the environmental impact criterion that shall be used in the multicriteria decision-making process using the AHP method.

4.2 HBERT verification results

Table 2 shows the results of total embodied CO_2 emissions for the three alternatives. It is found that:

- OPC has the highest total embodied CO_2 with 1530 tons, while GGBFS has the lowest (the best) embodied CO_2 with 962 tons. It is the same result generated from the One-Click LCA.
- The manufacturing module (overall material EC) has the highest environmental impact category of the three alternatives, while the second-highest category is the construction module for the three alternatives.
- The results of both One-Click LCA and HBERT are approximately identical even though each software has its own EPD database. The manufacturing module has the highest contribution among other modules with a big gap. However, other categories are not close to each other, due to the differences concerning material EPD database between the LCA add-in tools.

4.3 Embodied energy results

Embodied energy results of OPC traditional concrete, 30% fly ash concrete, and 50% GGBFS concrete have been calculated by identifying the embodied energy impact for 1 ton of concrete (Higgins, 2006) and multiplying it by the total amount of concrete needed

Table 2 HBERT results

Material: name	HBA traditional concrete Cast in Situ 25/30	HBA concrete 30% fly ash Cast in Situ 25/30	HBA concrete 50% GGBFS Cast in Situ 25/30
Material: Volume (m^3)	4177.26	4177.26	4177.26
Overall material weight (waste inc.) (tons)	9649.48	9649.48	10088.09
Overall material EC (ton CO_2e)	1370.23	1138.64	861.52
Overall transport EC (ton CO_2e)	41.11	34.16	25.85
Overall construction EC (ton CO_2e)	91.35	75.91	57.43
Overall end of life EC (ton CO_2e)	27.40	22.77	17.23
Overall EC sum (ton CO_2e)	1530.09	1271.48	962.03

Table 3 Embodied energy impact results

Impact	Traditional concrete (OPC)	Concrete 30% fly ash (FA)	Concrete 50% GGBFS (GGBFG)
Embodied energy (MJ)	4,469,668	3,863,966	3,174,718

Table 4 Cost estimate for concrete alternatives

	Components	Quantity	Unit Price (LE)	Mix design	Cost (LE)	Total Cost (LE)
OPC concrete	Cement (ton)	1253.178	760	0.3	952415.28	1,739,244
	Sand (m^3)	1670.904	110	0.4	183799.44	
	Aggregate (m^3)	3341.808	180	0.8	601525.44	
	Water (Liter)	626.589	0.0024	150	1503.8136	
30% Fly ash	Cement(ton)	877.2246	760	0.21	666690.7	1,749,019
	Sand (m^3)	1670.904	110	0.4	183799.44	
	Aggregate (m^3)	3341.808	180	0.8	601525.44	
	Water (Liter)	626.589	0.0024	150 L	1503.8136	
	Fly ash (ton)	375.9534	786	30% of cement	295499.37	
50% GGBFS	Cement (ton)	626.589	760	0.15	476207.64	1,775,586
	Sand (m3)	1670.904	110	0.4	183799.44	
	Aggregate (m3)	3341.808	180	0.8	601525.44	
	Water (Liter)	626.589	0.0024	150	1503.8136	
	GGBFS (ton)	626.589	818	50% of cement	512549.8	

for constructing multi-story garage model. The total embodied energy of the three alternatives is shown in Table 3. It shows that using concrete with 50% GGBFS has been the most effective in the conservation of embodied energy, as its embodied energy equals 3,174,718 MJ, which preserves 1,294,950 MJ of using OPC traditional concrete. OPC traditional concrete has the most energy consumption.

4.4 Cost results

Table 4 presents the quantities and percentages of concrete mixture components. Consequently, the cost of the three alternatives of concrete is calculated based on Egyptian market prices as presented in Table 4. It can be noticed that OPC traditional concrete has the lowest cost with LE 1,739,244 due to the higher prices of FA and GGBFG than the cement.

