Building envelopes toward energy-efficient buildings: A balanced multi-approach decision making

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Abstract:

The worldwide environmentally friendly trend has focused the last decade on emphasizing the value of energy conservation and reducing the carbon footprint in buildings, achieving zero energy buildings. Presently, viable building techniques, in developing countries, are insufficient to achieve zero energy buildings. Thus, authorities should implement policies mandating new developments and renovations to establish “energy-efficient buildings”; nevertheless, design solutions should be properly evaluated and assessed preceding execution. The conservation of energy without jeopardizing human comfortability is a huge challenge for any designer. Occupants are less interested in making a major investment to save some expenses over the next two decades, especially nowadays that energy is still affordable. Therefore, improved indoor environmental conditions are perhaps another important parameter toward energy-efficient buildings. Through dynamic simulations, this study examines the energy efficiency and thermal comfort achieved by integrating retrofitting strategies in an institutional building in three different ASHRAE hot climate zones represented by three cities of Egypt (Aswan, Cairo, and Alexandria). The built-up baseline model is validated using actual energy usage data. The validated baseline model is then subjected to local sensitivity analysis to determine the driving parameters influencing the building's energy demand. The study at hand focuses on a broader perspective on sustainability. With a multi-approach decision-making methodology based on the most recent measures, the study highlights the outcomes through an environmental-economic assessment and indoor thermal comfort depending on experts’ weighting, responses, and recommendations. The outcomes postulate that the implementation of reflective paints solutions would achieve the highest percentages of whole-building energy savings with 21%, 19%, and 17% for Aswan, Cairo, and Alexandria, respectively, improving indoor thermal comfort levels.

Keywords: *Building Performance Simulation; Energy-efficiency; Thermal Insulation; Carbon Footprint; Cost Efficiency; Techno-economic Assessment; Thermal Comfort*

1. *Introduction*

In several nations, the transition to alternative energy infrastructure is being started as fossil fuels are entering their tertiary phases. The most critical issue nowadays would be to handle this transition, minimizing negative effects and combining various technological solutions over time: short-term carbon reduction and sequestration of fossil fuel, implementation of energy-efficient technologies, alternating to green energy resources [1,2]. Buildings are currently the world's largest electricity consumer, probably accounting for over one-third of global energy consumption [3]. Building end-uses account for about 30-40% of global energy demand in 2019 [4–6]. Most of this energy is being used for Heating, Ventilation, and Air-conditioning (HVAC) systems [3,7]. A building's HVAC system operation, guaranteeing human comfort and maintaining air quality, is vital for energy optimization [8]. Among building end-uses, HVAC systems represent approximately 50% [4,9,10]. Population growth and thermal comfort are the main contributors to the continuing increase in buildings' energy demand. In developing countries, approximately half of the energy in a building is used for space conditioning, with an additional 20% of plug loads, illumination, and other internal processes [11]. Researches in developing nations argue that HVAC and lighting consumption can sum up to 77% of the building energy demand [12,13]. In hot regions, HVAC can contribute to about 50%, while lighting can reach more than 35% of the building's aggregate energy use [9,10,13,14]. Buildings' HVAC energy utilization can be affected directly by overestimations leading to systems oversizing [10,15,16]. Sustainable building designs meeting all of our citizens' operating demands are an immense task in this era. Since a substantial portion of a country's energy demand is related to the built environment, productive approaches should be taken to decrease energy consumption while ensuring that human comfort/health and environmental protection expectations are fulfilled.

Many building owners in developing countries have been conditioned to believe that energy efficiency must be more expensive; however, well-designed, energy-efficient buildings can be developed for less cost than traditional ones. For instance, enhancing the envelope to fit the climatic conditions, can significantly reduce the size of the mechanical systems. Energy conservation without lowering comfort levels contributes to improved use of power. It is not about rationing, reductions, or load disposal, but simply a process of identifying excess energy areas and implementing steps to minimize usage [17]. There are significant prospects to decrease power utilization while boosting buildings' performance. Energy-efficient designs are substantially different from each other for hot, dry, and humid regions [17]. New constructions are expected to minimize average power demand by 20% to 50% by considering appropriate design strategies in building envelopes, HVAC, illumination, appliances, and others (e.g., workplace appliances). Substantial savings over 50% of energy demand compared to an existing building can be attained [18,19]. Early design stages contribute significantly to future performance in terms of resource and energy utilization, and this is where the optimization potential can be leveraged most efficiently and at a relatively low cost. Passive building design parameters ought to be designed to decrease building energy demands, increasing building energy efficiency, as well as the efficiency of active components as HVAC systems should be optimized to reduce energy consumption [18].

a. *Literature review*

A building envelope has a substantial effect on energy use as well as peak loads. As the insulating properties of the envelope worsen, energy consumption and peak loads rise. This thermal layer should have an efficient barrier for heat transfer through the building structure, which can be accomplished through an adequate choice of insulators [20]. Annual cooling demand for buildings can be substantially decreased in thermally insulated facilities in hot-dry and hot-humid environments [19]. The use of simulation models and the estimation of building loads enables the optimization of envelope properties by changing the configurations of the walls, roof, or glazing in one-parameter increments [16]. A variety of approaches are being established to create energy models simulating a building/plant model for forecasting loads or cost cuts [12]. These models alter widely in extent from a wall to a full building model by simulating temperature-varying spaces [12].

To enhance building efficiency, a technique is known as the 'parametric simulation process' should be used. This methodology allows quantifying the impact of the selected variables on the building energy performance through the iterative execution of several simulation batteries. Local and global sensitivity analysis can be carried out [21]. Local studies are focused on the effects produced by each variable around the base case, modifying one parameter while the rest are keeping constant. Global studies are more interested in quantifying the influences of uncertain inputs over the whole input space, so several parameters are modifying at the same time. Numerous studies previously have looked at the selection of passive building factors to reduce energy utilization in buildings under various climatic conditions.

In four different Iranian environmental conditions, Delgarm et al. [22] performed an optimization analysis relying on EnergyPlus models, taking the annual illumination and cooling demands as the objective functions and the design parameters are the orientation of the building, glazing dimensions, and overhang specification. They concluded that the optimization of building design factors could substantially reduce the energy consumption of buildings. Elsafty et al. [23] have been researching the saving of energy usage in commercial buildings in Egypt and its environmental effects. Since a significant portion of energy consumption is consumed by Egyptian commercial buildings, HVAC consumption has been examined. Theoretical research was conducted to use insulation to reduce the energy consumption of the HVAC system. The reductions in HVAC power usage helped solve excess power consumption in Egypt during peak periods of the summer days. Assessing the needed calculations using established software, they found that the inclusion of insulation produced savings around 15% of the annual HVAC energy usage, in addition to reducing ($7.78x10^{-7}$) tons CO_2 emissions per kWh saved. Bolatturk [7] stated in his research that one of the most important energy-saving strategies in buildings is thermal insulation. He postulated that the determination and selection of the insulation thickness is, therefore, the key focus of many engineering investigations. The structures of walls vary by climate. Bricks or concrete bricks are only coated with thin plaster layers in warm climates, while sandwich walls are used in cold climates. In the research, he opts for extruded polystyrene board as an insulation material. He concluded that the optimum insulation thickness of the polystyrene board in buildings varies between 3.2 and 3.8 cm.

Evin and Ucar [24] examined the optimal thickness of thermal insulation added to the building envelope of a four-story residential building in 4 different climatic zones in Turkey. They concluded that the energy cost was decreased dramatically when the roof is insulated with polystyrene relative to the non-insulated roof. Finally, they recommended applying the same methodology to other building types and in different climatic regions. López et al. [25] suggest that the addition of thermal insulation to the built exterior facade is one of the upgrading steps of the building envelope. They also refer to the need to adapt the implementation of successful refurbishment strategies to the climatic conditions and to legalize that in the constructive regulations. Finally, they concluded that, with a reasonably low cost, the façade modification achieves energy savings of about 3%. Yilmaz [26] postulated that the heat capacity of the building envelope should be controlled in hot and dry climatic conditions due to it plays a vital role in usable energy. He concluded that a dynamic model of heat transfer during the design phase should be evaluated, particularly in regions located in continental environments. In this design phase, it should be taking into account the ability of the building envelope, as a function of its thermal mass, to regulate the entry of the thermal wave into the building. In their research, Ghose et al. [27] analyzed the environmental effects of renovated buildings in New Zealand. They revealed that effective HVAC and smaller WWR (window-wall ratio) should be prioritized in large buildings, whereas the option of façade materials with minimal embodied impacts should be prioritized in small buildings. In the end, all the buildings were planned to have undergone deep energy retrofitting steps, leading to a reduction in operational energy usage by at least 60%.

