Article

Studying Energy Performance and Thermal Comfort Conditions in Heritage Buildings: A Case Study of Murabba Palace

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Abstract: Heritage buildings are significant historical and architecture added value, which requires deep and precise preliminary brainstorming when considering upgrading or retrofitting these valuable buildings. In this study, we opted to highlight some passive design architecture interventions to improve the thermal comfort and the required cooling energy for buildings. The Murabba Palace in Riyadh was selected as a case study. DesignBuilder software was used to evaluate the energy performance of ten passive architectural design alternatives throughout different seasons in an attempt to improve the energy performance and thermal comfort of heritage buildings. The ten passive design scenarios encompassed double low-E glass, double reflected glass, double low-E glass and double wall with an air gap, double low-E glass and double wall with thermal insulation, double low-E glass and double wall with lightweight thermal insulation, double low-E glass and double wall with sprayed foam insulation, double reflected glass and double wall with an air gap, double reflected glass and double wall with thermal insulation, double reflected glass and double wall with lightweight thermal insulation, and double reflected glass and double wall with sprayed foam insulation. The results show that using double low-E glass and applying a double wall with polystyrene thermal insulation can enhance the thermal comfort inside the building and reduce the energy performance and CO2 emissions to 17% and 9%, respectively.

Keywords: heritage buildings; passive design; energy conservation; reduction in CO2 emissions

1. Introduction

Heritage buildings are integral parts of modern life, in which they gain their significance from their historical, archeological, and cultural added value, and signify the rich histories of countries [1–4]. In addition, heritage buildings are recognized for their abilities to improve the cultural and architectural significance of societies [5]. It is found that existing buildings contribute to 40% of the total primary energy consumption and 36% of carbon dioxide emissions [6]. Moreover, it was reported that energy consumption in built environments increases by 1.5% per year [7]. Heritage buildings represent a considerable proportion of existing buildings across different countries [8]. It was delineated that retrofitting existing buildings has prospective capabilities to diminish the levels of energy consumption and greenhouse gases [9,10].

In view of the rapid growth of energy consumption, it is necessary to improve the energy performance and indoor thermal comfort of an as-built building and preserve its heritage value through energy-efficient retrofitting measures. This is the role of introducing passive architectural design by precisely choosing building materials and additions [11–13].
Accordingly, the aim of this research was to highlight some passive architectural alternatives that can enhance indoor thermal comfort, reduce the energy required for cooling, and minimize CO\textsubscript{2} emissions.

Heritage buildings inherited from the past are a crucial component of our modern society. Heritage buildings include structures, artifacts, and historical, aesthetically, and architecturally significant areas. Figure 1 shows the number of world heritage properties inscribed each year per region. As of July 2019, 1121 World Heritage Sites were located in 167 states around the globe. Additionally, three key factors determine whether a property is worth being listed as heritage—historical significance, integrity, and historical context. Historical relevance is related to the property’s value to a community’s history, archaeology, engineering, or culture. This includes any heritage building associated with a past event or an important person and buildings with distinctive physical characteristics. Historic integrity is relevant to the authenticity of a building’s identity with existing evidence of its unique physical characteristics during the building’s historical period [14].

According to Al-Sakkaf et al. [3,4,15], the trends of protection and the use of heritage buildings and cultural heritage components testify to the increasing attention paid to studying heritage and legacy. Studies have shown that project life cycle phases have been developed to evaluate the performance of buildings in general. Nevertheless, heritage buildings and their need have not been considered. In heritage building projects, there are six life cycle phases, including (a) planning, (b) manufacturing, (c) transportation, (d) construction, (e) operation, and (f) maintenance phases. In addition, there is a lack of a comprehensive rating system that could assess the heritage buildings’ elements and study the possibility of passive design architecture interventions to evaluate the thermal comfort interims of energy for heritage buildings.

