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OPTIMIZING ENERGY CONSUMPTION AND STRUCTURAL PERFORMANCE OF OFFICE BUILDINGS IN TEHRAN CITY USING COST-EFFECTIVE SOLUTIONS: A MODELING AND SIMULATION-BASED ANALYSIS

Amin Mohammadi[1]*, Shariyeh Hosseininasab[2], Seyed Mohammad Mousavi[1]

[1]Persian Gulf University (PGU), 75169, Bushehr, Iran
[2]COMSATS University Islamabad (CUI), Lahore Campus, Lahore, Pakistan

*Corresponding author's email: aminmohammadi@pgu.ac.ir

Abstract
Introduction: Office buildings in big cities consume enormous amounts of energy resources every year and the resulting carbon dioxide emissions are significant. In addition, the design, construction, and maintenance of these buildings are extremely expensive, so it is necessary to pay special attention to their durability, stability, and useful life during the design phase. **Purpose of the study:** The main goals of this research were to optimize energy consumption and structural performance of office buildings in megacities by using cost-effective solutions. **Methods:** An office building in Tehran (the capital of Iran) was selected as a case study and simulated using DesignBuilder, Revit, and Robot Structural Analysis software as a baseline model. Then to achieve the main goal, a number of cost-effective solutions were applied in developed and proposed models of this building in a simulation environment. **Results:** The results of this simulation-based analysis showed that the economic solutions used in the proposed model could reduce not only the annual energy consumption and carbon dioxide emissions by 50 %, but also the weight of the materials in the external walls and ceilings by up to 16 %. The suggested methods can significantly reduce the cost of reinforcing the structure and can also increase the building's useful life, durability, and stability. The results of this research can be used in the design phase of office buildings in megacities such as Tehran.

Keywords: office buildings; energy optimization; structural performance; modeling; simulation.

Introduction

In recent decades, many researchers have been very concerned with global warming. The consumption of fossil fuels and the emission of large amounts of carbon dioxide are the most important factors in climate change. Meanwhile, buildings account for more than 40 % of energy consumption in big cities. Administrative buildings located in big cities are considered important urban centers, serving as the main decision-making hubs for urban management and city implementation issues. Consequently, a significant amount of money is spent on their design, construction, repair and maintenance. However, they can have a lot of negative effects on the urban environment, and with the reduction of their useful life or in times of natural disasters, they bear the risk of vulnerability and possible damage. Office buildings consume more energy than other types of buildings. Depending on their equipment, lighting and air conditioning systems, as well as their location and dimensions, energy consumption can vary between 100 and 1,000 kWh/m^2 per year (Siew et al., 2011). Therefore, to increase the lifespan and physical stability of such buildings, reduce their adverse effects on the urban environment, and optimize their performance in terms of energy consumption, certain measures should be taken in their design, construction, and performance optimization. In recent years, researchers have already examined many ways to achieve this goal. Khodakarami and Ghobadi (2023) presented simple and practical solutions to optimize energy consumption and establish thermal comfort in a high-rise office building equipped with a smart management system in Tehran. They concluded that it is possible to save 35 % to 40 % in energy consumption per year. Ghiai and Hajjar (2014) investigated the relationship between the opening ratio and energy consumption of high-rise office buildings in Tehran using eQuest simulation software. They concluded that these two variables have a direct relation: reducing the ratio of openings by 20 % can reduce annual energy consumption by 17 %. Moulaii et al. (2019) investigated the optimization of dimensions and proportions of openings in the office spaces of Tehran in terms of lighting and energy consumption by using simulation. The results of this research showed that the most optimal window-to-wall ratio was between 20 % and 28 %, and the optimal length and width were respectively 53.6 and 9 meters on average. Haghani et al. (2017) used simulation to determine the effect

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of shutters in four main directions on the optimization of energy consumption of office buildings in Tehran. They concluded that the presence of this type of shade had a significant effect on glare and annual thermal loads. Mohammadi et al. (2023) chose an office building in Tehran as a case study to improve the indicators of Iran's national standard in the field of evaluating the energy performance of non-residential buildings by comparing it with the LEED standard. Akeiber et al. (2016) reviewed phase change materials for passive cooling in buildings and concluded that most of the research conducted in this field was done with real-scale tests and numerical modeling. Therefore, the use of such materials in the external walls of buildings had already been highlighted in the past researches.

In another research, Alvand et al. (2017) examined cost-effective solutions for energy consumption in buildings, including the use of thermal insulation, shading systems, high-efficiency windows, and solar renewable energy in Iran. They concluded that optimizing energy consumption and achieving energy-efficiency in buildings was not possible without government subsidies. Anvari-Moghaddam et al. (2015) presented an innovative system for the energy management of Iranian buildings with optimization of energy consumption and thermal comfort, which can be economically viable. Azari et al. (2016) presented a multipurpose optimization algorithm for the optimal design of the components of a low-rise office building in Seattle, USA, taking into account energy consumption, the life cycle of consumable materials, and their impact on the environment. Insulation materials, the type of windows and their frames, the thermal resistance of the walls, and the window-to-wall ratio used in the south and the north sides were important parameters in this project. The authors used the eQuest software for the simulation. They obtained the best results with R-17 thermal insulation, fiberglass frame with three-pane glass, and the window-to-wall ratio including 60 % on the south side and 10 % on the north side. Using genetic algorithm and simulation, Baniassadi et al. (2016) investigated the economic optimization of thermal insulation thickness and the thickness of the phase change material layer in Tehran, Isfahan, Shiraz, Bandar Abbas, Yazd and Tabriz. The results of EnergyPlus software showed that the thickness determined for the layer of phase change materials in all the investigated cities was zero, while the thickness of the thermal insulation in the cities of cold regions should be up to 6 cm. However, in the current economic conditions of Iran, the cost of thermal insulation is higher than that of phase change materials. Fathalian and Kargarsharifabad (2018) investigated energy consumption in an office building in Semnan city. The results of the model simulated by the software and its comparison with the measurement of the actual energy consumption of the building based on electricity and gas bills showed an error of 1.6 %, which illustrated the accuracy of the modeling. The solutions used in this building to optimize energy consumption included double-glazed windows, thermal insulation of external walls, and horizontal shades on its facade. The results showed that each of these solutions saved up to 18 %, 14 %, and 13 % in the energy consumption of the building, respectively. In another research, Heravi and Qaemi (2014) evaluated the design and construction of buildings considering the optimization of energy consumption in Iran. The research results showed that the use of solar energy can be considered the most widely used renewable energy system in Iran. Javid et al. (2019) developed a multi-objective optimization framework with the lowest economic costs and the lowest impact on global warming. New energy-efficient technologies for supporting and using energy systems were implemented on and investigated in two educational buildings in Sharif University of Technology campus in Tehran. These systems reduced carbon dioxide emissions by 18–20 %. Mohtashami et al. (2016) conducted a research to determine strategy and policy-making in architectural design to achieve optimal conditions in terms of health and safety of the interior space of buildings by using interviews and logical reasoning. Movahhed et al. (2019) investigated the combination of solar panels and green roofs to optimize energy consumption in a common building using DesignBuilder and PVsol software. The research showed that the reduction in energy consumption as a result of the use of green roofs was very limited, while solar panels produced up to 26 megawatt hours of energy per year, and the payback period was between 6.5 and 7.5 years. Moreover, they could prevent the production of 16.3 tons of carbon dioxide annually. Solgi et al. (2019) investigated the role of light phase change materials along with night ventilation to optimize energy consumption in three different types of climates. The research results showed that in tropical climates, the use of these two strategies together was ineffective. However, in subtropical as well as hot and arid climates, the cooling set-point of HVAC systems and thermal insulation played a key role in the performance of phase change materials and night ventilation. In addition, thermal insulation was more effective in optimizing night ventilation than phase change materials. Tahsildoost and Zomorodian (2015) examined the retrofitting of two common educational buildings in Iran. Replacing the windows, sealing the openings appropriately, and using thermal insulation on the roof were among the solutions considered in this research, while the payback period was also taken into account. After the simulation, the results included a 30 % to 38 %

