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Assessment of Passive Retrofitting Scenarios in Heritage Residential Buildings in Hot, Dry Climates

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Abstract: Retrofitting heritage buildings for energy efficiency is not always easy where cultural values are highly concerned, which requires an integrated approach. This paper aims to assess the potential of applying passive retrofitting scenarios to enhance indoor thermal comfort of heritage buildings in North Africa, as a hot climate, a little attention has been paid to retrofit built heritage in that climate. A mixed-mode ventilation residential building in Cairo, Egypt, was selected as a case study. The study combines field measurements and observations with energy simulations. A simulation model was created and calibrated on the basis of monitored data in the reference building, and the thermal comfort range was evaluated. Sets of passive retrofitting scenarios were proposed. The results (based on the ASHRAE-55-2020 adaptive comfort model at 90% acceptability limits) showed that the annual thermal comfort in the reference building is very low, i.e., 31.4%. The application of hybrid passive retrofitting scenarios significantly impacts indoor thermal comfort in the reference building, where annual comfort hours of up to 66% can be achieved. The originality of this work lies in identifying the most effective energy measures to improve indoor thermal comfort that are optimal from a conservation point of view. The findings contribute to set a comprehensive retrofitting tool that avoids potential risks for the conservation of residential heritage buildings in hot climates.

Keywords: adaptive thermal comfort; reference building; mixed-mode building; building simulation; field measurements; Egypt; downtown Cairo; Khedivial Cairo

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1. Introduction

The building sector, specifically residential buildings, is a significant contributor to global energy consumption [1,2]. Therefore, it is considered a promising sector for reducing energy use and the associated carbon emissions [3–6]. Accordingly, decreasing energy consumption in the building sector should include new construction, as well as existing and heritage buildings. On a global scale, heritage buildings constitute a large portion of the existing buildings [7]. Accordingly, enhancing their energy performance is an urgent need, particularly in hot climates [8]. Climate is an important factor in such contexts since it influences energy use to achieve comfort level. Moreover, attempts to reduce energy consumption usually are linked to thermal comfort improvements [9]. Therefore, two main groups of strategies for controlling indoor thermal comfort are active and passive strategies [10]. Passive strategies have become a fundamental approach of the retrofitting processes in hot climates [11].

Furthermore, building envelope as a fundamental factor in lowering energy consumption and responsibility for the solar and heat gains that influence indoor comfort conditions should be taken into serious consideration [12]. Additionally, the airtightness of building envelope components is another important building property that is usually overlooked. Poor airtightness usually causes some air movement through openings, cracks, and leaks in the building envelope, which affects its thermal performance [13]. Moreover, poor airtightness can lead to reduced indoor thermal comfort and increased ventilation and infiltration rate, affecting the indoor climate and energy use [14]. The process of retrofitting must also concern with the aspect of conservation of cultural values. Bastian and Alexandra (2015) noted that to improve heritage buildings' performance and preserve their character, windows and shading are important factors that should be dealt with care [15]. Additionally, external insulation materials are acceptable if they do not change the external appearance without any difference from the original render. The aerogel, for instance, is a type of insulation material applied in most retrofitted heritage building projects and is considered the proper type for this type of buildings [16–19].

Regarding the local picture, for instance, according to the Köppen climate classification system, the climate of Cairo, the capital of Egypt, is classified in Group B, which is known as an extremely hot and dry zone [20,21]. The change of climate conditions in Cairo for the past 30 years has led to depending mainly on electricity as a source of ventilation and cooling systems [22]. Moreover, in the period of 2016–2020 in Cairo, the average heating degree days (HDD), with a base temperature of 18.3 (°C), have been 390 days [23–25]. On the other hand, the average cooling degree days (CDD) during the same period, with a base temperature of 10 (°C), have been 4943 days [23–25]. In Cairo, 87% of the building stock, which consists of more than 688,000 buildings, belongs to residential buildings [26]. Moreover, Cairo has about 3300 heritage buildings, and most of them are also residential [27]. In Egypt, residential buildings consume about 42.3% of the total electricity consumption [28]. Furthermore, the insulation levels in residential buildings in Egypt are low, which in turn increases energy consumption [4,29]. More importantly, there are two Egyptian laws to conserve heritage buildings, and they do not include any improvements of energy performance or indoor thermal comfort. Likewise, Egyptian energy codes exclude the heritage buildings from their contents, which are considered the main obstacles that face retrofitting procedures in the Egyptian context [30–32].

On the basis of the above introduction, we are able to note that further studies are still required to find appropriate scenarios to retrofit such buildings in which their cultural values can obstruct retrofitting initiatives. This work contributes to filling the gap in this research field. Thus, it is organised into five sections. The literature review, research problem, and objectives are identified in this section. Section 2 explains the research methodology, which is divided into eight subsections. Section 3 analyses the results and specifies the indoor thermal comfort in the reference buildings. Sections 4 and 5 discuss the study results, their implications, and limitations.

1.1. Literature Review

With respect to the international picture, in southern Europe, where a warm summer continental climate prevails [33], retrofitting existing residential buildings has been addressed to improve indoor comfort conditions and reduce energy consumption. In Seville, southern Spain, Domínguez et al. (2013) assessed indoor conditions and energy consumption of 218 social housing units, considering inhabitants' behaviour to implement efficient, cost-effective intervention policies and energy actions. The results emphasised that in order to develop catalogues of retrofitting interventions, the socio-economic characteristics of inhabitants for each individual case should be investigated [34]. In Seville, Blázquez et al. (2019) proposed retrofitting strategies as a methodology of enhancing thermal comfort and energy saving of a heritage residential complex listed by the Andalusian Institute of Heritage Database [35]. The proposed methodology depended on mixing passive strategies such as improving window frame and glazing, increasing airtightness, installing controlled mechanical ventilation, and adding a thermal insulation layer. Another study conducted by Caro et al. (2020) in Seville, Spain, evaluated the indoor environment and energy performance of a representative residential heritage building in the summer season [36]. They concluded that some restrictions of retrofitting measures could be faced in the case study buildings because of their heritage assets. In Cordoba, southern Spain, Suárez et al. (2015) proposed a combination of passive retrofitting strategies such as adding thermal insulation for façades, increasing airtightness, adding solar protection, and allowing night-time ventilation [37]. These passive retrofitting strategies were applied in a residential building with 68 social housing units [37]. The results showed that around 38% reduction of the total energy demand was achieved compared to the base case [37]. In Donostia-San Sebastián, Spain, a study was conducted that focused on analysing airtightness in eight heritage buildings constructed between 1882 and 1919 [38]. The study carried out 37 tests in the eight buildings by using the Blower door test. The results classified the buildings into three levels on the basis of airtightness values: low, medium, and high, with a wide range between 0.68 and 37.12 air changes per hour (hereinafter, ach/h). Moreover, the results showed that five out of eight buildings are in the medium level of airtightness within the value range of 3–20 (ach/h) [38]. In addition, the study confirms that there is an undeniable distinction between the measured airtightness levels in heritage buildings and the values that are published about more recent buildings in other studies.

In Catania, southern Italy, Evola et al. (2015) analysed the transient behaviour of the building envelope of a 19th-century historical residential building by observing thermal comfort during the summer period [39]. The results showed that the night ventilation strategy is more effective than other passive cooling techniques. Adding a small layer of insulation can improve thermal comfort in the summer season [40]. In Naples, Italy, Rospi et al. (2017) highlighted that a significant improvement of energy use can be achieved in a hot climate by enhancing building envelope (opaque envelope and windows). Such improvements on the buildings' envelope allow maximum energy savings up to 27% [41]. They added that there is no better retrofitting scenario, but each scenario should be evaluated according to the building characteristics. In Naples, another study was carried out in a historical building by Bellia et al. (2015). The results indicated that thermal mass had a slight impact on improving indoor thermal comfort, while solar control and evaporative cooling significantly improved indoor thermal comfort [12]. In Perugia, Italy, a study reached great retrofitting achievements using integrated solutions by replacing window glazing as one of these solutions, using this glass type with "low-emissivity double pane glass with Argon in the cavity" [42].

In Athens, Greece, on the basis of EN ISO 13790, a study was conducted which classified naturally ventilated single-family buildings into three categories in terms of their airtightness: low, medium, and high, at a 50 Pa pressure difference between indoor and outdoor air [43]. The study revealed that buildings in the low category had airtightness of 10 (ach/h), medium had 4 to 10 (ach/h), and high had 4 (ach/h).

Regarding the local picture, on the one hand, many studies have been carried out to investigate energy use, thermal comfort, or both in existing residential buildings in Cairo, such as [3–5,20,22,29,44–47]. Most of these studies focused on building envelope and aimed at improving indoor comfort level and increasing the building energy efficiency of free-running (naturally ventilated) residential buildings. The studies discussed the effectiveness of passive strategies such as natural cross ventilation, thermal mass, and insulation. They also showed how passive techniques have a significant impact on reducing energy use in hot climates. On the other hand, very few studies have investigated the energy use or thermal comfort of heritage residential buildings in Cairo, such as [48,49]. Likewise, those studies focused on the building envelope of free-running buildings and highlighted that passive retrofitting strategies such as thermal mass and passive cooling can significantly improve indoor thermal comfort associated with low energy consumption.

1.2. The Research Problem and Objectives

The above literature shows a wide gap regarding the integration of thermal comfort, energy performance, and cultural values in hot climates, more specifically North Africa.

The selection of compatible retrofitting solutions requires an in-depth analysis of cultural values. Therefore, there is a need to investigate heritage buildings' thermal performance and provide updated recommendations to enhance indoor thermal comfort in "mixed-mode" residential buildings located in hot, dry climates. "Mixed-mode" buildings refer to the use of a mixed ventilation control inside buildings [50]. Natural ventilation is used and then switched over into air-conditioned mode whenever the natural ventilation is insufficient to provide occupants' comfort level. It should be noted that applying mixed-mode ventilation inside these buildings in such severe climates is considered a great potential and challenge at the same time [51]. Therefore, we aimed at assessing the potential of applying passive retrofitting scenarios to enhance indoor thermal comfort in a reference heritage residential building in a hot climate. Moreover, we also aimed at identifying the optimal passive retrofitting scenarios regarding indoor thermal comfort and compatibility with heritage conservation. Accordingly, the following questions were asked:

- To what extent can passive retrofitting strategies improve indoor thermal comfort in heritage residential buildings in hot, dry climates?
- What optimal scenarios can enhance indoor thermal comfort for such buildings while keeping their cultural values?