This paper will assist facility managers in their rehabilitation decisions. The authors opted to highlight some passive design architecture interventions to improve the thermal comfort and the required cooling energy for buildings. Accordingly, the case study used in this research was the Murabba Palace in Saudi Arabia.
Heritage buildings require reliable restoration, preservation procedures, and evaluations of the performance of heritage building interiors in terms of thermal comfort and user satisfaction. Therefore, it is essential to develop a sustainability rating system that accounts for socioeconomic factors to manage the maintenance of heritage buildings. For instance, BREEAM and LEED rating systems cannot be employed in the Middle East because of different climatic conditions and local contexts [4,16]. A sustainability rating tool can be defined as a systematic methodology to examine the overall sustainability assessment of a whole building. This includes economic, environmental, social, cultural, and value-based aspects. Thus, the outcome of such a tool can be used as a means of comparison with other buildings [2]. Around the globe, many rating systems pertain to different areas of sustainable development. By March 2010, there were 382 registered building software tools for sustainability development [3]. Nevertheless, only a few systems are well established and recognized by the World Green Building Council. This comprises Green Globes, Green Building Index, Green Building Program (GBP), Green ship Indonesia, Green Globes, BREEAM, LEED, and more.

Another essential aspect that affects building performance is orientation. Building orientation can maximize opportunities for passive solar heating when needed, solar heat gains avoidance during cooling time, natural ventilation, and daylighting throughout the year. For example, southern exposure is the key physical orientation feature for passive solar energy in the northern hemisphere. In general, a south-facing orientation within 30° east or west of true south will provide around 90% of the maximum static solar collection potential. The optimum directional orientation depends on site-specific factors and on local landscape features, such as trees, hills, or other buildings, which may shade the sunspace during certain times of the day. Rectangular buildings should be oriented with the long axis running east–west, so the east and west walls receive less sunlight in the summer. In the winter, passive solar heat gain occurs on the south side of the building [3,16,17].

The primary objectives of the present research paper include the following:
1. Review state-of-the-art models pertinent to the analysis of energy consumption in heritage buildings.
2. Propose a simulation-based model for analyzing energy consumption and the thermal comfort of passive architectural design alternatives.

This paper follows several steps, starting with a brief introduction that describes the problem statement and the aim. Then, Section 3 presents the methodology, the case study data, the DesignBuilder simulation software calibration, data entry, and passive design alternatives and data entry. The paper ends with the results and a conclusion.

2. Literature Review

This section addresses the work pertinent to the assessment of sustainability and energy efficiency of heritage buildings. Fiore et al. [18] introduced a multi-criteria decision-making approach for comparing intervention alternatives for historic buildings. The evaluation criteria were preservation, seismic safety, energy efficiency, environmental sustainability, disturbance to users, time of realization, and economic sustainability. It was highlighted that the developed approach can enable delegated agencies and administrations to plan for intervention actions of historic buildings. Ruiz-Jaramillo et al. [19] presented a global index to prioritize municipal historic preservation projects. Different construction components were studied, including foundations, vertical structures, horizontal structures, roofs, envelopes, partitions, finishes, and water facilities. It was illustrated that the resultant ranking index could enable the diagnosis of the conservation of heritage buildings.

Abdelrazik and Marzouk [20] explored the parameters influencing the maintenance of heritage buildings. Thirty-six parameters were gathered and divided into six main categories, namely cultural, architectural, geotechnical, structural, materials, and external. In this regard, a relative importance index was utilized to prioritize the influential parameters according to a five-point Likert scale. It was concluded that the top important parameters
involved the settlement of infrastructure, building characteristics, soil bearing strength, groundwater level, and the assessment of the foundation’s condition. Sodangi et al. [21] presented a visual inspection-based model to interpret the physical condition of heritage buildings. Several defects were studied, such as leakage, cracks, cracks, faulty installation, decay, and sagging. An average prioritization index is computed based on the severity levels of defects. It was indicated that the developed model could boost maintenance management practices in heritage buildings.

Mushtaha et al. [22] deployed an analytical hierarchy process to investigate sustainability indicators in heritage and modern buildings. A survey was created to gather feedback from the experts regarding the importance of sustainability criteria and sub-criteria. The main criteria encompassed materials, environmental design, economic design, and social dimension. A sensitivity analysis was carried out to measure the effect of the main criteria on the ranking of targeted alternatives. It was concluded that environmental design and economic design nearly share the same relative importance, and materials were found as the least important main criteria, with 12.3%. Ismail et al. [23] proposed a decision support system for the assessment of heritage concrete buildings. The developed framework encompassed a defect reporting assessment such that the components of the buildings were evaluated based on cracking, jointing, and leaking. A maintenance index was then constructed based on the severity levels of defects to collectively diagnose the structural conditions of the heritage building.

