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Techno-economic evaluation of building envelope solutions in hot arid climate: A case study of educational building

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Abstract

Building energy use is becoming increasingly important worldwide, with the increasing necessity to attain indoor thermal conditions. The high temperatures in hot climates cause human dissatisfaction resulting in higher use of air conditioning systems. As a result, energy in those buildings rises regularly driven by the increase in the air conditioning systems operation. In the non-residential building sector, the air conditioning system consumes the majority of the building's energy to satisfy the thermal comfort requirements. With this aim, simulations have nowadays become an important tool to fulfill various high-performance buildings. Dynamic simulations have often been used by designers to evaluate buildings' energy performance to accomplish specific goals, as minimizing energy usage and environmental impacts. This study analyzes the energy savings obtained by the execution of retrofitting measures in an educational building located in Egypt through dynamic simulations of the building performance. The main objective is the creation of a decision matrix to select an optimal solution for the building envelope based on the effectiveness of thermal insulation, cost, and environmental factors. Based on the precise physical characteristics of the building's vacancy schedule, geographical location, weather conditions, and the nature of construction, overall energy consumption would be determined. A sensitivity analysis is undertaken to assess the key factors that influence building energy consumption through the validated baseline model. The envelope is chosen as it is vital for the building's energy efficiency and could account for up to 50% of the total heat gain in a building. Thermal insulation is one of the most effective implementations to provide desirable thermal comfort and minimize heat transfer into buildings, resulting in an energy consumption reduction. Two insulation materials are assessed through the building simulation model, the cost of each measure is estimated, and the emissions mitigation produced is obtained. With this information, a decision matrix is created that allows highlighting the best option based on the effectiveness of the measure in Egyptian hot arid climates. Among different insulations surveyed in Egypt, the study highlighted the effectiveness of using Extruded polystyrene insulation (XPS) with a thickness of 25 mm, resulting in reductions of about 16% in Heating, Ventilation, and Air-Conditioning (HVAC) energy consumption and 8% of the overall energy consumption with a payback period of about 25 months and a 29% Return on investment (ROI).

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Nomenclature and Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTO	Building Technologies Office
CO_2	Carbon Dioxide
DBT	Dry Bulb Temperature
DOE	US Department of Energy
EPS	Expanded Polystyrene
GW	Gigawatts
HVAC	Heating, Ventilation and Air Conditioning
kWh	Kilowatt-hours
LPD	Lighting Power Density
PU	Polyurethane
RMSE	Root Mean Square Error
SHGC	Solar Heat Gain Coefficient
U	Overall Heat Transfer Coefficient
WBT	Wet Bulb Temperature
WWR	Window-Wall Ratio
XPS	Extruded Polystyrene