In order to find answers for these questions, we carried out a proposed conceptual framework, which is presented in Section 2. The added value of this work is not only to contribute to upgrade heritage retrofitting policies, guidelines, and building codes in the local context, which lacks such initiatives, but also to extend the results to more contexts with similar conditions and provide guidance for policymakers to upgrade standards of these vintage buildings.

2. Materials and Methods

We summarised the research methodology of this work in Figure 1. It is based on eight axes, which are described in the following subsections. Previous studies inspired the methodology of this research, such as the work of Mahar and Semahi [52,53].

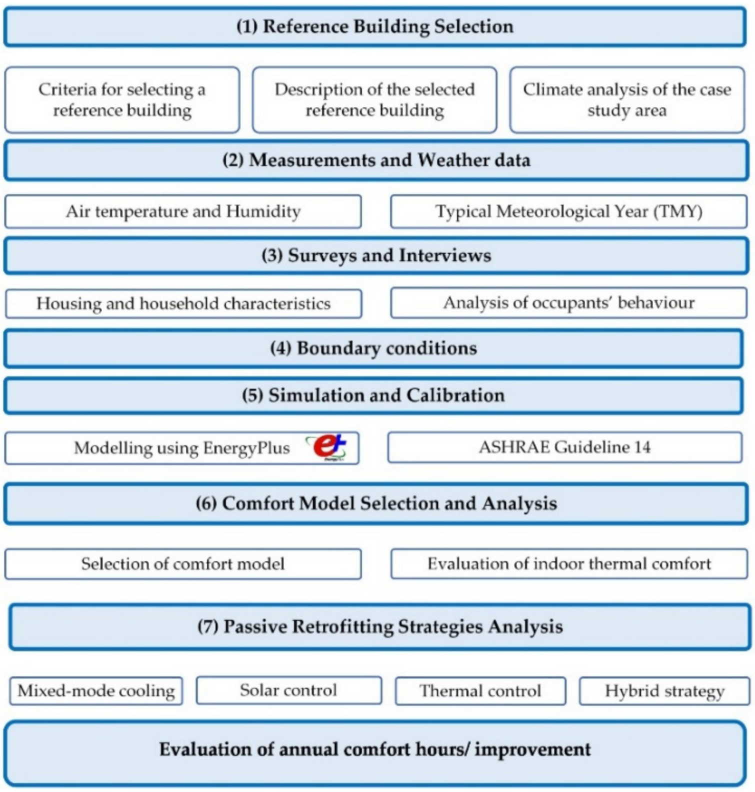

Figure 1. Conceptual study framework.

2.1. Reference Building Selection

A reference building in Khedivial Cairo (an area in downtown Cairo that acts as a "buffer zone" for the UNESCO Heritage Site of "Historic Cairo") acts as a case-study building to expand this concept to similar heritage residential buildings in other contexts with similar conditions. This area was chosen due to its significant cultural value [54–56]. According to the National Organisation of Urban Harmony (NOUH), Khedivial Cairo has 650 heritage buildings [27]. A total of 432 (68%) of them are residential buildings, comprising most of the buildings [26]. These buildings are classified into three categories as follows: A, B, and C, depending on the importance of the associated heritage values [55]. We selected A reference building inhabited by middle-income occupants as addressed by CAPMAS [26] to assess thermal comfort and a list of passive retrofitting scenarios.

2.1.1. Criteria for Selecting a Reference Building

Two criteria were used to select the reference building. The first criterion was the selection of the most significant building types that represent many of the buildings under this study. The second criterion was based on the ability of data collection and accessibility. There are substantial obstacles in accessing these buildings and carrying out field measurements and data collection surveys due to the valuable nature of the buildings and the fact that people inhabit them. This situation makes any field measurement and retrofitting intervention a challenging task. According to the work of Ibrahim et al. (2021), we classified (typology-based) the residential heritage stock in Khedivial Cairo into 12 classes that represented 12 reference buildings. Therefore, the most significant building class in terms of the number of buildings was selected. This class represented 20.8% of the total listed buildings, equal to 100 heritage residential buildings [8].

2.1.2. Description of the Selected Reference Building

In accordance with the above-mentioned criteria, we identified the reference building as a semidetached, multi-story building with a reinforced concrete structure (see Figure 2). The building was established in the 1900s with a New-Classic style. It is an apartment building, except for the fact that the ground and first floors are used commercially. An apartment on the seventh floor was selected, according to residents' willingness/acceptance, to install measurement tools and data loggers during the survey period. The selected building is a mixed-mode ventilation building that uses a mixed ventilation control inside spaces, natural ventilation and air conditioning (AC), split air conditioning units in summer, and personalised heating units in winter.

(**a**) (**b**) (**c**)

Figure 2. (**a**) Northern-west facade of the reference building; (**b**) main entrance; (**c**) typical plan of the seventh floor and the selected apartment (first author's Ph.D. research).

2.1.3. Climate Analysis of the Case Study Area

Cairo is located at a latitude of 30.1167 degrees north and longitude of 31.383 degrees east. The city falls in the arid climate zone with annual total radiation above 2409 bankable (kWh/m^2) per annum, with approximately 3300 h of full sunshine. Cairo receives about 8.15 mm of rain per year, especially in winter. The monthly average temperatures for July (summer) are 37 °C (highest degree) and 26 °C (lowest degree), while the monthly averages in January (winter) are 19 °C (highest degree) and 10 °C (lowest degree) [45,57,58].

2.2. Measurements and Weather Data

On-site monitoring of the indoor air temperature and relative humidity was performed in the selected apartment during the summer of 2019 and the winter of 2021. The indoor air temperature and relative humidity were monitored in three weeks from 30 July 2019 to 18 August 2019. The indoor air temperature and relative humidity were monitored for a week from 21 to 28 February 2021. Measurements were carried out inside a living room space of an apartment on the seventh-floor level. The air temperature and relative humidity were measured using data loggers (HOBO U12-012). To analyse the microclimate in the reference buildings in terms of indoor thermal comfort, we used the last version of the Typical Meteorological Year (TMY2) hourly weather data file for Cairo (2003–2017), on the basis of a study carried out by Attia (2015) in Cairo [20]. This TMY2 hourly weather data file for Cairo was used to represent the outdoor weather conditions.

2.3. Surveys and Interviews

2.3.1. Housing and Household Characteristics

Field surveys were performed in the summer of 2019 and in the winter of 2021, utilising a semi-structured interview with residents to identify the household and housing characteristics. The data obtained from the field surveys were analysed in depth to understand the occupancy pattern and operation schedules of electrical appliances. It was found that the living rooms were the most occupied spaces in the apartments during the day and a large part of the night. Examples of the basic, most needed appliances that equipped all apartments were fans, televisions, refrigerators, water heaters, and washing machines. Sixty people inhabit the reference building, and the selected apartment, which has data loggers, is inhabited by five people. An interview was conducted with the head of the household to collect the necessary information, which includes the household size, daily routines including activities, clothes usually worn at home, and weekday and weekend hours. This approach is inspired by the work of Attia (2015) and Mahar (2019) [20,52].

2.3.2. Analysis of Occupants' Behaviour

On the basis of the survey analysis, we found that the residents usually use different methods to adapt to the indoor environment. To change the indoor climate to satisfy their needs in summer, they change the set point of the air conditioner, open windows, ceiling fans, etc. Table 1 shows the most common methods to modify the indoor environment in the summer and winter seasons by occupants. It is noticed that the residents use mixed methods during day and night in order to modify the indoor thermal comfort in the summer. For example, they enhance natural ventilation in different ways and change the set point of air conditioning (split air conditioning units) when the indoor temperature exceeds 29 °C. On the other hand, in winter, the occupants usually use personalised heating units to adapt to the indoor environment, as shown in Table 1.

Table 1. Adaptive measures taken by occupants to modify the indoor environment in summer and winter.

Season	Adaptive Measures	Percentage of Occupants (%)
Summer	Opening windows	61.7
	Closing windows	18.2
	Opening outside blinds	11.2
	Closing outside blinds	9.3
	Opening doors	24.3
	Close doors	15.4
	Opening ceiling fans	38.8
	Opening inside curtains	25.2
	Closing inside curtains	18.7
	Opening portable fans	33.6
	Taking off some clothes	18.2
	Changing the set point of the air conditioner	57.7
	Others, taking a shower	0.9
Winter	Closing windows	68.2
	Closing outside blinds	9.3
	Putting on more clothes	44.6
	Drinking something hot	61.7
	Eating something hot	57.7
	Using personalised heating units	11.2

2.4. Boundary Conditions

This study is concerned with how to improve indoor thermal comfort in heritage residential buildings in the hot, dry climate of Egypt. Thus, the observable facts do not apply to other types of climates. More importantly, four physics phenomena were considered in this study: solar and internal heat gains, thermal conductivity, and airtightness/air infiltration of building envelope components. Presently, both solar heat gains and thermal conductivity are assumed to be variables. Additionally, since the heritage residential buildings of Khedival Cairo are actual existing buildings inhabited by residential households, the internal heat gains were therefore assumed to be constant values. Due to the lack of measurements of airtightness in the study area (Khedival Cairo), the airtightness was assumed to be a constant value. Moreover, the window-to-wall ratio (hereinafter, WWR) was assumed to be constant for the following reasons: (1) heritage value restrictions, (2) large annual solar irradiation, (3) the windows of these buildings are bigger than usual in relation to other window measurements within the Egyptian context, and finally (4) these buildings were perfectly designed in terms of daylighting with their current WWR.

Finally, building orientation is a crucial factor for investigating indoor thermal comfort, but in some cases, it might have no tangible impacts as in our present work. The urban tissue of the study area is characterised by wide streets, and in most buildings, only their main façades overlook to these streets, and all rest (if there) overlook the secondary or very narrow street (alley) [8]. Thus, in this present work, the selected building has three façades just one overlooking to the main street. Accordingly, only the current orientation of the selected building was studied.

2.5. Simulation and Calibration

DesignBuilder is a building energy modelling software package that is used to control internal building conditions. It was used in this study in order to create a virtual model which reflects reality on the basis of the collected data from surveys, interviews, and measurements. To simulate the internal building comfort condition, we conformed to comfort models/standards and provided a comprehensive thermal simulation. Afterwards, manual calibration was used to validate the virtual model of the reference building. A similar approach was used in previous studies [35,36,42,52,53].