Lstiburek [28] argues that wall assembly should include control approaches for moisture and thermal transfer. He mentioned that one of the most efficient materials combining both approaches for the hot-dry and hot-humid conditions is polyurethane. An-Naggar et al. [29] investigate, through DesignBuilder modeling software, the effect of walls and roof insulation (glass wool) on energy usage and CO_2 reduction in Egyptian residential properties. Almost 40% of the reduction in the energy used by the air conditioning system is obtained once heat insulation is used in external walls and roofs, reflecting a substantial decrease in energy bills. Al-Saadi et al. [30] studied the energy performance of a residential house in Oman (hot climate). They concluded that adding polystyrene insulation to walls and roofs contributed to about 18% annual energy savings. Radwan et al. [15] explore the influence of construction materials on buildings' energy consumption. They concluded that 8% of energy reduction in hot-humid climates may be achieved through building construction materials. Sala et al. [31] investigated the building performance employing insulating envelopes. They recommended an overall heat transfer coefficient (U-value) of the exterior building facades and roofs (0.32 $W/m^2.K$ for external walls and 0.26 $W/m^2.K$ for the roof) as low as possible to reduce energy losses and the summer overheating on exposed surfaces (southern, western, and eastern exposure).

Aditya et al. [32] reviewed the various insulating materials that relate to buildings. They classified the insulating materials' heat exchange properties into 2 categories, 1) mass insulation category, which are materials that can slow the heat transfer by conduction, 2) reflective insulations reflect radiation heat due to a low emittance reflective surface, preventing transfer from one side to another. Moujaes and Brickman [33] studied the effect of reflective paints on energy usage in U.S residential buildings in hot arid climates. Their research resulted in 11% energy reductions when reflective paint is applied to the building roof only. Zhang et al. [34], stated in their study that applying high reflectivity materials coatings building external walls proved to be an effective way to reduce heat gains from solar radiation and reduces energy needs. They concluded that building exterior walls with reflective coatings can reduce about 15% of energy. Raimundo et al. [35] aimed at identifying the most energy-efficient and cost-effective thermal insulation options in five buildings in Portugal's region. They concluded that EPS (Expanded Polystyrene Insulation) is the most cost-effective thermal insulation material, and its ideal location is in the midsection of the building envelope. Verichev et al. [36] applied an energy simulation in Chile to determine the thermal transmittance of exterior walls for single-family buildings and the energetically optimum thickness of thermal insulation. They argue that by designing the house with a mind on energy efficiency, the carbon emissions may be decreased by 20%. According to

Zilberberg et al. [37], structural engineers typically disregard energy performance. They ensured, using models, that adding insulation resulted in a substantial reduction in operating energy usage while minimizing the relative impact of non-insulated thermal mass in the building envelope in hot semi-arid climates. Anh and Pasztory [38] analyzed numerous thermal insulation materials that have been produced in recent years and declare that they have proven their usefulness in buildings due to benefits such as low density, high thermal resistance, and cost-effectiveness.

b. Research gap and aims

Previous studies show that energy conservation is critical research that legislators are carrying out in their efforts; however, it is overlooked in many developing countries. To the authors' understanding, this literature shows a research gap investigating building energy conservation in different hot climate zones (as those of Egypt). When an energy conservation approach argues that installing insulation reduces energy usage, operational costs and ecological effects, the resulting indoor thermal comfort response should be considered in the decision-making process. Finding a comprehensive approach that considers the different aspects of energy efficiency is a way to assist project decision-makers through their designs and retrofits. Even though there is a simulation tool that evaluates multiple sustainability aspects, decision-makers find it difficult when considering widely different aspects. This study presents these aspects in various forms of quantitative measures for various insulating materials. It also demonstrates how it could be implemented through an enviro-economic evaluation and the resulting thermal comfort, evaluated through Fanger PMV and DCH, on an existing institutional building in three different ASHRAE climatic zones in Egypt.

With Egypt’s vision 2030, the authors aim to address this gap, with this article, by presenting a method that integrates various parameters affecting energy efficiency into the decision-making phase for the appropriate efficient design option for the facility owners and policymakers. The use of this methodology based on parametric analyzes that consider different cost functions (demands, cost, comfort), allows creating a decision-making matrix that helps when developing energy efficiency policies and normative in existing buildings that need renovation.

2. *Theoretical Analysis*

The management of various dynamic interactions, illustrated in Figure 1, to achieve reliable buildings and system solutions that meet the future requires an integrated and comprehensive subsystem approach.

Figure 1. Building's subsystems dynamic interactions

BEM (Building Energy Models), primarily use physical methods to predict building efficiency, building energy use, evaluate building designs, inspect code compliance, and assess buildings based on standard-established rating requirements, among other potential applications before construction [39,40]. The energy consumption of buildings is the result of a plethora of different end-uses. Therefore, it may become difficult for building energy models to consider the thermal response of the building demands and to anticipate the operational and functional characteristics of the systems that react to these needs. Besides, HVAC simulations in building prototypes typically provide energy utilization outputs that allow the optimization of the building performance.

To evaluate the energy performance of the whole building, HVAC units, or the characterization of the building envelope, simulation tools are used. The sequence of analyzes carried out by a building modeling tool is fully described by Ayres and Stamper [41]. This modeling approach is broadly endorsed and implemented nowadays in global simulation tools [42–45], e.g. ESP-r, BLAST, TRNSYS, DesignBuilder, and EnergyPlus which have the opportunity to handle building dynamics effectively. Based on precise physical properties of buildings vacancy schedule, geographic environments, nature of construction, and weather conditions, these tools estimate total energy utilization as well as the energy used by HVAC, operational scheduling, illumination, etc. [46–49]. Nevertheless, the existence of certain accurate data is challenging and, in some situations, is difficult to collect, leading to different sources of uncertainties that influence the final results of the building performance.

A variety of commercial building benchmark simulations have been established by the U.S DOE (Department of Energy) providing a standardized framework for building energy models [50]. A typical BES model is formulated employing "first principles of building physics" and is considered a reliable model [51].

In this research, the dynamic simulation program, DesignBuilder, has been used to model the energy performance of buildings. This simulation tool considers specified internal heat gains, air exchange between zones, air exchange with the outside environment, and convective heat transfer from the zone surface to estimate the heat balance in each thermal zone through the use of an Integrate Simulation Manager that combines the Surface Heat Balance and, Air Heat Balance. This integrated simulation solution solves simultaneously building system, and plant configurations. The heat balance method is an iterative computation approach that requires the simultaneous solution of a set of equations for each hour of the day for the zone air and each of the external and interior surfaces, considering internal and external ambient conditions as well as physical properties of the construction layer [52,53].

The use of this simulation tool allows the dynamic calculation of the energy balance, linking the energy consumption of the building and the air conditioning load with the climatic conditions and the thermal inertia of the building envelope.

3. Methodology

The energy performance of an institutional building in Cairo (Egypt) has been evaluated using the dynamic simulation tool DesignBuilder. This software is able to analyze the energy quantification of the selected retrofitting behavior, analyzing the impact of the measure on the thermal loads of the building. Considering the climatic conditions for three representative cities in Egypt, as well as the current building's construction and operational data, a baseline model based on on-site measured consumption is validated using ASHRAE validation measures. Grounded on the annual thermal loads' outcomes of the validated baseline model, a local sensitivity analysis was performed to identify which factors are more sensitive to annual energy and peak design loads [21]. Accordingly, to this study, the installation of thermal insulation in façades and roofs, conventional and radiative insulators, has been advocated. With this aim, a series of simulations were conducted, considering the building needs as well as the normative constraints. The retrofitting parameter is modified from the original values in each simulation, while the rest remained unchanged. The series of tests were chosen based on data from retrofit products available on the Egyptian market.

The multi-approach decision-making in this study highlights the most influential insulation in comparison with the annual loads of the baseline, through a full techno-economic assessment as well as the environmental impact (CO_2) taking into consideration the resulting indoor thermal comfort, correlated with each insulation material, as a priority expressed in Fanger PMV and the number of DCH. The graphical methodology applied is illustrated in Figure 2.