4.5 AHP results

The pairwise comparison method is used to get the weights of the three considered criteria: CO_2 emissions, embodied energy, and cost. The resulting weights are 0.71, 0.09, and 0.20, respectively, as presented in Table 5. It is clear that CO_2 emissions criterion has the bigger weight because the environmental impacts had the highest importance. The consistency ratio is 0.03 which is less than 0.1; therefore, the judgment is acceptable. AHP method is applied, and the consistency ratios for CO_2 emissions, embodied energy, and cost are 0.01,

Table 5 AHP results

		CO_2 emissions	Embodied Energy	Cost	Score	Rank
Pairwise comparison	Weight	0.71	0.09	0.20		
	Consistency ratio (CR)	0.03				
AHP	OPC traditional concrete	0.12	0.12	0.51	**0.20**	**3**
	30% fly ash concrete	0.32	0.27	0.36	**0.32**	**2**
	50% GGBFS concrete	0.56	0.61	0.13	**0.47**	**1**
	Consistency ratio (CR)	0.01	0.06	0.09		

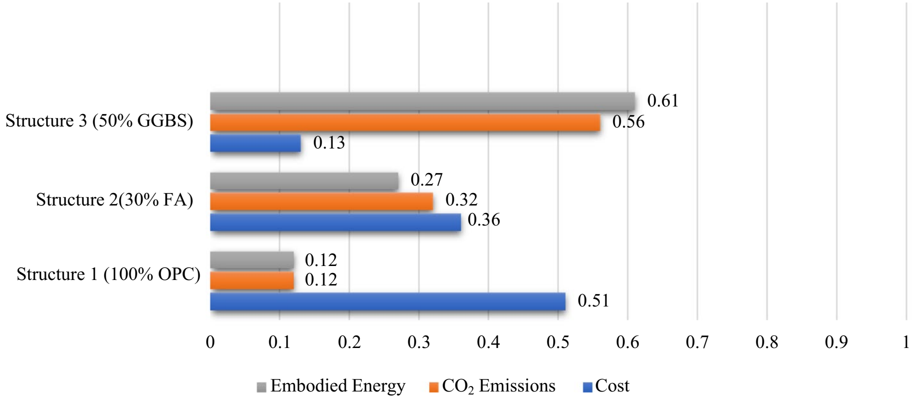


Fig. 7 Analysis of alternatives concerning criteria

0.06, and 0.09, respectively (accepted because each is less than 0.1). Table 5 presents the AHP outcome score and ranking for the three alternatives.

It is found that the concrete with 50% GGBFS has the highest ranking with a value of 0.47 (best sustainable alternative). The second-highest ranking is concrete with 30% FA with a value of 0.32, and the lowest ranking is traditional concrete (OPC) with a value of 0.2. Figure 7 analyzes alternatives concerning criteria.

It is found that the GGBFS alternative is better than the other two alternatives in both CO_2 emissions and embodied energy criteria with scores of 0.56 and 0.61, respectively, while the OPC alternative is better than the other two alternatives in the cost criterion with a score of 0.51. On the other hand, the FA alternative has the second rank for each of the three criteria.

5 Conclusions and recommendations

This research examines sustainable construction through the integration between LCA tools and BIM software to assess environmental impacts throughout the entire lifecycle of different building materials. The BIM software allows the designers to use local and non-local materials with different design parameters, whereas the LCA approach is a complicated methodology used to assess the environmental impacts of construction materials. Besides the research objective to demonstrate the benefit of the interoperability between LCA tools and BIM tools, it also aims to empower the decision-making process in the construction sector. The study compares three different construction materials which are traditional concrete, concrete with 30% fly ash, and concrete with 50% GGBFS. Accordingly, the AHP method is used for the decision-making process as it is an effective tool to know which type of used models is the most sustainable. According to AHP results, using 50% GGBFS has been the most sustainable type of material used between structure models. GGBFS has the lowest embodied CO_2 and embodied energy among other models with the overall highest score of 0.47, followed by fly ash with a 0.32 score, and lastly OPC with a 0.2 score.

This work highlighted critical points such as sustainability in the construction field must be taken into consideration from the design phase of construction phases. It is due to the huge environmental impact caused by the life cycle of constructing a building. Implementing LCA and BIM is helpful to assess the sustainability of structures. Using different types of EPD for the LCA of a project produces no significantly different result. One-Click LCA can be taken as the most effective tool for applying life cycle assessment for a project, due to its huge database, and the flexibility of using it with BIM software.

This research is limited to concrete structures and three sustainable criteria: CO_2, energy, and cost. Therefore, it is recommended to consider more sustainable criteria to compare the models, as well as taking into consideration a broader variety of construction materials using experimental design methodology. On the other hand, artificial intelligence can play a major role in that objective. It can help to assess the sustainability of different building materials over the entire life-cycle evaluation of buildings.

Acknowledgements The authors would like to express their gratitude to Nile University (NU) for supporting this research.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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