2.5.1. Modelling

The reference building was modelled by using DesignBuilder. Table 2 shows the thermal properties of materials used in the reference building in terms of conductivity, specific heat capacity, and density. Those properties are based on the Egyptian guideline for specifications of building construction materials [59]. However, the thickness is based on the real construction of the reference building. Table 3 shows the input parameter of the simulation model. The occupancy profiles, windows and parameters of doors were deduced from the survey analysis. The primary energy use equipment (e.g., appliances, air conditioners, ceiling fans, lighting, water heaters) were calculated.

Table 2. Thermal properties of the building elements of the base case.

No.	Building Element	Outside to Inside	Composition	Thickness (m)	Conductivity * (W/m.k)	Specific Heat Capacity * (J/kg.k)	Density * (kg/m^3)
				t	λ	c_p	D
1	Exterior wall	Layer 1	Limestone, soft	0.02	0.93	900	1650
		Layer 2	Cement mortar	0.02	0.9	896	1570
		Layer 3	Burnt-brick	0.25	0.85	480	1500
		Layer 4	Cement plaster	0.02	0.72	840	1760
2	Internal wall	Layer 1	Cement plaster	0.02	0.72	840	1760
		Layer 2	Burnt-brick	0.12	0.85	480	1500
		Layer 3	Cement plaster	0.02	0.72	840	1760
3	Internal floor	Layer 1	Mosaico tiles	0.02	1.6	840	2450
		Layer 2	Cement mortar	0.02	0.9	896	1570
		Layer 3	Sand	0.06	0.33	800	1520
		Layer 4	Reinforced concrete slab	0.15	1.9	840	2300
		Layer 5	Cement plaster	0.02	0.72	840	1760
4	Ground floor	Layer 1	Mosaico tiles	0.02	1.6	840	2450
		Layer 2	Cement mortar	0.02	0.9	896	1570
		Layer 3	Sand	0.06	0.33	800	1520
		Layer 4	Concrete, cast, no fines	0.3	1.44	840	2460
5	Roof	Layer 1	Roofing tiles	0.02	1.5	1000	2100
		Layer 2	Cement mortar	0.02	0.9	896	1570
		Layer 3	Sand	0.06	0.33	800	1520
		Layer 4	Reinforced concrete slab	0.15	1.9	840	2300
		Layer 5	Cement plaster	0.02	0.72	840	1760

* Most of the thermal properties of materials are extracted from the Egyptian guideline for specifications of building construction materials [59].

2.5.2. Calibration

To validate the base case simulation model by software program, we compared the recorded indoor measurements for indoor air temperature (T_{in}) in the specified period with the simulated ones by DesignBuilder for the same spot in the same apartment. Manual calibration was used by following ASHRAE Standard 14 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) for calibration of the building simulation model [61]. In order to verify the reliability of results and to ensure the validity of the simulated model, we considered two statistical indexes: the normalised mean bias error (*NMBE*), and the coefficient of variation (*CV*) of the root mean squared error (*RMSE*). The *NMBE* is used to calculate the differences between values predicted by a model and the values that are measured, and the *CV* and *RMSE* are used to measure the error variability of results and whether overall the model can behave similarly to reality [35,52,53]. The *NMBE* and *CV*(*RMSE*) were calculated by the following two equations (Equations (1) and (2)):

$$NMBE = \frac{\sum_{i=1}^{Np} \cdot (Mi - Si)}{\sum_{i=1}^{Np} \cdot Mi} \ (\%) \quad (1)$$

$$CV\ RMSE = \frac{1}{M} \sqrt[2]{\frac{\sum_{i=1}^{Np} \cdot (Mi - Si)^2}{Np}} \ (\%) \quad (2)$$

where *Mi* and *Si* are the measured and simulated data at a time interval, respectively, and *Np* and *i* are the total number of data values used for the calculation.

Table 3. Input parameters of the base case (simulation model).

Model Input Measures		Parameters *
Building	No. of Floors	7
	Area (m^2)	800.5
	Volume (m^3)	22,393.75
Envelope	Air tightness (ac/h)	17.9 **
	WWR (window to wall ratio) (%)	18.2 N, 21 W, 21 E
	Window U value (W/m^2.K) single clear 3mm	5.73
	SHGC (solar heat gain coefficient)	0.81
	LT (light transmission)	0.898
	SC (shading coefficient)	0.99
	Roof solar reflectance	0.3
Occupancy	Density (people/m^2)	0.04
	Schedules	See Appendix A (Figures A1 and A2)
Lighting	Installation power density (W/m^2) living rooms	17
	Installation power density (W/m^2) bedrooms	13
	Installation power density (W/m^2) other	9
	Schedules	See Appendix A (Figure A3)
Ventilation and air conditioning	Outside air (m^3/h per person)	20
	Indoor air velocity (m/s)	0.1
	Temperature setpoint (°C)	Heating 21, Cooling 23
	COP/EER	2.00/6.8
DHW	Period 1 (October–April) (l/m^2/day)	0.35
	Period 2 (May–September) (l/m^2/day)	0.05
	Schedules	See Appendix A (Figure A4)
Plug loads	Average installation power density (W/m^2)	6 ***
Activity (metabolic rate)	Metabolism level	1.2
Clothing	Summer clo	0.5
	Winter clo	1.0

* Most of the model input values were cross-checked with the work of Attia (2012 and 2015) [20,22]; ** airtightness value was calculated on the basis of air change method that was mentioned in the Egyptian code for energy efficiency improvement in buildings [32] (see Appendix B); *** the power density and lighting profiles were based on the work of Attia et al. (2017) [60].

According to ASHRAE Standard 14 [61,62], the simulation model is considered calibrated if hourly values do not exceed 10% and 30% for *NMBE* and *CV* (*RMSE*), respectively, and if monthly values do not exceed 5% and 15% for *NMBE* and *CV* (*RMSE*), respectively [61]. Additionally, to graphically assess the accuracy and correlation between real measurements and predicted ones, we used a linear regression (R^2) analysis method [52].

2.6. Comfort Model Selection and Analysis

As the selected building is a mixed-mode ventilation building, since there is uncertainty about control strategies of indoor thermal comfort in a mixed-mode building, we assumed that this building is more similar in its operation to a naturally ventilated building than to a fully air-conditioned one, as indicated by de Dear, Attia, and Luo [63–65]. Moreover, to select a suitable comfort model for the reference building, we relied on previous studies carried out in the same climate conditions [20,64]. These studies compared four comfort models for Cairo climate and indicated its relevant, appropriate comfort model.

2.6.1. Comfort Model Selection

According to the above-mentioned studies, we selected the adaptive model of ASHRAE 55-2020 to determine the comfort range in the reference building. Additionally, de Dear and Brager's work indicted that the ASHRAE 55-2020 adaptive comfort model is more appropriate in hot climates and applicable for outdoor temperature ranges of 10–33 °C [63,66,67]. As a consequence, we built analyses on the basis of the ASHRAE comfort zone for the simulated reference case. This model represents a relation between mean outdoor air temperatures and the corresponding acceptable indoor air temperatures. Thus, for comfort hours throughout the year to be predicted by applying this model, two parameters are required:

- Indoor operative air temperature.
- Mean outdoor temperature.

The comfort temperature was calculated as shown in the equation (where T_{out} is the mean hourly outdoor average temperature). The comfort range was specified from T_{in} + 2.5 °C to $T_{in} - 2.5$ °C, as shown in the following equations:

$$Tc = 0.31\ (T_{out}) + 17.8 \quad (3)$$

Upper 90% acceptability limit (°C): $T_c = 0.31(T_{out}) + 20.3$ 10 °C $\leq (T_{out}) \leq$ 33.5 °C (4)

Lower 90% acceptability limit (°C): $T_c = 0.31(T_{out}) + 15.3$ 10 °C $\leq (T_{out}) \leq$ 33.5 °C (5)

As per studies carried out in Cairo climate by Sedki (2014) and Attia (2015), if the air velocity is low, the dry-bulb air temperature is therefore equal to mean radiant temperature (Tmrt) and operative temperature (OT) [20,47]. Therefore, we considered the measured air temperature to carry out thermal comfort calculations in this present study. On the basis of the field survey, we calculated the metabolic rate of the different activities observed during the field surveys (interviews and observations), as shown in Table 2.

2.6.2. Evaluation of Indoor Thermal Comfort

The manual calibration equations in Section 2.5.2 were applied to validate the building performance simulation model. Afterwards, the annual thermal comfort and discomfort hours of the reference building were calculated. The simulation results and analysis are described in Section 3.

2.7. Passive Retrofitting Strategies Analysis

For the thermal comfort of the reference building to be improved, a sensitivity analysis is necessary to test proposed retrofitting intervention scenarios. The proposed interventions are divided into four strategies, as shown in the following subsections.

2.7.1. Mixed-Mode Ventilation

In this study, three different mixed-mode ventilation scenarios were carried out, as shown in Table 4. The examined natural ventilation scenarios are listed into two groups: the first is based on a site survey, and the second one is a hypothetical scenario based on the literature review of similar methodological studies such as those of Suárez, Silvero, and Ezzeldin [37,40,50]. It should be noted that each proposed scenario in this study was integrated with active cooling (split air conditioning units).

Table 4. List of mixed-mode cooling scenarios.

Scenarios		Description
Group 1	Scenario A	(Diurnal) Windows are opened from 7 a.m. to 5 p.m.
	Scenario B	(Diurnal and nocturnal) Windows are opened from 7 a.m. to 11 a.m. + 5 p.m. to 11 p.m.
Group 2	Scenario C	(Nocturnal) Windows are opened from 1 a.m. to 7 a.m.

2.7.2. Solar Control

Changing Window Frames and Glazing

Two proposed windows glazing, frames, and shading types can be found in Table 5. Scenario "D" is a glass type that was used in a recently retrofitted heritage building located in Downtown Cairo [68]. Scenario "E" is a glass type that was recommended by a comparative analysis study in Cairo [69]. In this work, windows were modelled in terms of thickness, shading coefficient (SC), solar heat gain coefficient (SHGC), and light transmission (LT), as shown in Table 5.

Table 5. List of solar control scenarios. UPVC = unplasticised polyvinyl chloride.