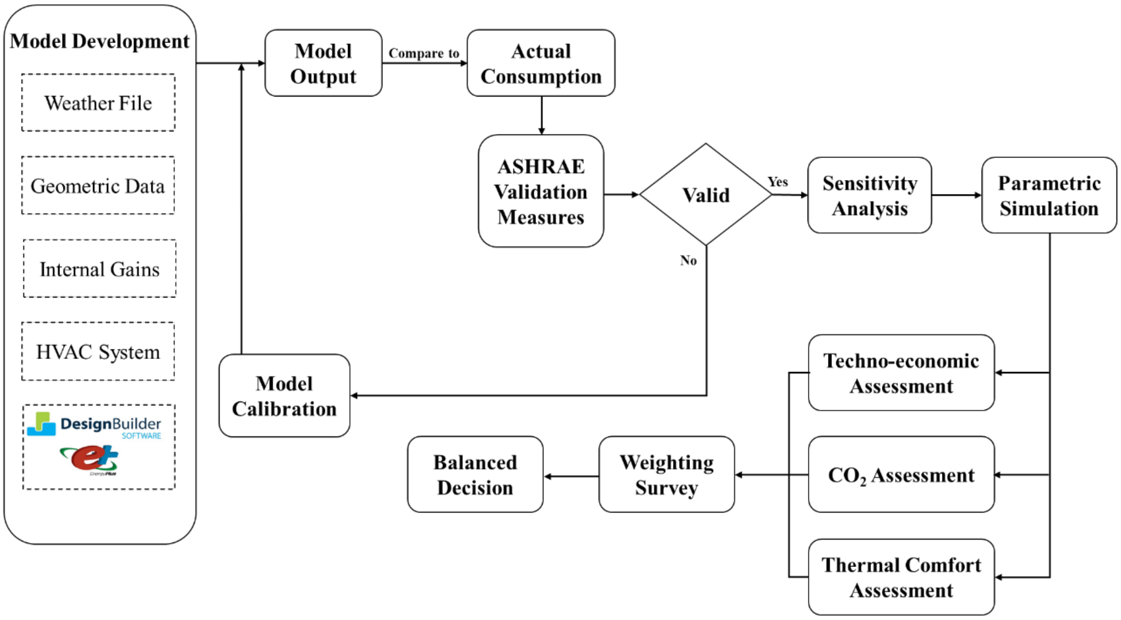


Figure 2. Graphical Methodology

4. *Climate Data*

The most recent cooling degree days (CDD) data for some Egyptian cities are summarized in Table 1 [54,55]. Typical climate conditions are prescribed for locations where most stations are subject to long-term hourly observations [56]. Building codes are usually related to representative climates within an enforcement jurisdiction. These climatic conditions are obtained as averages from local to regional databases based on 30-years of measurements [57]. The guidelines for these codes are setting up by national regulations, regional or international standards. This last category highlights the standards established by the Department of Energy (DOE) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). In collaboration with the DOE, ASHRAE, based on surface measurements, has developed climate zone maps used by several building codes [57].

The climate in Egypt is considered semi-desert with hot dry summers, moderate winters, and very little rainfall. According to the Köppen Geiger classification, two climate zones have been identified for Egypt [58,59]: BWh and BSh. Regions classified as BWh correspond to hot desert climates while regions classified as BSh correspond to hot semi-arid climates. Nevertheless, the ASHRAE classification [56] divides Egypt into three climatic zones: Very Hot-Dry (1B), Hot-Dry (2B), and Hot-Humid (2A). A representative city of each climate zone has been selected: Aswan, Cairo, and Alexandria. Table 1 shows the latest recommended annual design conditions based on 0.4% and average wind speed [56] for the three selected locations describing, besides, the annual Direct Normal Irradiation (DNI) [60].

Table 1. Design Conditions for three different locations [54–56]

Location	Cooling Degree Days	ASHRAE Climate Zone	Dry-Bulb Temperature (°C)	Wet-Bulb Temperature (°C)	Direct Normal Irradiation (kWh/m^2)	Wind Speed (m/s)
Aswan	6564.1	1B	44.1	21.1	2254	4.04
Cairo	4861.7	2B	38.2	21.2	2036	3.58
Alexandria	3739.9	2A	33.2	22.4	1955	3.92

5. *Building Model*

The base case of this research represents a building located in Cairo, Egypt. To develop the model of this base case, all the necessary information feeding the model is gathered: geometry, envelope characteristics, internal gains, and building zones. The validity of the model is checked from comparisons between the obtained outputs of the model and the experimental measurements registered in the real building placed in Cairo. Finally, the influence of the building uses has been analyzed highlighting the importance of the envelope characteristics.

a. Site Location

The building is located in the New Administrative Capital, Cairo, Egypt, as shown in Figure 7. New Cairo capital city is located 35 KM east of Cairo. The new capital is developed with the strategic vision for a smart city integrating its smart infrastructure to provide many services to citizens. The facility consists of approximately 11,350 m^2, as shown in Figure 3.

Figure 3. The building, the model, and the site location via Google Maps

b. Envelope Specifications

For the case study, the as-built data was collected from the facility management office. The wall area is 3473 m^2 while the roof area is about 1913 m^2. The building envelope components have almost the same values used in most non-residential buildings in the Egyptian market [9,10] and are listed in Table 2.

Table 2. Building Envelope Data

Exterior walls	
U-factor (W/ m^2 °C)	1.924
Roof	
U-factor (W/ m^2 °C)	2.27
Window	
Average Window Fraction (Window-to-Wall Ratio)	30%
Glass-Type	6 mm Double Blue Glass/ 6mm Air Gap
U-factor (W/m^2 °C)	3.094
SHGC	0.503

c. Internal gains

Internal gains are simply the internal loads generated inside the building, including occupancy, ventilation rates, lighting, equipment, and schedules.

i. Occupancy density and ventilation requirements

Occupant density and ventilation rates by space type were defined according to *ASHRAE Standard 62.1-2016* [61].

ii. Lighting and Plug loads

Lighting loads are set according to *ASHRAE Standard 90.1-2016* using the space by space method [62]. The energy used by appliances that are regularly wired into a socket, commonly involving office and other miscellaneous equipment, computers, and others that are hard to estimate is widely known as plug loads. These values were also set according to *ASHRAE Standard 90.1-2016* [62].

iii. Operating Schedules

The building is operating five days per week from 8 AM to 4:30 PM. As with most educational facilities, in August institutional buildings are operating with about 50% capacity due to the annual vacations.

d. Building Zones

The building consists of 13 different occupied zones as tabulated in Table 3.

Table 3. Building occupied zones

Zone	Area (m^2)	Area %
Call Center	43	0.5
Classrooms	693	7.9
Corridors	2253	25.8
Dry Lab	407	4.7
GYM	150	1.7
Lecture Halls	707	8.1
Libraries	466	5.3
Lobby	827	9.5
Lounges	453	5.2
Meeting Rooms	276	3.2
Offices	1584	18.2
Receptions	634	7.3
Restaurants	237	2.7
Total	8728	100

e. Model Validation

For the model to be effective, it should be capable of predicting the dynamics of the system and taking into consideration the relevant factors affecting the system. To build energy models that contribute to a sustainable energy future, the validity of the simulations should be guaranteed so that the findings of the simulations can be trusted. With this aim, the built-up model was validated with 2 different approaches which are recommended by the National Renewable Energy Laboratory (NREL) [63]. The annual Energy Use Intensity (EUI in kWh/m^2) obtained with the simulation model, has been compared with other institutional buildings located in hot climates and referenced in the literature, as illustrated in Figure 4. The comparative study is a useful technique because it does not require data from a real building, and it also highlights if further investigation is needed. Due to the absence of a model of reality, the comparative approach is most effective when used with other validation techniques.

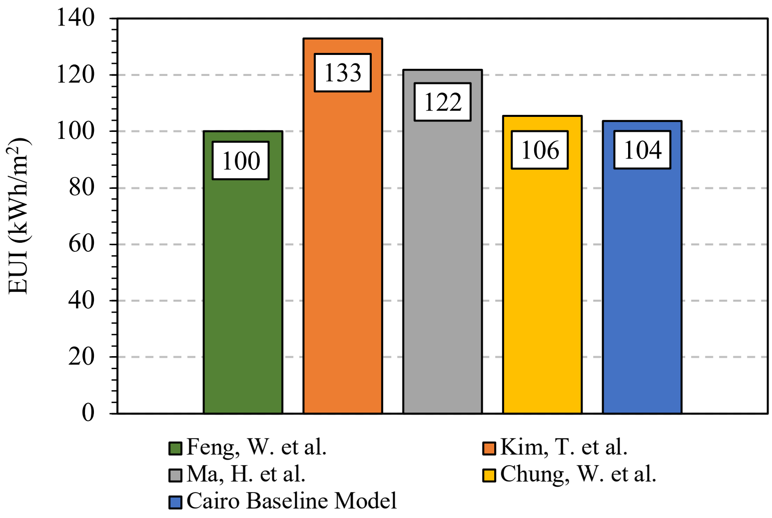


Figure 4. Cairo Baseline Model EUI compared to different studies [64–67]

In validation tests, building energy models are linked to measured data from existing buildings. Based on that, the second approach is validating the model EUI compared to the field site measurements extracted from the Building Management System (BMS). The validation data was graphed in Figure 5. To exhibit the representativeness of the simulation model based on the variability of the measured data, two indices have been calculated, as recommended by the ASHRAE guideline 14:2015 [68]: Coefficient of variation of the root mean square error (CVRMSE) and Normalized mean bias error (NMBE). According to this guide, the value must be less than ±10% for the NMBE coefficient and less than 30% for the CVRMSE coefficient. For the calibrated model, the estimated NMBE is 6%, while the CVRMSE is about 3%.

