Energy Efficiency (2023) 16:54
https://doi.org/10.1007/s12053-023-10129-1

ORIGINAL ARTICLE

Reducing energy consumption in operation and demolition phases by integrating multi-objective optimization with LCA and BIM

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Received: 3 May 2022 / Accepted: 19 May 2023 / Published online: 28 June 2023

Abstract This research aims to provide a design option with the lowest energy consumption in the two mentioned phases as the optimal solution. To this end, this study employs a combination of life cycle assessment (LCA), multi-objective optimization algorithm, and building information modeling (BIM) to improve sustainability in operation and demolition phases for the facade of an open office building. First, the destructive environmental effects caused by the demolition of 100 m^2 of each material were calculated by the LCA. Then after parametric modeling, geometric parameters and material data were selected from the previous step, simulation and optimization of objectives were performed, and the optimal solution was presented, which should be added to the BIM model by designing a plugin for data integration. Compared to the initial design options, selecting the appropriate parameters and materials and thus producing the optimal solution led to a 53.48 and 66.23% reduction in operational and demolition energy consumption, respectively. Applying this approach encourages architects to use innovative methods to take practical steps to improve the sustainability of their projects by choosing suitable design options.

Keywords Operational energy · Demolition energy · Life cycle assessment · Multi-objective optimization · Genetic algorithm · Building information modeling

Nomenclature

BIM	Building information modeling
CEUI	Cooling energy use intensity, kWh/m^2
DE	Demolition energy
E	Illuminance, lux
E_D	Energy required for building demolition
E_T	Energy used to transport waste
EU_i	Hourly energy demand, kWh
GA	Genetic algorithm
HEUI	Heating energy use intensity, kWh/m^2
i	Point belonging to the calculation grid
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	Life cycle assessment
LEUI	Lighting energy use intensity, kWh/m^2
M	Conditioning area, m^2
MOEA	Multi-objective evolutionary algorithm
N_c	Annual cooling hours

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N_h	Annual heating hours
N_l	Annual lighting hours
OE	Operational energy
t	Time (hour), h
TEUI	Thermal energy use intensity, kWh/m^2
UDI	Useful daylight illuminance, %
wf	Weighting factor
WWR	Window-to-wall ratio, %

Introduction

With about 40% of final energy consumption and natural resources, the construction industry has the highest energy consumption with adverse environmental effects (Noorzai, 2023). According to the International Energy Agency, global energy consumption will grow by 37% by 2040 (International Energy Agency, 2014). These statistics show that saving energy consumption at different building life cycle phases, especially office buildings, is an absolute necessity (Najjar et al., 2019; Ding and Ying, 2019; Wu et al., 2012).

The increase in population and the expansion of urbanization have led to an increase in construction (Noorzai, 2021; Gharouni Jafari & Noorzai, 2021) and, consequently, operational energy (*OE*) and the demolition of buildings. These issues prioritize energy reduction strategies in the operation and demolition phases, as the phases with the highest energy consumption and destructive environmental effects (Wu et al., 2012; Amaral et al., 2020; Ding and Ying, 2019).

Depending on the type of building, 40–95% of the total energy consumption of buildings is due to *OE* (heating, cooling, and lighting), and the rest is due to construction and demolition (Guan et al., 2015). Since the operation phase accounts for a substantial portion of energy consumption in the building life cycle, in some studies, improvements in energy consumption at this phase, especially in building facades, have been examined (Shahbazi et al., 2019; Najjar et al., 2019; Touloupaki and Theodosiou, 2017; Carlucci et al., 2015; Futrell et al., 2015a). Since the building facade separates the interior from the outside, it plays an essential role in transferring heat loads. As a result, its suitable design can reduce the annual *OE* demand of the building from 7.81 kWh/ft^2 to 0.93 (heating) and from 5.41 to 3.94 kWh/ft^2 (cooling) (Khodakarami et al., 2009; Shahbazi et al., 2019; Najjar et al., 2021).

In addition to the operation phase, the demolition of buildings has become an essential phase due to the increasing volume of construction and demolition waste, the lack of landfills, the adverse environmental effects of their landfill, and the annual production of more than 40 million tons of waste (Guan et al., 2015; Wu et al., 2012; Amaral et al., 2020). On the other hand, enacting laws such as Directive 2008/98/EC (Blengini, 2009) and studies that have emphasized the importance of maintaining natural resources in recent years have increased the importance of using waste reduction strategies at this phase (Blengini, 2009; Yeheyis et al., 2013). Nevertheless, a review of studies shows no sufficiently robust regulatory framework and enforcement mechanisms in this field (Yeheyis et al., 2013).

As a result of the increasing importance of using these strategies, materials with the least destructive environmental effects in the demolition phase should be selected (Giudice et al., 2005). The life cycle assessment (LCA) method makes it possible to understand this issue by evaluating the value of each of the environmental indicators of standard EN 15978 at each phase of the building life cycle (Najjar et al., 2019; Soust-Verdaguer et al., 2017).

Despite the importance of these phases, the study and simultaneous optimization of energy consumption in the phase of operation and especially demolition, in previous studies (Shahbazi et al., 2019; Najjar et al., 2019; Carlucci et al., 2015; Futrell et al., 2015a), have been less studied. In studies that have used the integration of building information modeling (BIM) and LCA to improve sustainability in building design, less attention has been paid to multi-objective optimization techniques (Cavalliere et al., 2019; Jalaei and Jrade, 2014a). Applying this technique in conjunction with BIM and LCA requires further research to investigate the parameters and generate optimal design options.

In the study of Abbasi and Noorzai (2021) and Najjar et al. (2019), the combination of BIM and LCA with optimization was proposed to develop previous research. However, they did not optimize essential phases of the building life cycle simultaneously. In addition, the parameters that define geometry and material were not considered variables. Inappropriate selection of any of these parameters in the early stages of design leads to the production of design options that account for a significant amount of energy consumption in the life cycle of projects (Futrell et al., 2015a).

Therefore, the purpose of this paper is to reduce *OE* and demolition energy (*DE*) consumption by developing a multi-objective optimization integration framework with LCA and BIM and by taking into account the parameters of the facade of an open office building.

In this approach, the destructive environmental effects of the studied material in the demolition phase were calculated by the LCA. Then, through office building modeling, building performance simulation, and multi-objective optimization, the objectives were optimized. In this process, the relationship between the parameters, the geometry produced from the building model, and the objective values were investigated. Finally, to apply the results obtained in the executive projects, the information of the optimal options acquired was retrieved and merged through BIM.

In this process, geometric parameters include the height of each building floor, the building orientation, and the window-to-wall ratio (WWR), and non-geometric parameters include the glazing material and the outer layer of the exterior walls. By changing the index of each of these parameters, a design option is generated with the different *OE* and *DE* consumption. Then the option that has the lowest energy consumption in two phases is selected as the optimal solution.

Using this approach, architects can choose the most optimal option by having different choices available and take a useful step towards the sustainability of their projects. To reduce the complexity, optimization time, and comparability of the results, this research was conducted on the facade of an open office building model. This approach can be extended to all building components and complex models with powerful computers and an expert team.

Literature review and background

The main stage of architectural design is the design phase when significant decisions are made (Golabchi & Noorzai, 2013), and the greatest effects on building performance are set. Simulation software programs that are used to study the environmental performance of buildings have become specialized tools in the profession. Using simulation design methods for decision-making, especially in countries like Iran where there is decision-making for sustainable design, enables architects to discover and design different and innovative solutions efficiently. As a result, they move towards optimal options in the early stages of design (Touloupaki and Theodosiou, 2017).

Parametric modeling, simulation, and optimization

The primary goal of this research is to simulate and optimize the performance of the building in terms of energy and harmful environmental effects. Then the synergy of the results was obtained in BIM software. Optimization includes steps such as modeling, identification, and control of parameters and limitations, selection of tools, determination of goals, selection of optimization algorithm, execution of the simulation, and presentation of final results.

Parametric modeling

All design aspects, such as location, orientation, shape, size of each building component, etcetera, can be considered parameters in architectural design. Parametric design, generator, or algorithmic connects parameters to geometry through visual programming and image codes (Eltaweel and Su, 2017).

In the conventional design method, when a prototype is created, a time-consuming and complex process must be repeated if the designer wants to change any parameter to consider all possible design options. The larger the project, the more complex and unpredictable these relationships become, to the extent that project data analysis is impossible without the help of parametric modeling software. It is only through parametric design that different design solutions can be found using algorithmic methods in response to architectural design problems (Noorzai et al., 2023; Touloupaki and Theodosiou, 2017).

The parametric design uses tools and software that effectively change and develop its design and modifications. The parametric design software was first created in 2008 and has been developed by many companies and software developers (Eltaweel and Su, 2017; Touloupaki and Theodosiou, 2017).

Simulation

The steps considered in this section are divided into two main categories: the first group includes functions related to daylight and the second deals with energy consumption.

Daylight performance Many studies show that the natural use of daylight should be such that in addition to providing the amount of light in the space, it does not cause inconvenience to users and increase energy consumption (Carlucci et al., 2015; Futrell et al., 2015a, b). With this in mind, the amount of light can be measured based on useful daylight illuminance (*UDI*), a parameter first introduced by Nabil and Mardaljevic in 2005. This indicator is the annual time fraction that indoor horizontal daylight illuminance at a given test point reaches in a given domain. Carlucci et al. (2015) define *UDI* as illuminances that is in the range 100 to 2000 lux.

UDI contains lower and upper thresholds and an acceptable range as $UDI_{underlit}$, $UDI_{overlit}$, and UDI_{useful}, respectively. The calculation of these values is shown in Eq. 1 (Nabil and Mardaljevic, 2005).

$$UDI = \frac{\sum_i \left(wf_i \cdot\ t_i \right)}{\sum_i t_i} \in [0, 1]$$

$$\begin{cases} UDI_{Overlit} & \text{with } wf_i = \begin{cases} 1 \text{ if } E_{Upper\ Limit} < E_{Daylight} \\ 0 \text{ if } E_{Upper\ Limit} \geq E_{Daylight} \end{cases} \\ UDI_{useful} & \text{with } wf_i = \begin{cases} 1 & \text{if } E_{Lower\ Limit} \leq E_{Daylight} \leq E_{Upper\ Limit} \\ 0 & \text{if } E_{Daylight} < E_{Lower\ Limit} \text{ v } E_{Upper\ Limit} < E_{Daylight} \end{cases} \\ UDI_{Underlit} & \text{with } wf_i = \begin{cases} 1 \text{ if } E_{Daylight} < E_{Lower\ Limit} \\ 0 \text{ if } E_{Daylight} \geq E_{Lower\ Limit} \end{cases} \end{cases} \tag{1}$$

Eq. 1. Calculation of UDI.

where t_i is each occupied hour in a year, h; $E_{Daylight}$ is the horizontal illuminance at a given point due to the sole daylight, lux; wf_i is a weighting factor depending on values of $E_{Daylight}$.