1. Introduction

The electrical installed capacity in Egypt, as of 2018/2019, was 58.353 GW, higher than the expected installed capacity in 2017/2018 of 55.213 GW with an increase of about 6%, according to the latest Egyptian official report [1]. The building sector is typically identified as one of the world's largest energy consumers and accounts for almost two-thirds of world energy demand [2]. In Egypt, the built environment utilizes around 70% of the total energy sold [3]. As buildings massively increase, more energy supply to satisfy new demand would need to increase too. Considering that, a significant proportion of a nation's energy demand is related to the built environment, sustainability action should be taken to minimize energy usage whilst ensuring that human comfort, environmental standards are fulfilled. Global climate change has also had measurable environmental consequences. Scientists have strong expectations that global temperatures will continue to rise over the coming decades, primarily due to greenhouse gasses based on human activities. Scientist claims that by 2050, about 80% of global greenhouse gas emissions are expected to be produced by urban areas [2]. Taking into account the trends produced by climate change, buildings built under outdated designs may not function efficiently. Designers will have to adapt to these changes and propose redesigning spaces, construction techniques, materials used, and efficient retrofit measures in existing buildings. Energy efficiency achievement is one of the most significant aspects, concerning this expectation, several international organizations have stepped up their efforts to promote the implementation of energy-efficient initiatives for building. Green buildings are one of the most common strategies in the last few years around the world. This approach is meant to design highly sustainable buildings, with energy conservation as a high priority. As a consequence, the shift of the built environment towards decarbonization has reached a new era with the extension of the focus on building science and simulations. Due to numerous factors influencing a building's energy usage, such as building envelope, physical characteristics, installed heating–cooling equipment, meteorological conditions, and the behavior of building occupants, estimating building energy performance remains a tough challenge. Large-sized air conditioning systems are required in hot zones however with climate and temperature changes. In developing countries located in hot climatic zones, about 50% of the entire building energy is used for space air conditioning [4–7]. The retrofitting of existing buildings or the introduction of energy-efficient techniques in new designs provides major opportunities to mitigate global energy-related greenhouse emissions. For the large-scale implementation of retrofit strategies, prior knowledge of existing buildings' energy performance is often necessary. A major technical concern, nevertheless, is the strategies for determining the most cost-effective energy reductions for individuals or combinations of retrofit measures for a particular building. Numerous studies have dealt with the application of passive design variables in order to reduce building energy costs under various climatic conditions. In their work, Pargana et al. [8] concentrated on the most popular thermal insulation materials available on the Portuguese market, including XPS, EPS, PU. They concluded that in Portuguese climates, insulation materials have proven to be a successful technique to minimize energy usage and therefore help to achieve sustainable buildings. Ozel [9] in this article examined the efficacy of thermal insulation, with a lifespan of 20 years, used to limit buildings' heat losses and gains under dynamic thermal conditions, using the Turkish climatological data. In steady periodic conditions, the dynamic thermal properties of the building's insulated walls were analyzed using Riyadh climate data with optimized insulation thickness by Al-Sanea and Zedan [10]. Thermal insulation was tested in Greece by Anastaselos et al. [11]. Their research concluded that there was a total energy reduction of around 17%. Finally, they proposed that the implementation of composite systems of external thermal insulation be favored in terms of energy, environmental and economic parameters. Al-Homoud [12] argues in his article that properly treated building envelopes, especially for envelope-load driven residences, can significantly improve thermal performance. Besides, he advocated the use of wall and roof insulation to reduce energy requirements for buildings in all climates. Saleh [13] measured the thermal performance of buildings, in hot-dry climates, with varying configurations, types, and thicknesses of thermal insulation. The improved performance was found when insulation was installed on the exterior surface of the building envelope. The effect of insulation/masonry layer distribution was studied by Bojic and Loveday [14]. It was concluded that: for intermittent heating, insulation/masonry/insulation structure is better, whereas, for intermittent cooling, masonry/insulation/masonry structure is better.

To the best of researchers' knowledge, energy-saving initiatives in hot-arid climatological areas are worthwhile, concurrently, there is a benchmarking gap for thermal insulation importance and selection in Egyptian markets. In this paper, the researchers aim, with the aid of a techno-economic assessment considering the latest available prices on the market, to investigate the effectiveness and the revenue of different building envelope solutions for buildings' owners through a case study of an educational facility accessible to the researchers at Cairo, Egypt.

2. Methodology

An institutional building in Cairo, Egypt, is selected for the examination based on the accessibility of data. The approach used in this study uses DesignBuilder as a building performance simulator to forecast building energy performance. DesignBuilder is considered as it offers a user-friendly interface for the EnergyPlus developed by the DOE's BTO. The methodology, illustrated in Fig. 1, starts with the baseline architectural modeling followed by the implementation of the latest recommended ASHRAE outdoor design conditions [15], the ventilation and internal gains recommended by both ASHRAE 2016 Standards 62.1 and 90.1. The baseline model is validated compared to the building's actual energy consumption measured on-site. The study follows a techno-economic assessment with an environmental impact (CO_2) assessment for a reliable decision.

3. Building description

An educational building located in Cairo; Egypt, hot arid climate [16], has been selected as a case study during this investigation. According to ASHRAE [15], Cairo, Egypt is classified as a Hot-Arid climate (Zone 2B) with a DBT and WBT of 38.2 °C and 21.2 °C. As shown in Fig. 2, the facility comprises six stories representing approximately 11,350 m^2 and usually operates from 08:00 to 16:00 5 days a week. As most institutional buildings worldwide, the building operates with approximately half capacity in August due to annual leaves.

