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# Toward a national life cycle assessment tool: Generative design for early decision support

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The life cycle assessment (LCA) has proven to be a reliable methodology for achieving sustainable development. The number of studies and attempts of integration at the building design stage is increasing. This study is aimed at developing a framework for a national LCA tool that considers Egyptian constraints and strikes a balance between embodied and operational impacts to serve as a decision-support tool for early design. This is achieved by first reviewing and analyzing LCA integration methods during the early design stages, emphasizing parametric methods. Second, studying the situation of LCA and energy efficiency in Egypt through publications, building codes, and residential building construction specifications. As a result of these steps, a suggested implementation method based on the generative design was developed as a tool framework that mainly focuses on residential building exterior walls as the first step of the national LCA tool to aid the design process and promote sustainable development. In addition to being the first initiative for a national LCA tool, the novelty of this work is the method of integration compared to other parametric LCA, which aims at optimizing both embodied and operational impact with respect to the Egyptian conditions while offering multiple solutions.



## 1. Introduction

Sustainability has become the target for practically all fields, and it is considered the primary objective for most modern building trends because the world is facing a lack of resources and an energy crisis that is expanding by the day. According to the International Energy Agency, the construction sector accounted for 36% of total energy consumption and 39% of energy-related greenhouse gas (GHG) emissions in 2018 [1], aside from being responsible for 40% of natural resource depletion and 25% of waste generation [2].

Life cycle sustainability assessment (LCSA), which is composed of life cycle cost, life cycle assessment (LCA), and social life cycle assessment, incorporates the three dimensions of sustainability (economic, environmental, and social) [3]. LCA is a method for evaluating the environmental impact of a product over its entire life cycle using inputs and outputs [4]. It is a tool in the hands of building professionals to understand the energy use and environmental burdens associated with each life cycle stage of the building, as LCA uses a quantitative approach to measure the environmental impacts resulting from all stages in a product or a whole building life cycle, and it is considered the most accurate assessment method recently used in the construction industry [5], which is the main scope of this study.

LCA consists of four steps, according to ISO 14040 and 14044 [4]: goal and scope definition, inventory analysis, impact assessment, and interpretation. The life cycle stages of a building are classified into the materials production stage (A1–A3), construction stage (A4–A5), use of the building stage (B1–B7), and the building's end-of-life stage (C1–C4), according to EN15978 [6]. In addition to these boundaries, there is (D), which includes any benefits or loads that occur beyond the building's life cycle.

*Abbreviations:* ADP, Abiotic Depletion Potential; AP, Acidification Potential; BAIA, Building Attribute to Impact Algorithm; BIM, Building Information Modeling; CC, Climate Change; $CO_2$-eq, Carbon Dioxide equivalent; ECP, The Egyptian code for improving energy efficiency use in buildings; EP, Eutrophication Potential; FE, Freshwater Eutrophication; FFD, Fossil Fuel Depletion Potential; GHG, Greenhouse Gas; GWP, Global Warming Potential; ISO, International Organization for Standardization; $I_w$, Impact of the Wall [Points/kg or kg $CO_2$-Eq per kg]; K, Thermal Conductivity [W/m °C]; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; MDO, Multidisciplinary Design Optimization; ME, Marine Eutrophication; NRPE, Nonrenewable Primary Energy; OD, Ozone Depletion; $R_t$, Total Thermal Resistance Value [$m^2$ °C/W]; SFP, Smog Formation Potential; SM, Smog Creation.

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Key decisions are usually made during the early design stage, and LCA can be used to facilitate the design process, leading to the selection of lower impact alternatives for building material and assemblies which is a common recommendation in LCA studies [7] but the balance between operational and embodied impacts should also be considered [8–10]. However, the information available in this stage is limited, and LCA application will also involve design-oriented user requirements and simplification strategies [11]. Conventional LCAs are time-consuming and difficult to implement at this stage [12]. LCA is typically performed before construction.

Building LCA studies in the design stage have rapidly increased in the recent decade, with a higher amount in the design stage than in early-stage or streamlined LCA. Few review papers discussed the integration of building LCA and early design stages; some discussed facilitating BIM-based LCA [2,13,14], while others presented multiple methods of LCA integration in the design process [15,16] or other perspectives [17] in addition to the Annex 72 project [18], which is aimed at setting up guidelines and tools for building design and planning by integrating LCA. Moving on to national studies related to buildings LCA (section 4.1), only one of the few presented national publications considered the design stage [19].

Building information modeling (BIM), without a doubt, facilitated LCA by allowing for easy material take-off. Several review articles have discussed BIM-LCA integration during the design stage [2,13,14,20–23] to reveal the challenges and simplify LCA application, whereas publications focusing on BIM-LCA integration at the early design stage mostly aim to support decision-making [24–35], some concerns should also be heading toward interoperability facilitation with BIM as a trending recommendation [36] because the conventional LCA approaches are the least suitable for use by designers, and have higher error probability due to manual data input, some tools tried to semi automate the process to avoid human error such as Tally but the LCA still follows a static approach. The need for multiple design options is a common observation in early design, parametric approaches and methods have proven to be effective at this stage. Studies that presented parametric approaches are extensively discussed in Section 3.

According to the literature review, implementing LCA at the early design stage still has limitations and unsolved gaps, national studies are very bounded, parametric methods can be favorable for the early stage as it offers and compares multiple options. This paper focuses mainly on:

- Parametric methods used to conduct LCA at the initial design stage
- Egyptian specification related to operational energy efficiency and construction methods and harmonizing it with embodied impact
- Enabling designers to make environmentally responsible choices

The outcome of this paper is a novel approach forming the framework of the first national LCA decision support tool for early design stage. it uses generative design to offer multiple options of residential building exterior walls with minimum environmental embodied while also considering the operational impact of the building in accordance with national specifications in Egypt.

## 2. Methodology

Forming the framework for the national LCA tool necessitated a thorough grasp of current methods for integrating LCA at the early design stage and how it is implemented, as well as recognizing the situation and constraints in Egypt. After a brief introduction, the paper proceeded with the following steps and methods (Fig. 1): (i) reviewing different parametric methods used in conducting LCA by presenting a number of studies and how did these studies offer optimized solutions; (ii) analyzing some focused articles that used algorithms or probabilistic methods which proved to be effective when dealing with uncertainties about building components, or design parameters at the early design stage, the analysis aims at understanding aspects of implementation, scope and method (both steps are in Section 3); (iii) to further understand the applicability of such probabilistic methods to the Egyptian situation, the third step is reviewing and analyzing national constraints in Egypt, including national LCA studies as well as building codes and methods (Section 4); (iv) defining the scope and method of implementation where exterior walls are selected as a building component for the prototype tool, after a detailed analysis of regional building codes, construction methods, and building materials to balance the embodied and operational impacts (Section 5.1); (v) formulating the framework of the tool and its scope including inputs, programing, the background calculations and algorithm, outputs (Section 5.2); (vi) expressing the conclusion and study limitations and introducing the tool framework in Fig. 4 and Fig. 5 (Section 6).

## 3. Parametric methods and LCA - review and analysis

In recent years, generative design has gained much interest as artificial intelligence and computational tools help to speed up the design process [37]. Parametric methods can support the environmental design process by providing multiple alternatives; they outperform generic LCA tools in terms of time and optimal design solution selection [16,38,39].

Grasshopper was used to conduct LCA of buildings as a parametric design method through some studies [10,26,38,40–44] by integrating a simplified LCA with the design process. At the national level, Gomaa *et al.* [45] developed a framework that integrates LCA with the traditional design process. Algorithms are another method for simplifying the design process by using a set of parameters or variables.

Multidisciplinary design optimization (MDO) methods allow designers to explore a wide range of design alternatives and evaluate many design options to identify optimal or near-optimal solutions [46]. Some studies [47,48] have utilized MDO in investigating the trade-offs between life-cycle environmental impact and cost. Basbagill *et al.* [46] proposed a novel approach to existing MDO methods by leveraging probability distribution functions to support sequential decision-making processes.