reduction in energy consumption in two educational buildings, and the results of the questionnaires also indicated an improvement in the thermal condition inside the building. Vakiloroaya et al. (2014) showed that a combination of different technologies of mechanical air conditioning systems can be useful for reducing energy consumption and improving thermal comfort. Yousefi et al. (2017) investigated the effect of users' behavior on the energy performance of building components. For this purpose, a typical apartment building in Iran was selected and its energy simulation results were compared with the actual energy consumption results of that building. The energy consumption of buildings in different climates, before and after the amendments, was simulated using EnergyPlus software. The sensitivity analysis in this research showed that the behavior of users had a great impact on the thermal energy consumption of the building in hot climates and could change the cooling and heating loads of the building up to 90 %.

The literature review shows that the simultaneous use of cost-effective solutions for optimizing energy consumption and structural performance of office buildings has not been investigated so far. This study goes beyond this stage to examine the optimization of energy consumption and structural performance of office buildings as the main objectives of the research in a simulation environment with respect to cost-effective solutions. To this end, three models including a baseline model of an office building, a developed model, and a proposed model are simulated and analyzed in two steps. The research process diagram of this study is shown in Fig. 1. In the first step, we model and simulate the selected office building in Tehran city in DesignBuilder software. Then we review the annual energy consumption of this baseline model in different sections and identify the important parts. Then, to optimize the annual energy consumption in the baseline model, a number of passive and active strategies are selected and utilized in a developed model. At the end of the first step, we develop a model of the office building with optimized energy consumption. In the second step of this study, the architectural and structural modeling and simulation are necessary for analyzing the structural performance of the case study building in a simulation environment. For this purpose, after modeling the baseline and developed model in Revit Architecture software, we obtain a proposed model of the office building with lightweight materials in its external walls in Revit Architecture as well. Then, for modeling and simulation of the structural performance, all models are transferred to Revit and Robot Structural Analysis software. Finally, the findings of the model-based simulations are compared and analyzed. We suggest an optimized model of the office building in terms of energy consumption and structural performance and make theoretical predictions.

Methods

This research employs a methodology that focuses on modeling and simulation techniques to enhance energy efficiency and structural integrity in office buildings. We chose this technique for its ability to measure multiple performance indicators without the financial and logistical challenges of conducting real-world experiments. The virtual testing space

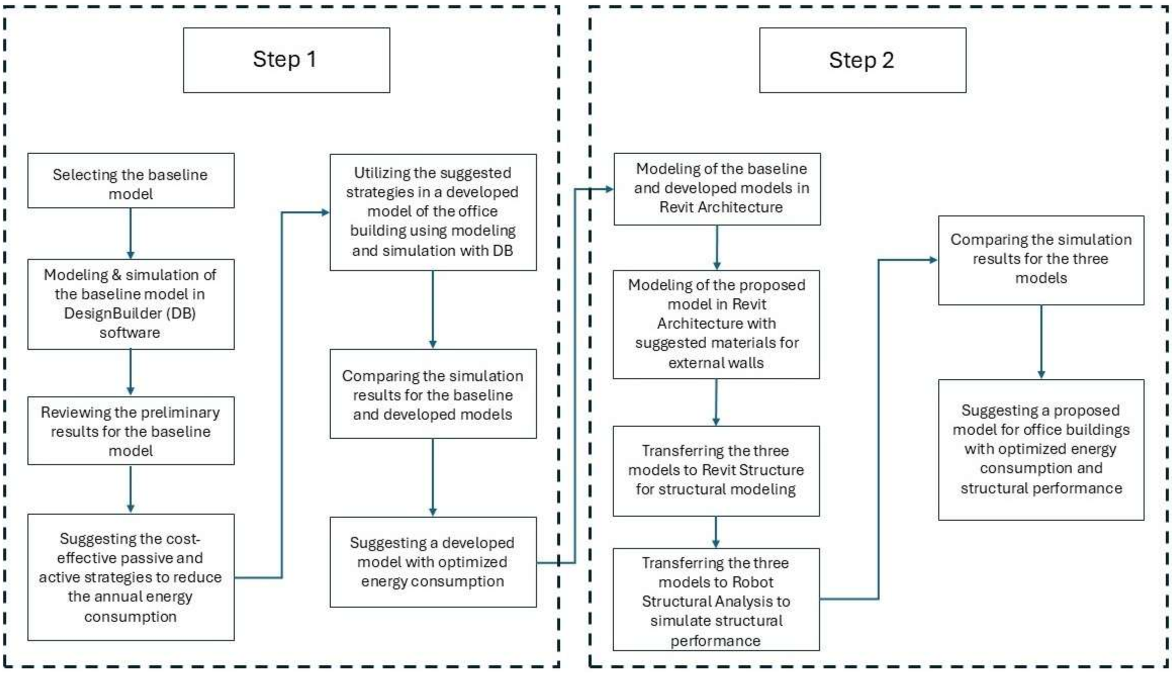

Fig. 1. Research process diagram

facilitates in-depth examination and evaluation of various situations, offering valuable information on possible enhancements in energy conservation and the strength of structures. Given that the study aims to evaluate both energy consumption and the loads on structures, simulation-based modeling is an especially appropriate technique. It allows for theoretical forecasts involving various factors, including energy consumption for cooling, heating, lighting, hot water for domestic use, and cooking, along with enhancements in structure through alterations in materials.

In this study, we formulate three separate models, each serving a particular purpose. The baseline model reflects the real-world performance of the building, pointing out its energy inefficiencies. This model is essential for grasping current challenges; it provides a basis for ongoing optimization efforts. The developed model combines several passive and active methods to lower energy consumption, revealing how targeted interventions can significantly improve building performance. Lastly, the proposed model retains the energy-efficient strategies of the developed model and introduces lightweight materials for the external walls, focusing on reducing dead loads and enhancing the overall structural performance of the building.

The entire process of calculation occurs in a simulated framework, and the outcomes rely on theoretical insights rather than practical experimentation. This method provides adaptability and accuracy when assessing different design options, making it a perfect fit for fulfilling the goals of this research.

In the first part of the methodology section, which is about energy optimization, the general specifications of the case study building, suggested strategies to be used in the developed model, and the simulation results of the baseline and developed models are described and compared in terms of energy optimization and cost-effectiveness of the retrofit actions. Then in the second and third parts, we describe and compare the architectural and structural modeling process of the baseline, developed and proposed models.

Energy Optimization

An office building in Tehran with the specifications indicated in Table 1 was selected as a case study. The first part of this research was carried out by using modeling and simulation in DesignBuilder software (Fig. 2a) and hourly climatic data of Tehran city along with the occupancy schedule.