Scenarios	Glass and Frame Type	Shading	SC	SHGC	LT
Scenario D	Low-E double-glazed clear 6 mm/6 mm argon, UPVC window frame	Outside shading, venetian blinds	0.40	0.344	0.518
Scenario E	Low-E double-glazed clear 6 mm/13 mm Air UPVC window frame	Outside shading, venetian blinds	0.65	0.568	0.745

Cool Roofing

Cool roofing techniques are known to have positive thermal comfort results for residential buildings, especially in climates that receive a large amount of solar radiation [70–73]. Therefore, in this study, white acrylic paint was used for the roof, as scenario "F", with the following specifications: thickness = 0.02 m, conductivity = 0.20 w/m-K, specific heat capacity = 1500.00 J/kg.k, density = 1050.00 kg/m^3, and reflectance = 0.99. These properties are based on the default materials in the DesignBuilder software (6.1.8.021).

2.7.3. Thermal Control

A list of proposed thermal insulation materials can be found in Table 6. The thermal insulation materials were modelled in terms of thickness, conductivity, specific heat capacity, and density.

Table 6. List of insulation materials that were modelled.

Scenarios	Location	Proposed Materials	Thickness (m)	Conductivity (w/m-K)	Specific Heat Capacity (J/kg.k)	Density (kg/m^3)
Scenario G	External walls, external insulations	Render Fixit 222 Aerogel *	0.02	0.028	1070	220
Scenario H	External walls, internal insulations	EPS (expanded polystyrene) **	0.1	0.035	1400	25
Scenario I	Roof	XPS (extruded polystyrene) **	0.1	0.034	1400	35

* The thermal properties of Render Fixit 222 Aerogel were extracted from aerogel application guideline [74] and were checked with [17]; ** the thermal properties of materials were extracted from the Egyptian guideline for specifications of building construction materials [59].

2.8. Evaluation of Annual Simulated Comfort Hours and Compatibilities with Legislations

Passive retrofitting scenarios were carried out, and the annual simulated comfort hours of the reference building were evaluated for each proposed retrofitting scenario, with the recommendation of the best scenario in each proposed strategy. Moreover, the proposed scenarios were evaluated in terms of two other performance targets: the potential of energy savings and compatibility with conservation of heritage significance. For the passive retrofitting scenarios to be effective regarding energy efficiency, we calculated annual energy use in kWh/m^2 and compared it with the base case. Additionally, to ensure the compatibility of these scenarios with local energy requirements, we compared the results to the Egyptian energy code of the existing residential buildings [32]. In addition, to guarantee that the scenarios respected the cultural values of the building components, we cross-checked the proposed scenarios with a checklist of the retrofitting interventions allowed in the Egyptian heritage grades revealed by Ibrahim et al. (2021) [8,68]. It is worth noting that in-depth analysis of energy use is not in our research scope and is somehow far from the study objectives, which were mentioned previously, but the potential of energy saving was mentioned in this present work for the previously mentioned reasons. The simulation results are analysed and are graphically presented in Section 3.

3. Results

3.1. Modelling and Validation

The measured indoor air temperatures were used to calibrate the simulation model for three weeks in the summer season. Thus, the *NMBE* and *CV* (*RMSE*) equations were applied, considering the limits accepted as mentioned in Section 2.4. Figure 3 shows the comparison between the measured and simulated indoor temperatures for the monitored periods. The *NMBE* of the calibrated model was −0.06%, and the *CV* (*RMSE*) was 1.08%. These values are lower than the recommended limits mentioned in ASHRAE Guideline 14. Accordingly, the simulation model was calibrated using hourly data.

We performed linear regression analysis to check the correlation between the simulated and monitored data. This method is also used to check the accuracy of the simulated model. The correlation coefficient (R^2) of 0.9118 shows a strong correlation to verify the calibration of the simulated model. (see Appendix A, Figure A5).

3.2. Annual Simulated Comfort Hours in the "Base Case"

The results of calculated comfort hours in the reference building can be found in Figure 4. It presents the comfort hours in the base case of the reference building (31.4%) from the total hours. It should be noted that the comfort percentage was calculated on the basis of the number of comfort ranges of the ASHRAE-55 adaptive comfort model at 90% acceptability limits.

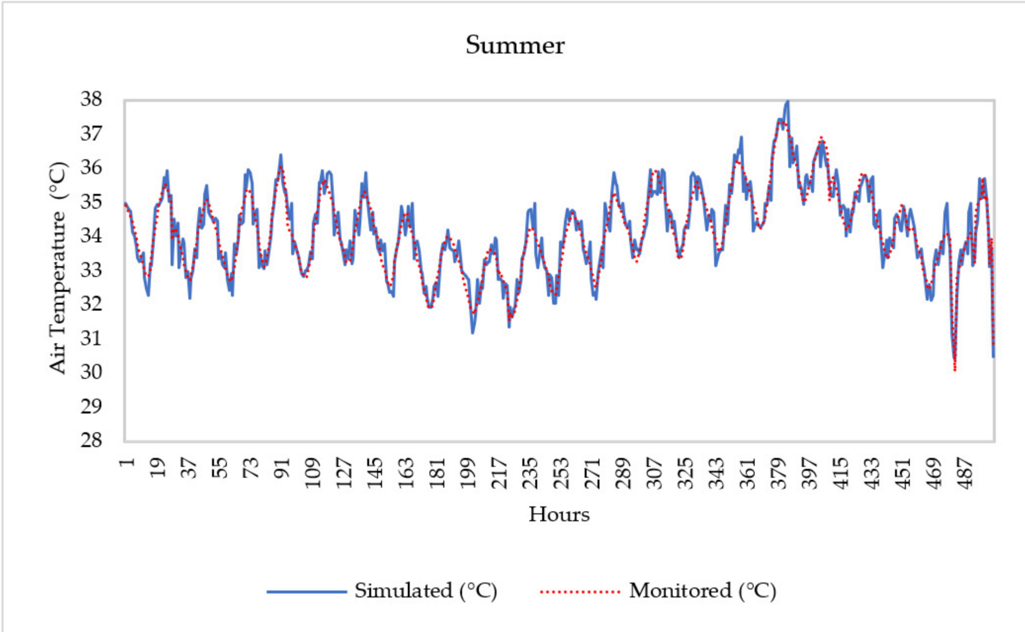

Figure 3. Validation of the calibration based on measured and simulated air temperature in the living room of the selected base case building during summer 2019.

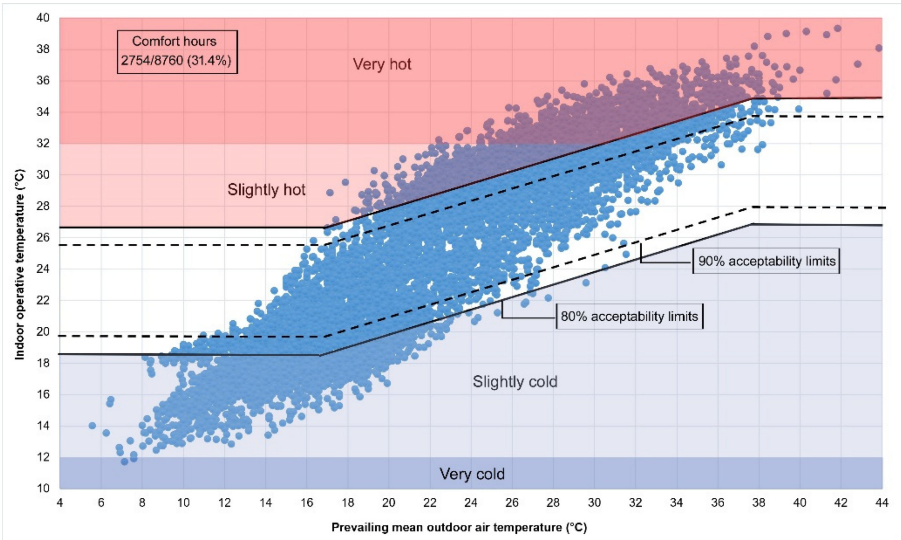

Figure 4. Comfort result and analysis of the base case of the reference building based on the ASHRAE-55-2020 adaptive comfort model at 90% acceptability limits.

3.3. Effect the Proposed Mixed-Mode Ventilation Strategy

The results of thermal comfort calculation hours in the reference building by applying mixed-mode ventilation scenarios can be found in Figure 5. Scenarios "A" and "B" increased the comfort hours in the reference building at 32.2% and 35.5% from the total hours, respectively. Scenario "C" increased the annual thermal comfort hours in the base case of the reference building from 31.4% to 42.2%. It can obviously be noticed that scenario "C" is the best mixed-mode ventilation scenario with comfort hours throughout the year, as shown in Figure 5.

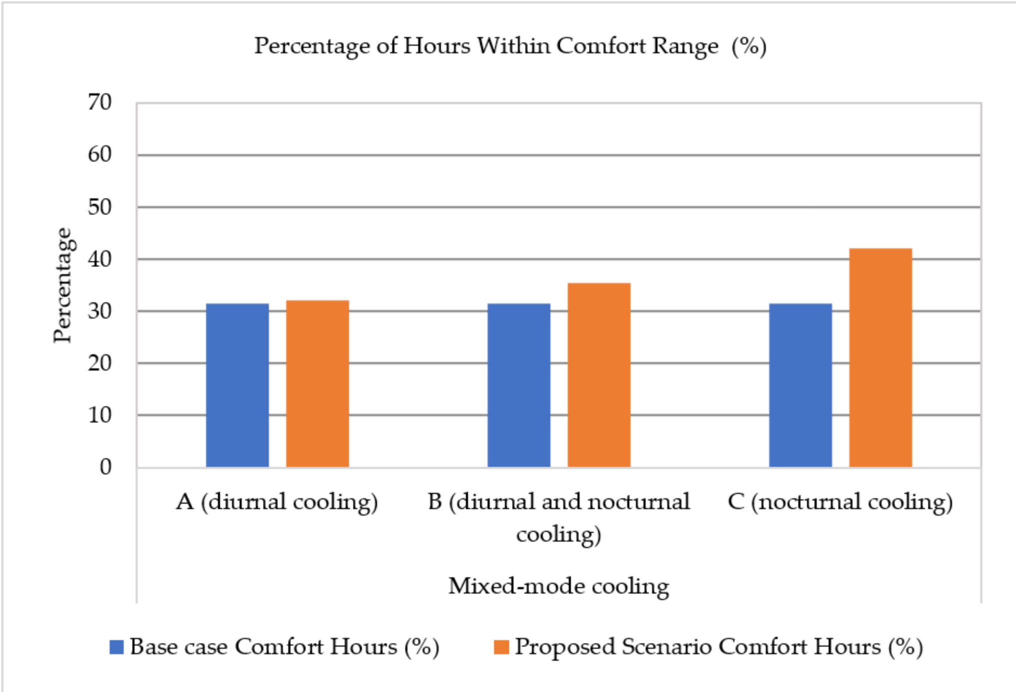

Figure 5. A comparison between the comfort hours in the base case and the proposed cooling scenarios.