Genetic algorithms have been used in a variety of research in the field of green building design, such as selecting the location and size of windows in an office building [37], or analyzing the trade-offs between economic and environmental factors [49–51]. Genetic algorithms are also used for refurbishment and renovation optimization studies [52,53] and for building envelope optimization [54,55]. Other algorithms and probabilistic methods, as well as genetic algorithms, have gained interest in LCA studies.

The Building Attribute to Impact Algorithm (BAIA), which is a streamlined LCA method that uses probabilistic triage to calculate impact [56], uses algorithms to simplify the building design process into a set of parameters or variables using Monte Carlo simulation [16]. In some studies [56–58], the BAIA at the early stages can guide decision-making in design selection and lead to optimal solutions.

Using statistics to deal with uncertainties through sampling, sensitivity analysis, regression techniques, or other probabilistic methods has proven to be particularly effective in early LCA as it allows users to explore several alternatives by iteratively evaluat-

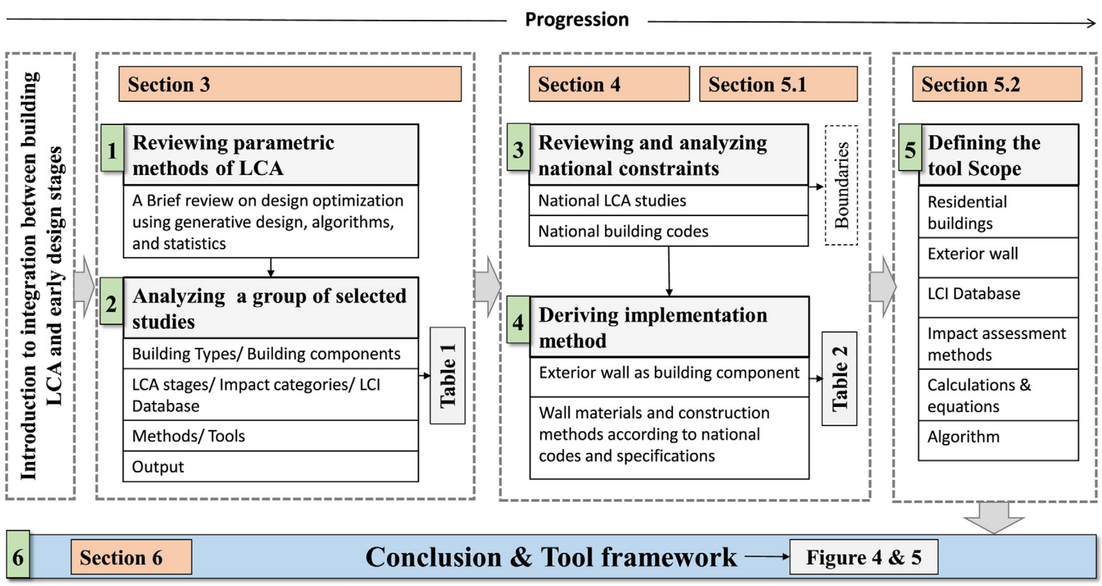



**Fig. 1.** Graphical image of research steps and methodologies.

ing design variables. In previous studies, probabilistic methods, such as sensitivity analysis, have been included in early LCA studies to guide in reducing the embodied environmental impacts of building component materials and dimensioning choices [29], as well as to identify the influential factors of building LCA [59–61]. Regression models were also used in early LCA studies [62,63], while structured under-specification, a probabilistic method for streamlining LCA, was developed and tested in two recent studies [64,65].

After reviewing early LCA studies integrated with various parametric methods, a group of studies was selected and analyzed, with emphasis on those that used algorithms and probabilistic methods. Table 1 presents and analyzes the studies that used parametric methods to select building materials, components, or design parameters (shape, location, geometry, envelope, etc.) at the early design stage, including the building type, study scope, life cycle inventory (LCI) database, method, tool, and visualization of the results.

Table 1 and Fig. 2 reveal that different types of residential buildings are the central interest of most research, with only one case focusing on office buildings. Ecoinvent is the most reliable LCI database; it was listed in all of the articles that included data sources, either alone or in combination with other LCI databases. To make the probabilistic triage or analysis, multiple analysis tools were used, including Excel plugin and statistical software JMP, as well as programming languages. Production (A1–A3) and operational energy use (B6) are the most dominant LCA stages, according to most of the selected studies. Further, both stages have the highest environmental impacts. Most of the studies used box plots to represent the results because of their ability to display variation since involving probabilistic and uncertainty gives a wide range of options.

Since integrating LCA at the early design optimization of sustainable buildings is new trend, and most of the selected studies (see Table 1) offers initiative approach or a method, a lot of limitations and gaps is not solved yet, in addition to facilitating the process to the building designers is essential, not to mention that work on LCA in Egypt still in progress. The novelty of this work is extracting the parameters from standards and specification related to operational energy efficiency and traditional construction methods in Egypt and combining it with their related embodied impact in a generative design process offering several solutions in an easy used tool for architects and designers.

## 4. National constraints forming the LCA tool framework

A review of LCA studies conducted in Africa revealed that the number of total publications in the continent is very low, possibly less than half of a developed country, such as Germany. Only 8% of total LCA studies are related to construction, and only about five of the 23 LCA studies conducted in Egypt are related to building materials [68]. This section reviews and analyzes national LCA studies and national building codes related to energy efficiency to further develop a method paving the way for the tool. Construction methods and building materials for the Egyptian situation will be further discussed in (Section 5).

### *4.1. National LCA studies related to building in Egypt*

Initiative LCA of a typical residential building in Egypt was implemented for a full building LCA according to ISO 14040 standards [69]. Two other studies investigated the impact of structural and construction systems, as one conducted an LCA of a residential building in Egypt to investigate the stages and materials with higher impact using the Tally plugin, while the other developed an LCA framework for embodied environmental impacts of building construction systems to be used as decision support at the early design stage [19,70]. Four publications presented LCA studies on building materials and components, such as bricks [71], cement [72], glazing systems [73], and pile foundation [74]. On the other hand, a framework for developing a national LCI database was suggested [75], while, in the construction management scope, the potentials and challenges of using an LCA-BIM integration procedure to achieve a sustainable management process were investigated [76].

The results or outcomes of these studies may support the design process, but there is no national publication or study that investigated LCA as a guide during architectural design, and unlike some other sustainable architectural design attempts [77,78], the Abou-hamad and Abu-Hamd [19] or Gomaa *et al.* [45] studies, which concerned early design didn't consider national codes [79,80].