To estimate the building energy consumption, we utilize the energy balance equation, which is used to maintain indoor thermal comfort conditions. Various components including cooling, heating, lighting, and domestic hot water (DHW) are typically considered. A general approach to these equations (1–4) is presented as follows:

Table 1. **Specifications of the case study building**

Physical specifications and equipment	Baseline model
Area	2,133.5 (m^2)
Number of floors	5
Shading (north)	None
Shading (south)	None
Shading (west)	Not needed
Shading (east)	Not needed
Natural ventilation set point	None
Natural ventilation schedule	None
Mechanical ventilation	Air handling unit (AHU)
Rate of air change per hour (ACH)	3 (1/h)
Cooling system, seasonal CoP	Fan coil units connected to the chiller, 1.8
Heating system, seasonal CoP	Fan coil units connected to the boiler, 0.85
Lighting system	Fluorescent, normalized power density 5 W/m^2
Domestic hot water (DHW), seasonal CoP	Instantaneous hot water, 0.85
Window frame and thickness	Aluminum, 4 cm
Number of panes and glazing	2, generic clear
Heat transfer coefficient of glazing	3.128 W/(m^2k)
Solar heat gain coefficient of glazing	0.71
Thickness of external walls	26.5 cm
Materials of external walls	Granite, cement mortar, brick, gypsum plastering, polyester resin
Heat transfer coefficient of external walls	0.35 W/(m^2k)
Occupancy schedule	8 am – 4 pm
Holidays	Thursday and Friday

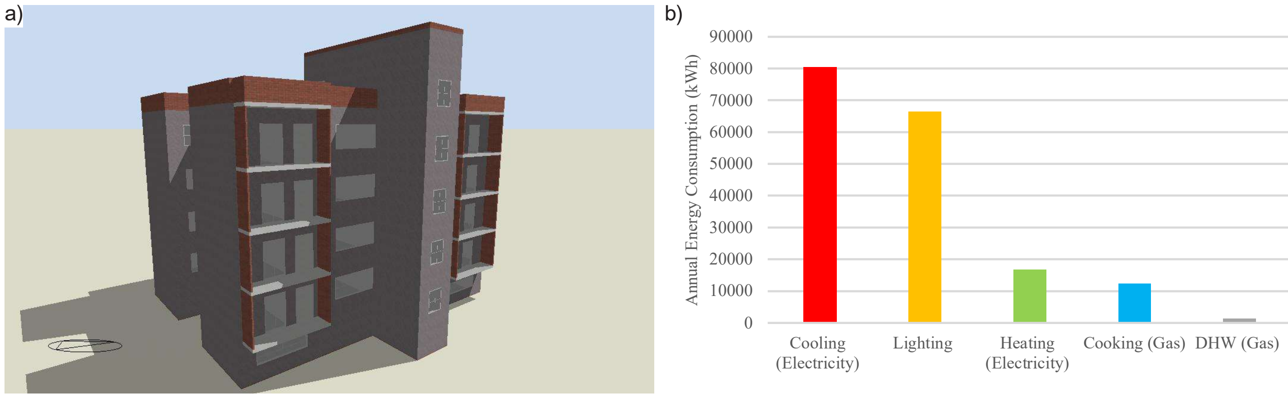

Fig. 2. (a) Baseline model in DesignBuilder, (b) annual energy consumption of the baseline model in different sections

1. Cooling and heating load calculation.

The basic equation for cooling and heating load is as follows:

$$Q = U \times A \times \Delta T, \quad (1)$$

where:

Q — thermal load in Watts or BTU/hr;

U — heat transfer coefficient in W/m^2 K or BTU/(hr.ft^2 °F);

A — area of the building envelopes like walls, windows, roofs, etc. in m^2 or ft^2;

ΔT — temperature difference between indoor and outdoor environments in °C or °F.

The heat loss or gain through the building envelope is calculated using Eq. (1). The sum of the loads calculated for each building surface is considered the total cooling or heating load of the building.

2. Energy consumption for lighting.

Energy consumption for lighting can be estimated as:

$$E = P \times H, \quad (2)$$

where:

E — total lighting energy consumption in kWh;

P — total power of lighting in kW;

H — number of operational hours for lighting in hrs;

3. Domestic hot water (DHW) demand.

The required energy for domestic hot water (DHW) can be estimated as follows:

$$Q_{DHW} = m \times c \times \Delta T, \quad (3)$$

where:

Q_{DHW} — required energy for heating the water in J or BTU;

m — stands for the mass of the water in kg or lb;

c — specific heat capacity of the water, which is 4.18 kJ/(kg°C) or 1 BTU/(lb°F);

ΔT — temperature rise that is needed to reach the desired water temperature.

4. Total annual energy consumption.

The total annual energy consumption (Q_T) can be expressed as:

$$Q_T = \Sigma\,(Q_{cooling} + Q_{heating} + Q_{lighting} + Q_{DHW}). \quad (4)$$

By aggregating the multiple energy requirements, Eq. (4) presents a holistic view of the building's energy usage over a year.

This collection of equations is essential for evaluating energy performance and uncovering optimization strategies through simulations in a modeling environment.

The annual energy consumption of the office building in different sections is shown in Fig. 2b. According to this figure, cooling, lighting, and heating have the highest share of annual energy consumption in this building. To optimize the annual energy consumption in these sections, a combination of cost-effective passive and active strategies was employed in the developed model of the office building. Table 2 shows these suggested strategies for the developed model.

By utilizing the suggested strategies of Table 2 in the developed model of the office building, the annual energy consumption and the carbon dioxide emissions can be reduced by 50 %. In addition, in Table 3, the amount of annual energy consumption, annual carbon dioxide emissions, and the cost of retrofit actions in the baseline model of the office building are compared with those in the developed model.

The economic analysis in Table 3 and Fig. 3 shows that the amount of saving in annual energy consumption in the developed model compared to the baseline model is 129 124.32 kWh. Considering the global price of energy (0.24 GBP per one kWh), 30 989.83 GBP can be saved in a year and the cost of retrofit actions in the developed model (15 130.6 GBP) can be compensated within 7 months (Fig. 3a). However, taking into account the domestic price of energy in Iran (2,100.5 IRR per kWh), financial savings of 271 225 634 IRR per year can be made, and the retrofit cost in the developed model (1 149 622,988 IRR) can be compensated in 5 years (Fig. 3b). Considering the payback period, it seems that the solutions used to optimize the baseline model are economically justifiable.

Table 2. **Strategies suggested for the developed model**

No.	Strategies
1	Changing the cooling set point from 24 °C to 25 °C
2	Changing the heating set point from 22 °C to 18 °C
3	Changing the natural ventilation set point to 24 °C
4	Adding 7 cm of polyurethane foam to the external walls
5	Changing window frames to UPVC
6	Replacing double pane windows with an air layer with double panes with a 13-mm layer of argon gas
7	Changing the type of external doors from iron to aluminum with a 2 cm air layer
8	Removing internal shading In the southern and northern facades of the building, the depth of the horizontal shading was considered to be 120 and 110 cm, respectively; vertical shading with the same depths was added next to the horizontal ones on both facades.
9	We selected a lighting system based on ASHRAE standards for office buildings and changed its power density from 5 W/m^2-100 Lux to 3.2 W/m^2-100 Lux. The building's lighting system was set to use natural light during the day and artificial light only when needed.