Energy performance

- Operational energy

The Honeybee plugin simulates daylight and thermal by linking its Radiance and EnergyPlus/OpenStudio simulation engines to the Grasshopper visual programming interface (Futrell et al., 2015a, b). Thermal performance evaluation is based on the thermal energy use intensity (*TEUI*), which is the sum of annual cooling energy use intensity (*CEUI*) and heating energy use intensity (*HEUI*). Similar to *CEUI* and *HEUI*, the lighting energy use intensity (*LEUI*) is also calculated. The calculation of these values is shown in Eq. 2 (Futrell et al., 2015a, b; Noorzai et al., 2023).

$$HEUI = \sum\nolimits_{i=1}^{i=N_h} \frac{EU_{hi}}{M} \tag{2}$$

$$CEUI = \sum\nolimits_{i=1}^{i=Nc} \frac{EU_{ci}}{M}$$

$$TEUI = HEUI + CEUI$$

$$LEUI = \sum\nolimits_{i=1}^{i=N_l} \frac{EU_{li}}{M}$$

Eq. 2 Calculation of OE (heating, cooling, lighting).

where EU_i is hourly energy demand, kWh; N_h is the annual heating hours; N_c is the annual cooling hours; N_l is the annual lighting hours; M is the level of conditioning, square meters.

- Demolition energy

Energy and destructive environmental effects of building demolition, storage, and transportation of waste from the building to the landfill are considered the energy of the demolition phase (Guan et al., 2015; Blengini, 2009).

Dajadian and Koch (2014) noted that 33% of waste generation and its destructive effects in the demolition phase are due to the wrong decisions of designers to select materials and design options. The design process is the primary source of errors and mistakes, and choosing appropriate materials at this phase requires the consideration of several environmentally friendly objectives that are often conflicting. Therefore, designers must create a balance of these objectives to find the best solution in the design phase

(Giudice et al., 2005). The calculation of DE is also shown in Eq. 3 (Blengini, 2009).

$$DE = E_D + E_T \tag{3}$$

Eq. 3 Calculation of DE.

where DE is the demolition energy, E_D is the energy required for building demolition, and E_T is the energy used to transport waste.

Multi-objective optimization

Optimal solutions are design options with the lowest energy consumption at different building life cycle phases. The multi-objective optimization approach creates an optimization model based on simulation between design parameters and objective functions to achieve these solutions (Bakmohammadi and Noorzai, 2022). In this approach, parameters are values that control geometry or design features, and objective functions are building performance criteria calculated by simulation tools (Futrell et al., 2015a). To find optimal solutions in design problems, due to the complex physical functional relationships between parameters and building performance, optimization algorithms are proposed (Futrell et al., 2015b).

Genetic algorithms (GAs) are a particular category of evolutionary algorithms and the most common type of optimization algorithms that use evolutionary biology-inspired methods such as inheritance, mutation, selection, and crossover to solve problems (Bakmohammadi and Noorzai, 2022; Mortezaei Farizhendy et al., 2020). These algorithms have proven valuable for addressing multi-objective design problems, calculating multiple performance metrics, and finding near-optimal solutions in many studies (Eltaweel and Su, 2017; Shahbazi et al., 2019).

The Grasshopper plugin in Rhino software can enable the user to evaluate different design options using evolutionary solutions such as Galapagos, Wallacei, and Octopus, based on GAs (Touloupaki and Theodosiou, 2017; Shahbazi et al., 2019; Ali et al., 2021).

Galapagos can only optimize one objective and cannot execute extreme energy data (Touloupaki and Theodosiou, 2017). Wallacei and Octopus are multi-objective evolutionary algorithms (MOEAs) that use different GAs (Wallacei uses NSGA-II and Octopus uses SPEA-2). The Wallacei is faster, more accurate, and up-to-date and also has a neutral indicator that identifies the design problem. Finally, when implementing the GA in this plugin, comprehensive results are provided by tracking the algorithm's progress and examining the correlation between the objectives (Eltaweel and Su, 2017; Ali et al., 2021).

Previous studies related to integrate LCA, optimization, and BIM

- LCA

The LCA is an objective method and sustainable decision-making for assessing activities and materials' energy and environmental impacts. This approach includes the life cycle of buildings from extraction and processing of raw materials, transportation to the site, construction, operation, and maintenance, until demolition (Asgari and Noorzai, 2021).

In the second half of the 1990s, the International Organization for Standardization (ISO) published the well-known essential standard of the LCA method (ISO, 2006). In 2011, the European Committee for Standardization published a new standard called EN15978. This European standard for evaluating the environmental performance of a building performs calculations based on LCA (EN15978, 2011).

There are tools such as general and specific building LCA tools to evaluate the building life cycle. Quantifying building materials and performing calculations using general building LCA tools is time-consuming and requires a high level of experience, while the specific building LCA tools, such as the Athena Impact Estimator for Buildings, facilitate the use of LCA in the building sector and require a medium level of experience (Asgari and Noorzai, 2021).

Finally, after selecting the study scope of the LCA and the software, the information obtained from the LCA can be added to the BIM models by programming and upgrading the software capabilities. BIM-LCA integration can reduce the time to evaluate and improve the environmental performance of buildings in the early stages of design (Soust-Verdaguer et al., 2017).

- BIM

As an integrated digital process, BIM is a new approach to construction projects that manages project data throughout the building life cycle and provides an excellent opportunity to perform environmental analysis (Najjar et al., 2019; Golabchi et al., 2016). In addition, as a multi-dimensional modeling platform, it has been extended from a three-dimensional geometric model to the fourth-dimension (time), the fifth-dimension (cost), the sixth-dimension (energy), the seventh-dimension (facility management), and the eighth-dimension (safety) (Jalaei and Jrade, 2014a).

Using BIM as an information reference makes data analysis and input more efficient and reusable for existing data during model development. In addition, it allows a controllable digital model to be attached to the results of a simulation program that analyzes the energy performance of buildings. The best advantage is that the optimization results can be immediately applied and integrated into the design models, and eventually, the sustainability aims can be achieved (Abbasi and Noorzai, 2021; Soust-Verdaguer et al., 2017).

- **Integrate LCA, optimization, and BIM**

In research that has used BIM and LCA integration to improve sustainability in building design, less attention has been paid to combining this approach with multi-objective optimization techniques (Cavalliere et al., 2019; Jalaei and Jrade, 2014a). Some studies have used Autodesk Revit to develop the BIM model, Such as the work of Jalaei and Jarde (2014b). Jalaei and Jarde (2014b) developed a plug-in for the BIM tool to measure the environmental and energy effects of building components. To investigate the parameters and thus produce optimal design options, the application and development of this approach require further research.

Research by Kiss and Szalay (2020) has been developed to integrate LCA and multi-objective optimization to reduce environmental impact. In this research, the importance of using the data and results obtained from the proposed framework in BIM tools and thus the development of design dimensions in executive projects has not been considered.

Abbasi and Noorzai (2021) used the combination of BIM and LCA with optimization for trading between embodied and *OE*. Moreover, Najjar et al. (2019) used the combination of BIM and LCA with optimization to increase the *OE* efficiency of construction projects. However, in both of these studies, the parameters defining geometry were not considered variables. The inappropriate selection of any of these parameters in the early stages of design leads to the generation of design options that allocate a significant amount of energy consumption in the life cycle of projects (Futrell et al., 2015a).

Combining optimization algorithms with LCA is a promising approach to minimize the environmental effects of construction projects. In the early stages of design, many parameters are floating, so integrating LCA, BIM, and optimization can reduce the time to evaluate and improve the environmental performance of buildings (Kiss and Szalay, 2020; Abbasi and Noorzai, 2021).

In addition, low energy consumption in the demolition phase, complexity of calculations, and lack of expertise has led researchers to not pay enough attention to the destructive effects on the environment at this phase. Also, the short duration of demolition and straightforward release of waste into the environment, compared to other phases, are issues that researchers have not addressed. With this in mind, architects can significantly reduce the environmental impact of building waste by spending a short time and choosing suitable materials and parameters (Amaral et al., 2020; Dajadian and Koch, 2014; Blengini, 2009). On the other hand, *OE* also accounts for a high percentage of energy consumption in all building life cycle phases (Futrell et al., 2015a).

Despite the necessity to simultaneously optimize energy consumption in these two phases, researchers have not sufficiently considered this issue (Shahbazi et al., 2019; Najjar et al., 2019; Carlucci et al., 2015; Futrell et al., 2015a).

Therefore, this paper aims to reduce *OE* and *DE* consumption by developing a multi-objective optimization integration framework with LCA and BIM, taking into account the parameters of the facade of an open office building.

Materials and methods

This study examines the LCA combination framework, multi-objective optimization, and BIM to analyze the facade's *OE* and *DE* performance, one of the essential factors in building design. Figure 1 provides an overview of the research stages, which are discussed in detail below.