**Table 1**
Parametric LCA studies analysis.

| Year & Country | Reference | Building Type | Building Components/ Design Parameters | LCA Stages | Impact Categories | LCI Database | Methods/ Algorithm | Analysis Tool | Output |
|---|---|---|---|---|---|---|---|---|---|
| 2021 China | Song et al. [66] | Housing | Exterior wall | A1–A5, B2, B6, C1–C3 | Energy consumption (GJ) | Ecoinvent, Chinese electricity mix and transportation | Optimization Method | C# | Bar chart |
| 2019 China | Xikai et al. [63] | Residential buildings in China | 12 Design factors for predictive model related to (geometry, envelope, and carbon emissions) | A1–A5, B6, C1–C4 | Carbon emissions ($LCCO_2$) | – | Four regression techniques (PCR, RF, MLP and SVR) | – | Scatter chart |
| 2019 USA | Tecchio et al. [65] | Single-family, and Multifamily | Building structure, envelope, and internal assemblies | A1–A3 | AP, EP, GWP, SM | Ecoinvent, USLCI, Athena, GaBi | Structured under-specification and probabilistic triage approach | – | Box plots |
| 2019 USA | Hasik et al. [67] | Medium office buildings | Parameters related to shape, location, materials, and components (structure, enclosure, and some interior components) | A1–A3, B3, B4, B6, B7 | ODP, GWP, SFP, AP, EP, FFD, cost | Ecoinvent | Sensitivity analysis | Python | Parallel coordinate, and scatter plot charts |
| 2018 USA | Hester et al. [56] | Hypothetical single-family residential building | Foundation, exterior and interior walls, windows, doors, floors, and ceiling | A1–A5, B4, B6, C1–C4 | GWP | Ecoinvent 2.2, GaBi, Athena Impact Estimator | BAIA | Microsoft Excel + the Oracle Crystal Ball plug-in | Box plots |
| 2018 USA | Hester et al. [57] | Residential building | Roof exterior, attic interior, exterior walls, interior walls, windows, doors, floor and ceiling, foundation | A1–A5, B4, B6, C1–C4 | GWP, cost | Ecoinvent, Athena, USLCI, GaBi | Sequential specification and genetic optimization coupled with BAIA | MATLAB | Pareto frontier |
| 2018 South European | Rodrigues et al. [58] | Single-family house (retrofits) | Exterior walls, roof, floors, and windows within 33 design attributes related to (geometry, envelope, thermal properties, and occupancy) | B1–B6, C1–C4 | CC, NRPE, OD, ME, FE, terrestrial acidification, cost | Ecoinvent | BAIA | Statistical software JMP | Box plots & stacked bar chart |
| 2018 USA | Tecchio et al. [64] | Residential building | Exterior wall options | A1–A3 | AP, EP, GWP, SM | Ecoinvent 2.2, USLCI, Athena, GaBi | Structured under-specification | Microsoft Excel plug-in (Oracle Crystal Ball) | Box plots |
| 2017 USA | Hester et al. [62] | Single-family residential buildings | Parameters related to building form (area, shape, number of floors) orientation, insulation, glazing, and some HVAC parameters | B6 | Energy consumption (GJ/year) | – | Regression metamodel, Monte Carlo simulations, and sensitivity analyses | MATLAB | Box plots |
| 2014 USA | Basbagill et al. [46] | Residential complex | Substructure, shell, interiors, services (within 27 design variables) | A1–A3, B2–B4, B6 | GWP, cost | Ecoinvent, Athena | Multi-objective feedback method | ModelCenter software (using sampling algorithm) | Bar chart |
| 2013 USA | Basbagill et al. [29] | A mid-rise multi-building residential | Substructure, shell, interiors, services | A1–A3, B2–B4 | $CO_2$ eq | Ecoinvent, Athena | Sensitivity analysis | ModelCenter | Histograms |

Abbreviations: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Climate Change (CC), Eutrophication Potential (EP), Fossil Fuel Depletion Potential (FFD), Freshwater Eutrophication (FE), Global Warming Potential (GWP), Marine Eutrophication (ME), Nonrenewable Primary Energy (NRPE), Ozone Depletion (OD), Smog Creation (SM), Smog Formation Potential (SFP).

### 4.2. National building codes

As part of its mission, the Housing and Building National Research Center developed "The Egyptian code for improving energy efficiency use in buildings," ECP 306/1–2005 (Part one: residential buildings) [79] and ECP 306/2–2009 (Part two: commercial buildings) [80]. The code divides Egypt into eight regions (see Fig. 3) based on the external envelope requirements, because the location, wall orientation, external surface absorbance, and building conditioning determine the minimum thermal resistance value

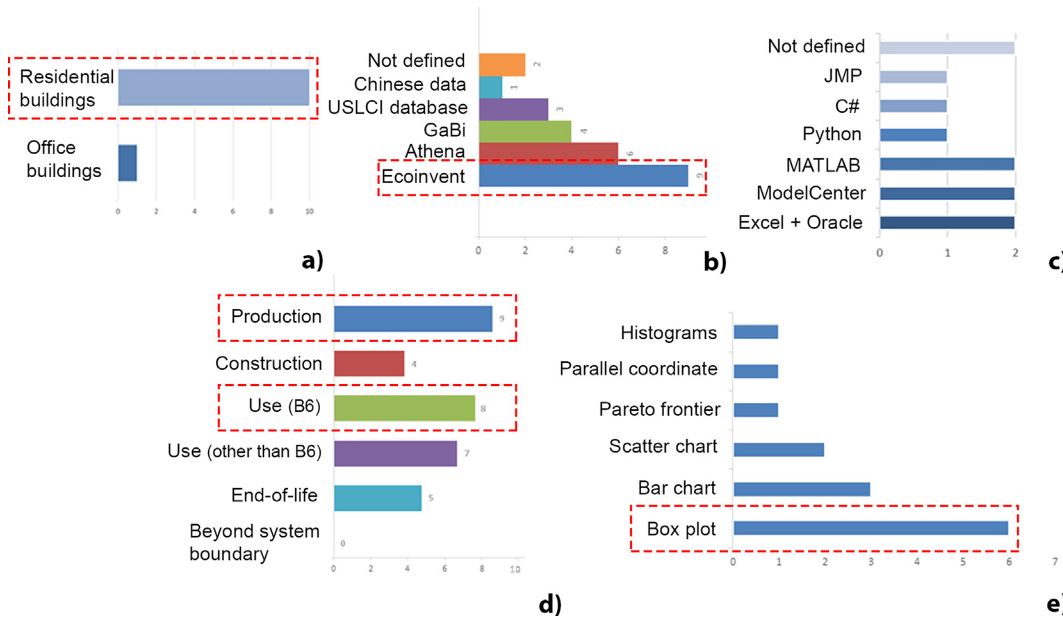



**Fig. 2.** Summary of data analysis in the reviewed articles, a) building type, b) LCI database, c) analysis tool, d) LCA stages, and e) output.

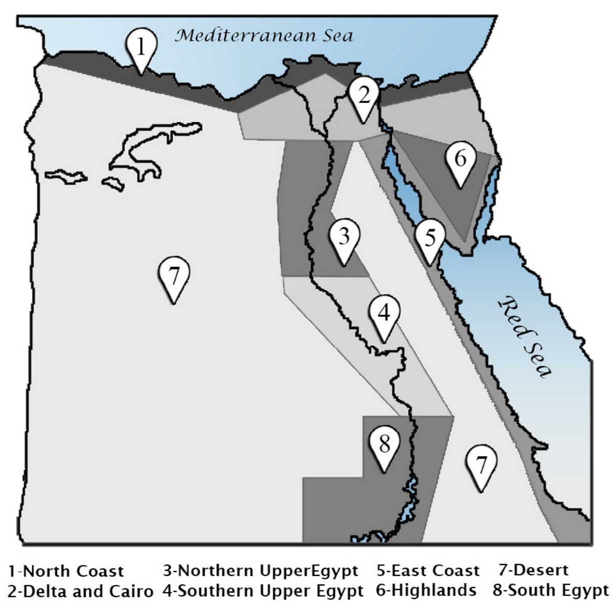



**Fig. 3.** Climatic regions in Egypt.

($R_t$) for each wall (see Table A.1). Other national building codes [81,82] were also used as references for construction and thermal insulation.

## 5. Results and discussion

Following a comprehensive review and analysis of the previous two sections, a conceptualization of the implementation method for the national LCA tool using the generative design is presented, with a focus on residential building exterior walls.

### 5.1. Implementation

This section suggests a hypothesis that uses generative design as a parametric method to be implemented on residential building exterior walls, paving the way for a future tool with national standards to further include all building components using LCA as decision support at the early design stage.

#### 5.1.1. Selection criteria based on national codes and construction methods

A detailed analysis of regional building codes, construction methods, materials, and design is required to balance embodied and operational impacts. Residential buildings were selected to be inspected among building types because, according to the Central Agency for Public Mobilization and Statistics of Egypt [83], they represent about 83% of total buildings in 2017. ECP 306/1–2005 [79] and "specifications for thermal insulation: design and execution requirements" [82] were used to define the exterior wall constraints.

*5.1.1.1. Exterior wall as a building component.* The embodied impact of a building is affected by its envelope and the used material, but the operational impact is also influenced by the material type and thickness selected. The exterior wall is selected as the scope of the study.