Table 3. **Comparison of the baseline and developed models**

Model name	Annual energy consumption (kWh)	Annual carbon dioxide emissions (ton)	Annual energy cost savings (GBP*/year)	Cost of retrofit actions (GBP*)	Payback period*, considering the global price of energy (GBP*)	Payback period*, considering the domestic price of energy (IRR**)
Baseline model	258 053.59	150.70	–	–	–	–
Developed model	128 929.27	75	30 989.83	15 130.6	7 months	5 years

* British pound (£); ** Iranian rial; 1 £ = 759,800 IRR
* Payback period = (Cost of retrofit actions / Annual energy cost savings)

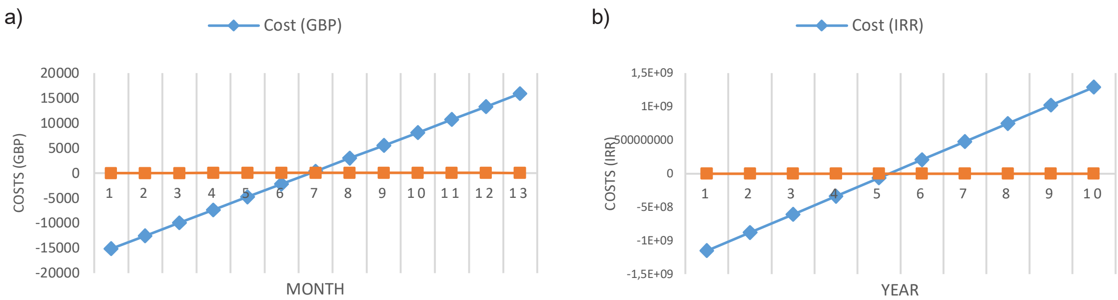

Fig. 3. Payback period diagram of the developed model considering (a) global price of energy and (b) domestic price of energy

As mentioned earlier, in the second part of this study, the objective is not only to retain the 50 % reduction in the annual energy consumption in the proposed model, but reduce the weight of the materials used in the external walls (while preserving their functional quality) to lower the dead loads. This way, the structural performance of the building is strengthened against dynamic loads such as earthquakes and wind, and its useful life is increased. The weight of the materials used in the external walls of all three models and their details are extracted with the help of DesignBuilder software and compared with each other in Section 2–2. Moreover, the amount of dead loads from the external walls and roof are specified for loading in the structural model. Then, by using Revit software, architectural and structural modeling is done for the developed and proposed models, and their structural loading is determined. Furthermore, we used Robot Structural Analysis to calculate dead loads from external walls and ceilings by directly sending Revit structural models to the software. Robot Structural Analysis was the primary tool for the relevant calculations. In the end, the effects of reducing the weight of external walls in the structural models are compared with each other.

Architectural Modeling

Introduction of the baseline model

The baseline model of the case study office building (Figs. 4 and 5) has five floors, including a basement, a pilot space, parking, and three floors of administrative spaces. The architectural modeling of the case study is done in Revit Architecture software.

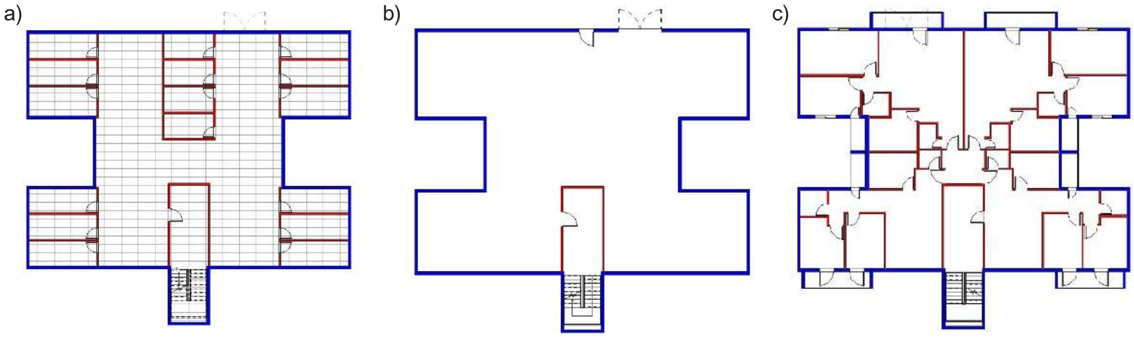

Fig. 4. (a) Basement, (b) parking, (c) administrative spaces of the baseline model

Fig. 5. Baseline model in Revit Architecture

Table 4 shows a summary of the weight of the materials used in the external walls and roof of this model.

The baseline model's external walls, ceilings, and roof weigh about 2 320 204.8 kg, with external walls at 1 334 432.5 kg and ceilings and roof at 985 772.3 kg. Fig. 6 presents the details on the external walls of the baseline model.

Introduction of the developed model

The architectural spaces in the developed model are not different from the baseline model and the floor plans are the same. Its architectural modeling is done in Revit Architecture software as well. The developed model's external walls differ from the baseline, with an added 7 cm layer of polyurethane insulation. Table 5 also shows a summary of the weight of the materials used in the external walls and the roof of this model.

The developed model's total weight for external walls, ceilings, and roof is about 2 321 218 kg, with external walls weighing 1 335 445.7 kg and ceilings and roof weighing 985 772.3 kg. Fig. 7 presents the details on the external walls of the developed model.

Introduction of the proposed model

The architectural spaces and floor plans in the proposed model are identical to the baseline. The architectural 3D modeling was done in Revit software. The proposed model uses the same energy optimization solutions as the developed model, but the external wall materials differ from those both in the baseline and developed models. We added a light polystyrene thermal insulation roll layer with a 7 cm thick wooden support frame and a 2 cm air layer. In addition, we replaced the 20 cm thick bricks and 0.5 cm gypsum plastering of the external walls with 20 cm thick light concrete blocks and 1 cm light plaster sheets. Table 6 shows a summary of the

Table 4. **Summary of the weight of the materials used in the external walls and roof of the baseline model**

Baseline model	
	Mass (kg)
External walls	1 334 432.5
Ceilings and roof	985 772.3
Total	2 320 204.8

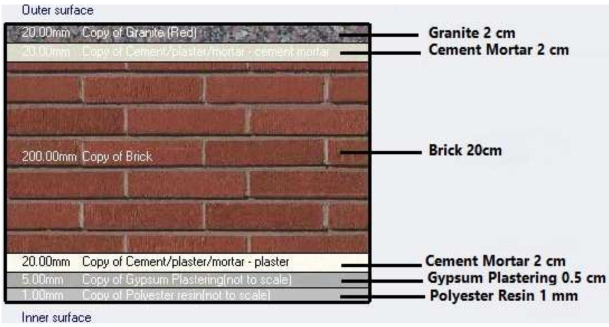

Fig. 6. Details on the external walls of the baseline model

Table 5. **Summary of the weight of the materials used in the external walls and the roof of the developed model**

Developed model	
	Mass (kg)
External walls	1 335 445.7
Ceilings and roof	985 772.3
Total	2 321 218

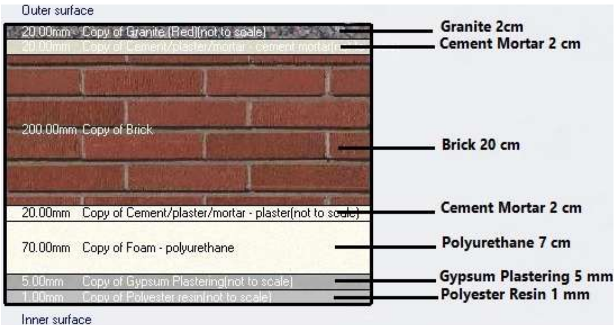

Fig. 7. Details on the external walls of the developed model

Table 6. **Summary of the weight of the materials used in the external walls and roof of the proposed model**

Proposed model	
	Mass (kg)
External walls	961 339.1
Ceilings and roof	985 774
Total	1 947 113.1

weight of the materials used in the external walls and the roof of this model.