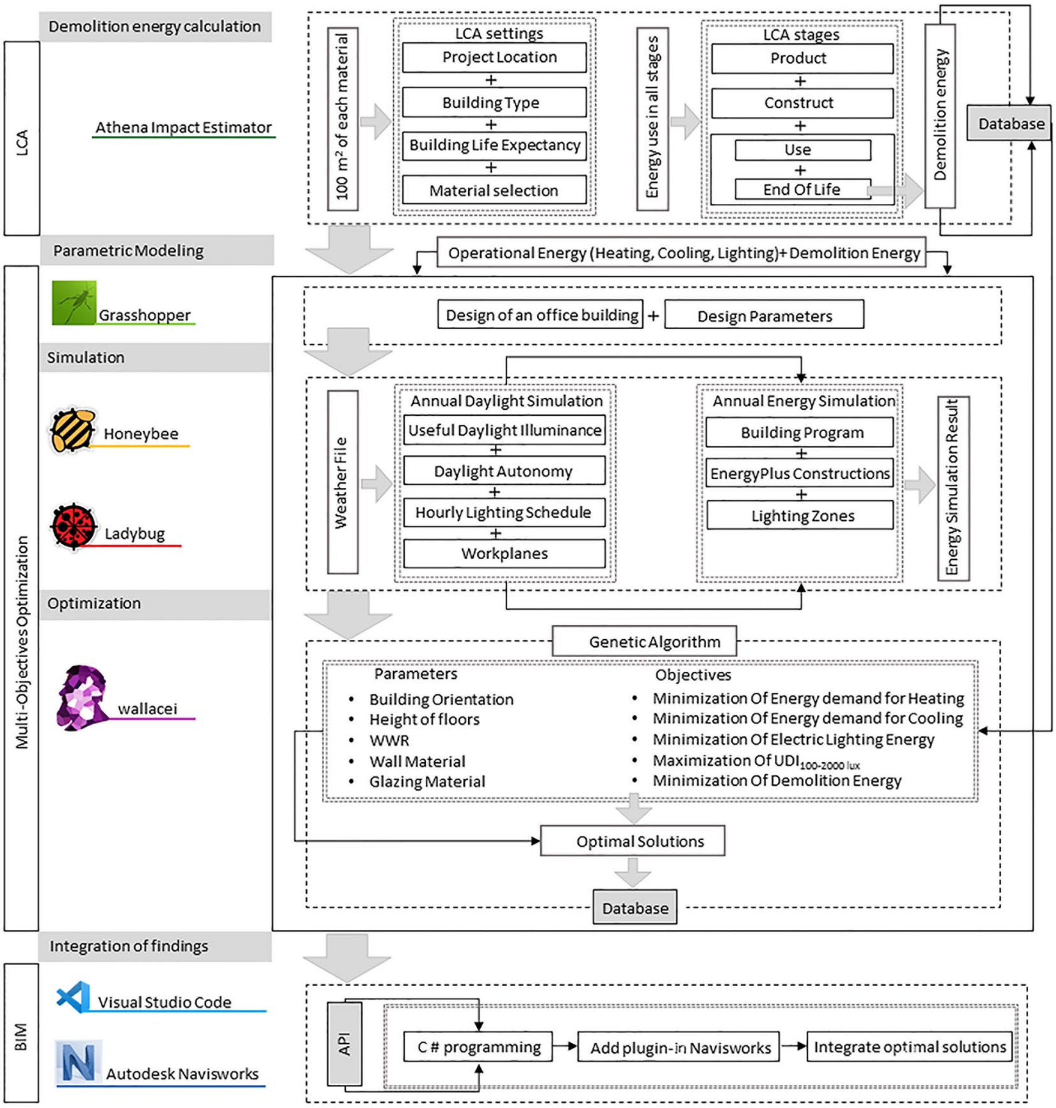


Fig. 1 General research method

Material life cycle assessment

This study used Athena Impact Estimator for Buildings version 5.4 software, developed by Athena Sustainable Materials Institute, to perform LCA calculations. In these calculations, selecting a database is the first necessary step; Athena software has a compliant database with the International Organization of Standardization (ISO) 14040 (2006) and 14044 (1997) standards.

This software utilizes Athena's life cycle inventory and follows the four steps in a standard LCA as established by the ISO standards. The data developed by the Athena Institute includes life cycle inventories of specific industries, product groups, transportation, construction processes, and maintenance tasks.

The results of an LCA depend on the assumptions and the system's boundary. The geographical area is very important in using LCA data and software. Considering that Iran has not provided any data and LCA software related to its geographical area, therefore, using the ASHRAE standard, the study area in Iran was matched with the Atlanta in the USA. It is true that the lack of LCA data and related software in this field in Iran is one of the limitations of this study. But, because the focus of this study is on the analysis method, the estimated data will not compromise the credibility of the analytic procedure.

Another determining factor in the environmental impact of building materials is the lifespan of the building. For a given material with a given environmental impact and lifetime, the annual environmental impact will be greater when the lifetime of the building is shorter than the lifetime of the materials (Grant et al. 2014). Therefore, considering this point, in the next step, the building life expectancy was set to 60 years by default by selecting office application. In fact, for each type of building, simplified profiles can be made in the same way, and comparisons can be made for similar buildings in terms of performance and average lifespan.

Finally, a LCA was performed for 100 m^2 of each of the 24 common building materials used in facade design. After performing the mentioned adjustments, calculations were performed. The amount of each of the environmental indicators of EN15978 standard for each material was determined, shown in Table 1. Then materials were selected that have the least amount of destructive environmental effects during demolition, transportation, and landfill. These values were considered inputs for the modeling, simulation, and optimization process. When optimizing objectives, the total energy of the demolition phase changes automatically by changing the type and amount of building facade material used in the design options produced.

Modeling, simulation, and optimization of goals

The steps taken in this section to produce optimal solutions are divided into three main parts of modeling, simulation, and optimization, which are as follows.

Parametric modeling

One of the widely used software for parametric design is Grasshopper. This graphical algorithm editor links to Rhinoceros 3D as parametric modeling and helps designers quickly generate parametric forms with no formal programming background. Grasshopper can provide substantial performance in the design and optimization process by using various plugins (by developing an environmentally conscious architectural design) (Eltaweel and Su, 2017).

Therefore, in this research, three-dimensional parametric modeling of an open office building prototype was developed in Rhinoceros software with the help of the Grasshopper plugin. Then Grasshopper plugin and Honeybee and Ladybug Tools (v 1.2.0) plugins were used for simulation, environmental and thermal analysis, and energy consumption. The Wallacei plugin was then used to apply multi-objective GAs and find optimal design solutions. It is effective to use these tools, and methodology, to combine modeling and simulation tools for helping design decisions based on different parameters (Abbasi and Noorzai, 2021).

Reference office design parameters and geometry For the study building located in Tehran, a geometry suitable for office application and required interior spaces was selected and designed. The framework presented in this research was done by selecting the appropriate geometric and non-geometric parameters of the building facade to improve the performance of sustainability in the operation and demolition phases.

Due to the limitations of multi-objective optimization, time, and technical support required for optimization, this research was conducted on a five-story module of this building, with dimensions of 30 by 30 m, which is part of the designed office building. Each floor of this module consists of nine smaller modules with dimensions of 10 by 10 m. The middle module includes service spaces and vertical communication. Evaluations were performed on eight perimeter modules that are an open office space (Fig. 2). To optimize the objective functions, parameters were selected as inputs, the correct choice of which in the early stages of design is the concern of sustainability architects. Table 2 presents the simulation parameters along with their values.

Simulation

To carry out the simulation, settings should be checked to enter data related to daylight, environmental, and climatic analysis of the project site, building schedules, and materials.

Useful daylight illuminance *UDI* diversifies depending on the type of activity. Less than 100 lux is not suitable for computer work, 100–300 lux is suitable for office/computer work, and 300–500 lux is suitable for office work/ideal for computer work. Finally, more than 500 lux is ideal for office/computer work (Ahmed, 2021).

Table 1 Amounts of energy and environmental destructive effects caused by demolition, for 100 m^2 of each material

N.	Types of materials	Global warming potential (kg CO$_2$ eq.) GWP	Acidification potential (kg SO$_2$ eq.) AP	HH particulate (PM2.5eq.) HHP	Eutrophication potential (kg (PO4)3-eq.) EP	Ozone depletion potential (kg CFC 11 eq.) ODP	Smog potential (kg O$_3$ eq.) SP	Total primary energy (MJ) TPE	Non-renewable energy (MJ) NRE	Fossil fuel consumption (MJ) FFC
1	Wood bevel siding	40.30	0.53	0.02	0.03	0.00	17.50	598.00	598.00	597.00
2	Metal wall cladding-commercial (26Ga)	39.00	0.41	0.09	0.03	0.00	13.10	569.00	569.00	568.00
3	Insulated metal panel (IMP) wall cladding	34.10	0.41	0.04	0.03	0.00	13.50	502.00	502.00	501.00
4	Brick-Modular(metric)	134.00	1.47	0.09	0.09	0.00	47.10	1970.00	1970.00	1960.00
5	Curtain wall Frame type: aluminum window frame double pane Glazing type: double glazed hard coated air	218.00	1.10	0.09	0.03	0.00	14.60	2840.00	2810.00	2700.00
6	Curtain wall Frame type: aluminum window frame double pane Glazing type: triple glazed hard coated air	225.00	1.16	0.10	0.04	0.00	16.50	2930.00	2910.00	2790.00
7	Curtain wall Frame type: aluminum window frame triple pane Glazing type: double glazed hard coated air	224.00	1.13	0.09	0.03	0.00	14.90	2920.00	2890.00	2770.00

Table 1 (continued)

N.	Types of materials	Global warming potential (kg CO_2 eq.) GWP	Acidification potential (kg SO_2 eq.) AP	HH particulate (PM2.5eq.) HHP	Eutrophication potential (kg (PO4)3-eq.) EP	Ozone depletion potential (kg CFC 11 eq.) ODP	Smog potential (kg O_3 eq.) SP	Total primary energy (MJ) TPE	Non-renewable energy (MJ) NRE	Fossil fuel consumption (MJ) FFC
8	Curtain wall Frame type: aluminum window frame triple pane Glazing type: triple glazed hard coated air	231.00	1.19	0.10	0.04	0.00	16.80	3010.00	2980.00	2860.00
9	Curtain wall Frame type: fiberglass window frame double pane Glazing type: double glazed hard coated air	189.00	0.97	0.08	0.03	0.00	13.40	2460.00	2440.00	2340.00
10	Curtain wall Frame type: fiberglass window frame double pane Glazing type: triple glazed hard coated air	195.00	1.03	0.08	0.03	0.00	15.30	2550.00	2530.00	2430.00
11	Curtain wall Frame type: fiberglass window frame triple pane Glazing type: double glazed hard coated air	189.00	0.97	0.08	0.03	0.00	13.50	2460.00	2440.00	2340.00