Ali *et al.* [69] assessed the environmental impacts of a typical Egyptian residential building at all stages, and the main conclusions were that impact related to building materials was the second-largest contribution to overall impact after the operational stage. Redbrick accounted for 25% of the total impact among other materials, according to a detailed analysis of the study. Furthermore, the LCA results of multi-residential building research [25] displayed a comparison between different building assemblies in the material production stage and discovered that the foundation and exterior wall are the main sources of the building's environmental impacts in the material production stage. Furthermore, Hollberg *et al.* [84] evaluated the embodied global warming potential (GWP) throughout the whole design process of a real building and discovered that walls are one of the main contributors to the total embodied carbon of a building, among other construction elements. Other studies have also revealed that walls are one of the highest contributors to a building's embodied impact [33,85,86].

*5.1.1.2. Wall materials and construction methods.* Building materials properties were structured based on Egyptian codes and specifications because conventional materials and construction methods are commonly used in the residential sector. Herein, the study focused on exterior wall materials and how they are typically applied in the construction sector. Exterior walls are mainly constructed using clay, cement, or sand-lime bricks, and if necessary, insulation materials with appropriate finishing. Insulation materials are classified based on type as follows:

a) Loose-Fill insulation materials: *Perlite and Vermiculite*
b) Semi-Rigid insulation materials: *Cork, Rock wool, and Glass wool*
c) Rigid insulation materials: *Expanded polystyrene, Extruded polystyrene, and polyurethane (rigid foam)*
d) Foamed insulation materials: *Polyurethane foam*

The insulation material type is selected and installed based on one of the methods listed in Table 2 [82], which include normal single wall, externally insulated wall, double-wall, and internally insulated wall, and each method determines the appropriate insulation type.

It is worth noting that the impact of wall mortar, adhesives, framing, and vapor barrier are neglected. When single walls are used, the $R_t$ of a wall may fulfill the code requirement without any insulation. When employing the internally insulated wall method, which uses insulation from the interior surface of the wall, the R-value of the insulation material is reduced by 30% [79]. Appendix A, from Table A.2 to Table A.6 provides additional information on bricks, insulation material, and other wall layers' properties, which further will be embedded in the tool.

### 5.2. Forming the tool framework

ISO divides the process of addressing potential environmental impacts into four correlated phases [4]. Step 1: the goal and scope will include the embodied impact of the material production stage (A1–A3) and replacement (B4) of the exterior walls of typical residential buildings. Step 2: inventory analysis will use ecoinvent [87] as the source of the LCI data for impact calculations because there is currently no national LCI. Data about the expected service life of the used materials will be based on information from local contractors and other references [88,89]. Step 3: impact assessment, which will include two suggested impact assessment methods as options. First, the ReCiPe Endpoint (H, A) [90] for assessing damage to ecosystem quality, human health, and resources metrics, and second, the IPCC 2013 [91] for measuring GWP. Step 4: interpretation is determined after the results.

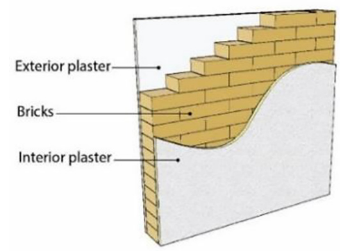
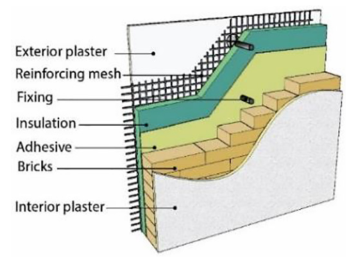
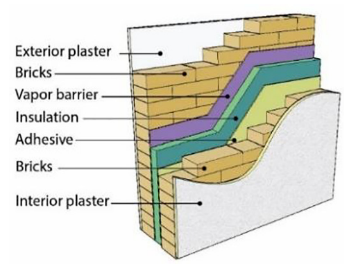
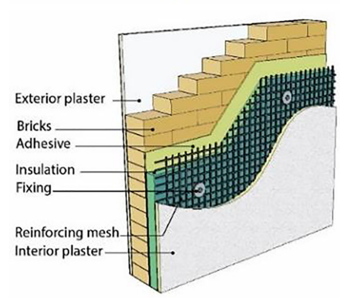
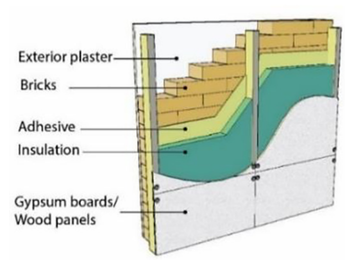
Numerous wall design options are expected to be iteratively generated by the tool using algorithms by experimenting with different types of materials and thicknesses for each layer of the wall according to methods and other national constraints, as well as environmental and expected service life which all are listed in Table A.1 to Table A.6.

#### 5.2.1. Generative design algorithm and calculations

After analyzing the data and all inputs to identify the best algorithm for the prototype tool generative design process, the grid search algorithm was selected for hyperparameter optimization within the C# programming language. In addition to the embodied impact of material production, the algorithm is used to generate multiple wall design options following national and user constraints.

The total R-value of the walls is calculated as the sum of all R-values of the wall layers, including the wall core, exterior, and interior finishing, the surface resistance of the outside and inside air film (0.17 to 0.18 $m^2$°C /W), thermal insulation, and air gaps if any exists, according to the methods in Table 2 with different brick

**Table 2**
Code-compliant installation methods for wall insulation materials.

| Exterior wall section | Installation method |
| --- | --- |
|  | Single wall (without insulation) |
|  | From the wall outside surface: in this case, adhesives are used for fixing the insulation (type b, c), then reinforcing mesh (expanded metal mesh) is applied to the whole wall area and covered with cement plaster or appropriate cladding |
|  | Inside a double wall: in this case, fewer required fixtures are used, and the insulation material is totally protected, this method is appropriate for all insulation types (a, b, c, d) |
|  | From the wall inside surface: in this case, the same used method in the wall outside surface (reinforcing mesh for insulation type b) or either gypsum/wood boards are used for support (insulation type c), but the efficiency of insulation is affected. |
|  | |

thicknesses and insulation using the following equations. Note that each R-value is either established by the code such as (Bricks) or calculated by dividing the layer thickness by its thermal conductivity like (Insulation materials) [79]:

$$\boldsymbol{R_t} = 0.178 + \frac{\boldsymbol{x}_1}{\boldsymbol{k}_1} + \frac{\boldsymbol{x}_2}{\boldsymbol{k}_2} + \cdots + \frac{\boldsymbol{x_n}}{\boldsymbol{x_n}} \quad (1)$$

where $R_t$ is the total thermal resistance of the wall ($m^2$ °C/W), $k_1$, $k_2$, etc. are thermal conductivity of a layer of the wall (W/m °C), and $x_1$, $x_2$, etc. are their thicknesses (m).

*5.2.1.1. Layer thickness and related mass calculations.* Samples in each trial use equation (2) to calculate a particular material and related quantity is based on their environmental and thermal properties from Table A.2 to Table A.6. The mass of each layer is calculated by multiplying the wall area by the chosen layer thickness and density, as well as the number of replacements times.

$$\boldsymbol{m_l} = {}_{l} \times \boldsymbol{l_w} \times \boldsymbol{h_w} \times \boldsymbol{x_l} \times \boldsymbol{D_l} \tag{2}$$

where $m_l$ is the layer mass (kg), $\varnothing_l$ represents times of replacements, $h_w$ and $l_w$ are the wall height and length (m), respectively, $x_l$ is the chosen layer thickness (m), and $D_l$ is the layer material density (kg/m$^3$).

*5.2.1.2. Impact calculations.* Environmental Impacts are calculated by multiplying the mass of each layer (material) of the wall by its impact factor, which can be determined by the user using either total environmental impact (ReCiPe) or GWP (IPCC 2013) method.

$$\boldsymbol{I_w} = \sum \boldsymbol{m_l} \times \boldsymbol{i_l} \tag{3}$$

where $I_w$ is the environmental impact of the entire wall (Points or kg $CO_2$-eq), $m_l$ is the material mass of a layer of the wall (kg), and $i_l$ is its impact factor (Points/kg or kg $CO_2$-eq per kg) then summing over all layers of the wall.