The proposed model's external walls, ceilings, and roof weigh about 1 947 113.1 kg, with 961 339.1 kg for the walls and 985 774 kg for the ceilings and roof. Fig. 8 presents the details on the external walls of the proposed model.

Structure Modeling

The type of structural system used in the case study building is a bending frame; the structure is made of reinforced concrete. The structural system of all three models considered in this study is the same. Fig. 9 shows the foundation and structure plan of all three models and specifies the exact location of columns, beams, and reinforced concrete slabs of the ceilings. The dimensions of the columns and beams are 60 x 60 cm; the concrete slabs of the ceilings are 30 cm thick. The individual footing foundations measure 2 x 2 meters with a height of 1 meter.

All three models in this study were simulated using DesignBuilder, which also provided the weight

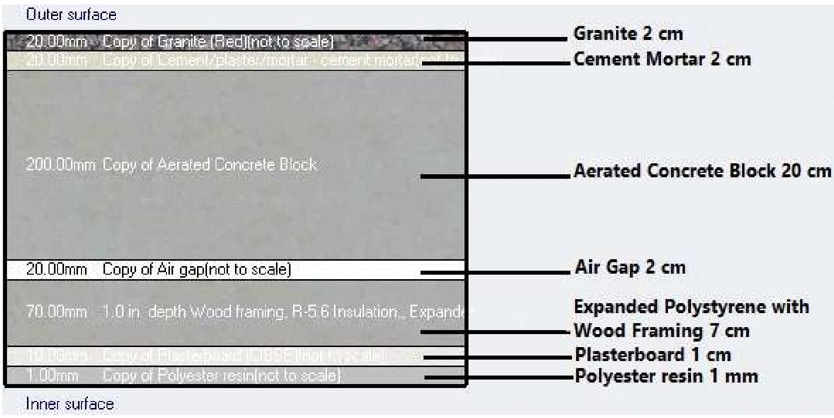

Fig. 8. Details on the external walls of the proposed model

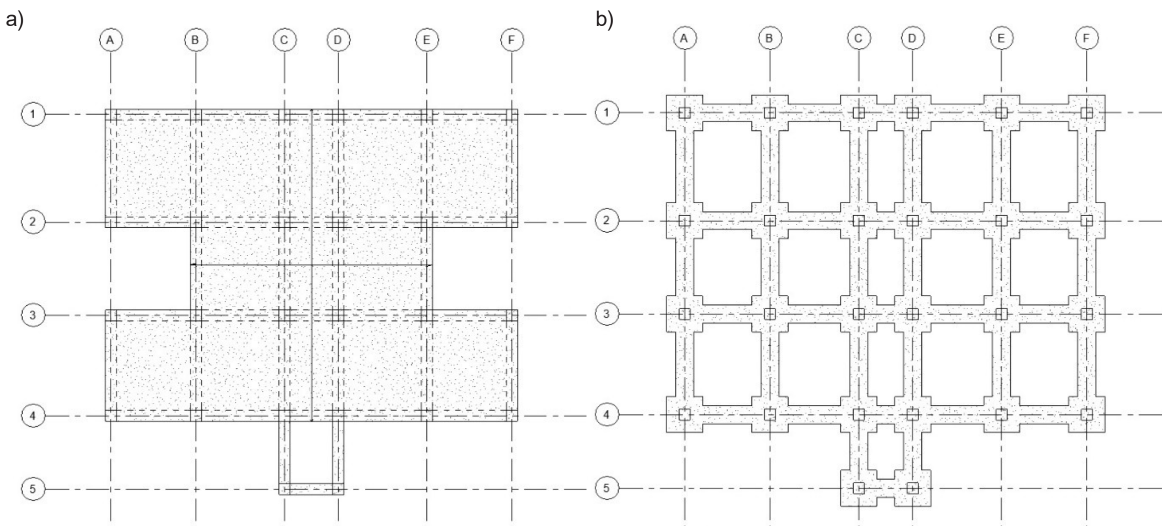

Fig. 9. (a) Reinforced concrete slabs of the ceilings, (b) foundation of the three models in Revit Structure software

of materials for the external walls and ceilings. After modeling the structure in Revit Structure software, it is necessary to apply structural loading based on the weight of the external walls and ceilings that were previously imported. For this purpose, the amount of dead loads caused by the external walls and ceilings should be specified for loading in the models.

Table 7 shows the amount of dead load caused by the weight of external walls and ceilings for loading in structural models. The table shows that ceiling loading is extensive (hosted area load) and consistent across all three models because they use the same materials. However, the proposed model's external wall loading is linear (hosted line load) and differs from the other two models due to different materials. After loading the structure into Revit Structure to perform the calculations of the forces on the supports and the torques (moments) on the structure, the built model was transferred to the Robot Structural Analysis. Figs. 10a and 10b show the image of one of the models loaded in Revit Structure and Robot Structural Analysis, respectively.

The subsequent primary equations (5–16) can be employed to assess the forces and moments at the base of a building structure, specifically where the columns attach to the foundation, along with the reactions at the various supports:

1. Calculating forces at the base

The total forces acting at the base can be expressed as:

$$Fx = \sum_{i=1}^{n} Fxi; \tag{5}$$

$$Fy = \sum_{i=1}^{n} Fyi; \tag{6}$$

$$P = \sum_{i=1}^{n} Pi, \tag{7}$$

where:

F_x and F_y are the horizontal forces (e.g., seismic loads, wind loads) acting along the x and y axes in kN;

P is the total vertical load (e.g., dead load, live load) in kN;

F_{xi} and F_{yi} are the horizontal forces on the ith floor in the x and y directions in kN;

P_i is the vertical force acting on the ith floor in kN.