3.1. Building envelope

The baseline model of the building was developed according to Egyptian development and construction industry records. The U-values (W/m^2 K) of the baseline model walls and roof are 1.924 and 2.27 respectively [7]. The on-site, 6 mm Double Blue Glass/6 mm air gap, glazing U-value and SHGC specifications are 3.094 and 0.503 respectively with a WWR of about 30%.

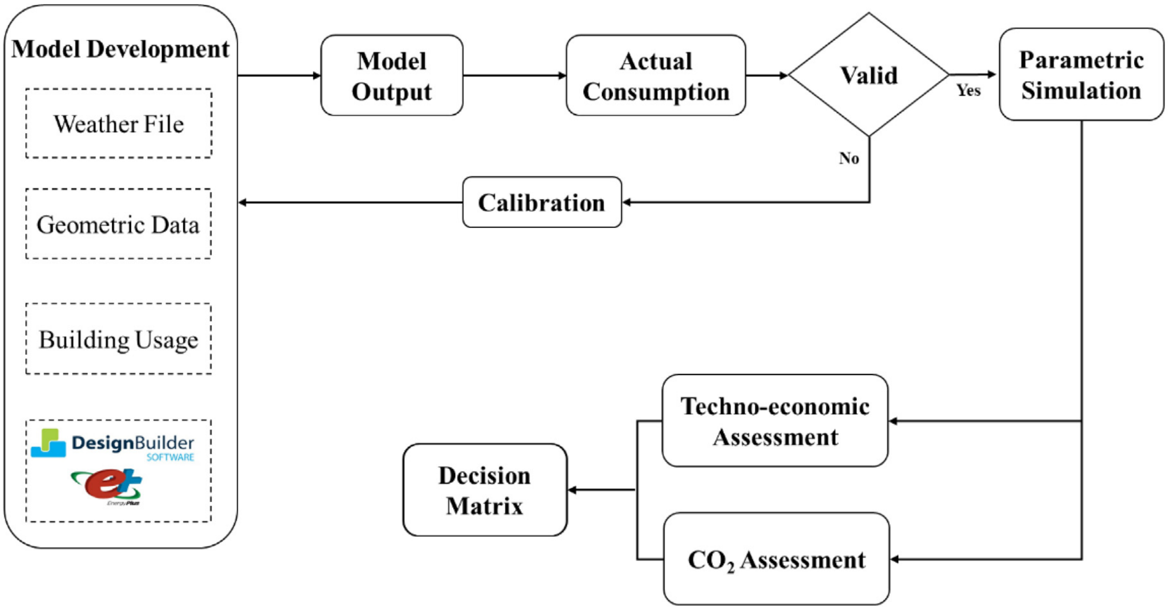

Fig. 1. Modeling flowchart.

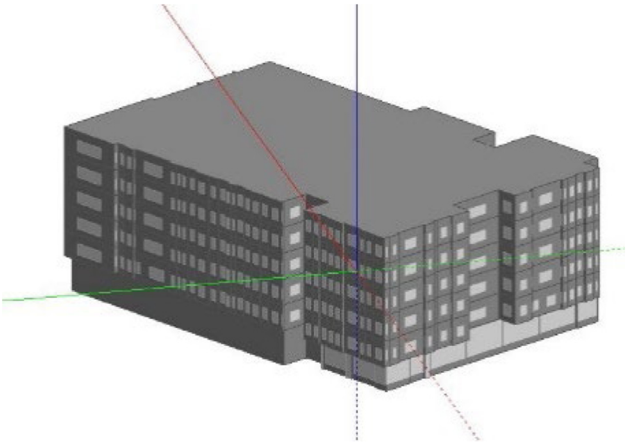

Fig. 2. Baseline model axonometric.

3.2. Internal gains

Internal gains are essentially the inner loads produced indoors, including the occupancy, ventilation rates, lighting, and appliances. Table 1 summarizes ventilation rates, occupant densities [17] along with the recommended LPD using the space-by-space method [18].