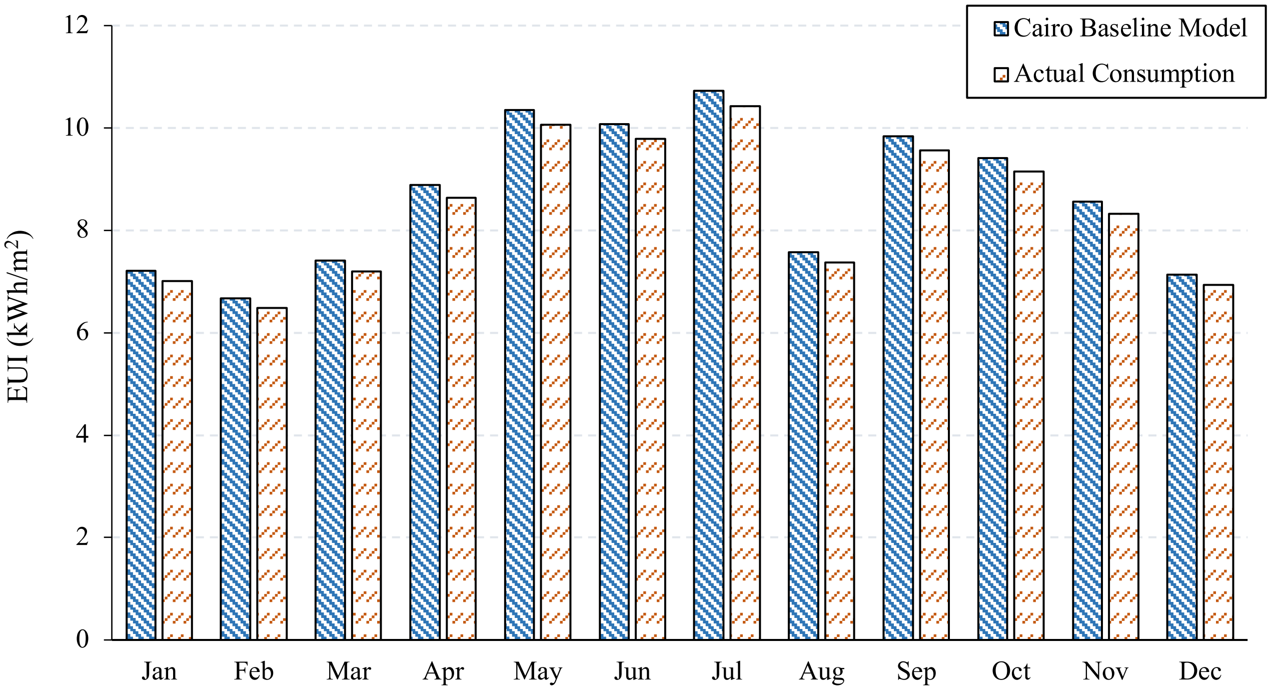


Figure 5. Cairo Baseline Model Validation - Cairo, Egypt

f. Building Energy Use

In building energy analytics, sensitivity analysis plays a vital role. From both energy simulations and empirical analysis, it can be used to identify the key variables influencing building thermal performance. Analyzing the building energy use, approximately HVAC systems compromise half the building energy use, which aligns with [9,10,13,17,67]. A sensitivity analysis was undergone for the validated baseline model to quantify the portion of each parameter affecting the building energy usage, as illustrated in Figure 6. This differential sensitivity analysis shows that the most influential variables in the total heat gain are the walls and the roof, reaching a percentage of approximately 40%. Based on this result, this study aims to investigate the effectiveness of different types of insulating materials and thicknesses in different hot climatic zones of Egypt.

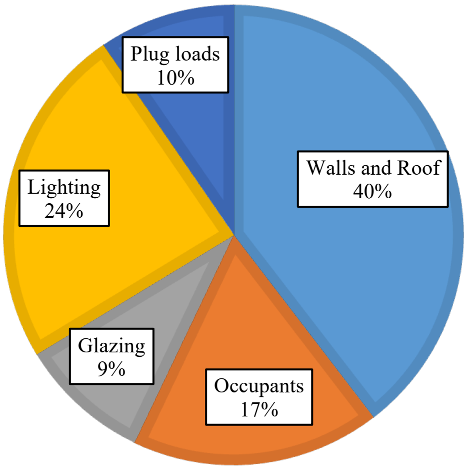


Figure 6. Cairo Baseline Model Sensitivity Analysis

g. *Insulation in buildings*

In Egypt, the thermal performance of the building envelope is quite important in the morning and late afternoon, when a significant amount of solar radiation is occurring. The thickness of the insulation material can be determined depending on the building's annual cooling/heating energy requirements. Since Egypt has a wide geographic location and numerous climatic regions, it has been divided by ASHRAE into three climate zones. Some Egyptian governates, such as the South Region and the Mediterranean coastal governates, differ among very hot dry, hot dry, and hot humid climates with a longer cooling season than the heating season.

In terms of the energy economy, ensuring efficient thermal insulation in regions where the cooling demands in buildings are predominant in contrast to the heating requirements is quite necessary. In these regions, more studies focusing on indoor comfort related to the implementation of insulation must take place in parallel with the development of a country's energy economy.

This study analyzes the behaviour of a building in different climatic zones, modeled with the same architectural and physical characteristics except for the insulating material and its thickness. The materials under investigation are conventional in the Egyptian market such as XPS (Extruded Polystyrene), PU (Polyurethane), GW (Glass-wool), and imported material such as RP (Reflective Paint). The available thickness for the three insulating materials is 25 mm, 50 mm, 75 mm, and 100 mm, respectively.

6. *Results and Discussion*

The outcomes of the proposed retrofits are analyzed and discussed in order to evaluate the building performance annually. With this aim, an enviro-economic assessment is carried out to address the energy and carbon footprint reductions and the resulting thermal comfort according to the implementation.

a. Building Energy Performance (BEP)

This section evaluates the building response to the implementation of different insulation materials as well as different thicknesses for the three proposed cities. The results obtained by the simulation batteries are tabulated in Table 4.

Table 4. BEP due to insulation

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	EUI (kWh/m^2)		
Baseline	115.55	103.77	96.09
25 mm PU	101.51	96.33	91.89
25 mm XPS	100.59	95.41	91.10
25 mm GW	101.23	95.78	91.29
50 mm PU	98.71	94.93	91.53
50 mm XPS	97.91	94.23	90.63
50 mm GW	98.46	94.56	90.80
75 mm PU	97.39	94.20	91.24
75 mm XPS	96.58	93.66	90.51
75 mm GW	97.07	93.83	90.57
100 mm PU	96.76	94.10	91.18
100 mm XPS	95.80	93.29	90.47
100 mm GW	96.26	93.46	90.41
RP	91.73	83.59	79.78

The results revealed that in different Egyptian regions, the building performance differs. For areas with warmer climatic conditions (Aswan: zone 1B), the energy requirements are higher. As expected, greater insulation thicknesses achieve greater energy savings, but this progression follows a logarithmic profile as shown in Figure 7. The highest percentages of energy savings are achieved with the reflective paint material (21%, 19%, and 17% for Aswan, Cairo, and Alexandria, respectively) followed in descending order by extruded polystyrene (maximum savings of 17% for Aswan, 10% for Cairo and 6% for Alexandria), glass-wool (maximum savings of 17% for Aswan, 10% for Cairo and 6% for Alexandria) and polyurethane (maximum savings of 16% for Aswan, 9% for Cairo and 5% for Alexandria).