3.4. Effect of the Solar Control Strategy

The results of calculated comfort hours of the solar control strategy in the reference building can be found in Figure 6. In both scenarios "D" and "E", which included changing window frames and glazing, the comfort hours in the reference building increased to 39.6% and 38.5% from the total hours, respectively. Scenario "F", which dealt with cool roofing, resulted in increasing the comfort hours in the reference building to 47.2%. It should be noted that the proposed scenario "F" is the most effective solar control scenario with white solar-reflective roof painting and comfort hours throughout the year, followed by scenario "D", which included double glazing windows with outside Venetian blinds, as shown in Figure 6.

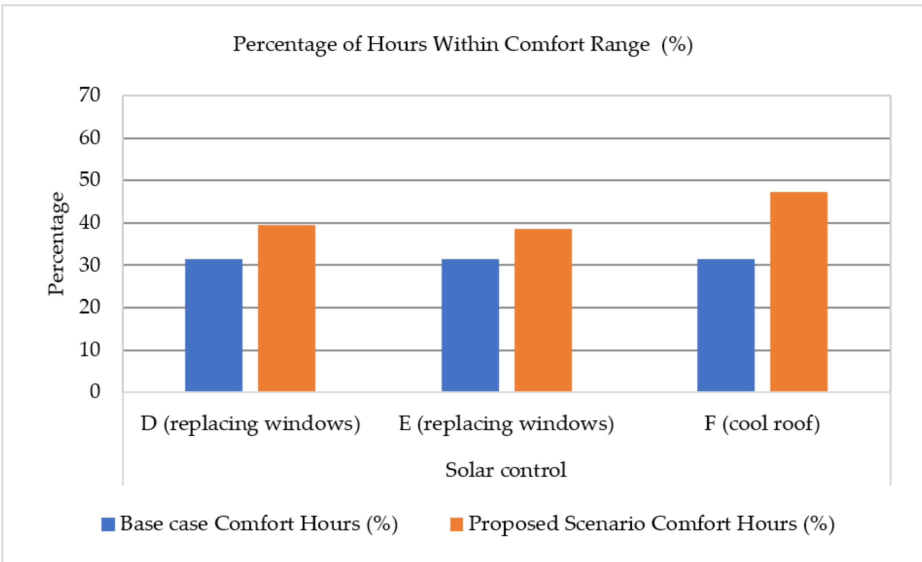

Figure 6. A comparison between the comfort hours in the base case and the proposed solar control strategy.

3.5. Effect of the Thermal Control Strategy

The results of calculated comfort hours of the thermal control strategy in the reference building can be found in Figure 7. Both scenarios "G" and "H" increased the annual thermal comfort hours in the base case of the reference building from 31.4% to 34.9% and 36.9% from the total hours, respectively. Scenario "I" increased the annual thermal comfort hours from 31.4% to 44.3% from the total hours. It should be noted that the proposed scenario "I" was the most effective thermal control scenario, using XPS roof thermal insulation material, with comfort hours throughout the year, as shown in Figure 7. It was followed by scenario "H", which included EPS wall internal insulation material.

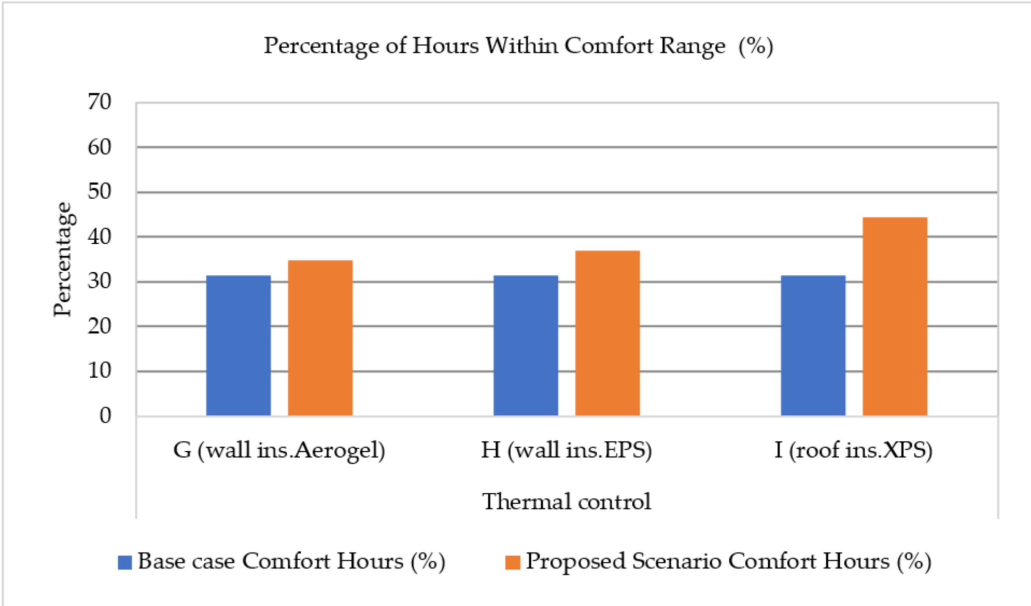

Figure 7. A comparison between the comfort hours in the base case and the proposed thermal control strategy.

3.6. Effect of the Hybrid Strategy

The results of calculated comfort hours of the hybrid strategy in the reference building can be found in Figure 8. By combining the best-obtained results from each above strategy, we found that the annual thermal comfort hours in the reference building were increased compared with the base case of the reference building, as shown in Figure 8. Moreover, the most effective hybrid scenario was scenario "M", followed by "L" and then "K". Accordingly, these hybrid scenarios "M", "L", and "K" increased the annual thermal comfort hours in the base case of the reference building from 31.4% to 65.9%, 62.6%, and 62.2%, respectively.

3.7. Evaluation of Annual Comfort Improvements and Compatibilities with Legislations

The proposed passive strategies and their impact on indoor thermal comfort were analysed, as shown in Table 7. This table provides all proposed scenarios together with the corresponding comfort improvement. Additionally, the table provides a description of changing the thermal performance of the base case by applying some passive retrofitting scenarios. Moreover, the table assesses each proposed scenario in terms of energy improvement and compatibility with local legislations. The proposed scenario "M" was considered the "optimum case" in regard to three performance targets: comfort, potential energy saving, and conservation of cultural values. Figure 9 shows the improvement of indoor thermal comfort of the "optimum case".

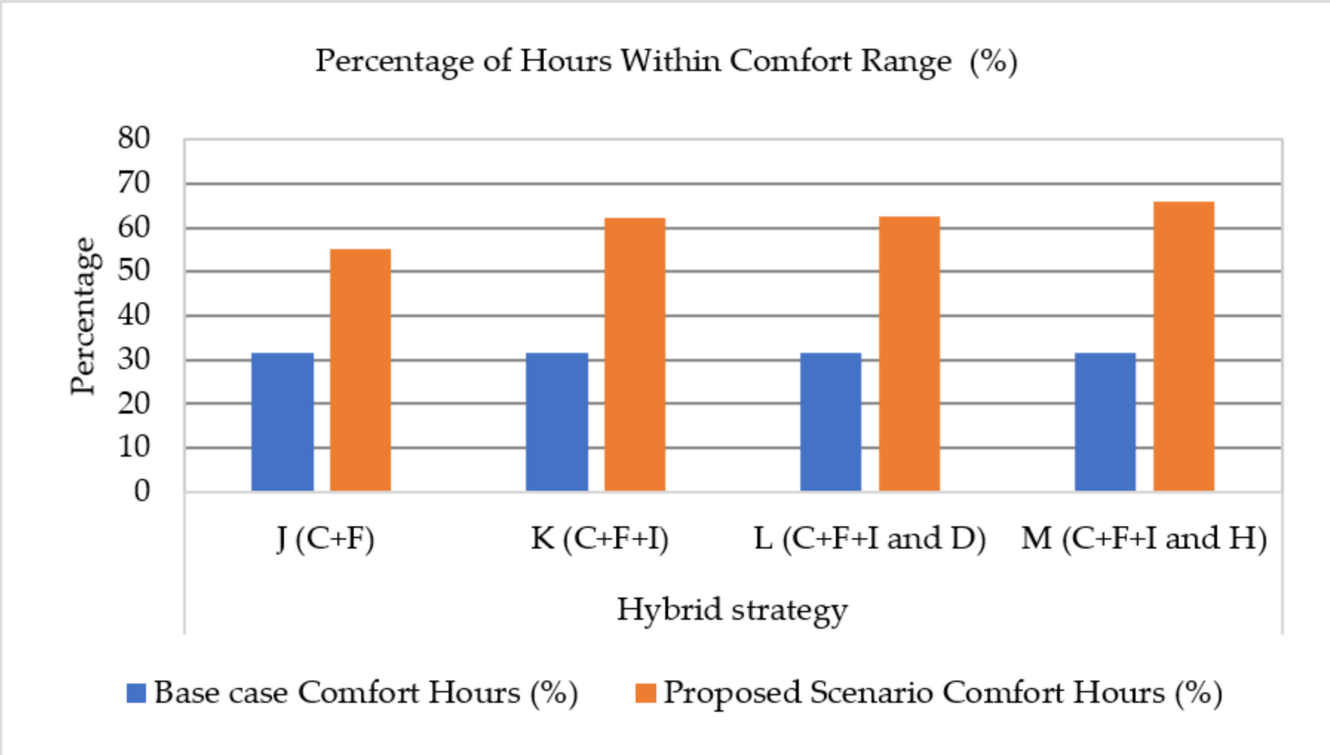

Figure 8. A comparison between the comfort hours in the base case and the proposed hybrid scenarios.