3.3. Model validation

There are numerous strategies for validating building energy simulations. These strategies are broadly classified into three categories: analytical, laboratory, and actual techniques, with the third being the highly precise (comparing simulation results to actual data) [19]. The actual validation entails linking data from building measurements with simulation data. In this study, the baseline model is validated compared to the building's actual energy consumption as shown in Figs. 3a and 3b. Error analysis is a vital part of any scientific experiment; therefore, it is crucial to

Table 1. Recommended ventilation rates, occupant densities, and LPD of Institutional buildings.

Zone	Ventilation rate (L/s-person)	Ventilation rate (L/s-m^2)	Occupant density (#/100 m^2)	LPD (W/m^2)
Classroom	3.8	0.3	65	13.4
Coffee Stations	2.5	0.3	20	7
Computer lab	5	0.6	25	18.4
Conference/Meeting	2.5	0.3	50	13.3
Corridors	–	0.3	–	9.9
Laboratories	5	0.9	25	15.5
Lecture hall	3.8	0.3	150	13.4
Libraries	2.5	0.6	10	11.5
Lounge	2.5	0.6	50	7.9
Main entry lobbies	2.5	0.3	10	9.7
Office Spaces	2.5	0.3	5	12
Reception Areas	2.5	0.3	30	5.9
Restaurants	3.8	0.9	70	11.6

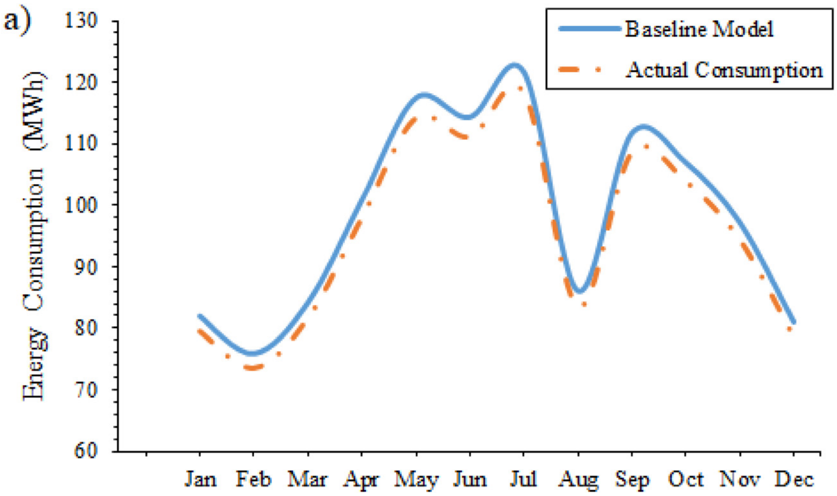

Fig. 3a. Model monthly validation.

estimate the error for any measures. The RMSE for the model is estimated resulting in an acceptable value of 0.2448.

The energy use assessment of the baseline model is carried out by measuring each component's contribution to overall energy usage. Fig. 4 illustrates the monthly energy consumption of each component.

Following the baseline model validation, a sensitivity analysis was carried out showing about 50% of building heat gain is related to the building envelope. About 40% of this heat gain is related to walls and roof. The building's energy breakdown revealed the HVAC contribution to the whole building energy consumption of about 45% which aligns with the HVAC energy consumption in similar climates of [5–7,20,21]

3.4. Thermal insulation

A building's HVAC system aims to maintain a comfortable indoor environment for its occupants. Reducing thermal losses allows for the use of a smaller, more efficient, and less expensive HVAC system significantly reducing HVAC energy consumption. As a result, the energy demand for cooling and heating buildings is reduced, and GHG emissions are reduced. As a consequence, building insulation is a simple but energy-efficient procedure that could be used in the residential and commercial buildings sectors. Thermal insulators consist of materials that have the ability to minimize the heat flow rate due to their high thermal resistance characteristic. The use of thermal insulation

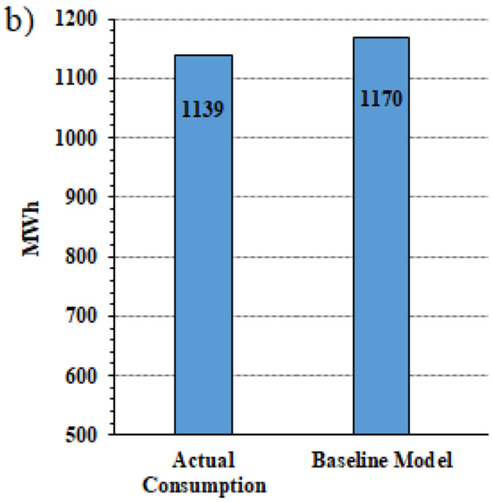

Fig. 3b. Model annual validation.