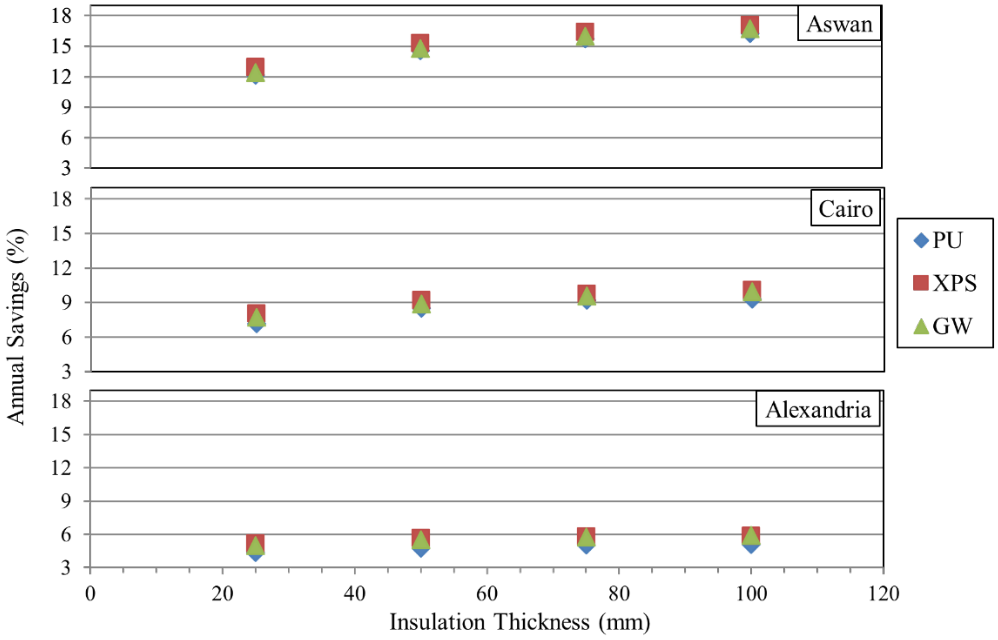


Figure 7. Annual energy savings based on the insulation thickness for the three studied cities.

b. Carbon footprint assessment

Reducing energy utilization minimizes carbon footprint and deterioration of the environment. The EPA [69] has reported that 0.0007 CO_2 tons are produced by 1 kWh of consumer electricity. Relative to the baseline model, Table 5 indicates the reduction percentage of CO_2 emissions in the three locations when different insulation thicknesses are considered. The higher the insulation thickness, the higher the reductions achieved in the CO_2 emissions. The best environmental material tested is reflective paint followed by extruded polystyrene, glass-wool, and polyurethane.

Table 5. Carbon Dioxide Reduction Percentage

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	CO_2 Reduction %		
25 mm PU	12.15	7.17	4.37
25 mm XPS	12.94	8.06	5.19
25 mm GW	12.39	7.70	5.00
50 mm PU	14.57	8.52	4.75
50 mm XPS	15.26	9.19	5.68
50 mm GW	14.79	8.87	5.51
75 mm PU	15.71	9.22	5.04
75 mm XPS	16.42	9.74	5.81
75 mm GW	16.00	9.58	5.75
100 mm PU	16.26	9.31	5.11
100 mm XPS	17.09	10.10	5.85
100 mm GW	16.69	9.93	5.91
RP	20.62	19.45	16.98

c. Techno-economic assessment

Techno-economic analysis is a cost-benefit assessment based on multiple approaches. These evaluations are used for tasks including:

- Assess the economic viability of a given project
- Investigate lifetime cash balances (e.g. investments)
- Assess the possibility of various levels and implementations of technology
- Compare the economic efficiency of various technological solutions offering a similar function.

The cost assessment is discussed in this section, defining the terminology used and indicating the assessment methods. Four indicators have been evaluated: Internal Rate of Return (IRR), Return on Investment (ROI), Net Present Value (NPV), and Payback Period (PBP) [10,70]. The indicator IRR is used in the economic analysis to measure the profit margins of potential investments. The indicator ROI is defined as the ratio to measure the benefit of the investment of capital. In the present money is worth more than the same amount in the future due to the time value of money. The difference between both the present value of cash inflows and the present value of cash outflows is the indicator NPV. A positive NPV indicates that the proposed earnings generated by the investment surpass the anticipated costs. Finally, the PBP indicator is the time before the cash inflows repay the initial investment. The examination takes into account the most recent electricity prices of 1.6 EGP per kWh in Egypt for commercial buildings. The investment in this study is the increased cost between the baseline model and the proposed models with a constant discount rate of 10% among all models. The insulation costs according to the latest Egyptian market prices and the economic assessment outcomes are summarized in Table 6. The full economic analysis is introduced in the Appendix.

Despite the environmental impact of increasing the insulation thickness, Table 6 reflects that the addition of 25 mm of XPS tends to be the most cost-efficient insulation among the conventional insulations studied for Egypt. On the other hand, a tremendous IRR indicator is shown with the implementation of the RP insulators to the building envelope.

Table 6. Techno-economic assessment outcomes

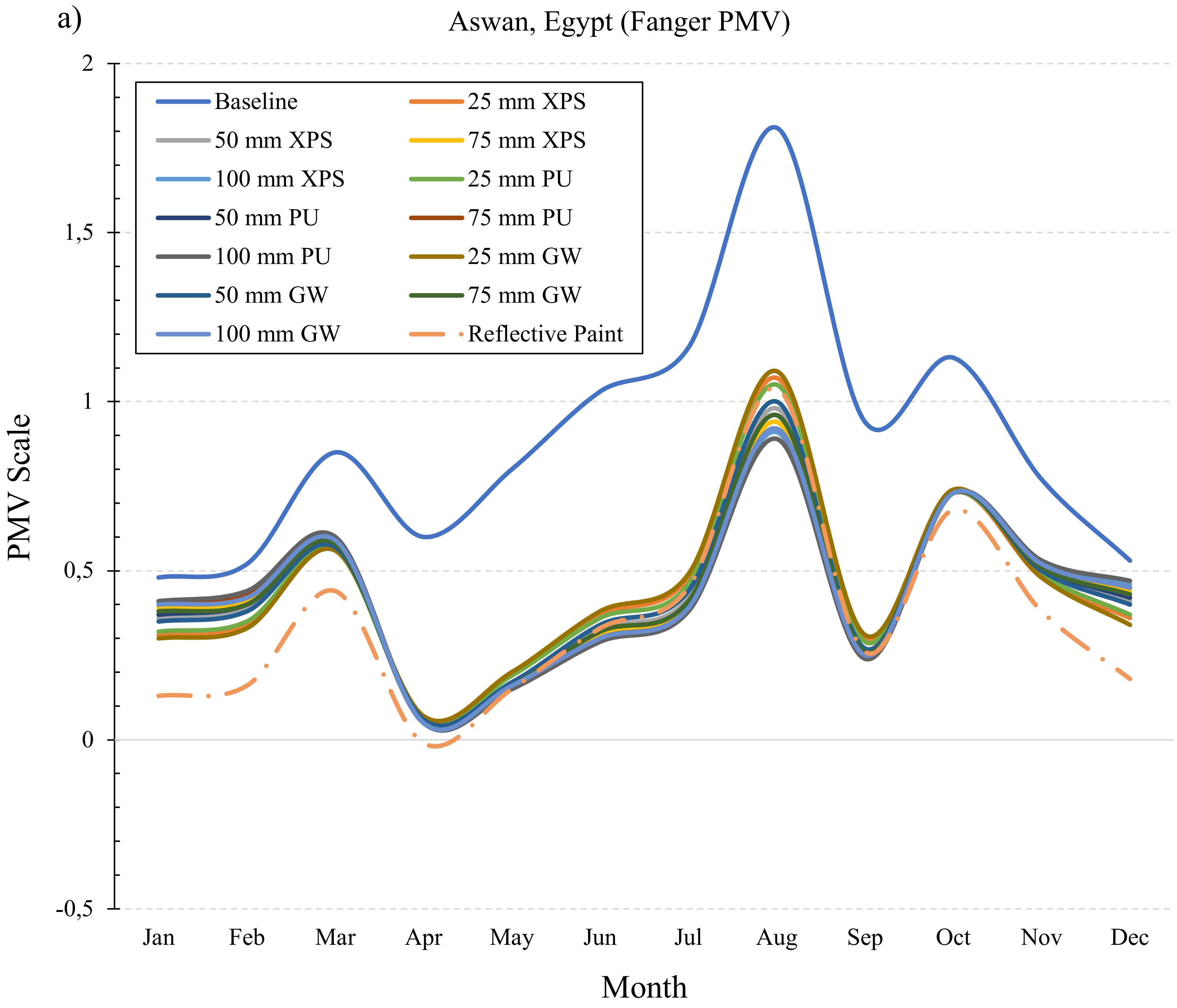
Model	**EGP/m^2**	**Aswan, Egypt**		**Cairo, Egypt**		**Alexandria, Egypt**	
		IRR	**PBP (Years)**	**IRR**	**PBP (Years)**	**IRR**	**PBP (Years)**
25 mm PU	115	41.51%	2.2	19.12%	4.2	5.56%	7.5
50 mm PU	200	27.27%	3.2	9.67%	6.1	-2.96%	11.9
75 mm PU	283	18.90%	4.2	4.03%	8	-7.47%	15.9
100 mm PU	358	13.65%	5.2	-0.15%	10.1	-10.62%	19.9
25 mm XPS	63	81.55%	1.1	45.27%	2.1	25.12%	3.4
50 mm XPS	103	59.18%	1.6	30.63%	2.9	13.98%	5.1
75 mm XPS	140	46.36%	2	22.33%	3.8	7.36%	6.8
100 mm XPS	165	40.69%	2.3	18.86%	4.3	4.19%	8
25 mm GW	71	69.79%	1.3	38.20%	2.4	20.53%	4
50 mm GW	119	49.45%	1.9	24.58%	3.5	9.85%	6.1
75 mm GW	165	37.85%	2.4	17.21%	4.5	3.85%	8.1
100 mm GW	201	31.71%	2.8	13.04%	5.3	0.63%	9.7
RP	56	145.30%	0.6	123.36%	0.8	100.01%	0.9