Table 7. Evaluation of the proposed scenarios to define the "optimum case".

Strategy	Scenario	Description	Comfort Hours (%)	Comfort Improvements (%)	* Energy Improvements (%)	** Compatibility with Egyptian Energy Code	*** Compatibility with the Limits of the Interventions Allowed in Heritage Grade B		
							Visual	Physical	Spatial
Cooling	**A**	Diurnal cooling	32.24	0.8	0.2	-	-	-	-
	B	Diurnal and nocturnal cooling	35.49	4.1	2.5	-	-	-	-
	C	Nocturnal cooling	42.17	10.7	11.0	-	-	-	-
Solar control	**D**	This scenario reduced SHGC of the external windows from 0.861 to 0.345, and SC was reduced from 0.99 to 0.4	39.61	8.2	19.2	✓	✓	✓	✓
	E	This scenario SHGC of the external windows from 0.861 to 0.568, and SC was reduced from 0.99 to 0.65	38.49	7.1	18.8	✓+	✓	✓	✓
	F	This scenario raised solar reflection factor of the roof from 0.3 to 0.9	47.23	15.8	24.4	✓	✓	✓	✓
Thermal control	**G**	This scenario raised the thermal resistance of the external walls from 0.53 to 1.08 m^2K/W	34.91	3.5	37.9	×	-	✓	✓
	H	This scenario raised the thermal resistance of the external walls from 0.53 to 3.22 m^2K/W	36.91	5.5	40.6	✓+	✓+	✓+	✓+
	I	This scenario raised the thermal resistance of the roof from 0.18 to 3.09 m^2K/W	44.33	12.9	44.9	✓+	✓+	✓+	✓+
Hybrid strategy	**J**	Combination of scenarios C and F	55.1	23.7	32.9	✓+	✓	✓	✓
	K	Combination of scenarios C, F, and I	62.2	30.7	36.7	✓+	✓	✓	✓
	L	Combination of scenarios C, F, I, and D	62.6	31.2	37.7	✓+	✓	✓	✓
	M	Combination of scenarios C, F, I, and H	65.9	34.5	56.3	✓+	✓+	✓+	✓+

* Electricity was the primary source of cooling, ventilation, heating system, lighting, and other systems, while natural gas was only used for cooking and domestic hot water (see Appendix A, Figure A6). ** The simulation results were compared to the Egyptian energy code of existing residential buildings in Cairo climate [32] (see Appendix A, Tables A1 and A2). *** The impact of each proposed scenario on the cultural values of the building was analysed in terms of the visual, physical, and spatial aspects (see Appendix, Table A3): (×) means incompatible, (-) means neutrally compatible, (✓) means compatible, (✓+) means highly compatible.

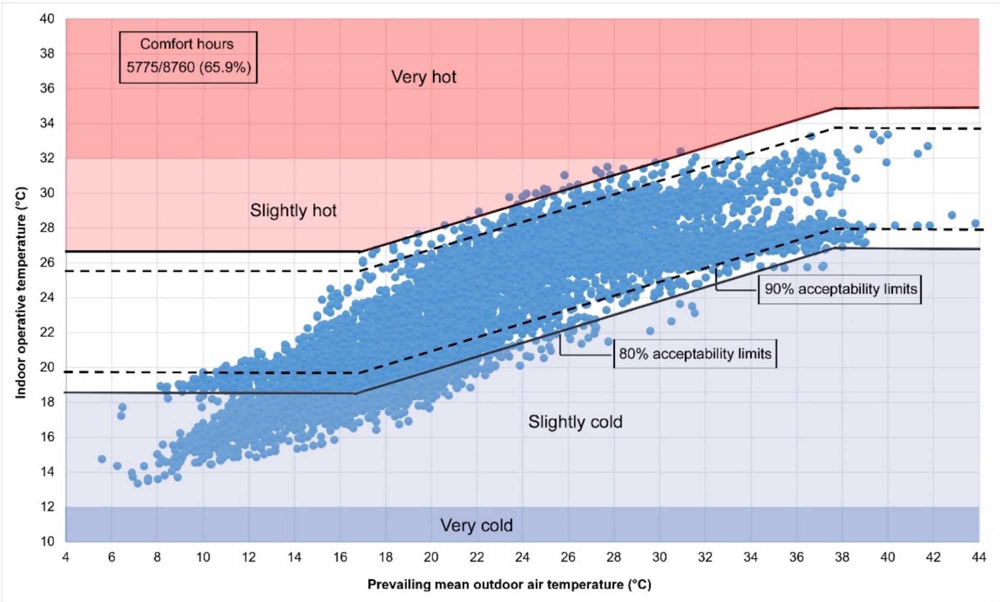

Figure 9. Comfort result and analysis of "optimum case" based on the ASHRAE-55-2020 adaptive comfort model at 90% acceptability limits.

4. Discussion

The results of this study were divided into three subsections: main findings and recommendations, strengths and limitations of the study, and study implications and future research.

4.1. Main Findings and Recommendations

The main findings of this study, which are listed below, show the potential of applying passive retrofitting strategies in a reference building in a hot, dry climate. The simulation results based on the ASHRAE-55-2020 adaptive comfort model at 90% acceptability limits showed that the reference building's base case has a very low indoor thermal comfort with an annual indoor comfort percentage of 31.4% from the total hours. According to this result of the reference building, about 20.8% of heritage residential buildings of Khedivial Cairo suffer under indoor thermal discomfort conditions. In order to improve indoor thermal comfort in the reference building, three passive retrofit strategies were proposed. The proposed strategies include mixed-mode ventilation, solar control, and thermal control.

By applying a mixed-mode ventilation strategy and diurnal natural ventilation, we found that the reference building's comfort hours barely increased with comfort improvement (0.8%) compared to the base case. By applying a combination of diurnal and nocturnal modes of ventilation, we found that the comfort hours in the reference building slightly increased with a comfort improvement of (4.1%). Moreover, up to (10.7%) of comfort improvement could be achieved by applying nocturnal natural ventilation with turning on supplementary active cooling (split units) only in the afternoons in summer. This scenario slightly reduced the annual energy use from 46.9 to 41.8 kWh/m^2, and it is neutrally compatible with the cultural values of the building components. Moreover, it is also neutrally compatible with the Egyptian Energy Code [32]. Accordingly, nocturnal natural ventilation is considered the most effective natural ventilation scenario to achieve indoor thermal comfort in the reference building.

By applying solar control strategy, we found that our results showed that 8.2% of comfort improvement can be achieved by replacing the original single-glazed windows with wooden frames and blinds with double-glazed, low emissive windows (6 mm + 6 mm argon gas) and more air-tight window frames (UPVC window frame), together with outside shading devices (Venetian blinds). Consequently, this scenario reduced SHGC of the external windows by 46% and reduced SC by 59% compared to the base case. More importantly, the results show that up to 15.8% of comfort improvement can be achieved by adding reflective material (acrylic white paint with thickness 0.02 m) for the roof. This scenario raised the solar reflection factor of the roof by 69.6% compared to the base case, reduced the annual energy use from 46.9 to 35.5 kWh/m^2, and is compatible with cultural values and the Egyptian Energy Code. It should be added that the application of cool roof technique is effective since the selected base case apartment is located on the top floor. However, this technique may not be useful for the apartments located on the intermediate floors.

By applying the thermal control strategy, we found that our results showed that only 3.5% of comfort improvement could be achieved by adding external thermal insulation material (Render Fixit 222Aerogel with thickness 0.02 m) for external walls. This scenario improved the external walls' thermal resistance by 50.5% compared to the base case. However, this scenario is incompatible with the Egyptian Energy Code regarding minimum requirements of resistance value (R) for Cairo climate (see Appendix A.).

Additionally, the results show that 5.5% of comfort improvement could be achieved by adding internal thermal insulation (EPS with thickness 0.1 m) for walls. Consequently, this scenario improved the thermal resistance of the external walls by 83.4% compared to the base case. More importantly, the results showed that up to 12.9% of comfort improvement can be achieved by adding thermal insulation (XPS with thickness 0.1 m) for the roof. Consequently, this scenario improved the thermal resistance of the roof by 94% compared to the base case, significantly reduced the annual energy use from 46.9 to 25.9 kwh/m^2, and was highly compatible with cultural values and the Egyptian Energy Code.

By comparing the above results to each other, we noticed comfort improvement in scenarios C (10.7%), F (15.8%), and I (12.9%), which are considered the best-obtained results. In addition, another comfort improvement was noticed in both scenarios D (8.2%) and H (5.5%). Therefore, these scenarios were combined for comfort improvement, as shown in scenarios J (23.7%), K (30.7%), L (31.2%), and M (34.5%). Scenario M reduced annual energy use from 46.9 to 20.5 kWh/m^2. Moreover, this scenario is highly compatible with cultural values and fully respects the heritage grade restrictions and retrofitting interventions allowed by the reference building recommended by Ibrahim et al. [8,68]. Accordingly, scenario M is the "optimum case" in terms of the three performance targets: comfort, potential energy saving, and conservation of cultural values.

Finally, in order to propose optimal retrofitting scenarios from comfort, energy, and conservation points of view, the initial step should be to determine possible interventions in each heritage significance grade/category. This will ensure preserving the cultural values of the heritage buildings. This work is a part of an ongoing wider scale PhD research project in which the previous phase focused on selecting a set of possible interventions and conservation scenarios based on experts' feedback, as well as analysing a real retrofitted heritage building. To summarise the benefits of the proposed scenarios, we have listed a set of recommendations below:

A. The application of mixed-mode ventilation in integrating nocturnal passive cooling strategies with active units only when strictly needed positively improves indoor thermal comfort. It offers further energy saving in hot, dry climates.
B. The application of solar control strategy—more specifically, painting roof surfaces with white solar-reflective paint—is a very effective way to reduce heat discomfort conditions. For example, flat roofs—as in Cairo—are exposed to a large amount of solar heat gains over the years, which influence indoor comfort conditions.
C. The application of a thermal control strategy—using thermal insulation materials for external walls or roofs—raises the thermal performance of the building envelope. The application of thermal control strategy is an essential approach in such severe climates.
D. The constraints of architectural visual values of heritage buildings can be a challenging aspect. For example, using very thin external insulations, such as Render Fixit 222 Aerogel, may not be good enough to improve indoor comfort. More importantly,

avoiding risks with architectural values is highly recommended if there are appropriate alternatives. Additionally, the disadvantage of adding aerogel is their high price compared to other insulation materials [17]. Thus, we recommend that an in-depth investigation of the economic aspect of selection materials is needed.