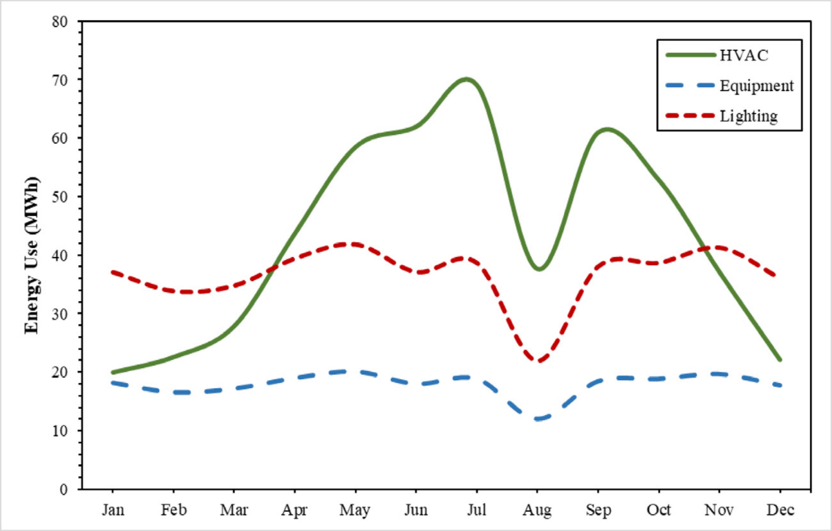

Fig. 4. Monthly baseline model energy analysis (MWh).

on a building results in significant reductions in energy consumption and, as a result, power generation. According to ASHRAE [22], it takes approximately 3 kWh of total energy to generate and deliver 1 kWh to the consumer because electrical energy production and delivery are only around 33% efficient.

Except for the insulation material and thickness, the building characteristics in this analysis remain similar. Two different thermal insulation materials with their thicknesses, available on Egyptian markets 2021, have been evaluated in this study. The two insulations are XPS and PU with thicknesses of 25, 50, 75, and 100 mm, respectively.

4. Results and findings

The outcomes of various thermal insulation variables will be presented in order to assess the impact of each type on energy efficiency. Each parameter was examined independently to determine its effect on the amount of energy consumed.

Table 2. Models Consumption and CO_2 reduction.

Model	Total consumption (GWh)	HVAC consumption (GWh)	CO_2 reduction %
Baseline	1.17	0.52	–
25 mm XPS	1.083	0.429	8.06
50 mm XPS	1.069	0.416	9.19
75 mm XPS	1.063	0.409	9.74
100 mm XPS	1.059	0.405	10.1
25 mm PU	1.093	0.439	7.17
50 mm PU	1.077	0.423	8.52
75 mm PU	1.069	0.416	9.22
100 mm PU	1.068	0.415	9.31