Fig. 4 presents the conceptual framework of the prototype tool. The framework shows the main constraints and the scope of the tool which the exterior walls of residential buildings in the Egyptian region are selected for the application, production (A1–A3) and replacement (B4) are the included stages for assessment. Wall methods and material properties are extracted from national building codes, as well as location constraints which determine the required R-value. while ecoinvent is the source of the environmental database. The calculation process in the tool through grid search algorithm for hyperparameter optimization basically tries every combination (in this case different materials and thicknesses for each layer of the wall for the five mentioned methods in Table 2) of values seeking optimal solutions that meet codes requirements with minimum embodied impact for the wall using the previously mentioned equations. Fig. 5 further explains the tool input options including the available parameters for the tool user such as selecting the climatic region, wall orientation, external surface absorbency, preferred impact factor, conditioning, and desired wall thickness. then briefly interprets how the calculation process goes based on the entered parameters by iterative trials of all possible solutions, and finally gives samples of the tool output and how the results are presented in graphical wall sections indicating each layer material type and thickness with dimensions on the drawings, in addition to data related to wall method, R-value, total thickness, and impact per m$^2$ for each proposed solution.

## 6. Conclusions

This study is aimed at proposing a national LCA tool framework that can be used as an early design decision support tool to promote sustainable development, in compliance with Egyptian constraints. To achieve this, it is crucial to review and analyze methods and publications for using LCA at the early design stage of buildings, as well as to investigate the potential of implementation in the Egyptian environment by studying and examining national boundaries and standards. Thereafter, an appropriate conception of the tool is drawn.

The main conclusions of this study are that generative design and using algorithms as a parametric method of LCA can have a positive impact on the early design process, as evidenced by the reviewed studies and analysis. Egyptian constraints clarified how LCA could be integrated with the national context aligned with building codes by reviewing national LCA studies and analyzing national codes and standards. The study focuses on the exterior wall as a component that affects both embodied and operational impacts of residential buildings since its total thermal resistance determines the wall layers (method of construction), materials, and thickness. Using the grid search algorithm for generative design offers numerous wall designs that reach the total required R-value of a specific wall with minimum environmental embodied impact.

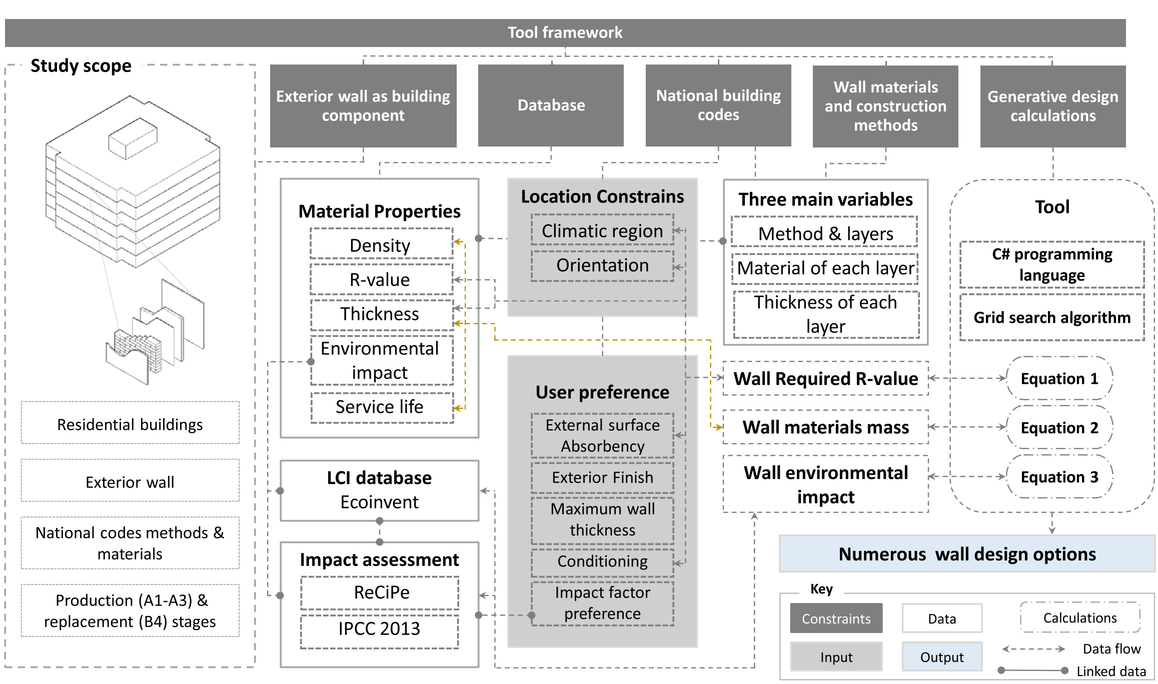



**Fig. 4.** Conceptual framework of the national LCA prototype tool, including constraints, scope, inputs and output, data, and calculations.

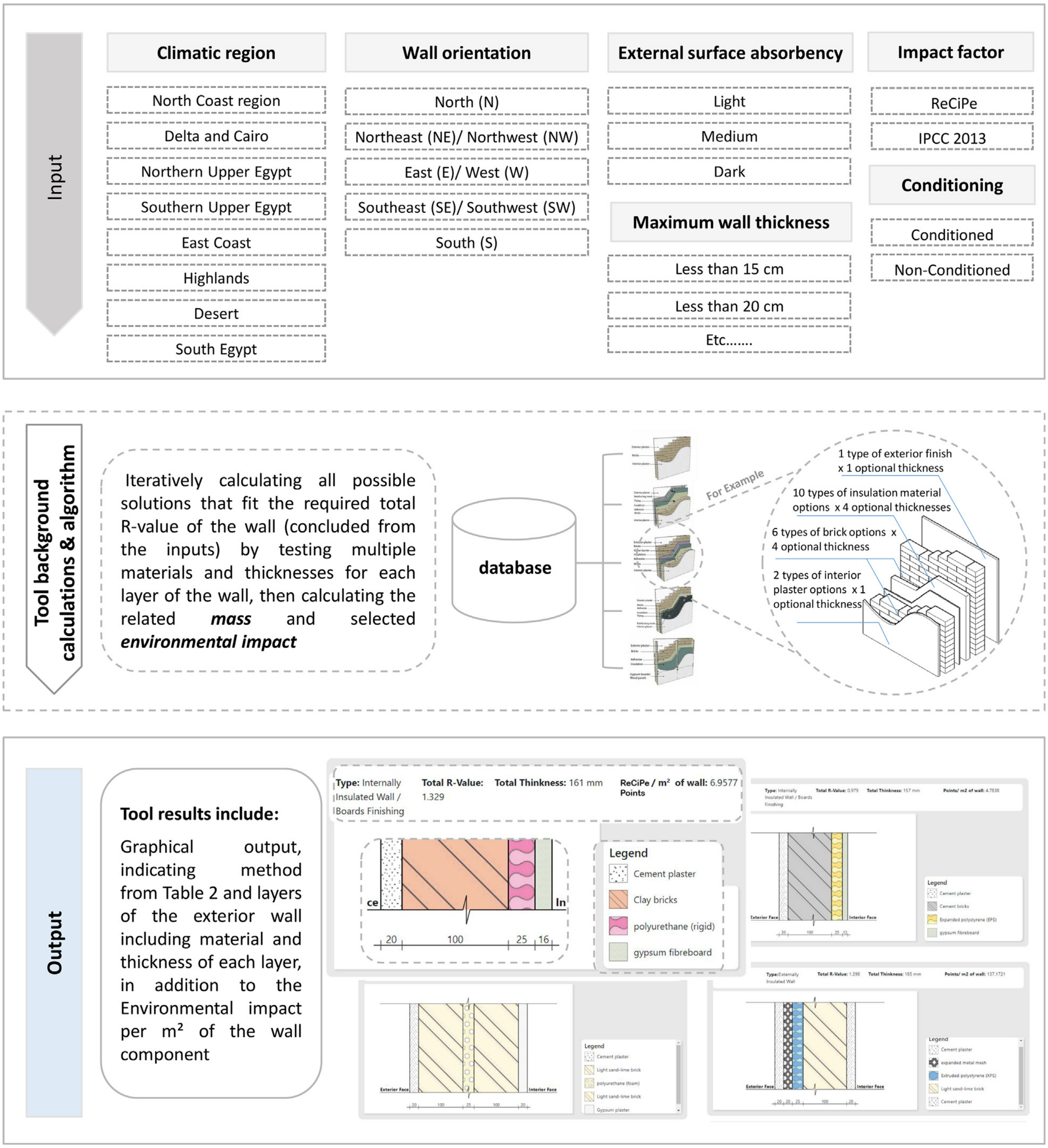



Fig. 5. An illustration of the tool inputs, optimization calculations, and outputs.