Prieto et al. [24] investigated the impacts of intervention actions on the functionality of heritage buildings. A fuzzy inference system that incorporated the use of an expert knowledge survey was designed to interpret the functional level of buildings and assess variations over their service life. The results showed that the restoration of religious elements in the building does not implicate their functionality level. Pavlovskis et al. [25] introduced an integrated model of building information modeling and multi-criteria decision making to analyze heritage building conversion alternatives. Digital photogrammetry and 3D model was created for the accurate representation of external textured and internal features of historic buildings. The heritage preservation solutions were assessed based on five groups of criteria, namely economic benefit, influence on the social environment, impact on the natural environment, cultural value, and architectural possibilities. A rough weighted aggregated sum product assessment was employed for the sake of ranking three building conversion design alternatives. It was shown that preserving a building’s authenticity was found as the most important criterion, while benefits for private business criteria were ranked as the least important. In addition, the alternative of the establishment of a tourist information center with a permanent museum was determined as the most optimum building conversion criterion.

Haroun et al. [26] introduced a multi-criteria decision-making framework to address the reuse selection of heritage buildings. The evaluation criteria included heritage value, architectural value, economic performance, social value, and environmental impact. An analytical hierarchy process was employed to weigh the attributes and rank the four design alternatives of hotel, museum, office building, and mixed uses. It was illustrated that the created framework could improve the decision-making process of adaptive reuse in heritage buildings. Kayan et al. [27] introduced a green maintenance model for analyzing paint repair options in heritage buildings. The green maintenance framework was designed to compute the total embodied carbon expenditure consumed by three maintenance options, namely one coat, two coats, and three coats of paint repair on roof surfaces. It was derived that three coats of paint repair has the highest longevity; however, it exhibits the highest consumption of embodied carbon expenditure.

Dyson et al. [28] studied critical success factors in implementing retrofitting measures in heritage buildings. Semi-structured interviews were undertaken to gather the opinions of stakeholders regarding the critical success factors. Four relevant critical success factors were identified, including research, matching function, design, and minimal change. It was also urged that addressing these critical success factors could enable minimizing the
uncertainties pertaining to commercial risk, building layout, and latent conditions. Kutut et al. [29] proposed a multi-criteria decision-making model for the appraisal of building alternatives for the preservation of building alternatives. An analytical hierarchy process was exploited to compute the relative importance weights of judging attributes. These attributes comprised the value of the building, pollution of the façade, the investment required for restoration of cultural property, distance from the center of the old town, and more. An additive ratio assessment was used to identify the alternative with the highest utility degree. It was argued that the investment required for restoration was the most important criterion, with 34.4%, and the pollution of the façade was the least important, with 2.9%. In view of the above, it can be seen that there is a lack of studies that have analyzed the energy consumption and thermal comfort of retrofitting measures of heritage buildings.

3. Methodology

The methodology of this research that was followed to enhance the energy performance of the Murabba Palace heritage building was divided into three main parts, as described in Sections 3.1–3.3 in detail, with (1) the case study description, (2) DesignBuilder software calibration and data entry, and (3) passive design alternatives and energy simulation.

3.1. Case Study Description

Murabba Palace is in Riyadh, Kingdom of Saudi Arabia. It was built around 150 years ago. Murabba Palace is one of the most famous historic buildings in the Kingdom, with an area of 988,464 m² [30,31]. Figure 2 depicts plans such that according to these AutoCAD® plans, the BIM model was generated based on the DesignBuilder® platform, as shown in Figure 3. The building gets its name from its square shape. It is one of the city’s museums and comprises 12 designated areas with conference rooms, meeting rooms, and administrative offices. The primary materials used in its construction were bricks, indigenous stones, tamarisk trunks, and palm-leaf stalks. The building’s walls were built using straw-reinforced adobe with engraved ornaments on the coating, as shown in Figure 4.

Figure 2. Murabba Palace architectural plan using AutoCAD® software.
3.2. Case Study Data

As the case study is a heritage building and it is difficult and not recommended to perform real-life interventions for research purposes, only numerical simulations were used to examine the effect of different materials that can be introduced to the fenestrations and the outer walls to enhance the thermal comfort for occupants and minimize the energy consumption of the case study. DesignBuilder has been verified and validated in various studies [32–34] and was proved to have a very low error, which reached 3.17% from actual results. Moreover, DesignBuilder was approved by LEED and the tool meets the Performance Rating Method requirements of the ASHRAE 90.1 2007 and 2010 standards.