d. Insulation and Thermal Comfort

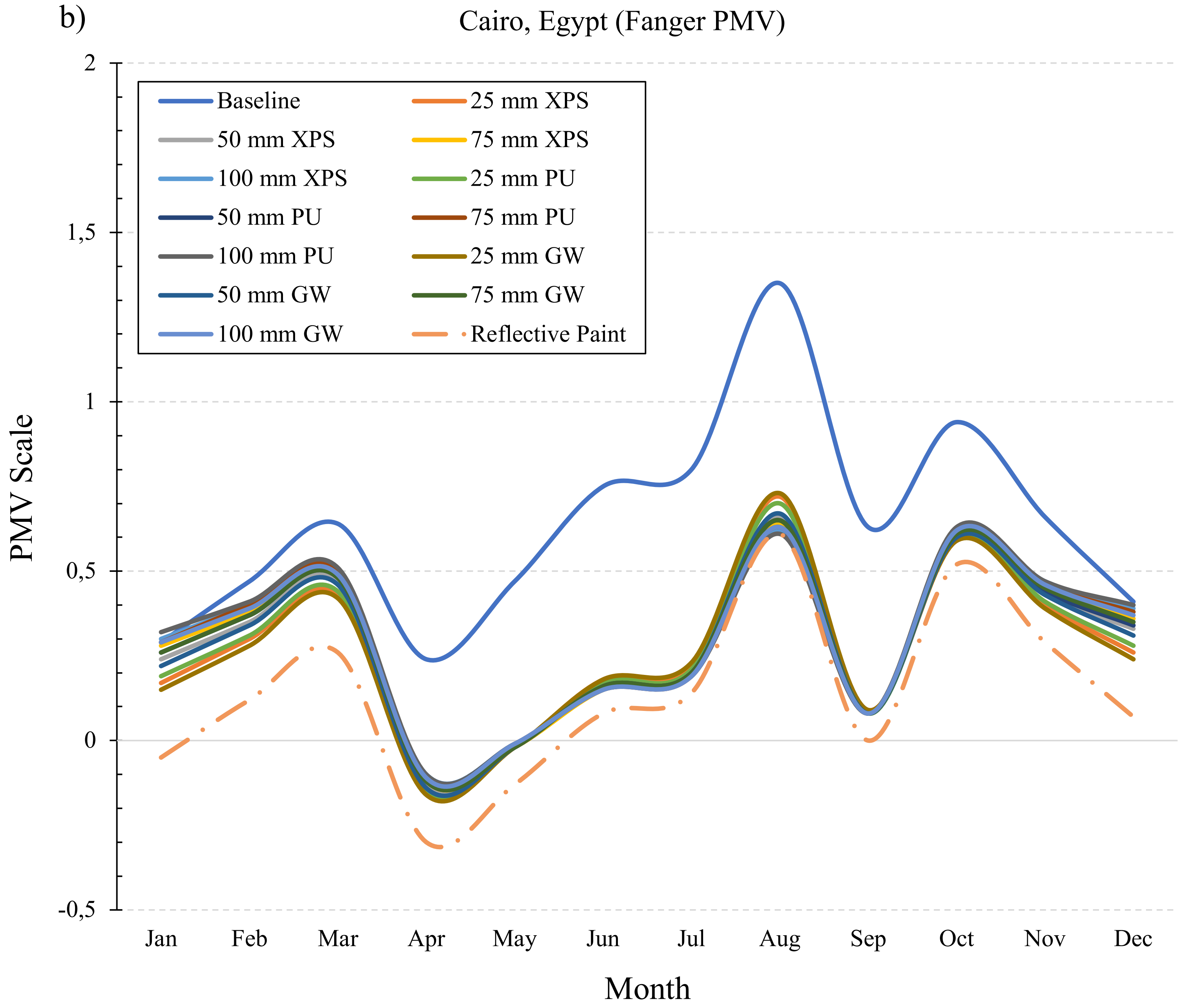
If facility managers can all agree on one aspect, it is that resident comfort concerns are their most common regular operational challenge. Thermal comfort is defined by ASHRAE as the “condition of mind that expresses satisfaction with the thermal environment” [71]. This is a subjective concept in which an individual may feel hot while another may feel cold nearby, being able to invert these arguments the next day. Even a new facility may struggle to keep most citizens satisfied the majority of the time. Although comfort is a highly personal experience for each individual, numerous standards highlight the optimum values for maintaining indoor ranges. Unfortunately, effective techniques in developing countries are rarely used in practice, perhaps because this information is not well accepted or recognized.

An obvious advantage of keeping residents more comfortable is that it will reduce complaints and, as a result, operating and maintenance expenses. Thermal comfort, when delivered intelligently and meaningfully, reduces the operational energy bills. Furthermore, buildings' thermal comfort and energy consumption are associated with design decisions during various design stages [69]. Therefore, with a priority on thermal comfort, environmental indoor quality, and the resources required to condition residents and facilities, designers should be founded to serve as a liaison between both the health and building sciences.

Heat storage and release are influenced by the material itself, thickness of the material (x), as well as other factors such as thermal conductivity (k) and specific heat capacity (C_p), which are natural thermophysical properties of the material [72,73]. To simplify the interaction between these parameters, the relationship between the insulation implementation (whether different material or thickness) and thermal comfort should be illustrated as well as the whole-building energy performance. Investigating and solving these puzzle components in a comprehensive framework almost often result in a better, more effective approach at a reasonable cost. This section examines the influence of building insulation's impact on thermal comfort using the Fanger methodology. To evaluate thermal comfort, Fanger created a 7-points scale standardized later by both ANSI/ASHRAE 55 [71] and ISO 7730 [74]. The PMV scale is often used to represent the comfort level scaled as follows: (+3 hot, +2 warm, +1 slightly warm, 0 neutral, −1 slightly cool, −2 cool, and −3 cold). In addition to thermal sensation, DCH analysis used in the study is an assessment based on whether the temperature and the moisture content indoors are within the ASHRAE thermal comfort range or not. Fanger PMV in parallel with DCH analysis is investigated. Figure 8 relates the resulting PMV to the insulation implementation, while Figure 9 illustrates the DCH related to the different simulated insulation materials for the three locations.


a)
Aswan, Egypt (Fanger PMV)
Baseline
25 mm XPS
50 mm XPS
75 mm XPS
100 mm XPS
25 mm PU
50 mm PU
75 mm PU
100 mm PU
25 mm GW
50 mm GW
75 mm GW
100 mm GW
Reflective Paint
PMV Scale
2
1,5
1
0,5
0
-0,5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

b)



Cairo, Egypt (Fanger PMV)
Baseline
25 mm XPS
50 mm XPS
75 mm XPS
100 mm XPS
25 mm PU
50 mm PU
75 mm PU
100 mm PU
25 mm GW
50 mm GW
75 mm GW
100 mm GW
Reflective Paint
PMV Scale
2
1,5
1
0,5
0
-0,5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

c)