E. The application of hybrid passive strategies—a combination of appropriate scenarios—greatly enhances indoor thermal comfort and reduces annual energy use in heritage residential building stock in hot, dry climates.

F. The application of the optimum case in the heritage residential building stock of Khedival Cairo would improve the indoor thermal comfort for 100 heritage buildings with comfort improvement of (34.5%), compared to their current state. Consequently, that will lead to further energy saving.

G. Eventually, in order to achieve further indoor thermal comfort improvement in hot climates, the study recommends that an in-depth investigation of the operative temperature is needed. Another in-depth investigation is needed of the airtightness of building envelope components such as external walls and openings to enhance indoor thermal comfort, especially in air-conditioned buildings.

4.2. Strengths and Limitations of the Study

The strengths of this study lie in selecting a representative reference building for an important historical vintage era (Khedivial era) that can be used in future studies to perform sensitivity analysis, uncertainty analysis, and multi-objective optimisation. Moreover, this work identified the most effective energy conservation measures and passive design strategies to improve thermal comfort. Furthermore, this work provides guidance for designers and policymakers and allows for the possible upgrading of the building code and standards of this vintage area. Additionally, this work will facilitate the selection and sizing of active cooling systems in an effective, energy-efficient way after improving the envelope performance. However, in this present work, most recommended strategies rely strongly on natural ventilation. On the one hand, there could be a considerably high risk that the elevated rate of air pollution and noise can compromise the effectiveness of such strategies. On the other hand, relying on ventilation systems, mechanical or natural, into such buildings could be an effective solution to reduce some other risks such as infectious airborne viruses, as pointed out by a very recent study conducted in a heritage building in Saudi Arabia (hot climate) [75]. Therefore, there must be further investigation of the feasibility of relying strongly on diurnal and nocturnal ventilation. Moreover, the urban heat island effects should be taken into consideration in the feasibility assessment.

4.3. Study Implications and Recommendations for Future Research

This study addresses investigating thermal comfort in heritage buildings as an essential step towards setting a comprehensive tool for making decisions regarding the most cost-effective retrofitting procedures of built heritage in hot, dry climates. This will help researchers, designers, building professionals, and policymakers to enhance thermal comfort and occupant's well-being in the residential buildings which are listed as heritage. A heritage residential building in Khedivial Cairo acted as a case study for expanding this concept to similar heritage residential buildings in North Africa and hot, dry climates in general. Future work may focus on updating the Egyptian Building Code to include improvements in energy performance and indoor thermal comfort of heritage buildings. Moreover, a complete sensitivity and uncertainty analysis should be performed, exploring more design alternatives and combination with a larger sample of solution space. Additionally, the effectiveness of active cooling systems, including VRF (variable refrigerant flow) and mixed-mode operation modes, should be tested. Finally, the use of the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) thermal comfort model of ASHRAE 55 should also be considered options for households with senior occupants under fully space-conditioned modes.

5. Conclusions

In this paper, we aimed to assess the potential of passive retrofitting scenarios to improve indoor comfort in heritage residential buildings in a hot, dry climate. Moreover, we aimed at identifying the retrofitting solutions which are optimal in terms of three performance targets: indoor thermal comfort, potential energy saving, and conservation. The central questions revolved around to what extent passive retrofitting strategies can improve indoor thermal comfort in heritage residential buildings in hot, dry climates, and what potential scenarios that can enhance indoor thermal comfort for such buildings are while preserving their existing cultural values. A reference building in Khedivial Cairo was selected on the basis of specific criteria to expand this concept to other buildings with similar conditions in hot, dry climates. To find answers, we proposed sets of passive retrofitting strategies which we applied in the selected building. The proposed strategies include the following scenarios: (1) mixed-mode ventilation, (2) solar control, (3) thermal control, and (4) hybrid scenarios. The study's main findings revealed that the annual thermal comfort hours inside the base case of the reference building was at 31.4%, which is very low. The application of mixed-mode ventilation scenarios greatly impacts indoor thermal comfort, which offers further energy saving in hot climates. Moreover, the application of solar control scenarios such as replacing single-glazed windows with low emissive double-glazed ones for the external windows provides up to 8.2% indoor thermal comfort improvement. Additionally, painting roof surfaces with solar reflective material provides up to 15.8% comfort improvement. The application of thermal control scenarios such as adding thermal insulation material for roofs provides up to 12.9% comfort improvement. Finally, the application of hybrid scenarios can significantly improve the indoor thermal comfort inside heritage residential buildings. The "optimum case", for example, includes nocturnal passive cooling, adding white acrylic paint with thickness of 0.02 m for the roof, EPS with thickness of 0.1 m for walls, and XPS with thickness of 0.1 m for the roof. This scenario raised the reference building's annual thermal comfort from 31.4% to 65.9% from the total hours and improved the annual energy use of kWh/m^2 by 56.3% compared to the base case. Furthermore, this scenario was highly compatible with the cultural values of the building heritage grade.

The study results revealed many findings that can be useful for designers and policymakers to set a future direction for the improvement of indoor thermal comfort in heritage buildings located in hot climates. However, this study is limited by focusing on indoor thermal comfort in heritage residential buildings in hot climates. It does not address the feasibility of relying on natural ventilation or the effects of the urban heat island in this feasibility assessment. For future research, further important aspects such as the cost-effectiveness of selected materials should be considered in the preparatory phase of the retrofitting process.

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Institutional Review Board Statement: The institutional review board of FUE, Egypt, and ULB, Belgium, provided consent for this research and had no objections.

Informed Consent Statement: The residents of the buildings were informed regarding the research, survey, interview, and data collection. The authors can provide the essential data upon request, considering privacy and data protection.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the study's design; in the collection, analysis, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Schedules

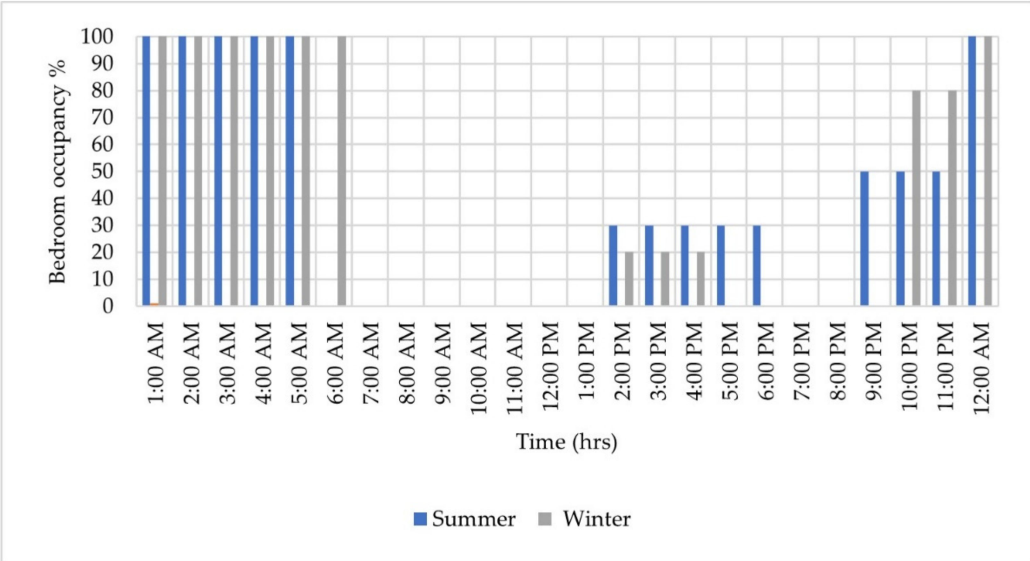

Figure A1. Bedroom occupancy schedule.

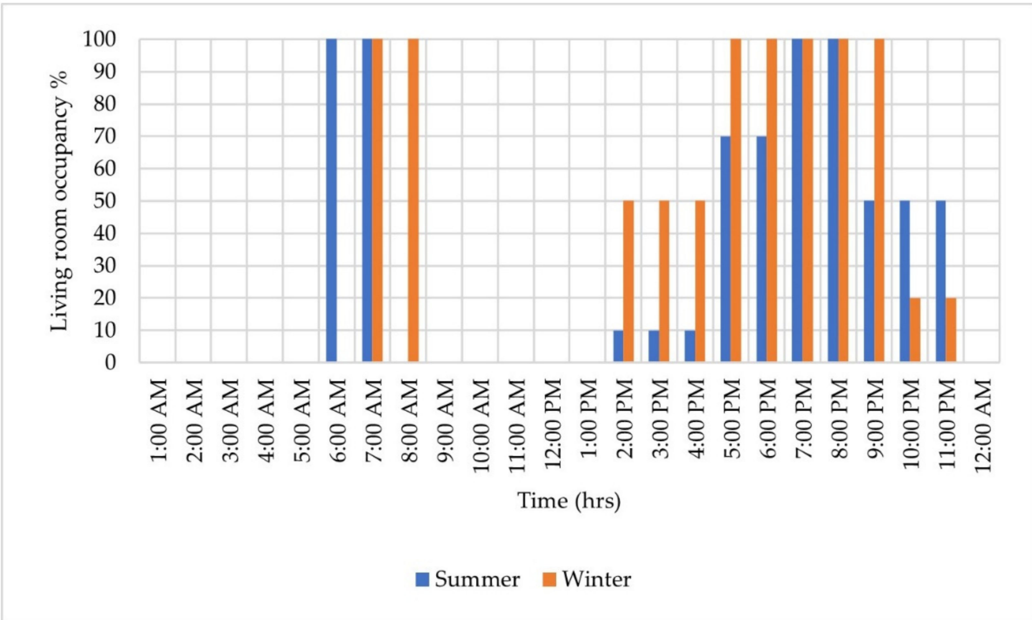

Figure A2. Living room occupancy schedule.