DesignBuilder software [35] version 4.5.0.148 was utilized to perform the energy simulations for the selected passive design insulation retrofitting for Murabba Palace. The location of the building in Riyadh and the chosen weather data from the software template
was SAU_RIYADH_IWEC. The activity template was set to “Generic Office Area”. The building had no lighting control. The used HVAC system was a central unit VAV air-cooled chiller. The mechanical ventilation was turned on and no heating system was utilized. Moreover, natural ventilation and mixed-mode were both set in action in the software. The windows in the building are composed of single-layer 6 mm clear glass.

The construction material properties were extracted based on references [36–41] and the data entry was divided into four categories—(1) roof floor layers, (2) ground floor layers, (3) typical floor levels, and (4) external wall layers. As shown in Figure 5, the roof comprises a wooden athel beam 15–20 cm in diameter, a palm bot layer 3 cm thick, 1 cm of date palm leaves, a non-woven layer, and a stabilized soil layer 20 cm thick. Furthermore, the ground floor consists of compacted filling material, polyethylene layer for thermal insulation, 10 cm of reinforced concrete, 2 cm of cement mortar, and 6 cm of Riyadh stones, as shown in Figure 6. As shown in Figure 7, the first-floor layers are divided into 15 cm of wooden athel tree trunk beam, 3 mm of palm bot, 1 cm of palm leaves, a non-woven polyester layer, 10 cm of mud soil, and 10 cm of stabilized earth. Finally, the external wall is stabilized earth bricks 40 cm thick with external and internal stabilized earth render 3 cm thick. The total U-values for the roof floor, the ground floor, the first floor, and the external wall layers are 0.441 W/m²·K, 0.779 W/m²·K, 0.406 W/m²·K, and 1.737 respectively.

Figure 5. Roof floor layer: (a) as-built detail, (b) DesignBuilder data entry roof layer.

Figure 6. Ground floor layer: (a) as-built detail, (b) DesignBuilder data entry ground layer.
3.3. Passive Design Alternatives and Energy Simulations

According to the heritage character of the building, the selected passive interventions took place to improve the energy performance of the building and indoor thermal comfort. The improvement took place with minimum intervention and retrofitting actions to preserve the heritage entity of the exterior building shape and the internal character of the building as much as possible. A total of 10 scenarios that were utilized, as shown in Figure 8, including (1) replacing the existing single glass with double low-E glass with a 13 mm air-filled gap that decreases the U-value from 5.360 W/m²·K, as in the base case, to 1.622 W/m²·K; (2) replacing the existing single glass with double reflected glass with a 13 mm air gap that decreases the U-value from 5.360 W/m²·K to 2.294 W/m²·K; (3) using the low-E glass, as in the first scenario, in addition to a 5 cm air gap and 12 cm of rammed earth brick, making the U-value 1.614 W/m²·K; (4) using the low-E glass, as in the first scenario, in addition to 5 cm of expanded polystyrene thermal insulation and 12 cm of rammed earth brick, which achieves a U-value of 0.568 W/m²·K; (5) using the low-E glass, as in the first scenario, in addition to 5 cm of expanded polystyrene lightweight thermal insulation and 12 cm of rammed earth brick, which achieves a U-value of 0.626 W/m²·K; (6) using the low-E glass, as in the first scenario, in addition to 5 cm of expanded polystyrene lightweight thermal insulation and 12 cm of rammed earth brick, which achieves a U-value of 1.408 W/m²·K; (7) using the double reflected glass, as in the second scenario, in addition to a 5 cm air gap and 12 cm of rammed earth brick, making the U-value 1.614 W/m²·K; (8) using the double reflected glass, as in the second scenario, in addition to 5 cm of expanded polystyrene thermal insulation and 12 cm of rammed earth brick, which achieves a U-value of 0.568 W/m²·K; (9) using the double reflected glass, as in the second scenario, in addition to 5 cm of expanded polystyrene lightweight thermal insulation and 12 cm of rammed earth brick, which achieves a U-value of 0.626 W/m²·K; (10) using the double reflected glass, as in the second scenario, in addition to 5 cm of expanded polystyrene lightweight thermal insulation and 12 cm of rammed earth brick, which achieves U-value 1.408 W/m²·K.
4. Results and Discussion