2. Calculating torques (moments) at the base

The torques (moments) on the x, y, and z axes can be estimated as follows:

$$Mx = \sum_{i=1}^{n} (Fyi \ . \ hi); \tag{8}$$

$$My = \sum_{i=1}^{n} (Fxi \ . \ hi); \tag{9}$$

$$Mz = \sum_{i=1}^{n} \left[(dx \ . \ Fy) - (dy \ . \ Fx) \right], \tag{10}$$

where:

M_x, M_y, and M_z are the torques (moments) on the x, y, and z axes in kNm;

Table 7. **Amount of dead load of external walls and ceilings for loading in the models**

	Baseline model	Developed model	Proposed model
Each floor area	356.5 m^2	356.5 m^2	356.5 m^2
Each floor perimeter	99.8 m	99.8 m	99.8 m
Hosted line load on each floor	33.4 kN/m	33.4 kN/m	24 kN/m
Hosted line load in roof	11.1 kN/m	11.1 kN/m	8 kN/m
Hosted area load on each floor	5.5 kN/m^2	5.5 kN/m^2	5.5 kN/m^2
Hosted area load in dome roof	0.7 kN/m^2	0.7 kN/m^2	0.7 kN/m^2

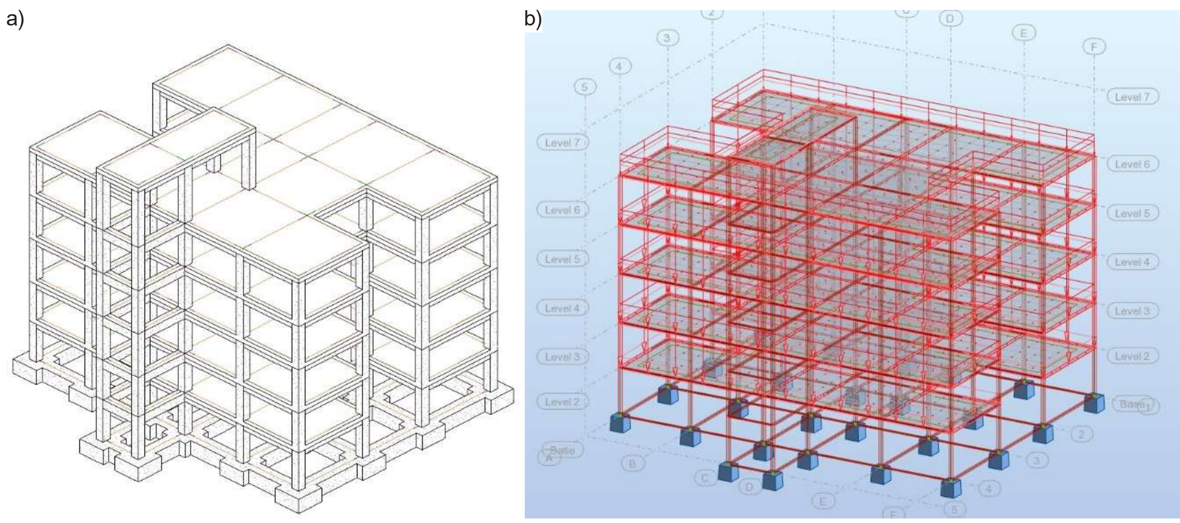

Fig. 10. (a) Baseline model in Revit Structure, and (b) in Robot Structural Analysis

h_i is the height from the base to the ith floor in m;

d_x and d_y represent the distances from the center of the building to where the forces F_x and F_y act, highlighting the eccentricities for rotational moments in the horizontal plane.

3. Calculating total reaction at supports

To maintain static equilibrium in the building, the reactions at the supports need to offset the overall vertical load, horizontal forces, and torques (moments) acting on it. The following conditions must be met for equilibrium:

$$\sum Rx = Fx; \tag{11}$$

$$\sum Ry = Fy; \tag{12}$$

$$\sum Rz = P, \tag{13}$$

where: R_x, R_y, and R_z are the reactions at supports along the x, y, and z axes in kN.

For the torques (moments):

$$\sum Msx = Mx; \tag{14}$$

$$\sum Msy = My; \tag{15}$$

$$\sum Msz = Mz, \tag{16}$$

where: M_{sx}, M_{sy}, and M_{sz} are the torques (moments) at supports in kNm.

These equations provide a fundamental structure for determining the forces and torques at a building's foundation, ensuring that the supports can adequately resist and maintain balance.

Results and Discussion

The findings outlined in this part are solely based on the computational models created to evaluate energy efficiency and structural integrity within the simulated setting. The baseline, developed and proposed models were all intentionally designed to achieve specific aims within this study: recognizing energy inefficiencies, adopting optimization strategies, and enhancing the performance of the structure. With these models, we were able to recreate a variety of scenarios linked to energy usage for cooling, heating, lighting, domestic hot water, and cooking, in addition to analyzing structural changes via modifications in materials.

The baseline model served as a point of reference, indicating the current inefficiencies in energy consumption within the actual facility. Building on this basis, the developed model incorporated both passive and active approaches designed to improve energy efficiency. The proposed model put forward expanded upon these upgrades by incorporating lightweight materials in the external wall, aiming for better structural performance while still upholding the energy efficiency characteristics of the developed model.

The structure of the studied models includes 26 columns, the location of each can be seen in Fig. 9b. In this study, the estimated amount of forces and torques on the lowest part of the structure (where the columns are connected to the foundation) and the total reaction of the supports against the total of these forces and torques were calculated using Robot Structural Analysis. Table 8 and Figs. 11a and 11b show the estimated amount of forces and torques on the lowest part of the structure for all 26 columns in the baseline and developed models and the total reaction of the supports. As indicated in

Table 8. **Estimated amount of forces and torques on the lowest part of the structure for all 26 columns in the baseline and developed models**

Node/Case	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)
1/ 1	21.81	29.96	1696.94	31.52	-22.13	-0.02
2/ 1	0.95	27.86	2321.64	33.63	-2.69	0.01
3/ 1	-11.34	21.72	2077.12	6.62	19.09	-0.02
4/ 1	11.12	21.79	2081.25	6.55	-19.46	0.01
5/ 1	0.40	6.77	578.38	25.76	-17.49	-0.02
6/ 1	-0.70	6.75	582.69	25.79	16.81	-0.02
7/ 1	-1.25	28.36	2342.74	33.15	2.25	-0.01
8/ 1	-21.04	30.24	1787.90	31.25	22.78	0.03
9/ 1	23.19	-29.06	1741.41	20.84	-20.80	0.04
10/ 1	23.44	33.27	1800.77	-15.49	-20.52	-0.05
11/ 1	21.84	-35.21	1696.39	-34.84	-22.16	0.07
12/ 1	0.42	-33.14	2253.31	-37.05	-3.25	0.01
13/ 1	-12.18	-26.87	1896.53	-43.39	18.28	0.02
14/ 1	11.94	-26.95	1899.58	-43.29	-18.55	-0.04
15/ 1	-0.91	-33.65	2265.13	-36.46	2.73	-0.02
16/ 1	-21.37	-35.61	1703.60	-34.30	22.61	-0.09
17/ 1	-23.35	33.01	1885.56	-15.08	20.49	0.02
18/ 1	-22.88	-28.69	1910.87	20.50	20.98	-0.04
19/ 1	-1.20	-6.19	2881.03	-2.20	2.39	-0.02
20/ 1	1.09	9.33	2794.10	8.58	-2.59	-0.01
21/ 1	-12.34	6.71	2257.45	11.17	18.10	-0.00
22/ 1	12.44	6.72	2275.29	11.17	-18.10	-0.01
23/ 1	-1.33	8.92	2927.39	9.05	2.24	-0.01
24/ 1	11.92	-4.81	2293.94	-3.62	-18.63	-0.01
25/ 1	1.24	-6.38	2738.33	-2.04	-2.47	0.02
26/ 1	-11.93	-4.87	2273.85	-3.57	18.50	-0.00
Case 1	DL1					
Sum of val.	0.00	0.00	52963.20	4.27	-1.60	-0.14
Sum of reac.	0.00	0.00	52963.20	420107.21	-599203.09	0.00
Sum of forc.	0.0	0.0	-52963.20	-420107.21	599203.09	0.0
Check val.	0.00	0.00	0.00	-0.00	-0.00	0.00
Precision	1.62037e-07	1.51360e-17				