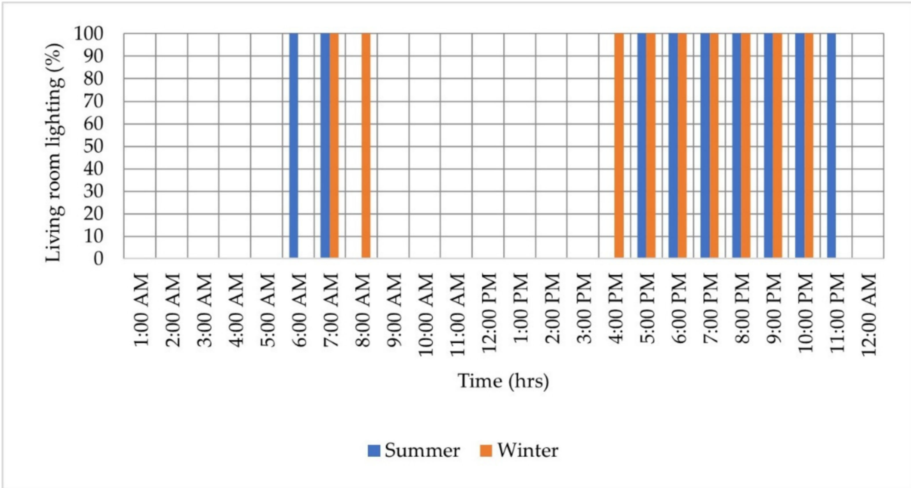

Figure A3. Lighting schedule of living room.

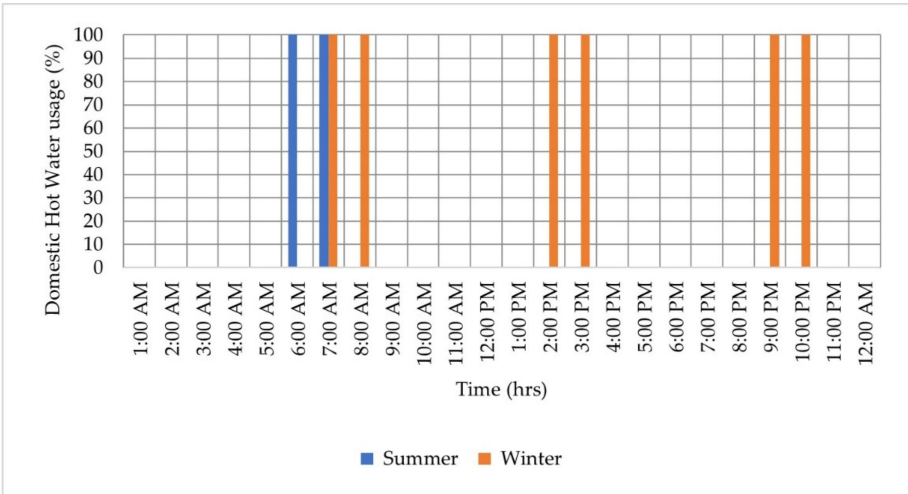

Figure A4. Domestic Hot Water schedule.

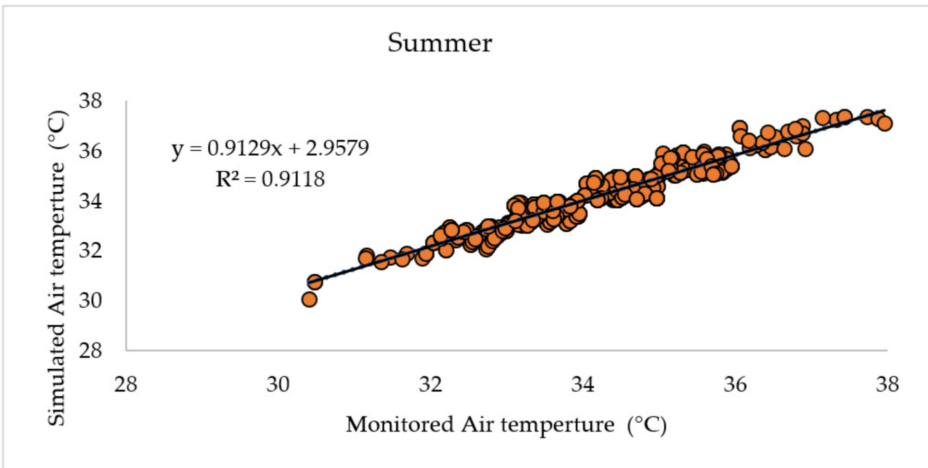

Figure A5. Linear regression analysis of calibration of the simulation model for summer.

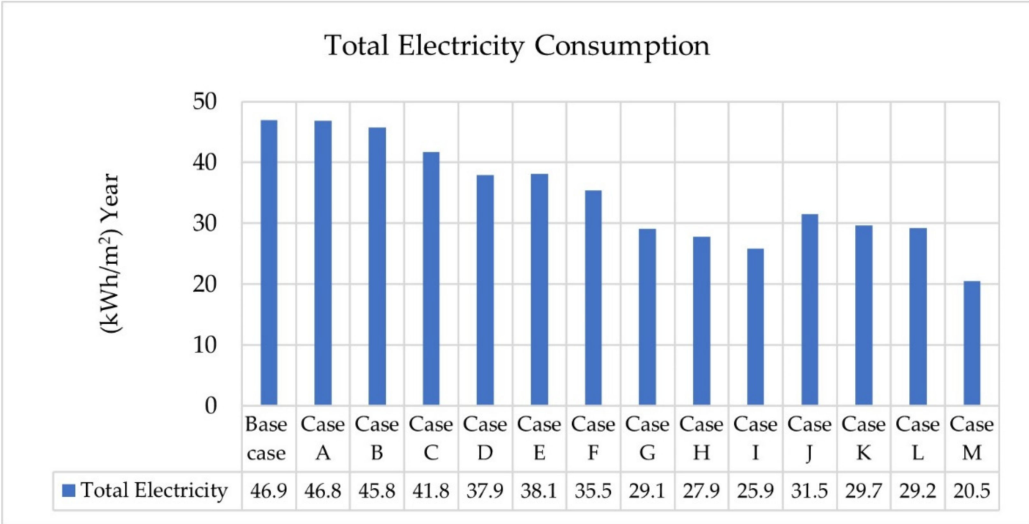

Figure A6. A comparison between the electricity consumption of the base case and the proposed scenarios.

Appendix A.1. Egyptian Energy Code of Existing Residential Buildings in Cairo Climate

Table A1. Minimum requirements of resistance value (R) for Cairo climate [32].

Location	Minimum Required of R Value (m^2.k/w)	
	Naturally Ventilated Building	Air-Conditioned Building
Roof	2.7	2.7
Northern wall	0.67	0.82
Northern-east wall	1.03	1.18
Northern-west wall	1.03	1.18
Southern wall	0.89	1.04
Southern-east wall	1.17	1.32
Southern-west wall	1.17	1.32
Eastern wall	1.35	1.5
Western wall	1.35	1.5

Table A2. The maximum value allowed for solar heat gain coefficient (SHGC) for Cairo climate with the window wall ratio (WWR) 10–20% [32].

Location	Solar Heat Gain Coefficient (SHGC)	SC
	For Naturally Ventilated and Air-Conditioned Building	
Northern wall	Not required	Not required
Northern-east wall	0.55	0.63
Northern-west wall	0.55	0.63
Southern wall	0.64	0.74
Southern-east wall	0.45	0.52
Southern-west wall	0.45	0.52
Eastern wall	0.45	0.52
Western wall	0.45	0.52

Appendix A.2. Checklist of Sustainable Retrofitting Scenarios

Table A3. Checklist of sustainable retrofitting scenarios for heritage Grade (B) in the Egyptian context, based on [8,30,55,68].

Heritage Value Locations	Elements	The Limits of the Interventions Allowed in Heritage Grade B		
		Heritage Value Types		
		Visual	Physical	Spatial
Urban district	Streetscape	P	P	P
	Roofscape	P	P	P
Building exterior	Finishes	P	R or C	P
External walls	Insulation	A *	A	A
	Decoration	P	R	P
	Finishes	R	R or C	R
Roof	Insulation	A	A	A
	Decoration	P	R	P
	Parapet	R	R or C	R
Windows	Glazing	R	R or C	R
	Frame	R	R or C	R
	Joints	R	R or C	R
	Shading	R	R or C	R
Doors	Frame	R	R or C	R
	Finishes	R	R or C	R
	Glazing/wooden	R	R or C	R
	finishes	R	R or C	R
Balconies	Decoration	P	R	P
	Handrail	R	R or C	R
Shops	Glazing	R	R or C	R
	Frame	R	R or C	R
	Signs	R	R or C	R
Building interior	Finishes	R	R or C	R
Internal walls	Decoration	P	R	P
	Finishes	R	R or C	R
Ceiling	Finishes	R	R or C	R
	Decoration	P	R	P
Windows	Glazing	R	R or C	R
	Frame	R	R or C	R
	Joints	R	R or C	R
Doors	Frame	R	R or C	R
	Finishes	R	R or C	R
	Glazing/wooden	R	R or C	R

Note: P, elements must be preserved; R, elements can be retrofitted; C, elements can be changed; R or C elements can be retrofitted or changed; NA, not allowed to add; A, allowed to add appropriate materials for architectural, cultural values; A * allowed to add materials not affect visual appearance.

Appendix B. Air Change Method to Calculate the Air Tightness Based on Airchange Method Mentioned in the Egyptian Code for Energy Efficiency Improvement in Buildings

$$Qv = \rho a.CP.V\ \Delta T \tag{A1}$$

$$Qv = 1200\ V\ \Delta T$$

$$\text{Air change/hour} - \text{ACH},\ Qv = \frac{1200}{3600n} V\ \Delta T = 0.3V\ \Delta T = Cv\ \Delta T \tag{A2}$$

$$Cv = \frac{1}{3} n\ V$$

$$n = 0.49 + 0.09\ VS \qquad \text{for closed windows}$$

$$n = 1.03 + 0.29\ V2S \qquad \text{for opened windows}$$

$$\text{Air change/hour} - \text{ACH},\ Qv = Cv\ \Delta T = 8.9 * 2 = 17.9$$

where Qv is the volumetric flow rate (Q = m^3/s) of the natural ventilation (v), ρa is the density of air (ρa = 1.2 kg/m^3), C_P is the specific heat capacities of air (C_P = 1.00 kJ/kg. °C), V is the air volume of the room, ΔT is difference in indoor–outdoor air temperature (°C), C_v is natural ventilation factor (W/m^2), n is number of air volume changes per hour, and V_s is wind speed (m/s) (V_s = 3 m/s) [32].

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