According to the simulations performed using DesignBuilder software, the fourth case (double low-E glass with a double wall enclosing thermal insulation) achieves the minimum total energy consumption of 443,338 Wh/m$^2$ annually, which corresponds to an 8.3% reduction compared to the base case, which is attributed to the minimum U-value. The other nine cases consume 473,875 Wh/m$^2$, 479,941 Wh/m$^2$, 478,284 Wh/m$^2$, 445,552 Wh/m$^2$, 472,506 Wh/m$^2$, 437,958 Wh/m$^2$, 435,721 Wh/m$^2$, 437,086 Wh/m$^2$, and 464,540 Wh/m$^2$, respectively, as illustrated in Table 1 and Figures 9 and 10. Hence, the ten cases achieve reductions in the total energy consumption from the base case as follows: Case 1—2%; Case 2—1%; Case 3—1.1%; Case 4—58%; Case 5—7.9%; Case 6—2.3%; Case 7—9.5%; Case 8—9.9%; Case 9—9.6%; Case 10—3.9%.

Accordingly, the carbon emissions inherit the same reduction characteristics in the ten passive intervention cases, as shown in Table 2 and Figures 11 and 12. Double low-E glass possesses 287,168 Kg CO$_2$ equ, representing a 2% reduction from the base case. Applying double reflective glass emits 290,844 Kg CO$_2$ equ, equal to a 0.7% reduction from the base case. Utilizing double low-E glass and a double wall with an air gap represents a 1.1% reduction, with 289,840 Kg CO$_2$ equ. Applying double low-E glass and a double wall with thermal insulation emits 268,663 Kg CO$_2$ equ, equal to an 8.3% reduction from the base case. Utilizing double low-E glass and a double wall with lightweight thermal insulation emits 270,004 Kg CO$_2$ equ, equivalent to a 7.8% reduction from the base case. Using double low-E glass and a double wall with foam thermal insulation emits 286,338 Kg CO$_2$ equ, equal to a 2.3% reduction from the base case. Using double reflective glass possesses 265,402 Kg CO$_2$ equ...
equ, representing a 9.5% reduction from the base case. Utilizing double reflective glass and a double wall with an air gap means a 9.9% reduction with 265,402 Kg CO\textsubscript{2} equ. Applying double reflective glass and a double wall with thermal insulation emits 264,047 Kg CO\textsubscript{2} equ, equal to a 9.9% reduction from the base case. Utilizing double reflective glass and a double wall with lightweight thermal insulation emits 264,874 Kg CO\textsubscript{2} equ, equivalent to a 9.6% reduction from the base case. Using both double reflective glass and a double wall with foam thermal insulation emits 281,511 Kg CO\textsubscript{2} equ, which is equal to a 3.9% reduction from the base case.

The predictive mean value (PMV) indicates the degree of thermal comfort achieved in a particular space. The value of this metric ranges from a value of 3 to $-3$, and improvement takes place when the value tends to zero. Therefore, based on Table 3 and Figure 13, Case 4 has the best PMV values compared to the other ten cases, and it improves the indoor thermal comfort better than the base case throughout the twelve months of the year. Moreover, it can be recognized that applying double low-E glass achieves more improvement than using double reflective glass in the winter months.