Table 1 (continued)

N.	Types of materials	Global warming potential (kg CO_2 eq.) GWP	Acidification potential (kg SO_2 eq.) AP	HH particulate (PM2.5eq.) HHP	Eutrophication potential (kg (PO4)3-eq.) EP	Ozone depletion potential (kg CFC 11 eq.) ODP	Smog potential (kg O_3 eq.) SP	Total primary energy (MJ) TPE	Non-renewable energy (MJ) NRE	Fossil fuel consumption (MJ) FFC
12	Curtain wall frame type: fiberglass window Frame triple pane Glazing type: triple glazed hard coated air	194.00	1.03	0.08	0.03	0.00	15.30	2550.00	2520.00	2430.00
13	Curtain wall Frame type: PVC window frame double pane Glazing type: double glazed hard coated air	189.00	0.97	0.08	0.03	0.00	13.50	2470.00	2440.00	2350.00
14	Curtain wall Frame type: PVC window frame double pane Glazing type: triple glazed hard coated air	195.00	1.03	0.08	0.03	0.00	15.40	2560.00	2540.00	2440.00
15	Curtain wall Frame type: PVC window frame triple pane Glazing type: double glazed hard coated air	189.00	0.98	0.08	0.03	0.00	13.60	2470.00	2450.00	2350.00
16	Curtain wall Frame type: PVC window frame triple pane Glazing type: triple glazed hard coated air	196.00	1.03	0.08	0.03	0.00	15.50	2560.00	2540.00	2440.00

Table 1 (continued)

N.	Types of materials	Global warming potential (kg CO_2 eq.) GWP	Acidification potential (kg SO_2 eq.) AP	HH particulate (PM2.5eq.) HHP	Eutrophication potential (kg (PO4)3-eq.) EP	Ozone depletion potential (kg CFC 11 eq.) ODP	Smog potential (kg O_3 eq.) SP	Total primary energy (MJ) TPE	Non-renewable energy (MJ) NRE	Fossil fuel consumption (MJ) FFC
17	Oriented strand board (OSB) (an insulating layer of rigid core sandwiched between two layers of structural board)	57.50	0.77	0.02	0.05	0.00	25.30	853.00	853.00	851.00
18	Brick-concrete	336.00	4.31	0.15	0.27	0.00	141.00	4980.00	4970.00	4970.00
19	Cast in place-concrete	511.00	6.55	0.25	0.41	0.00	215.00	7570.00	7560.00	7550.00
20	Fiber cement siding	43.70	0.51	0.05	0.03	0.00	16.40	642.00	642.00	641.00
21	Natural stone	79.20	0.89	0.06	0.06	0.00	28.70	1160.00	1160.00	1160.00
22	Vinyl siding	48.70	0.48	0.05	0.03	0.00	14.30	691.00	689.00	680.00
23	Precast insulated panel	381.00	4.91	0.18	0.31	0.00	161.00	5650.00	5640.00	5630.00
24	Precast insulated panel with brick veneer	483.00	6.23	0.22	0.39	0.00	205.00	7150.00	7150.00	7140.00

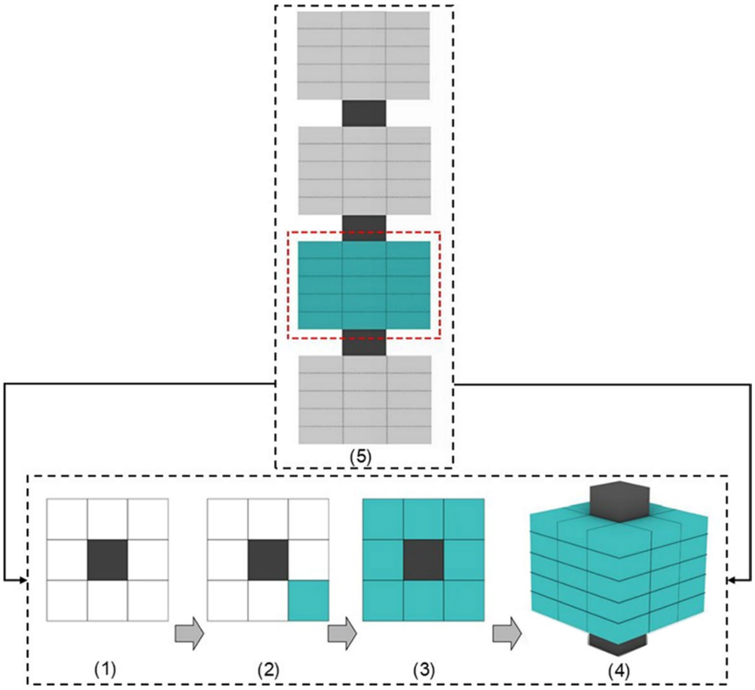


Fig. 2 Steps of forming a five-story module of an open office building. (1) 10×10 (meter) black module, the middle core of the building, (2) 10×10 (meter) blue module, one of the eight peripheral modules on each floor of the building, (3) 30×30 (meter) blue module, a one-floor module of the building, (4) 30×30 (meter) five-story module of the building on which research and investigations have been carried out, (5) Overview of the studied module in the whole of a high-rise office building

Table 2 Design parameters

Parameters	Attributes	No. of values
Height of each floor	3.00, 3.10, 3.20, 3.30, 3.40, 3.50, 3.60, 3.70, 3.80, 3.90, 4.00 (m)	11
Building orientation	(−30), (−20), (−10), 0, 10, 20, 30 (°)	7
Window-wall ratio (North and South)	20, 30, 40, 50, 60, 70, 80 (%)	7
Window-wall ratio (East and West)	20, 30, 40, 50 (%)	4
Glazing material	0, 1, 2	3
Exterior wall cladding material	0, 1, 2, 3, 4, 5, 6	7

*Scenarios “0, 1, 2, 3” and “0, 1, 2, 3, 4, 5, 6” detailed in Table 4

Therefore, it is suggested that any illuminance in the range of 100 to 2000 lux should be considered a potentially useful illuminance for the inhabitants of the space. Based on values set by reasonable international standards such as IESNA, a minimum of 400 lux is required to perform a simple task in an office environment. Hence, a brightness threshold of 400 lux was considered for the calculations. At the end of the modeling phase, the Honeybee plugin performed the annual daylight simulation at the calculation points in a 0.5 m by 0.5 m grid. Finally, the *UDI* values for each generated option were calculated; this was done only for the occupied hours of the year.

Building schedules The Honeybee plugin has a library of default building applications, using the OpenStudio simulation engine. The Open Office, one of Honeybee’s default applications, was extracted and used as CSV files in this study. Table 3 shows the settings assigned for the Open Office application in the proposed model.

Environmental analysis and climatic data of project location In addition, data related to environmental analysis and entering their information into the Ladybug and Honeybee plugins will be required. These data include environmental analysis data related to each application (in this study, an office application program was used) and

Table 3 Office application and input parameters for simulation

Attributes	Values
Project type	Office
Floor area	800 (m^2)
Zones program	Open Office
Climate zone	B3
Occupants of each zone	90
Number of people per area	0.0565(people/m^2)
Working hours	8 AM–4 PM
Equipment load per area	7.6424 (W/$m^{2)}$
Infiltration rate per area	0.0002 (m^3/s m^2)
Lighting density per area	11.8404 (W/m^2)
Ventilation per area	0.0003 (m^3/s m^2)
Ventilation per person	0.0024 (m^3/s)
Internal heat gain rate (occupants)	12 (W/m^2)
Internal heat gain rate (equipment)	15 (W/m^2)
Artificial lighting power rate (at 320 Lx)	9 (W/m^2)
Heating set point temperature	21°C
Cooling set point temperature	24°C

Tehran's weather data in the form of an epw file. The Tehran-Mehrabad 407540 (ITMY) ZIP file was downloaded from the EnergyPlus website and imported into the Ladybug plugin to run the simulation. Adequate attention to such information at the design stage is essential to prevent thermal and lighting loads disturbances.

Materials According to ASHRAE 169–2013 standard, the city of Tehran is located in the B3 climate zone. The material assigned to each component is selected by the material provided by ASHRAE for Climate Zone the B3. The materials selected from the first stage were made using the Honeybee plugin and assigned to the exterior walls of the 3D model. Three different types of glass were considered for the windows; a specific type of material was assigned to the ceilings and floors. Also, the thermal properties were calculated for each of the components mentioned in the Decompose EP Construction component of the Honeybee plugin.

Multi-objective optimization process

The technique of genetic optimization algorithm, a set of evolutionary algorithms, was used to find optimal solutions and investigate the functional relationships between the parameters and functional objective of the building (Futrell et al., 2015b; Touloupaki and Theodosiou, 2017). This technique can address multi-objective design problems by analyzing hundreds of design options and ultimately producing near-optimal solutions considering energy performance.

Multi-objective optimization is implemented using GA (NSGA-II), and by developing the initial population of size N in the first generation. This process includes the following steps, which are also indicated in Fig. 3: (1) the decision-maker sets the population size and the number of generations. (2) Then, the initial population is generated randomly. (3) The simulation engine calculates the objective functions by connecting to the input parameters (geometric and non-geometric) for each solution. For each scenario, based on the selected values and running the simulation, the values of all three objective functions (4), (5), and (6) are determined. (7) The integration of the simulation model and an optimization algorithm is done through a systematic approach that allows the exploitation of the best features of these tools simultaneously. (8) The next step is to evaluate the fitness values of the scenarios in the generation. (9) Convergence condition is evaluated in this step. (10) Consequently, generation evolution operations are applied on the entire population. (11) This procedure is iteratively repeated for all members in all generations until the convergence happens or a predefined number of generations is reached. (12) The results of the optimizations are formed in the Pareto front, which will be used to inform the decision-makers about the different scenarios and the relationships between them (Sharif and Hammad, 2019).

This research used the Wallacei plugin (v 2.65), a Grasshopper optimization plugin based on a GA. Wallacei is based on NSGA-II, an improved MOEA that is flexible enough to integrate with design optimization processes (Ali et al., 2021).