By outlining the national LCA tool framework, the objective is reached, but further data and information on the prototype tool will be proposed and investigated in future research. After the implementation of the case studies, the use of LCA at the initial design stages and its impact on the design process will be clarified, as will the variation of Egyptian eight regions' requirements and expected average impacts.

To state the limitations of this study, it should be clear that the decision-making process encompasses more than environmental impacts as a single criterion; to be more thorough, other criteria, such as cost, risk, and social dimensions must also be considered [92,93]. The study excludes criteria such as building geometry, other building components or LCA stages, transportation grids, and the ability to be integrated with other software (interoperability). Moreover, the varieties of the database are still narrow because the used material types and properties in the proposed tool are from the building codes. Furthermore, dynamic aspects of LCA, such as the degradation of thermal resistance of insulation materials over time [94], are also not taken into account.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Data integrated into the prototype tool are presented in tables (A1 to A6) in the supplementary material considering national codes and other references [79,82,87,95,96]. Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.112144.

## References

[1] I.E.A. and the U.N.E.P. Global Alliance for Buildings and Construction, 2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector, 2019. https://iea.blob.core.windows.net/assets/3da9daf9-ef75-4a37-b3da-a09224e299dc/2019_Global_Status_Report_for_Buildings_and_Construction.pdf.
[2] K. Safari, H. AzariJafari, Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development, Sustain. Cities Soc. 67 (2021), https://doi.org/10.1016/j.scs.2021.102728.
[3] W. Klöpffer, Life-cycle based methods for sustainable product development, Int. J. Life Cycle Assess. 8 (2003), https://doi.org/10.1007/BF02978462.
[4] ISO, 14040: Environmental management–life cycle assessment—Principles and framework, Int. Organ. Stand. (2006).
[5] C. Bayer, M. Gamble, R. Gentry, S. Joshi, Guide to Building Life Cycle Assessment in Practice, 2010.
[6] European Committee for Standardization, UNE-EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, Int. Stand. (2011).
[7] M. Norouzi, S. Colclough, L. Jiménez, J. Gavaldà, D. Boer, Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland, Energy Build. 261 (2022), https://doi.org/10.1016/j.enbuild.2022.111936.
[8] M.A. Cusenza, F. Guarino, S. Longo, M. Cellura, An integrated energy simulation and life cycle assessment to measure the operational and embodied energy of a Mediterranean net zero energy building, Energy Build. 254 (2022), https://doi.org/10.1016/j.enbuild.2021.111558.
[9] A. Aslani, C. Hachem-Vermette, Energy and environmental assessment of high-performance building envelope in cold climate, Energy Build. 260 (2022), https://doi.org/10.1016/j.enbuild.2022.111924.
[10] Z. Alwan, A. Nawarathna, R. Ayman, M. Zhu, Y. ElGhazi, Framework for parametric assessment of operational and embodied energy impacts utilising BIM, J. Build. Eng. 42 (2021), https://doi.org/10.1016/j.jobe.2021.102768.
[11] E. Meex, A. Hollberg, E. Knapen, L. Hildebrand, G. Verbeeck, Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design, Build. Environ. 133 (2018), https://doi.org/10.1016/j.buildenv.2018.02.016.
[12] E. Hochschorner, G. Finnveden, Evaluation of two simplified life cycle assessment methods, Int. J. Life Cycle Assess. 8 (2003), https://doi.org/10.1007/BF02978456.
[13] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Critical review of bim-based LCA method to buildings, Energy Build. 136 (2017), https://doi.org/10.1016/j.enbuild.2016.12.009.
[14] T.P. Obrecht, M. Röck, E. Hoxha, A. Passer, BIM and LCA integration: A systematic literature review, Sustain. 12 (2020), https://doi.org/10.3390/su12145534.
[15] T. Jusselme, E. Rey, M. Andersen, An integrative approach for embodied energy: Towards an LCA-based data-driven design method, Renew. Sustain. Energy Rev. 88 (2018), https://doi.org/10.1016/j.rser.2018.02.036.
[16] M. Roberts, S. Allen, D. Coley, Life cycle assessment in the building design process – A systematic literature review, Build. Environ. 185 (2020), https://doi.org/10.1016/j.buildenv.2020.107274 107274.
[17] L. Li, Integrating climate change impact in new building design process: A review of building life cycle carbon emission assessment methodologies, Clean. Eng. Technol. 5 (2021), https://doi.org/10.1016/J.CLET.2021.100286 100286.
[18] D. Satola, M. Balouktsi, T. Lützkendorf, A.H. Wiberg, A. Gustavsen, How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72, Build. Environ. 192 (2021), https://doi.org/10.1016/j.buildenv.2021.107619.
[19] M. Abouhamad, M. Abu-Hamd, Life cycle assessment framework for embodied environmental impacts of building construction systems, Sustain. 13 (2021), https://doi.org/10.3390/su13020461.
[20] T.P. Obrecht, M. Röck, E. Hoxha, A. Passer, The challenge of integrating Life Cycle Assessment in the building design process - A systematic literature review of BIM-LCA workflows, IOP Conf. Ser. Earth Environ. Sci. 588 (3) (2020) 032024.
[21] T.D. Mora, E. Bolzonello, C. Cavalliere, F. Peron, Key parameters featuring bim-lca integration in buildings: A practical review of the current trends, Sustain. 12 (2020), https://doi.org/10.3390/su12177182.
[22] M. Nilsen, R.A. Bohne, Evaluation of BIM based LCA in early design phase (low LOD) of buildings, IOP Conf. Ser. Earth Environ. Sci. 323 (1) (2019) 012119.
[23] S. Sobhkhiz, H. Taghaddos, M. Rezvani, A.M. Ramezanianpour, Utilization of semantic web technologies to improve BIM-LCA applications, Autom. Constr. 130 (2021), https://doi.org/10.1016/j.autcon.2021.103842 103842.
[24] M. Röck, A. Hollberg, G. Habert, A. Passer, LCA and BIM : Visualization of environmental potentials in building construction at early design stages, Build. Environ. 140 (2018) 153–161, https://doi.org/10.1016/j.buildenv.2018.05.006.
[25] F. Rezaei, C. Bulle, P. Lesage, Integrating building information modeling and life cycle assessment in the early and detailed building design stages, Build. Environ. 153 (2019) 158–167, https://doi.org/10.1016/j.buildenv.2019.01.034.
[26] F. Shadram, J. Mukkavaara, An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy, Energy Build. 158 (2018), https://doi.org/10.1016/j.enbuild.2017.11.017.
[27] B.M. Kotula, A. Kamari, Development of a BIM-based LCA tool to support sustainable building design during the early design stage, in: Proc. Int. Conf. Archit. Sci. Assoc., 2020.
[28] C. Cavalliere, G. Habert, G.R. Dell'Osso, A. Hollberg, Continuous BIM-based assessment of embodied environmental impacts throughout the design process, J. Clean. Prod. 211 (2019) 941–952, https://doi.org/10.1016/j.jclepro.2018.11.247.
[29] J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Build. Environ. 60 (2013) 81–92, https://doi.org/10.1016/j.buildenv.2012.11.009.
[30] F. Shadram, T.D. Johansson, W. Lu, J. Schade, T. Olofsson, An integrated BIM-based framework for minimizing embodied energy during building design, Energy Build. 128 (2016), https://doi.org/10.1016/j.enbuild.2016.07.007.
[31] F. Shadram, J. Mukkavaara, J. Schade, M. Sandberg, T. Olofsson, A BIM-based method for analyzing the trade-off between embodied and operational energy, in: ICCREM 2017 Ind. Regul. Sustain. Dev. - Proc. Int. Conf. Constr. Real Estate Manag. 2017, 2017. 10.1061/9780784481066.006.
[32] M. Dupuis, A. April, P. Lesage, D. Forgues, Method to Enable LCA Analysis through Each Level of Development of a BIM Model, Proc. Eng. 196 (2017) 857–863.
[33] M. Najjar, K. Figueiredo, A.W.A. Hammad, A. Haddad, Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings, Appl. Energy. 250 (2019), https://doi.org/10.1016/j.apenergy.2019.05.101.
[34] S.O. Ajayi, L.O. Oyedele, O.M. Ilori, Changing significance of embodied energy: A comparative study of material specifications and building energy sources, J. Build. Eng. 23 (2019), https://doi.org/10.1016/j.jobe.2019.02.008.
[35] B.M.K., C.P.L.S., A. Aliakbar Kamari, BIM-based LCA tool for sustainable building design during the early design stage, Smart Sustain. Built Environ. (2022), https://doi.org/10.1108/SASBE-09-2021-0157.
[36] N.A. Megahed, Towards a theoretical framework for HBIM approach in historic preservation and management, Archnet-IJAR. 9 (2015). 10.26687/archnet-ijar.v9i3.737.
[37] L.G. Caldas, L.K. Norford, A design optimization tool based on a genetic algorithm, Autom. Constr. 11 (2002), https://doi.org/10.1016/S0926-5805(00)00096-0.
[38] A. Hollberg, J. Ruth, LCA in architectural design—a parametric approach, Int. J. Life Cycle Assess. 21 (2016), https://doi.org/10.1007/s11367-016-1065-1.
[39] N.A. Megahed, Digital Realm: Parametric-enabled Paradigm in Architectural Design Process, Int. J. Archit. Eng. Constr. 9 (3) (2015) 130–147, https://doi.org/10.26687/archnet-ijar.v9i3.737.
[40] D. Davis, Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture, 2013.
[41] G. Lobaccaro, A.H. Wiberg, G. Ceci, M. Manni, N. Lolli, U. Berardi, Parametric design to minimize the embodied GHG emissions in a ZEB, Energy Build. 167 (2018) 106–123, https://doi.org/10.1016/j.enbuild.2018.02.025.
[42] A.H. Wiberg, M.K. Wiik, H. Auklend, M.L. Slake, Z. Tuncer, M. Manni, G. Ceci, T. Hofmeister, Life cycle assessment for Zero Emission Buildings - A chronology of the development of a visual, dynamic and integrated approach, IOP Conf. Ser. Earth Environ. Sci. 352 (2019), https://doi.org/10.1088/1755-1315/352/1/012054.
[43] S. Basic, A. Hollberg, A. Galimshina, G. Habert, A design integrated parametric tool for real-time Life Cycle Assessment - Bombyx project, IOP Conf. Ser. Earth Environ. Sci. 323 (2019), https://doi.org/10.1088/1755-1315/323/1/012112.
[44] S. Abbasi, E. Noorzai, The BIM-Based multi-optimization approach in order to determine the trade-off between embodied and operation energy focused on renewable energy use, J. Clean. Prod. 281 (2021), https://doi.org/10.1016/j.jclepro.2020.125359.
[45] M. Gomaa, T. Farghaly, Z. El Sayad, Optimizing a life cycle assessment-based design decision support system towards eco-conscious architecture, Comput. Methods Exp. Meas. XX (2021), https://doi.org/10.2495/cmem210041.