| Table 1. Monthly and annual total energy. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | As Built | Case 1 Wh/m\textsuperscript{2} | Case 2 Wh/m\textsuperscript{2} | Case 3 Wh/m\textsuperscript{2} | Case 4 Wh/m\textsuperscript{2} | Case 5 Wh/m\textsuperscript{2} | Case 6 Wh/m\textsuperscript{2} | Case 7 Wh/m\textsuperscript{2} | Case 8 Wh/m\textsuperscript{2} | Case 9 Wh/m\textsuperscript{2} | Case 10 Wh/m\textsuperscript{2} |
| January | 20,353 | 20,341 | 20,391 | 20,540 | 20,647 | 20,638 | 20,548 | 20,527 | 20,538 | 20,522 | 20,475 |
| February | 18,776 | 18,718 | 18,886 | 19,036 | 19,226 | 19,212 | 19,061 | 18,953 | 18,966 | 18,942 | 18,839 |
| March | 22,194 | 22,088 | 22,465 | 22,648 | 22,993 | 22,969 | 22,696 | 22,429 | 22,448 | 22,399 | 22,222 |
| April | 34,426 | 33,924 | 34,695 | 34,825 | 33,794 | 33,857 | 34,643 | 32,856 | 32,807 | 32,785 | 33,671 |
| May | 54,472 | 53,246 | 54,010 | 53,751 | 48,784 | 49,090 | 52,903 | 48,167 | 47,827 | 48,025 | 51,882 |
| June | 55,578 | 54,082 | 54,713 | 54,256 | 48,245 | 48,616 | 53,234 | 47,892 | 47,506 | 47,776 | 52,416 |
| July | 66,064 | 64,174 | 64,867 | 64,321 | 56,892 | 57,364 | 63,074 | 56,579 | 56,127 | 56,418 | 62,147 |
| August | 64,214 | 62,465 | 62,991 | 62,401 | 54,985 | 55,464 | 61,159 | 54,879 | 54,392 | 54,726 | 60,418 |
| September | 55,200 | 53,926 | 54,563 | 54,092 | 48,385 | 48,771 | 53,181 | 47,976 | 47,603 | 47,890 | 52,348 |
| October | 44,792 | 43,983 | 44,827 | 44,633 | 41,633 | 41,816 | 44,198 | 40,789 | 40,620 | 40,736 | 43,095 |
| November | 27,098 | 26,841 | 27,356 | 27,462 | 27,287 | 27,301 | 27,468 | 26,606 | 26,576 | 26,571 | 26,803 |
| December | 20,106 | 20,088 | 20,178 | 20,318 | 20,467 | 20,454 | 20,341 | 20,303 | 20,311 | 20,295 | 20,225 |
| Total | 483,273 | 473,875 | 479,941 | 478,284 | 443,338 | 445,552 | 472,506 | 437,958 | 435,721 | 437,086 | 464,540 |
Figure 9. Monthly total energy.
Table 2. Monthly and annual CO₂ emissions equivalents.

|         | As-Built | Case 1 Kg Equ. | Case 2 Kg Equ. | Case 3 Kg Equ. | Case 4 Kg Equ. | Case 5 Kg Equ. | Case 6 Kg Equ. | Case 7 Kg Equ. | Case 8 Kg Equ. | Case 9 Kg Equ. | Case 10 Kg Equ. |
|---------|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| January | 12,334   | 12,326         | 12,357         | 12,447         | 12,512         | 12,507         | 12,452         | 12,439         | 12,446         | 12,437         | 12,408         |
| February| 11,378   | 11,343         | 11,445         | 11,536         | 11,651         | 11,642         | 11,551         | 11,486         | 11,494         | 11,479         | 11,416         |
| March   | 13,449   | 13,385         | 13,614         | 13,725         | 13,934         | 13,919         | 13,754         | 13,592         | 13,604         | 13,574         | 13,467         |
| April   | 20,862   | 20,558         | 21,025         | 21,104         | 20,479         | 20,517         | 20,994         | 19,911         | 19,881         | 19,868         | 20,405         |
| May     | 33,010   | 32,267         | 32,730         | 32,573         | 29,563         | 29,749         | 32,059         | 29,189         | 28,983         | 29,103         | 31,440         |
| June    | 33,680   | 32,774         | 33,156         | 32,879         | 29,236         | 29,461         | 32,260         | 29,023         | 28,788         | 28,952         | 31,764         |
| July    | 40,035   | 38,889         | 39,309         | 38,979         | 34,477         | 34,763         | 38,223         | 34,013         | 34,189         | 37,684         | 37,661         |
| August  | 38,914   | 37,854         | 38,172         | 37,815         | 33,321         | 33,611         | 37,062         | 32,257         | 32,961         | 33,164         | 36,613         |
| September| 33,451  | 32,679         | 33,065         | 32,780         | 29,321         | 29,555         | 32,228         | 29,073         | 28,847         | 29,021         | 31,723         |
| October | 27,144   | 26,654         | 27,165         | 27,048         | 25,230         | 25,341         | 26,784         | 24,718         | 24,616         | 24,686         | 26,115         |
| November| 16,421   | 16,266         | 16,578         | 16,642         | 16,536         | 16,544         | 16,646         | 16,123         | 16,105         | 16,102         | 16,243         |
| December| 12,184   | 12,173         | 12,228         | 12,313         | 12,403         | 12,395         | 12,327         | 12,304         | 12,308         | 12,299         | 12,256         |
| Total   | 292,863  | 287,168        | 290,844        | 289,840        | 268,663        | 270,004        | 286,338        | 265,402        | 264,047        | 264,874        | 281,511        |
Figure 11. Monthly CO$_2$ emissions.
Figure 12. Annual CO₂ emissions.