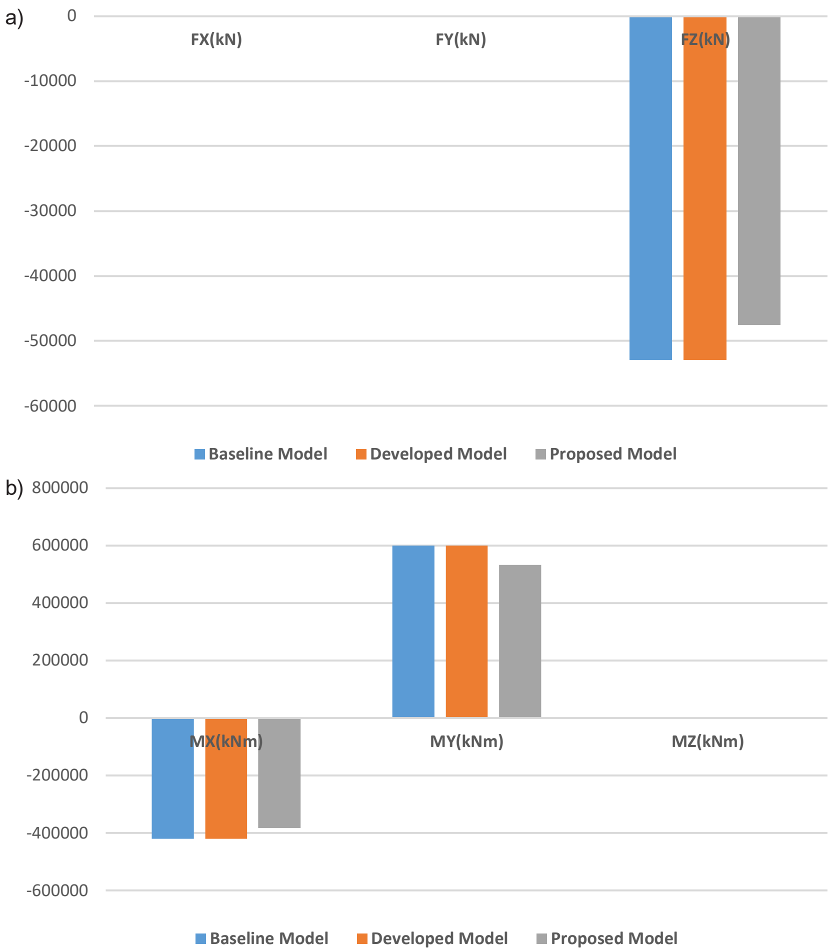

Fig. 11. Total (a) forces and (b) torques in the three models

the table and Fig. 11a, the horizontal forces (X and Y axes) from dead loads in both models are zero at the structure's base in the baseline and developed models. However, the vertical force (Z axis) is –52 963.20 kN (sum of point loads on the lowest part of all 26 structural columns), requiring a support reaction of 52 963.20 kN to maintain stability. In addition, Table 8 and Fig. 11b show that the sum of the torques on the lowest part of the structure in the vertical direction is zero. But in the horizontal direction, we can see significant values in the direction of the X and Y axes, so that in the direction of the X axis, the sum of the torques is estimated at –420 107.21 kNm. To keep the structure stable, the supports need a reaction of 420 107.21 kNm. Along the Y axis, the total torques are 599 203.09 kNm, requiring a support reaction of –599 203.09 kNm for stability.

Table 9 and Figs. 11a and 11b also show the estimated amount of forces and torques on the lowest part of the structure for all 26 columns in the proposed model and the total reaction of the supports. The table and figure indicate that the sum of forces from dead loads in the proposed model in the lowest part of the structure is zero in the horizontal (X and Y) directions. However, in the vertical (Z) direction, the sum is –47 572.84 kN (the sum of the point loads on the lowest part of all 26 structural columns), which requires a support reaction of 47 572.84 kN to maintain stability. The table and figure show that the sum of torques on the structure's lowest part is zero vertically, but significant in the X and Y horizontal directions. The X-axis torques total –382 413.01 kNm, requiring a 382 413.01 kNm reaction for stability. The Y-axis torques total 532 815.80 kNm, needing a –532 815.80 kNm reaction for stability.

The comparison of the three models in this study (from Tables 4, 5, and 6) shows that the weight of the materials used in the external walls and ceilings of the proposed model is 16 % less than in the other two models. This resulted in reduced dead loads in this model, and the total forces in the Z axis and the total torques in the X and Y axis on the lowest part of the structure in this model are 10 %, 9 %, and 11 % less than in the other two models, respectively. Table 10 shows that the proposed model saves 129 352.92 kWh annually compared to the baseline. With energy priced at 0.24 GBP per kWh, this results in a yearly saving of 31,044.70 GBP. The retrofit cost

Table 9. **Estimated amount of forces and torques on the lowest part of the structure for all 26 columns in the proposed model**

Node/Case	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)
1/ 1	19.22	26.53	1413.54	34.99	-24.67	-0.02
2/ 1	1.28	28.12	1984.50	33.42	-2.26	0.01
3/ 1	-9.69	21.59	1840.45	6.81	20.86	-0.01
4/ 1	9.60	21.61	1840.56	6.79	-20.87	0.01
5/ 1	0.65	5.76	543.95	26.89	-17.00	-0.00
6/ 1	-0.57	5.76	543.26	26.89	17.17	-0.00
7/ 1	-1.60	28.21	1984.89	33.34	2.03	-0.01
8/ 1	-18.69	26.59	1412.69	34.95	25.30	0.02
9/ 1	20.60	-25.09	1530.09	16.84	-23.28	0.02
10/ 1	20.97	29.02	1585.27	-11.11	-22.89	-0.02
11/ 1	19.55	-30.98	1486.78	-39.03	-24.40	0.06
12/ 1	0.82	-32.89	2053.77	-37.23	-2.77	0.01
13/ 1	-10.63	-27.33	1745.73	-42.87	19.92	0.02
14/ 1	10.50	-27.34	1746.11	-42.86	-19.92	-0.03
15/ 1	-1.13	-33.01	2056.53	-37.10	2.59	-0.02
16/ 1	-19.04	-31.03	1486.11	-38.95	25.05	-0.07
17/ 1	-20.58	29.05	1584.09	-11.12	23.40	0.02
18/ 1	-20.31	-25.11	1529.12	16.89	23.68	-0.02
19/ 1	-4.29	-8.09	2531.11	-0.27	-0.62	-0.01
20/ 1	4.04	11.16	2599.69	6.79	0.48	0.00
21/ 1	-11.86	6.50	2235.84	11.43	18.69	-0.00
22/ 1	11.64	6.57	2235.43	11.37	-18.80	-0.00
23/ 1	-4.28	11.14	2600.92	6.83	-0.61	-0.00
24/ 1	11.11	-4.38	2237.67	-4.00	-19.34	-0.00
25/ 1	4.09	-7.95	2529.29	-0.42	0.52	0.01
26/ 1	-11.41	-4.39	2235.45	-3.99	19.13	0.00
Case 1	DL1					
Sum of val.	0.00	0.00	47572.84	5.28	1.40	-0.03
Sum of reac.	0.00	0.00	47572.84	382413.01	-532815.80	0.00
Sum of forc.	0.0	0.0	-47572.84	-382413.01	532815.80	0.0
Check val.	0.00	0.00	0.00	-0.00	-0.00	0.00
Precision	1.12652e-07	3.46992e-19				

of 7 064.46 GBP can be recouped in three years, making it justifiable (Fig. 12a). Considering the domestic energy price in Iran (2,100.5 IRR per kWh), annual financial savings of 271 705 808.46 IRR can be achieved, allowing the retrofit cost in the proposed model (5 367 338 131 IRR) to be recouped in 21 years (Fig. 12b). Considering the payback period, it seems that the cost of retrofit actions in the proposed model is economically justified with respect to the global price of energy, however, the payback period can be prolonged, as long as the energy price in Iran is far from the global reality and is accompanied by government subsidies.