[46] J.P. Basbagill, F.L. Flager, M. Lepech, A multi-objective feedback approach for evaluating sequential conceptual building design decisions, Autom. Constr. 45 (2014) 136–150, https://doi.org/10.1016/j.autcon.2014.04.015.
[47] J.A. Wright, H.A. Loosemore, R. Farmani, Optimization of building thermal design and control by multi-criterion genetic algorithm, Energy Build. 34 (2002), https://doi.org/10.1016/S0378-7788(02)00071-3.
[48] P. Geyer, Component-oriented decomposition for multidisciplinary design optimization in building design, Adv. Eng. Inform. 23 (2009), https://doi.org/10.1016/j.aei.2008.06.008.
[49] P. Inyim, Y. Zhu, A framework for integrated analysis of building designs using a life-cycle assessment and energy simulation, in: ICCREM 2013 Constr. Oper. Context Sustain. - Proc. 2013 Int. Conf. Constr. Real Estate Manag., 2013. 10.1061/9780784413135.030.
[50] W. Wang, R. Zmeureanu, H. Rivard, Applying multi-objective genetic algorithms in green building design optimization, Build. Environ. 40 (2005), https://doi.org/10.1016/j.buildenv.2004.11.017.
[51] Y. Schwartz, R. Raslan, I. Korolija, D. Mumovic, A decision support tool for building design: An integrated generative design, optimisation and life cycle performance approach, Int. J. Archit. Comput. 19 (2021), https://doi.org/10.1177/1478077121999802.
[52] Y. Schwartz, R. Raslan, D. Mumovic, Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building refurbishment case study, Energy 97 (2016), https://doi.org/10.1016/j.energy.2015.11.056.
[53] S.A. Sharif, A. Hammad, Simulation-Based Multi-Objective Optimization of institutional building renovation considering energy consumption, Life-Cycle Cost and Life-Cycle Assessment, J. Build. Eng. 21 (2019), https://doi.org/10.1016/j.jobe.2018.11.006.
[54] F. Flager, J. Basbagill, M. Lepech, M. Fischer, Multi-objective building envelope optimization for life-cycle cost and global warming potential, EWork Ebus. Archit. Eng. Constr. - Proc. Eur. Conf. Prod. Process Model., 2012, ECPPM 2012, 2012. 10.1201/b12516-32.
[55] R. Azari, S. Garshasbi, P. Amini, H. Rashed-Ali, Y. Mohammadi, Multi-objective optimization of building envelope design for life cycle environmental performance, Energy Build. 126 (2016), https://doi.org/10.1016/j.enbuild.2016.05.054.
[56] J. Hester, T.R. Miller, J. Gregory, R. Kirchain, Actionable insights with less data: guiding early building design decisions with streamlined probabilistic life cycle assessment, Int. J. Life Cycle Assess. 23 (2018) 1903–1915, https://doi.org/10.1007/s11367-017-1431-7.
[57] J. Hester, J. Gregory, F.J. Ulm, R. Kirchain, Building design-space exploration through quasi-optimization of life cycle impacts and costs, Build. Environ. 144 (2018) 34–44, https://doi.org/10.1016/j.buildenv.2018.08.003.
[58] C. Rodrigues, R. Kirchain, F. Freire, J. Gregory, Streamlined environmental and cost life-cycle approach for building thermal retrofits: A case of residential buildings in South European climates, J. Clean. Prod. 172 (2018) 2625–2635, https://doi.org/10.1016/j.jclepro.2017.11.148.
[59] C. Rodrigues, F. Freire, Environmental impacts and costs of residential building retrofits – What matters?, Sustain Cities Soc. 67 (2021), https://doi.org/10.1016/j.scs.2021.102733.
[60] M.L. Pannier, P. Schalbart, B. Peuportier, Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment, J. Clean. Prod. 199 (2018), https://doi.org/10.1016/j.jclepro.2018.07.070.
[61] C. Peng, Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling, J. Clean. Prod. 112 (2016), https://doi.org/10.1016/j.jclepro.2015.08.078.
[62] J. Hester, J. Gregory, R. Kirchain, Sequential early-design guidance for residential single-family buildings using a probabilistic metamodel of energy consumption, Energy Build. 134 (2017) 202–211, https://doi.org/10.1016/j.enbuild.2016.10.047.
[63] M. Xikai, W. Lixiong, L. Jiwei, Q. Xiaoli, W. Tongyao, Comparison of regression models for estimation of carbon emissions during building's lifecycle using designing factors: a case study of residential buildings in Tianjin, China, Energy Build. 204 (2019), https://doi.org/10.1016/j.enbuild.2019.109519 109519.
[64] P. Tecchio, J. Gregory, R. Ghattas, R. Kirchain, Structured Under-Specification of Life Cycle Impact Assessment Data for Building Assemblies, J. Ind. Ecol. 23 (2019) 319–334, https://doi.org/10.1111/jiec.12746.
[65] P. Tecchio, J. Gregory, E. Olivetti, R. Ghattas, R. Kirchain, Streamlining the life cycle assessment of buildings by structured under-specification and probabilistic triage, J. Ind. Ecol. 23 (2019), https://doi.org/10.1111/jiec.12731.
[66] Y. Song, H. Zhang, H. Mo, A LCA-based optimization method of green ecological building envelopes: A case study in China, IOP Conf. Ser. Earth Environ. Sci. 696 (2021), https://doi.org/10.1088/1755-1315/696/1/012023.
[67] V. Hasik, M. Ororbia, G.P. Warn, M.M. Bilec, Whole building life cycle environmental impacts and costs: A sensitivity study of design and service decisions, Build. Environ. 163 (2019), https://doi.org/10.1016/j.buildenv.2019.106316 106316.
[68] S. Karkour, S. Rachid, M. Maaoui, C. Lin, Status of Life Cycle Assessment (LCA) in Africa, (2021).
[69] A.A.M.M. Ali, A.M. Negm, M.F. Bady, M.G.E. Ibrahim, Environmental Life Cycle Assessment of a Residential Building in Egypt: A Case Study, Proc. Technol. 19 (2015) 349–356, https://doi.org/10.1016/j.protcy.2015.02.050.