One of the advantages of multi-objective optimization is the definition of multiple objectives that can be evaluated simultaneously and ultimately balanced. This method can examine the correlation between different objectives, so it suggests more comprehensive results than single-objective optimization. In this process, after several repetitions and elimination of inappropriate solutions, a set of optimal design alternatives is generated that meet the set of objective functions (Shahbazi et al., 2019; Touloupaki and Theodosiou, 2017).

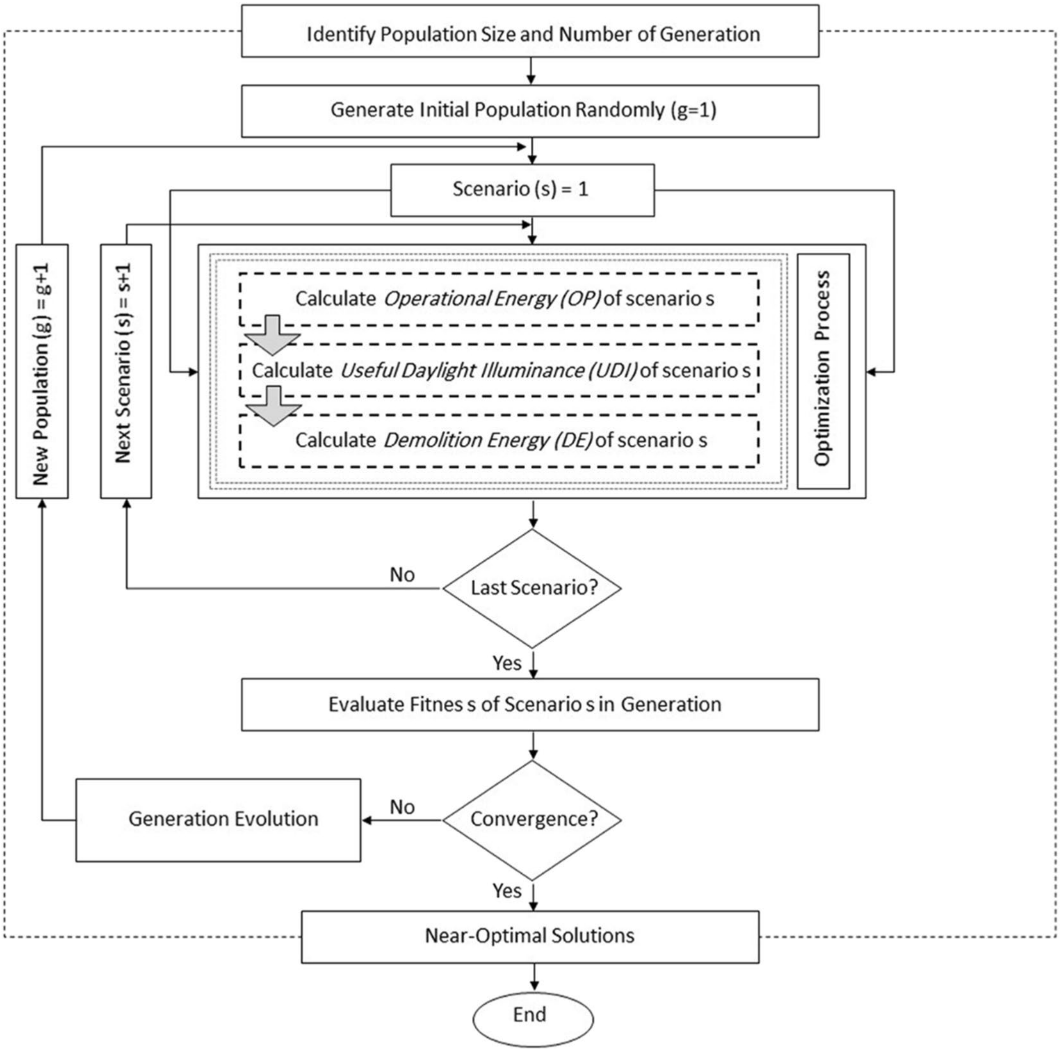


Fig. 3 Multi-objective optimization based on GA (NSGA-II)

The optimization problem can be formulated as follows.

Equation 4 shows three objective functions. To define the target functions, daylight and energy simulation outputs were used, which are *UDI* and annual *OE* consumption (cooling, heating, and lighting) and total energy and destructive environmental effects caused by demolition.

$$F1 : \min \ (OE = CEUI + HEUI + LEUI) \tag{4}$$

$$F2 : \min \ (DE)$$

$$F3 : \max \ (UDI100 - 2000 \ lux)$$

Eq. 4 Objective functions.

Therefore, after modeling, determining geometric parameters, entering the amount of *DE* for 100 m^2 of each material as nongeometric parameters, and entering climatic and simulation characteristics, optimization of objectives was performed. The defined parameters are changed using this method to minimize the annual thermal energy and light energy for the optimal solutions produced. Also, the least destructive environmental effects occur during demolition.

The reason for including the *UDI* as a complement to the objective functions is to challenge the fact that reducing the consumption of lighting and heating energy does not reduce the thermal comfort of the employees and the lighting required for office work. Also, the main reason for considering the subsets of cooling, heating, and lighting energy consumption for the objective function of *OE* is to analyze the fluctuations and changes of each of them accurately. In fact, with this action, the effects of each parameter on each of them can be examined and controlled separately.

Due to the model's dimension, many parameters and indexes associated with each, and the number of objective functions, the optimization process was performed on a server equipped with a 24-core processor and 40 GB of RAM and took approximately ten days.

Optimization settings

The GA settings are as follows:

Population size: 40
Maximum generation: 60
Crossover rate: 0.8
Mutation probability: 0.05
Mutation rate: 0.05
Elitism: 0.5

The optimization was performed with the settings of the Wallacei plugin GA, taking into account the parameters introduced in Table 2 and the settings mentioned in Tables 3 and 4.

Results

Based on the three steps carried out in this research, the results obtained from each step have been described step by step until reaching the final results.

Material life cycle assessment results

Table 1 shows the amount of energy and destructive environmental effects caused by the demolition

Table 4 Material specifications defined for building attributes

Attributes	Index number	Materials	U-value (W/(m2.K))	*DE* for 100 m^2
Exterior walls	0	Wood bevel siding-spruce—15 mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.19	1850.95
	1	Metal wall cladding-commercial (26 GA)—31 mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.54	1759.48
	2	IMP wall cladding (insulated metal panel)—76 mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.27	1554.07
	3	brick-modular (metric)—76mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.49	6076.82
	4	Structural board: oriented strand board (OSB)—15 mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.15	2640.19
	5	Fiber cement siding—15 mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.51	1986.44
	6	Natural stone—20 mm + M15 200 mm heavyweight concrete + I02 50 mm insulation board + G01a 19 mm gypsum board	0.52	3596.86
Glazing	0	Single clear—6 mm(SHGC:0.819) Frame type: PVC window frame pane	5.78	6115.34
	1	Double clear—6 mm/13 mm ARG (SHGC:0.704) Frame type: PVC window frame double pane	2.51	6410.54
	2	Triple clear—3 mm/13 mm ARG (SHGC:0.685) Frame type: PVC window frame triple pane	1.62	6987.98
Interior Floor	0	Interior floor: F 16 acoustic tile + F 05 ceiling air space resistance + M 11 100 mm lightweight concrete	1.44	/-/
Exterior roof	0	ASHRAE 90.1-2010 EXTROOF IEAD CLIMATEZONE 2-8: Roof membrane + IEAD roof insulation R-19.72 IP + metal decking	0.28	/-/

of 100 m^2 of each of the 24 types of facade materials calculated by the Athena Impact Estimator for Buildings software. The sum of the values obtained from this table for each material was considered *DE* (Table 4), which were selected as non-geometric inputs for the optimization step. In addition, Table 4 introduces the specifications of each material and building components under the title Index number and values of thermal properties that are needed for the next steps.

Optimization results

The annual demand for thermal and lighting energy and environmental effects of building demolition was optimized by writing an algorithm in the Grasshopper plugin. In this algorithm, the simulation loop was run for 60 generations and 40 genes per generation, and approximately 2400 design options were generated; by eliminating similar solutions, 1300 options were generated. Due to the time-consuming calculation of *OE*, its values was examined on an annual basis in this study.

The optimal solution is gradually created by producing generations and converging objectives in the optimization process. Before the optimization process is complete, when the objectives have not yet converged, and the parameters have not been controlled, options are generated that are not close to goals of this research. From the solutions created by the optimization, the most optimal and non-optimal options were selected, and the values related to the input parameters and their objective functions are specified in Fig. 4.

In Fig. 4, the parallel coordinate graph shows the relationship between the input parameters and the objective values for the generated solutions. This graph's black and yellow dashed lines are the lowest and highest energy consumption options, respectively. In the Pareto three-dimensional plot, the *x*-axis shows the *UDI*, the *y*-axis, the *DE*, the *z*-axis, and the total *OE* (cooling, heating, and lighting). The closer these points are to the axes of the graph, the closer they are to the optimal solutions of that objective function. When all three functions are considered simultaneously, with these points getting closer to the center of the intersection of the three axes of the graph, they become more efficient solutions. In this diagram, the best and worst options produced are marked with yellow circles.

Based on the analysis of the values specified in Fig. 4, the *DE* for the worst option was about 6217.51 kWh/m^2, which for the most optimal option generated was reduced to 2099.57 kWh/m^2. This 66.23% decrease is due to the appropriate choice of exterior wall cladding material, glazing material, WWR, and height of each floor. This reduction in this objective function leads to the preservation of the environment, reducing pollution, and the destructive effects of the environment in the phase of project demolition.