The results of this study for optimizing the structural performance of office buildings are new. The annual energy consumption of the proposed office building model in this study (75 kWh/m^2 per year) is 25 % less than the annual energy consumption of typical office buildings, which ranges between 100 and 1 000 kWh/m^2 per year. This is consistent with the Iranian national standard for non-residential buildings (National Standard Organization of Iran, 2011). However, the results are similar to those in the work of Alvand et al. (2017) in terms of energy consumption optimization and are better than those in the works of Ghiai and Hajjar (2014), Javid et al. (2019), Khodakarami and Ghobadi (2023), and Tahsildoost and Zomorodian (2015).

Conclusions

In this research, we aimed to reduce the annual consumption of energy resources in an office building in Tehran by implementing cost-effective solutions.

Table 10. **Comparison of the baseline, developed and proposed models**

Model name	Annual energy consumption (kWh)	Annual CO_2 emissions (ton)	Annual energy cost savings (GBP/year)	Cost of retrofit actions (GBP)	Payback period considering the global price of energy	Payback period considering the domestic price of energy
Baseline model	258 053.59	150.70	–	–	–	–
Developed model	128 929.27	75	30 989.83	15 130.6	7 months	5 years
Proposed model	128 700.67	74.86	31 044.70	70 641.46	3 years	21 years

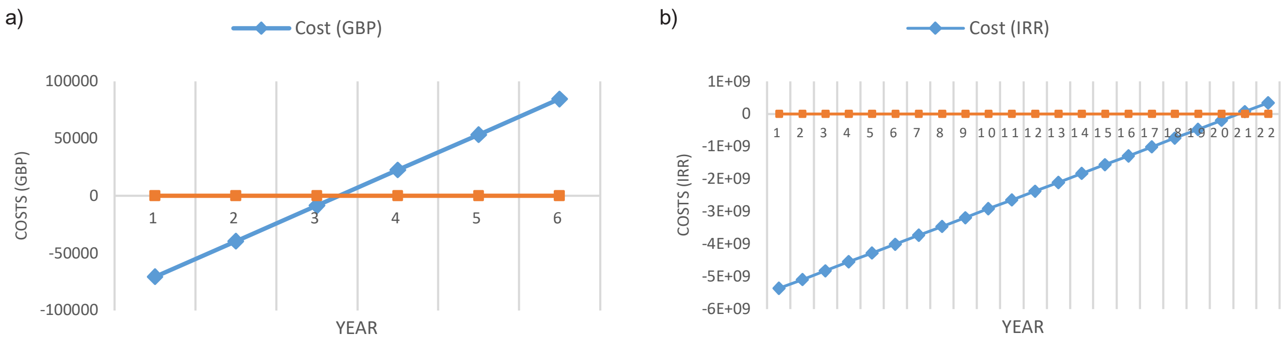

Fig. 12. Payback period diagram of the proposed model considering (a) global price of energy and (b) domestic price of energy

We also sought to decrease the dead loads resulting from the materials used in the external walls and ceilings. The results on reducing annual energy consumption align with previous research, but the materials in this model are cheaper, lighter, and have better thermal properties than those in the other two models. This not only reduces the building's weight, improves stability against wind and earthquakes, extends its lifespan, but also lowers strengthening costs. The study demonstrates that the proposed office building model reduces material weight in external walls and ceilings by up to 16 %, enhancing durability and stability, while also cutting annual energy consumption by 50 % and minimizing environmental impact. The strategies used in the proposed model of this research, including the solutions for optimizing energy consumption and reducing the dead loads of the building, can simultaneously improve the structural performance and increase the useful life of office buildings in megacities like Tehran while reducing their adverse environmental effects.

Although the outcomes of the simulation provide valuable perspectives on potential improvements in energy efficiency and structural strength, it is important to recognize that these findings are based on theoretical premises established within a controlled simulation environment. In order to verify that the suggested solutions are practical and functional in real-world scenarios, it is essential to conduct experimental tests that demonstrate the alignment of anticipated results with the building's actual performance. Upcoming research will focus on validating these simulated findings through experiments to assess their relevance in practical settings.

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ОПТИМИЗАЦИЯ ЭНЕРГОПОТРЕБЛЕНИЯ И ЭКСПЛУАТАЦИОННЫХ ХАРАКТЕРИСТИК ОФИСНЫХ ЗДАНИЙ В ГОРОДЕ ТЕГЕРАН С ИСПОЛЬЗОВАНИЕМ ЭКОНОМИЧЕСКИ ЭФФЕКТИВНЫХ РЕШЕНИЙ: АНАЛИЗ НА ОСНОВЕ МОДЕЛИРОВАНИЯ И СИМУЛЯЦИИ

Амин Мохаммади[1]*, Шарие Хоссейнинасаб[2], Сейед Мохаммад Мусави[1]

[1]Университет Персидского залива (PGU), 75169, Бушер, Иран
[2]Университет COMSATS в Исламабаде (CUI), кампус в Лахоре, Лахор, Пакистан

***E-mail: aminmohammadi@pgu.ac.ir**

Аннотация
Введение: офисные здания в крупных городах ежегодно потребляют огромные объемы энергии, также генерируя значительные выбросы углекислого газа. Кроме того, проектирование, строительство и обслуживание этих зданий требует больших затрат. На этапе проектирования необходимо уделять особое внимание их долговечности, устойчивости и сроку службы. **Цель исследования:** оптимизация энергопотребления и эксплуатационных характеристик офисных зданий в мегаполисах при помощи экономически эффективных решений. **Методы:** в качестве примера мы выбрали офисное здание в Тегеране (столице Ирана), а затем смоделировали его в DesignBuilder, Revit и Robot Structural Analysis как базовую модель. Для достижения основной цели в разработанной и предложенной моделях здания был использован ряд экономически эффективных решений. **Результаты:** результаты моделирования показали, что с экономическими решениями, использованными в предложенной модели офисного здания, можно не только сократить годовое потребление энергии и выбросы углекислого газа на 50 %, но и уменьшить вес материалов во внешних стенах и потолках до 16 %. Предложенные методы позволяют значительно сэкономить на стоимости усиления конструкции, а также увеличить срок службы строительной конструкции, ее долговечность и устойчивость. Результаты этого исследования могут быть использованы на этапе проектирования офисных зданий в таких мегаполисах, как Тегеран.

Ключевые слова: офисные здания; оптимизация энергопотребления; эксплуатационные характеристики; моделирование; симуляция.