[70] D.M.A. Morsi, W.S.E. Ismaeel, A.E.A. El-Hamed, Life cycle assessment of a residential building in Egypt: A case study, IOP Conf. Ser. Mater. Sci. Eng. 974 (2020), https://doi.org/10.1088/1757-899X/974/1/012028.
[71] M. Dabaieh, J. Heinonen, D. El-Mahdy, D.M. Hassan, A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks, J. Clean. Prod. 275 (2020), https://doi.org/10.1016/j.jclepro.2020.122998 122998.
[72] A.A.M.M. Ali, A.M. Negm, M.F. Bady, M.G.E. Ibrahim, M. Suzuki, Environmental impact assessment of the Egyptian cement industry based on a life-cycle assessment approach: a comparative study between Egyptian and Swiss plants, Clean Technol. Environ. Policy. 18 (2016), https://doi.org/10.1007/s10098-016-1096-0.
[73] Y.O. Elkhayat, M.G. Ibrahim, K. Tokimatsu, A.A.M.M. Ali, A comparative life cycle assessment of three high-performance glazing systems for office buildings in a hot desert climate zone, Clean Technol. Environ. Policy. 22 (2020), https://doi.org/10.1007/s10098-020-01891-2.
[74] M.K. Ay-Eldeen, A.M. Negm, Global warming potential impact due to pile foundation construction using life cycle assessment, Electron. J. Geotech. Eng. 20 (2015).
[75] A.A.M.M. Ali, A.M. Negm, M.F. Bady, M.G.E. Ibrahim, Moving towards an Egyptian national life cycle inventory database, Int. J. Life Cycle Assess. 19 (2014), https://doi.org/10.1007/s11367-014-0760-z.
[76] D.M.A. Morsi, W.S.E. Ismaeel, A.E.A. El Hamed, A.A.E. Othman, Applying LCA-BIM integration for a sustainable management process, in: ARCOM 2020 - Assoc. Res. Constr. Manag. 36th Annu. Conf. 2020 - Proc., 2020.
[77] M. El-Ahwal, ashraf elmokadem, N. Megahed, D. EL-Gheznawy, Methodology for the Design and Evaluation of Green Roofs in Egypt, Port-Said Eng. Res. J. 20 (2016). https://pserj.journals.ekb.eg/article_33631.html.
[78] M. El-Ahwal, ashraf elmokadem, D. EL-Gheznawy, Green Roof Analysis and Design Software Calculator in Egypt, Port-Said Eng. Res. J. 20 (2016). https://pserj.journals.ekb.eg/article_33626.html.
[79] The Egyptian code permanent committee, The Egyptian Code for Improving Energy Efficiency Use in Buildings (Part one: Residential Buildings), Housing and Building National Research Center, Egypt, 2005.
[80] The Egyptian code permanent committee, The Egyptian Code for Improving the Efficiency of Energy Use in Buildings (Part two: commercial buildings), Housing and Building National Research Center, Egypt, 2009.
[81] The Egyptian code permanent committee, The Egyptian Code for Masonry Design and Execution, Housing and Building National Research Center, Egypt, 2005.
[82] The Egyptian general standards permanent committee, Specifications for Thermal Insulation: Design and Execution Requirements, Housing and Building National Research Center, Egypt, 1998.
[83] Central Agency for Public Mobilization and Statistics of Egypt, https://www.capmas.gov.eg/Pages/StatisticsOracle.aspx?Oracle_id=1962&page_id=5109&YearID=23345 (accessed February 16, 2021).
[84] A. Hollberg, G. Genova, G. Habert, Evaluation of BIM-based LCA results for building design, Autom. Constr. 109 (2020), https://doi.org/10.1016/j.autcon.2019.102972 102972.
[85] R. Santos, A. Aguiar Costa, J.D. Silvestre, L. Pyl, Development of a BIM-based Environmental and Economic Life Cycle Assessment tool, J. Clean. Prod. 265 (2020). 10.1016/j.jclepro.2020.121705.
[86] J.P. Carvalho, I. Alecrim, L. Bragança, R. Mateus, Integrating BIM-based LCA and building sustainability assessment, Sustain. 12 (2020), https://doi.org/10.3390/SU12187468.
[87] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (2016), https://doi.org/10.1007/s11367-016-1087-8.
[88] E. Hoxha, G. Habert, J. Chevalier, M. Bazzana, R. Le Roy, Method to analyse the contribution of material's sensitivity in buildings' environmental impact, J. Clean. Prod. 66 (2014), https://doi.org/10.1016/j.jclepro.2013.10.056.
[89] S.E.L.E.C. for H. International Association of Certified Home Inspectors, InterNACHI's Standard Estimated Life Expectancy Chart for Homes, (n.d.). https://www.nachi.org/life-expectancy.htm (accessed April 8, 2021).
[90] M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, R. van Zelm, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, Int. J. Life Cycle Assess. 22 (2017) 138–147, https://doi.org/10.1007/s11367-016-1246-y.
[91] IPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013.
[92] M.N. Nwodo, C.J. Anumba, A review of life cycle assessment of buildings using a systematic approach, Build. Environ. 162 (2019), https://doi.org/10.1016/j.buildenv.2019.106290.
[93] R. Hoogmartens, S. Van Passel, K. Van Acker, M. Dubois, Bridging the gap between LCA, LCC and CBA as sustainability assessment tools, Environ. Impact Assess. Rev. 48 (2014), https://doi.org/10.1016/j.eiar.2014.05.001.
[94] K. Negishi, L. Tiruta-Barna, N. Schiopu, A. Lebert, J. Chevalier, An operational methodology for applying dynamic Life Cycle Assessment to buildings, Build. Environ. 144 (2018) 611–621, https://doi.org/10.1016/j.buildenv.2018.09.005.
[95] D. Kumar, M. Alam, P.X.W. Zou, J.G. Sanjayan, R.A. Memon, Comparative analysis of building insulation material properties and performance, Renew. Sustain. Energy Rev. 131 (2020), https://doi.org/10.1016/j.rser.2020.110038 110038.
[96] S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: A review and comparative analysis, Renew. Sustain. Energy Rev. 62 (2016) 988–1011, https://doi.org/10.1016/j.rser.2016.05.045.