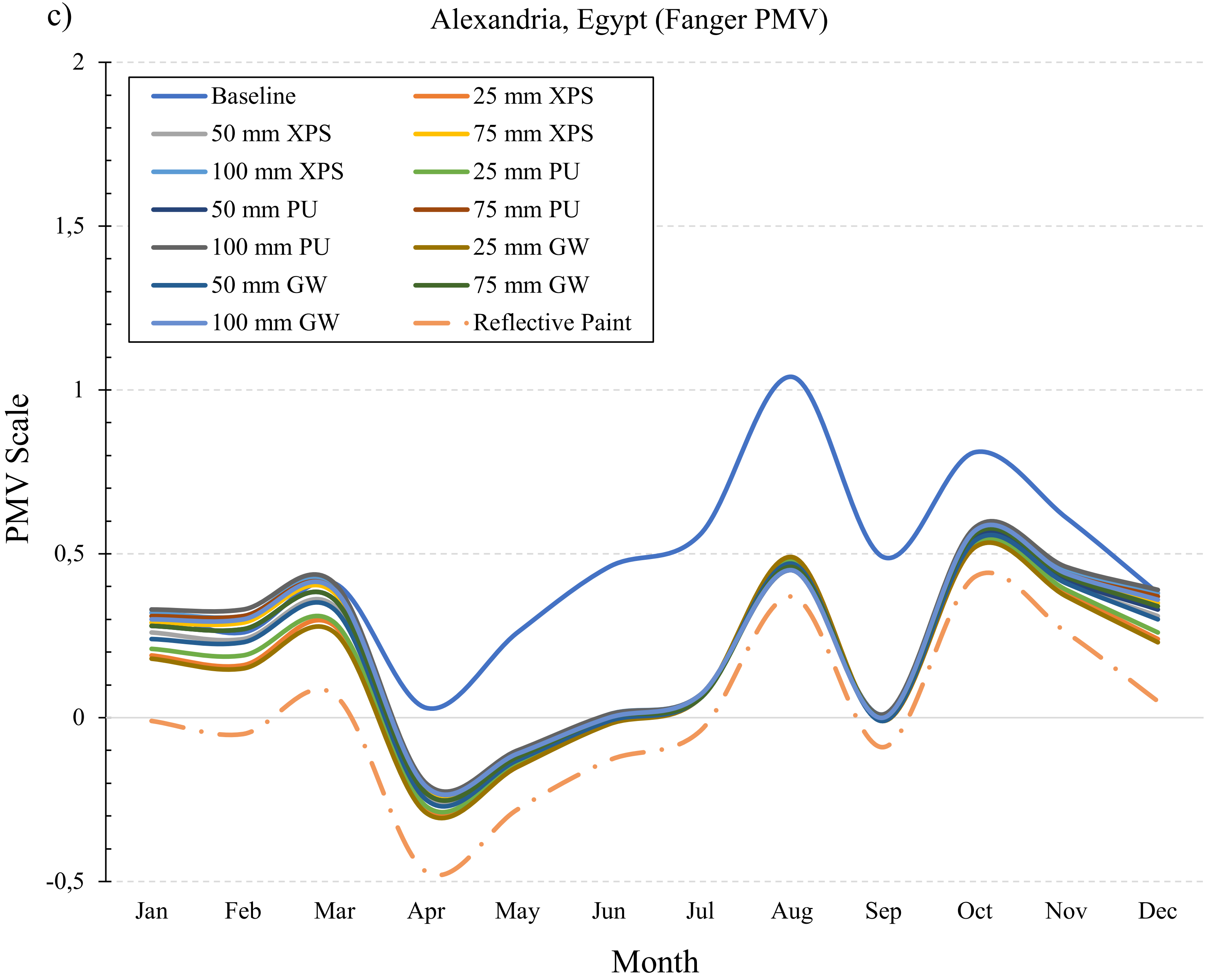


Figure 8. Resulting PMV of different insulations, a) Aswan, b) Cairo, c) Alexandria

Figure 8 illustrates the Fanger PMV outcomes for the three locations under investigation. In baseline models, the highest values of PMV are reached in Aswan, Cairo, and Alexandria, respectively. According to the dynamic simulations' outcomes, an improvement in indoor comfort can be easily noted. The simulations reveal that building envelopes retrofits in the three locations -almost efficiently- limit the human sensation between -0.5 (slightly cool) to +0.5 (slightly hot) most of the operating times.

Figure 9 relates the different insulating materials under investigation to DCHs and the percentage of their reduction. It highlights the importance of thermal insulation in reducing the resulting indoor discomfort. Besides the enviro-economic revenues, a percentage of discomfort hours reductions is notable due to the implementation. The study reveals that 100 mm PU reduces discomfort hours by about 30%. However, according to the balanced decision approach, PU is excluded due to its enviro-economic performance. Among the conventional insulations, a balanced decision would be the 25 mm XPS for both the enviro-economic and thermal comfort performance. Oppositely, the imported reflective paints thermal performance in Aswan is derived by the higher solar radiations in the location followed by Cairo and Alexandria. Due to its tremendous economic revenue, reflective paints should be imported and implemented in Egyptian buildings.

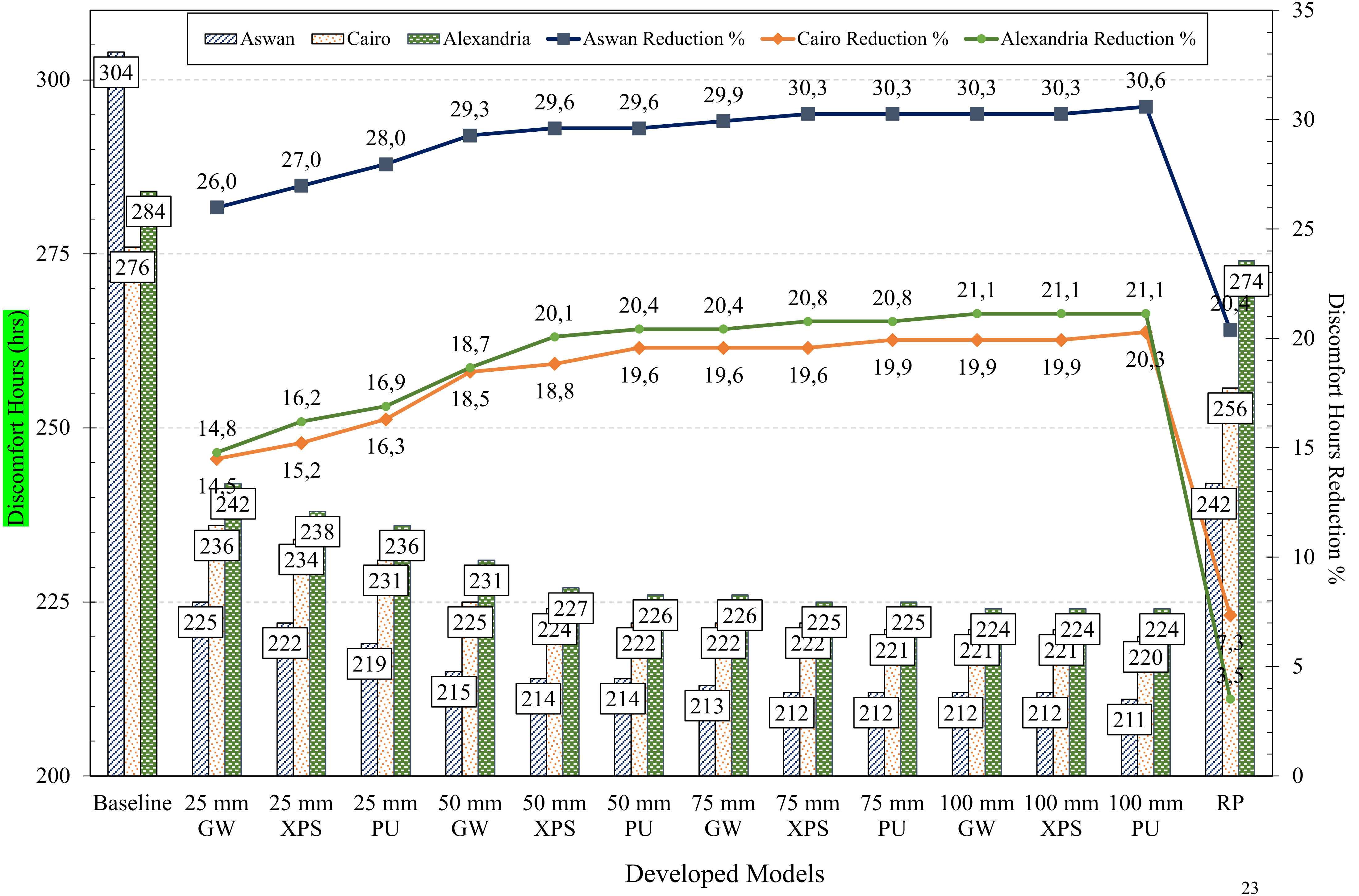


Figure 9. Discomfort hours and reduction percentage related to insulation type.

e. Weighted Decision

The decision-maker in a construction process should evaluate the efficiency of various energy-efficient solutions in terms of sustainability, making the multi-decision approach a useful tool for evaluating the whole system. Along with its high ability to weigh multiple alternatives with different factors for the selection of an appropriate solution, the multi-approach decision represents a reliable technique for analyzing difficult challenges.