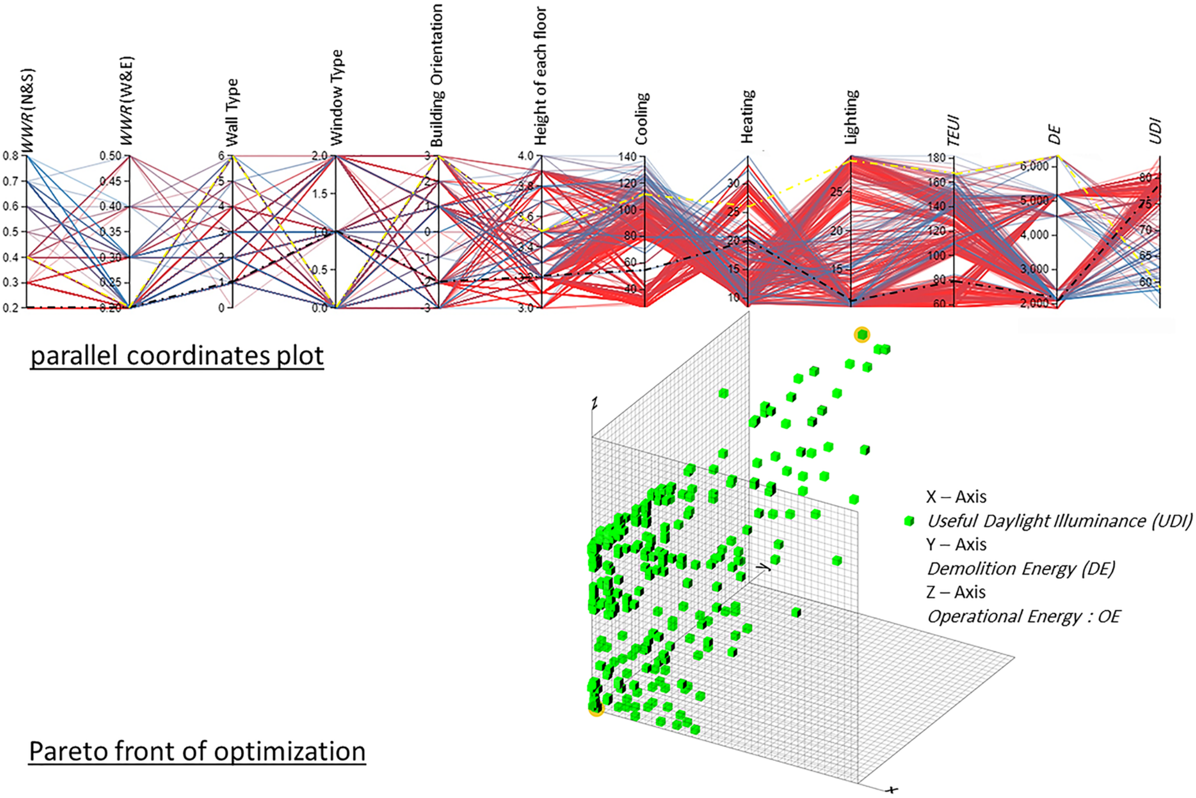
In addition, *OE* demand decreased from 166.42 to 77.41 kWh/m^2. This reduction of 53.48% can be very significant in reducing overall costs and energy resources. The percentage of *UDI* in the best option generated has increased by 32.05%, which means a reduction in energy consumption to meet the lighting needs of the employees of this office space.

By examining the parallel coordinate graph and the table in Fig. 4, in addition to the values of the objective functions, the geometric and non-geometric parameters of the options have also been determined. If the WWR for the north-south and east-west windows is 20%, the material of the external walls and the type of windows is with an index of 1, the orientation of the building is 20 degrees to the southwest, and the height of each floor of the building is 3.2 m, an option is produced, which can be considered the best design option to improve the stability of the building. It can be said that the best material obtained for exterior wall cladding, based on the objective functions investigated in this research, is metal wall cladding and for glazing, double clear 6 mm/13 mm ARG.

Figure 5, which is one of the outputs of the Wallacei plugin, shows the values related to *OE* subsets, which are energy consumption for cooling, heating, and lighting, for the best and worst options produced. In the graphs on the right side of this figure, the output of each of these values has been compared according to office application, space occupancy hours, climate, and other considered parameters. In this diagram, the highest amount of *OE* for both options is related to cooling energy, and the lowest is related to heating energy.

In this figure, *DE* subcategories, which are nine harmful environmental effects related to the EN15978 standard, are also compared in both cases of the best and worst solutions produced. In the best option, the number of harmful effects related to TPE, NR, and FFC is 2100.00 (MJ), which has decreased by 66.18% compared to their values in the worst option, which is 6210.00 (MJ). The least destructive effects in both cases are related to ODP, which is very small and negligible compared to the values of other effects.

	Inputs					**Outputs**				
	WWR (N&S- E&W) (%)	Exterior wall cladding material (Index number)	Glazing material (Index number)	Building orientation (°)	Height of each floor (m)	*HEUI* (kWh/m2)	*CEUI* (kWh/m2)	*LEUI* (kWh/m2)	*DE* (kWh/m2)	*UDI* (%)
Best Option	20 - 20	1	1	-20	3.2	20.25	46.34	10.82	2099.57	78.33
Worst Option	40 -20	6	0	30	3.5	26.53	110.26	29.63	6217.51	59.29



parallel coordinates plot

Pareto front of optimization

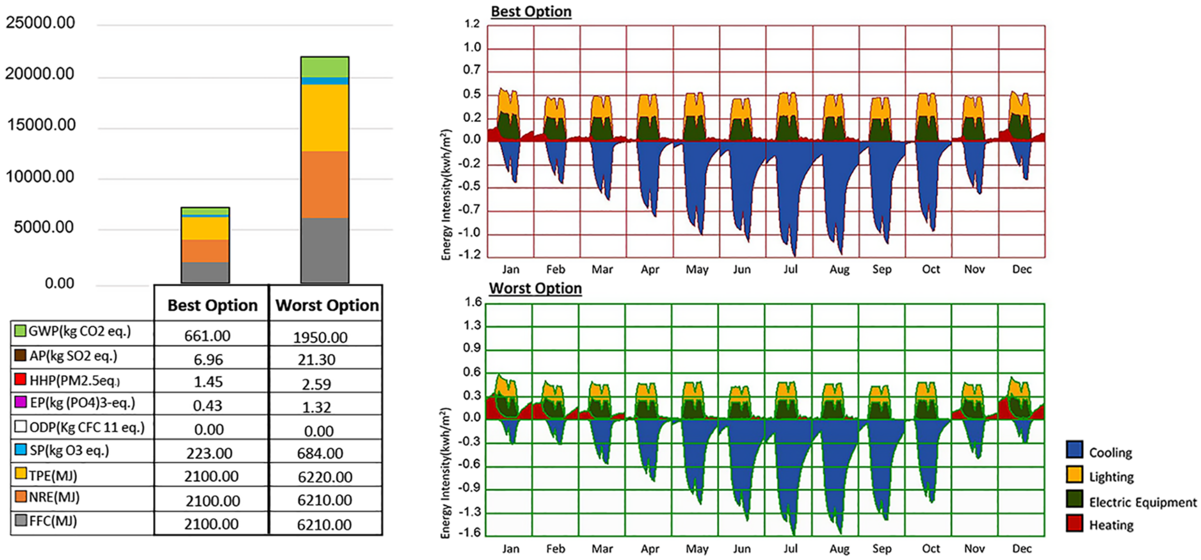
Fig. 4 Input parameters and output data in the best and worst option as a result of optimization

Evaluating and comparing the values between these two options, in addition to determining the effectiveness of optimization, shows that designers with each decision in the early stages of design have a significant impact on energy consumption at different phases of the project life cycle.

Synthesis of research data with building information modeling software

The final step of the research is to make the results of the optimization easy and reliable for the architects in the initial design phase and the development of their plans. Architects can also use this approach to use integrated data to design sustainable building facades and the next stages of developing their projects. To achieve this goal, the method of adding an application programming interface (API) to NaviseWorks Autodesk software extensions was used.

API is a software interface that allows two programs to interact. This API is developed in Visual Studio Code using C# programming language to implement research results in construction projects. The programming steps are as follows: First, desired code was written in the Visual Studio Code software, and a plugin was created in the user interface of the Navisworks software. By running this program, the user automatically enters the software environment. By clicking on the plugin, the help page opens, which contains several options. The information file and



	Best Option	Worst Option
🟩 GWP(kg CO2 eq.)	661.00	1950.00
🟫 AP(kg SO2 eq.)	6.96	21.30
🟥 HHP(PM2.5eq.)	1.45	2.59
🟪 EP(kg (PO4)3-eq.)	0.43	1.32
☐ ODP(Kg CFC 11 eq.)	0.00	0.00
🟦 SP(kg O3 eq.)	223.00	684.00
🟨 TPE(MJ)	2100.00	6220.00
🟧 NRE(MJ)	2100.00	6210.00
⬜ FFC(MJ)	2100.00	6210.00

Fig. 5 Comparing *OE* consumption results and standard environmental impacts between the best and worst options

specifications related to all optimal solutions are displayed in Excel format by clicking on each option.

With the help of this method, the optimized results of the optimization process along with the information related to each of the solutions, including the input parameters related to the percentage of windows in all facades of the building, the height of each floor of the building, the orientation of the building, and also the type of exterior material wall cladding and glazing, and the environmental effects of 100 m^2 of them were recovered and presented in the Navisworks environment.

At this phase, the initial BIM model, which was initially developed in Revit and only contained the general information of the geometric model, was included in Navisworks to improve and add information from the optimization (Fig. 6, steps 1 and 2). Then a feature was added to the model that can choose among the optimal solutions based on (1) energy and destructive environmental effects caused by the demolition of each option; (2) the amount of cooling, heating, and lighting energy that is consumed in the building operation phase if any of the options are selected; and (3) *UDI* (Fig. 6, step 3), and create a sustainable integrated model in BIM of project results and energy consumption information in optimal options. By choosing each of the optimal solutions, the information related to each of them can be applied to the model, and the results of this synergy can be seen in Fig. 6.

Discussion

In this section, the analysis of the objective functions and the importance of multi-objective optimization, tool validation tests, and simulations, as well as the detailed examination of the relationships between parameters and design objectives, have been discussed.

Analysis of objective functions

Figure 7 shows the range of optimal solutions for each objective function separately and all three functions together. In standard deviation graphs, the closer the bases of the graphs are to each other, and their color tends to be blue, the closer the desired function is to its optimal value. The mean value trendline graphs also show the trend of changing the values of each objective function to create their optimal value. When the oscillation of this graph decreases and tends to a straight line, it indicates that it is close to the optimal solutions. It should be noted that since several conflicting objectives are considered simultaneously in multi-objective optimization, these graphs can be changed to a certain extent and approach the optimal state.