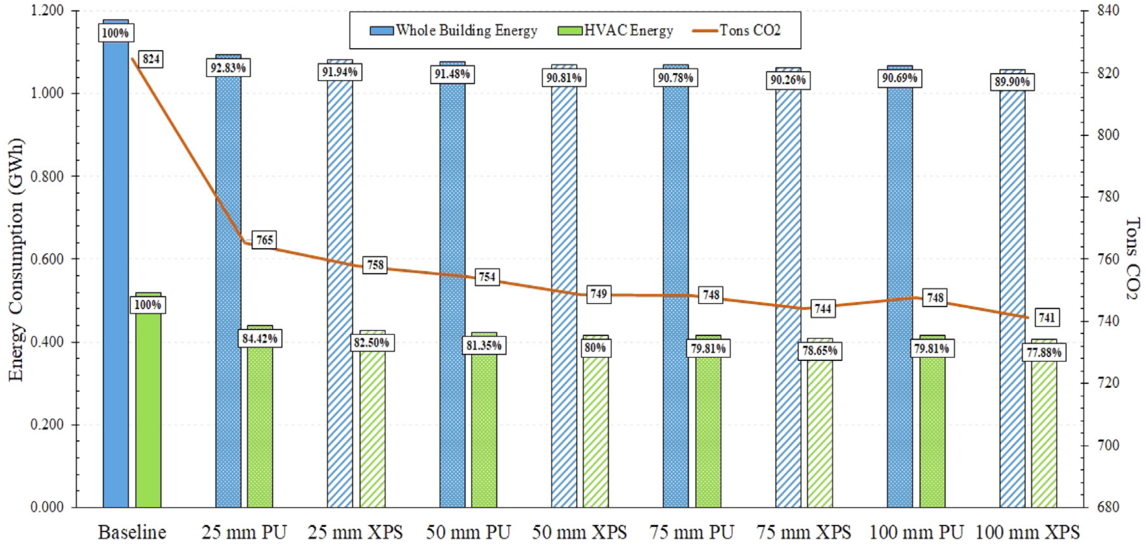

Fig. 5. Energy consumption and CO_2 emissions are related to various models.

The simulation reveals the effectiveness of implementing thermal insulation in Egyptian hot arid climates. Table 2 summarizes the various model response to the entire building energy use, HVAC energy consumption, and resulting CO_2 emission reductions related to the implementation of thermal insulations. Fig. 5 graphically illustrates the thermal insulation materials with different thicknesses related to the building's energy consumption, HVAC energy utilization, and CO_2 emissions.

Table 2 reveals the competitiveness of the building response to different insulations. In such a case, all proposed models should be subjected to a techno-economic analysis for an optimum decision.

As Fig. 5 shows, a minimum of about 7% reduction in energy costs could be accomplished thru the implementation of the minimum thermal insulation thickness of PU. About 60 tons of CO_2 reductions could be achieved through this minimum implementation [23]. The figure also shows the effect of thermal insulations on the HVAC energy consumption for various models. On the other hand, considering the latest Egyptian electricity tariff, in Egyptian pounds (EGP), of 1.6 EGP/kWh for commercial applications [24], the proper selection of thermal insulation based on techno-economic analysis is much preferred. The techno-economic technique represents the optimal implementation through both technical and economic outcomes. Table 3 summarizes the latest insulation cost in EGP. The cost includes the material cost, transportation cost, and fixture cost. The walls and roof areas are 3473 m^2 and 1913 m^2 approximately. Considering both the initial and running costs of the building, a techno-economic analysis [25] is adopted and the outcomes are simply represented in Table 3 along with the increased cost percentage compared to the initial cost.

Table 3. Techno-economic assessment of proposed insulations.

Insulation type	EGP/m^2	Initial cost increase	ROI	Payback period (Years)
25 mm XPS	63	3%	29%	2.1
50 mm XPS	103	5%	21%	2.9
75 mm XPS	140	7%	16%	3.8
100 mm XPS	165	8%	14%	4.3
25 mm PU	115	6%	14%	4.2
50 mm PU	200	10%	10%	6.1
75 mm PU	283	14%	8%	8
100 mm PU	358	18%	6%	10.1

5. Conclusion

The building envelope is a valuable factor for improving energy performance since it has a significant impact on the energy utilization of buildings in hot countries. This study aimed to determine the impact of the insulation materials on the energy efficiency of an institutional building. A valid model was generated using actual building energy data obtained in Cairo, Egypt. Following the model validation, a sensitivity analysis is conducted to quantify the influential factors affecting building energy use. The entire building energy efficiency is assessed depending on the insulation materials to successfully achieve a low energy building in hot environments. The tests reveal the competitiveness of the building response to different insulations. In such cases, it is recommended to undergo a full economic analysis to investigate the cost-effectiveness of the implementation.

The economic analysis showed a wide range of outcomes in terms of ROI and payback periods. To summarize, the economic analysis reveals that 25 mm XPS tends to be the most proper implementation, among the list tabulated in Table 3, with an initial cost increase of 3% and an ROI of 29% and a payback period of about 25 months. Therefore, policymakers in developing countries should legislate the implementation of energy-efficient insulations reducing both energy consumption and carbon footprint.

Declaration of competing interest

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

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