Two methods have been proposed to the weighting of sustainability evaluation criteria: 1) equalize the weights of the parameters, and 2) give particular weight to each parameter [75]. This study undergoes a weighting technique to accurately improve the whole-building performance. The weighting methodology in this study has used three cost functions: 1) economic assessment, 2) environmental impact, and 3) thermal comfort. Building owners, experts, and consultants' opinions are surveyed upon the weighting percentage of each of the three cost functions. The survey resulted in 45% for thermal comfort, 35% for economic revenue, and 20% for environmental impact. Accordingly, the weighting methodology is implemented, and the outcomes are graphically illustrated in Figure 10 below.

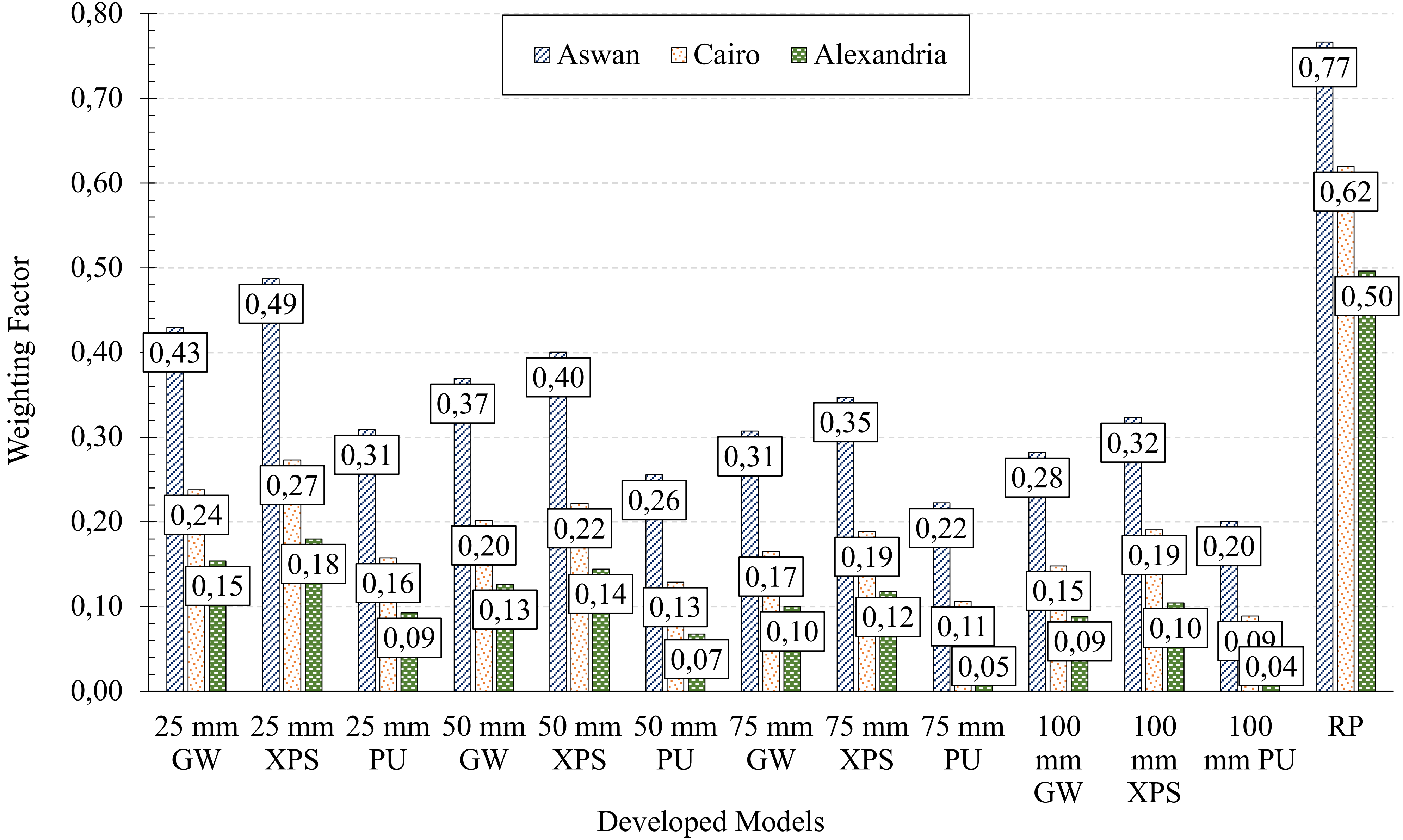


Figure 10. Weighted Decision Matrix outcomes

7. *Conclusion*

The multi-decision approach proposed in this study is a mindset about sustainability all in all, instead of one factor such as energy consumption. A local sensitivity analysis has been carried out to evaluate the influence of the insulating materials on the building's energy, thermal comfort, and performance of a previously validated institutional building in three different ASHRAE climate zones. This approach enables decision-makers to choose the most appropriate design options based on a balanced decision policy.

Concerning un-insulated buildings, the study outcomes can be outlined as:

1. The best energy and environmental response are obtained for the reflective paint material followed by extruded polystyrene, glass-wool, and polyurethane.
2. Among conventional insulating materials, the extruded polystyrene with 25 mm of thickness tends to be a cost-effective investment with the highest IRR, ROI, NPV, and the least PBP.
3. Nonetheless, thermal comfort should be given priority in the retrofit decision. Although reflective paints tend to be the best enviro-economic solution, the implementation of conventional insulations would reduce the DCH compared to baseline and reflective paints models in hot climates.
4. Reflective paints show the greatest enviro-economic benefits with energy savings of 21%, 19%, and 17% in parallel with a decrease in DCH of about 20%, 7.5%, and 3.5% respectively for Aswan, Cairo, and Alexandria.
5. Depending on the weights of different parameters, a balanced decision would be the reflective paints.

The local authorities in developing nations should consider enforcing energy standards to set energy efficiency minimum standards for newly developed buildings and to retrofit present buildings, ultimately contributing to reduced energy use, carbon dioxide emissions, and human discomfort hours.

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Appendix

This table represents the full economic analysis calculations.

Model	EGP/m^2	Aswan, Egypt				Cairo, Egypt				Alexandria, Egypt			
		IRR	ROI	NPV (EGP)	PBP (Years)	IRR	ROI	NPV (EGP)	PBP (Years)	IRR	ROI	NPV (EGP)	PBP (Years)
25 mm PU	115	41.51%	27.15%	1,062,393	2.2	19.12%	14.38%	271,514	4.2	5.56%	8.13%	-116,103	7.5
50 mm PU	200	27.27%	18.78%	942,969	3.2	9.67%	9.85%	-15,662	6.1	-2.96%	5.09%	527,367	11.9
75 mm PU	283	18.90%	14.27%	651,058	4.2	4.03%	7.52%	-377,475	8	-7.47%	3.81%	943,366	15.9
100 mm PU	358	13.65%	11.67%	322,579	5.2	-0.15%	6.01%	-770,100	10.1	-10.62%	3.05%	1,339,990	19.9
25 mm XPS	63	81.55%	52.72%	1,452,071	1.1	45.27%	29.47%	661,780	2.1	25.12%	17.58%	257,591	3.4
50 mm XPS	103	59.18%	38.24%	1,560,322	1.6	30.63%	20.69%	590,497	2.9	13.98%	11.83%	101,295	5.1
75 mm XPS	140	46.36%	30.15%	1,518,986	2	22.33%	16.07%	457,508	3.8	7.36%	8.86%	-85,666	6.8
100 mm XPS	165	40.69%	26.65%	1,478,102	2.3	18.86%	14.15%	368,154	4.3	4.19%	7.59%	-214,294	8
25 mm GW	71	69.79%	45.07%	1,334,618	1.3	38.20%	25.15%	576,458	2.4	20.53%	15.11%	194,565	4
50 mm GW	119	49.45%	32.08%	1,409,298	1.9	24.58%	17.28%	464,863	3.5	9.85%	9.93%	-4,241	6.1
75 mm GW	165	37.85%	24.94%	1,326,297	2.4	17.21%	13.41%	303,074	4.5	3.85%	7.45%	-226,218	8.1
100 mm GW	201	31.71%	21.31%	1,226,820	2.8	13.04%	11.39%	150,513	5.3	0.63%	6.27%	-404,113	9.7
RP	56	145.30%	94.63%	2,552,339	0.6	123.36%	80.17%	2,116,179	0.8	100.01%	64.81%	1,652,930	0.9

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