To analyze the objective functions and the importance of multi-objective optimization, Fig. 7 (the Wallacei plugin output) shows the range of optimal

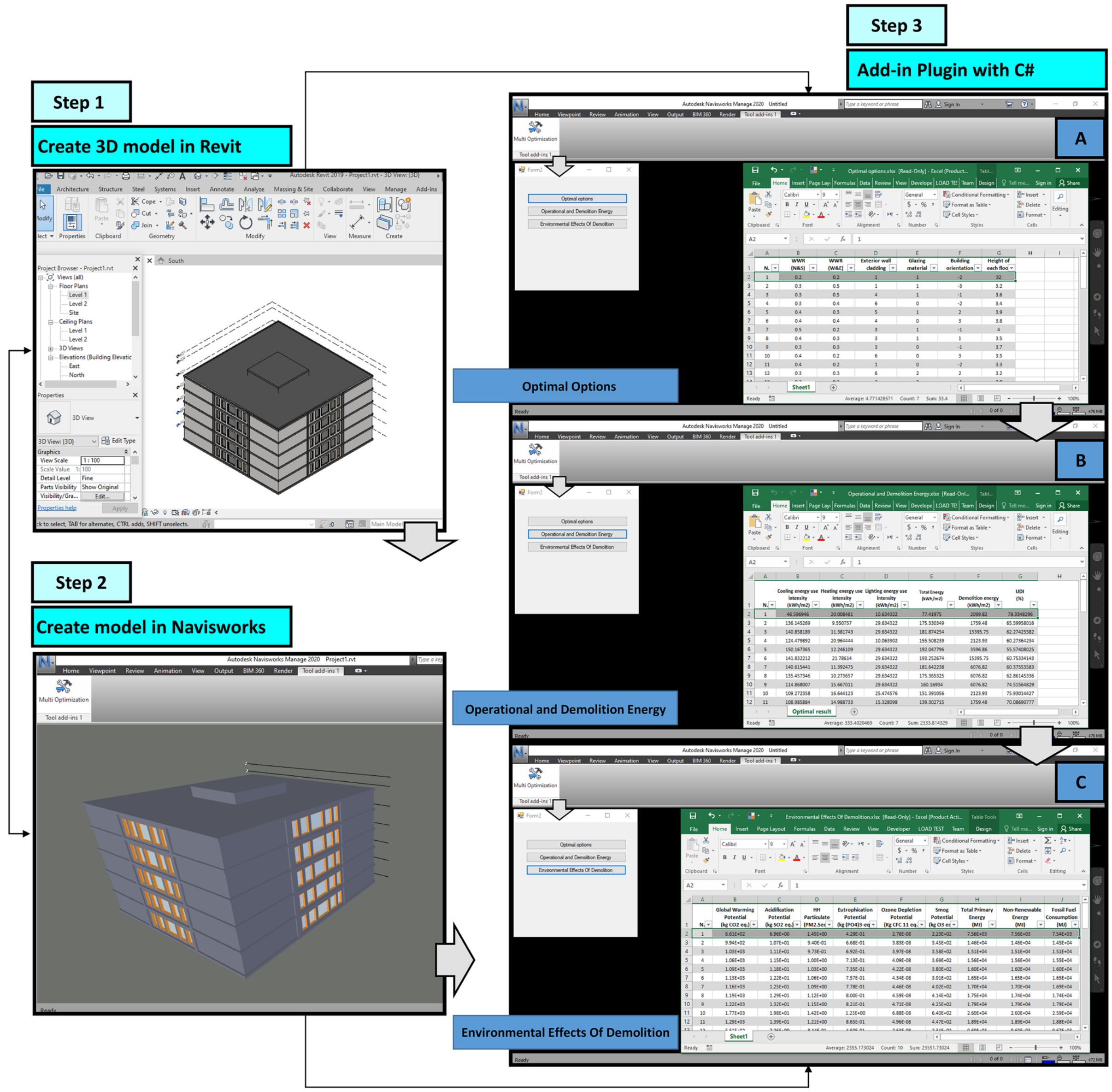
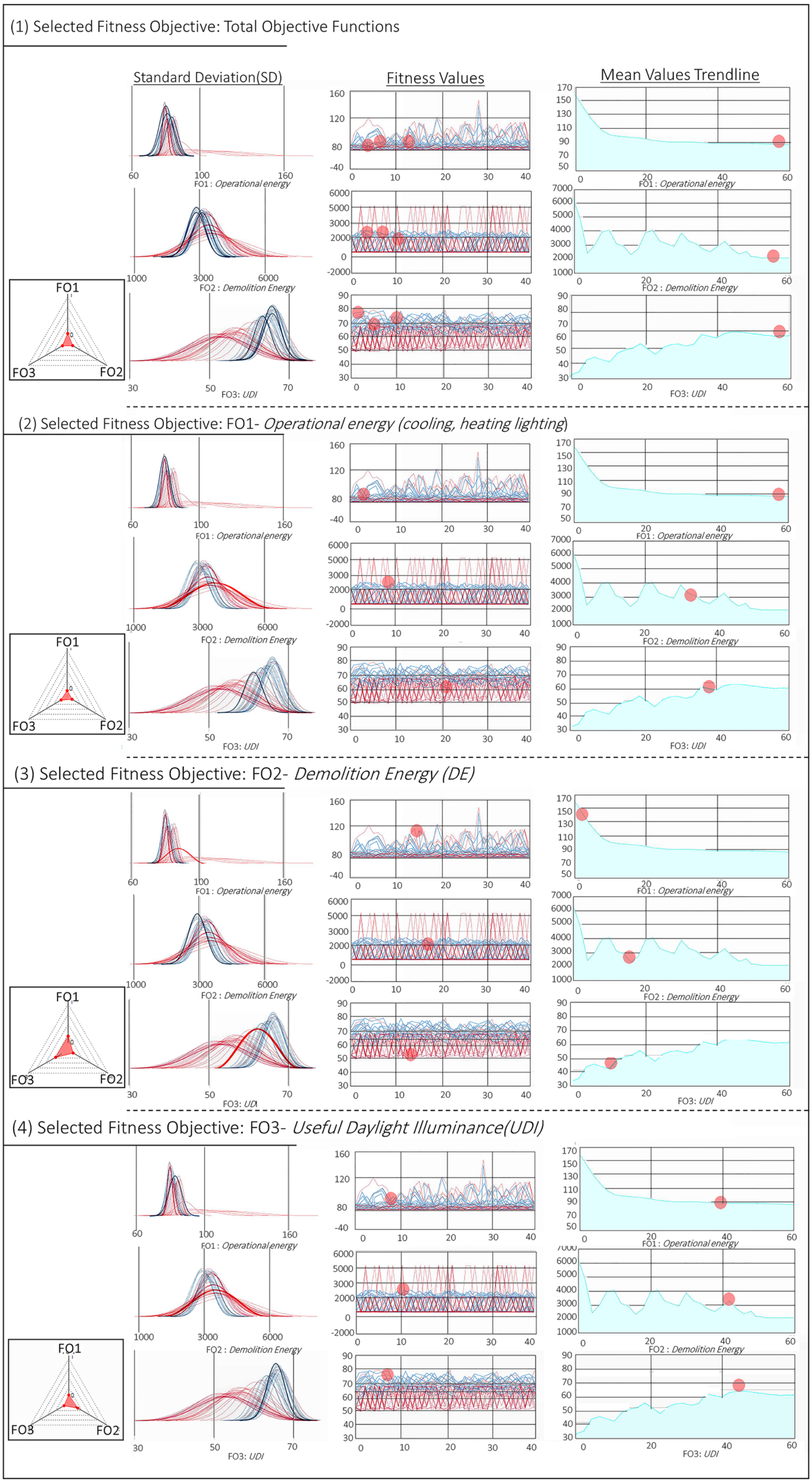


Fig. 6 Results of plugin creation and data synergy in Navisworks software

solutions according to the objective of considering each function separately and all three functions together. In each section, three graphs of standard deviation, fitness values, and mean values trendline are specified in three columns. These diagrams show the process of changing the values of each of the objective functions to create their optimal value.

In the first column, which is standard deviation, the closer the bases of the graph are to each other and the bluer their color is, it is a sign that the desired function is closer to its optimal value. In the fitness values diagram, the decrease in the fluctuation of the decrease lines and their tendency to a straight line indicates that it is close to the optimal solutions. Comparing the range of optimal solutions in the mean values trendline chart, when all three functions (section 1) and when only one function (sections 2, 3, and 4) are considered the objective function, shows the importance and score of multi-objective optimization compared to single-objective optimization.

Fig. 7 Analysis of objective function values on mean value trendline, fitness value, and standard deviation charts (Wallacei plugin output)



The rows in each section show the range of solutions for each of the objective functions separately in all three graphs. As it is known, the range of options produced in the optimization process of each selected fitness objective has been placed in the most optimal possible state in comparison with the other two functions. In Fig. 7, the range of all solutions is marked with red circles on each of the graphs. In addition to these diagrams, a coordinate diagram is specified in each section, the more symmetrical the red triangle that is in the center of this coordinate becomes, and the closer it is to the center of the coordinate, the generated solutions are in the range of optimal solutions.

Validation

Over the years, several articles have successfully performed the validation of Honeybee and Ladybug plugins and Athena software. In this study, the new versions of Ladybug and Honeybee (Ladybug Tools 1.2.0) were used to simulate daylight and energy, and Athena software was used to calculate energy from building demolition, transportation, and landfill/disposal of waste.

To test the validation of the tool and simulation, the first step was to select two close solutions in the Pareto front and calculate and compare their objective functions.

From the produced options, 89 designs were proposed as optimal options. Two of the most optimal solutions were selected on the Pareto front to test the validation of the process. The values of their inputs and outputs are compared in Table 5. Because the input variables are close in both cases except for the orientation of the building, the results do not differ much. Comparison of these numbers proves that the results are logical and reliable.

Table 5 Values of two optimal solutions on the Pareto front

Column3	Inputs	Column7	Column8	Column9	Column4	Outputs	Column2	Column23	Column232	Column24
	WWR (N&S-E&W) (%)	Exterior wall cladding material (index number)	Glazing material (index number)	Building orientation (°)	Height of each floor (m)	*HEUI* (kWh/m^2)	*CEUI* (kWh/m^2)	*LEUI* (kWh/m^2)	*DE* (kWh/m^2)	*UDI* (%)
1st option	20–20	1	1	−20	3.2	20.25	46.34	10.82	2099.57	78.33
2nd option	20–20	1	1	20	3.2	20.29	46.38	10.89	2099.57	78.29

Sensitivity analysis

To accurately evaluate the relationships between parameters and design objectives, by constantly considering other variables, the value of each variable changes individually for the base case. Examining and comparing the values in Fig. 8 shows the effect of each parameter on the cooling, heating, and lighting energy and the environmental indicators provided by EN15978. A summary of the results of these analyzes is as follows:

According to these results, when the building is located at 20 degrees to the southeast or southwest or precisely to the south, it has the lowest lighting and cooling energy consumption. Contrary to expectations, *OE* consumption varies with the height of the floors. The higher the height, the greater the amount of *DE*, but this does not mean that the lowest height is the most appropriate choice. The results of the optimal options show that under the influence of other variables and objectives, the most suitable height can be different.

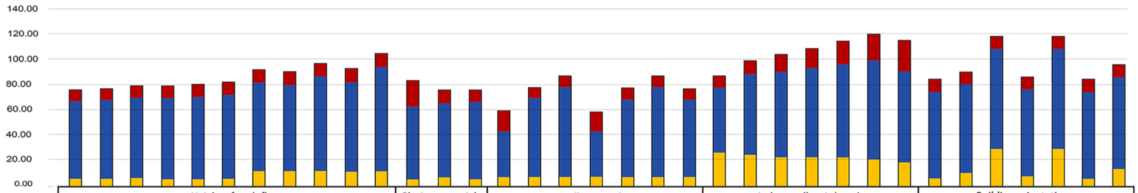
Compared to other materials, stone has the most, and insulated metal panel (IMP) wall cladding has the least destructive environmental effects. On the other hand, wood bevel siding and oriented strand board are the most suitable in terms of thermal energy and light, and IMP wall cladding and fiber cement are the most inappropriate choices.

Increasing the WWR (%) increases the heating energy demand and decreases the lighting energy demand. On the other hand, by changing the WWR, the consumption of glass and wall materials, and as a result, environmental effects in the demolition phase will be very diverse.

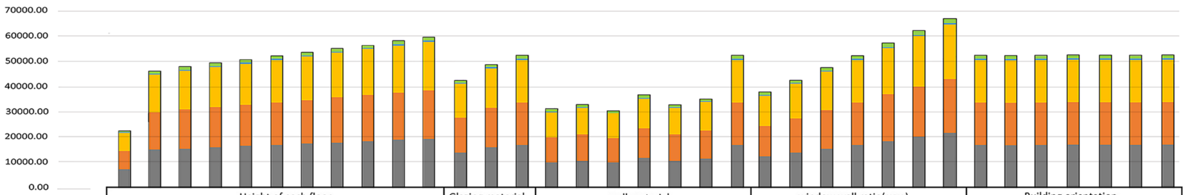
In general, the considered variables have the most significant impact on total primary energy, non-renewable energy, fossil fuel consumption, and global warming potential, respectively. Comparisons of these values show that designers' decisions in the very early stages of design are very influential on the destructive effects that occur when a building is demolished.

Conclusion

The present research proposes a process to reduce energy consumption and improve the performance of buildings using material LCA, parametric modeling, simulation, GA, and optimization. This method was tested in the design of a fictional open office building in Tehran. Applying this process allows designers to evaluate *OE* and *DE* for different designs based on parameters and objectives and finally find the options with optimal performance.



	Height of each floor											Glazing material			wall material							window wall ratio(*wwr*)							Building orientation						
Index Of Parameters	0	1	2	3	4	5	6	7	8	9	10	0	1	2	0	1	2	3	4	5	6	0	1	2	3	4	5	6	0	1	2	3	4	5	6
🟥 *HEUI* (kWh/m²)	8.66	8.89	9.17	9.37	9.61	9.87	10.09	10.34	10.34	10.79	10.79	22.34	11.63	9.87	18.08	9.44	9.65	17.14	9.82	9.66	9.84	10.01	11.75	15.71	16.87	19.85	22.71	26.92	9.87	9.73	9.69	9.85	9.77	9.83	9.83
🟦 *CEUI* (kWh/m²)	61.42	62.41	63.76	64.41	65.39	66.64	70.20	68.32	75.26	70.65	82.42	62.42	63.39	66.63	39.01	67.89	77.28	39.12	66.72	77.26	66.41	56.08	69.32	73.26	76.67	80.06	84.97	78.11	66.66	68.75	77.28	67.35	77.31	66.94	70.66
🟨 *LEUI* (kWh/m²)	6.62	6.51	7.13	6.31	6.23	6.55	12.63	12.73	12.63	12.23	12.63	6.46	8.42	6.53	8.51	8.51	8.51	8.51	8.51	8.51	8.51	29.38	27.63	25.63	25.61	25.48	23.63	21.14	6.69	10.82	29.63	8.21	29.63	6.43	13.87



	Height of each floor											Glazing material			wall material							window wall ratio(*wwr*)							Building orientation						
Index Of Parameters	0	1	2	3	4	5	6	7	8	9	10	0	1	2	0	1	2	3	4	5	6	0	1	2	3	4	5	6	0	1	2	3	4	5	6
🟩 GWP (kg CO2 eq.)	483.0	994.0	1030.0	1060.0	1090.0	1130.0	1160.0	1190.0	1220.0	1260.0	1290.0	917.0	1050.0	1130.0	661.0	704.0	653.0	806.0	704.0	753.0	1130.0	814.0	918.0	1020.0	1130.0	1230.0	1330.0	1440.0	1130.0	1130.0	1130.0	1130.0	1130.0	1130.0	1130.0
🟫 AP (kg SO2 eq.)	5.22	10.70	11.10	11.50	11.80	12.20	12.50	12.90	13.20	13.60	13.90	10.20	11.50	12.20	7.26	7.14	7.17	7.91	7.68	8.14	12.20	8.37	9.64	10.90	12.20	13.40	14.70	16.00	12.20	12.20	12.20	12.20	12.20	12.20	12.20
🟥 HHP (PM2.5eq.)	0.46	0.94	0.97	1.00	1.03	1.06	1.09	1.12	1.15	1.18	1.21	0.95	1.02	1.06	0.81	1.36	0.81	0.87	0.84	0.86	1.06	0.92	0.97	1.01	1.06	1.11	1.16	1.21	1.06	1.06	1.06	1.06	1.06	1.06	1.06
🟪 EP (kg (PO4)3-eq.)	0.33	0.67	0.69	0.71	0.74	0.76	0.78	0.80	0.82	0.84	0.87	0.63	0.71	0.76	0.45	0.44	0.45	0.46	0.48	0.51	0.76	0.52	0.60	0.68	0.76	0.84	0.92	0.99	0.76	0.76	0.76	0.76	0.76	0.76	0.76
⬜ ODP (Kg CFC 11 eq.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
🟦 SP (kg O3 eq.)	168.0	345.0	358.0	369.0	380.0	391.0	402.0	414.0	425.0	436.0	447.0	328.0	369.0	391.0	234.0	228.0	231.0	240.0	247.0	262.0	391.0	267.0	308.0	350.0	391.0	433.0	474.0	516.0	391.0	391.0	391.0	391.0	391.0	391.0	391.0
🟨 TPE (MJ)	7090.0	14600.0	15100.0	15600.0	16000.0	16500.0	17000.0	17500.0	17900.0	18400.0	18900.0	13500.0	15400.0	16500.0	9690.0	10300.0	9570.0	11600.0	10300.0	11000.0	16500.0	11900.0	13400.0	15000.0	16500.0	18000.0	19600.0	21100.0	16500.0	16500.0	16500.0	16500.0	16500.0	16500.0	16500.0
🟧 NRE (MJ)	7080.0	14600.0	15100.0	15600.0	16000.0	16500.0	17000.0	17500.0	17900.0	18400.0	18900.0	13500.0	15400.0	16500.0	9690.0	10300.0	9570.0	11500.0	10300.0	11000.0	16500.0	11900.0	13400.0	15000.0	16500.0	18000.0	19600.0	21100.0	16500.0	16500.0	16500.0	16500.0	16500.0	16500.0	16500.0
⬛ FFC (MJ)	7070.0	14500.0	15100.0	15500.0	16000.0	16500.0	16900.0	17400.0	17900.0	18400.0	18800.0	13500.0	15400.0	16500.0	9690.0	10300.0	9570.0	11400.0	10300.0	11000.0	16500.0	11900.0	13400.0	14900.0	16500.0	18000.0	19500.0	21100.0	16500.0	16500.0	16500.0	16500.0	16500.0	16500.0	16500.0

Fig. 8 Investigating the effect of parameters on the amount of *OE* consumption and destructive environmental effects according to the standard EN15978

In different parts of the research, the need to improve the performance of buildings in operation and demolition phases was addressed. As a result, it was decided to simultaneously reduce energy consumption in these two phases by using multi-objective optimization by changing the material and geometric characteristics of the building facade as the component that plays the most role in energy loss.

The framework presented in this study is a combination of LCA, multi-objective optimization, and BIM. In this approach, the initial selection of materials is through LCA, objectives optimization, through the process of modeling, simulation, and optimization, and finally, information retrieval and integration by BIM. The three objectives of *OE*, *UDI*, and *DE* were optimized, and optimal solutions were presented by changing the set parameters. In the optimal options offered, the most appropriate orientation of the building, floor height, WWR, exterior wall cladding material, and glazing material were also determined.

Finally, BIM technology was used to integrate and manage the optimization data in the early stages of the project. Using the C# programming language in Visual Studio Code software, a plugin was created to transfer and integrate optimal options data into Navisworks software automatically.

This plugin can be developed in future studies to examine the time and cost of optimal options and enhance BIM dimensions.

Also, to reduce the complexity, optimization time, and comparability of the results, this research was conducted on two of the most important phases of the life cycle of the facade of a simple building model. In future work, if you have more powerful technical support and computers with higher processing power, with limited changes in the algorithm, architectures can develop the presented framework for other parameters, uses, locations, components, and phases of the life cycle.

Declarations

Conflict of interest The authors declare no competing interests.

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