Table 3. Monthly Fanger PMV.

|       | As-Built | Case 1 Kg Equ. | Case 2 Kg Equ. | Case 3 Kg Equ. | Case 4 Kg Equ. | Case 5 Kg Equ. | Case 6 Kg Equ. | Case 7 Kg Equ. | Case 8 Kg Equ. | Case 9 Kg Equ. | Case 10 Kg Equ. |
|-------|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------------|
| January | −1.02 | −0.99 | −0.89 | −0.86 | −0.61 | −0.62 | −0.82 | −0.78 | −0.73 | −0.79 | −0.95 |
| February | −0.58 | −0.55 | −0.47 | −0.45 | −0.31 | −0.32 | −0.43 | −0.42 | −0.42 | −0.43 | −0.53 |
| March | −0.10 | −0.09 | −0.03 | −0.02 | 0.03 | 0.03 | −0.02 | −0.05 | −0.05 | −0.06 | −0.09 |
| April | −0.32 | −0.33 | −0.27 | −0.27 | −0.34 | −0.32 | −0.34 | −0.29 | −0.41 | −0.42 | −0.42 |
| May | 0.38 | 0.35 | 0.39 | 0.37 | 0.13 | 0.15 | 0.33 | 0.11 | 0.09 | 0.10 | 0.28 |
| June | 0.83 | 0.78 | 0.82 | 0.79 | 0.46 | 0.48 | 0.73 | 0.44 | 0.42 | 0.43 | 0.69 |
| July | 0.77 | 0.72 | 0.75 | 0.72 | 0.39 | 0.41 | 0.66 | 0.37 | 0.35 | 0.37 | 0.62 |
| August | 0.88 | 0.84 | 0.86 | 0.83 | 0.48 | 0.50 | 0.77 | 0.47 | 0.44 | 0.46 | 0.73 |
| September | 0.67 | 0.63 | 0.66 | 0.64 | 0.33 | 0.35 | 0.58 | 0.31 | 0.29 | 0.31 | 0.54 |
| October | 0.73 | 0.72 | 0.75 | 0.74 | 0.62 | 0.63 | 0.72 | 0.59 | 0.58 | 0.58 | 0.68 |
| November | 0.16 | 0.17 | 0.21 | 0.21 | 0.19 | 0.19 | 0.21 | 0.13 | 0.13 | 0.13 | 0.15 |
| December | −0.68 | −0.65 | −0.57 | −0.55 | −0.34 | −0.36 | −0.52 | −0.46 | −0.44 | −0.46 | −0.61 |
Figure 13. Fanger PMV thermal comfort.
5. Conclusions

Heritage buildings have significant character and add value to today’s architecture. In addition, the whole world must stand hand in hand to achieve sustainability through our daily practices, primarily in the building sector. Hence, heritage buildings possess specific difficulties in terms of conserving energy and enhancing their indoor thermal comfort while preserving their architecture materials and character. Accordingly, this study introduced several passive architecture treatments to improve indoor thermal comfort, reduce energy consumption, and minimize CO₂ emissions. The ten selected alternatives are (1) using double reflective glass, (2) using double low-E glass, (3) using double low-E glass with a double wall and an air gap, and (4) using double low-E glass with a double wall and thermal insulation, (5) using double low-E glass with a double wall and lightweight thermal insulation, (6) using double low-E glass with a double wall and foam thermal insulation, (7) using double reflective glass with a double wall and an air gap, and (8) using double reflective glass with a double wall and thermal insulation, (9) using double reflective glass with a double wall and lightweight thermal insulation, (10) using double reflective glass with a double wall and foam thermal insulation. The fourth alternative was able to achieve a reduction in total energy of 8.3%. The eighth alternative reduced carbon dioxide equivalent emissions to 9.8% better than the as-built base case. However, these findings require a deep life cycle cost analysis to stand for the economic worth of these passive designs compared to the improvements in energy and thermal comfort.

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References

1. Al-Sakkaf, A.; Zayed, T.; Bagchi, A.; Mahmoud, S.; Pickup, D. Development of a sustainability rating tool for heritage buildings: Future implications. Smart Sustain. Built Environ. 2020. [CrossRef]
2. Al-Sakkaf, A.; Zayed, T.; Bagchi, A. A review of definition and classification of heritage buildings and framework for their evaluation. In Proceedings of the 2nd International Conference on New Horizons in Green Civil Engineering (NHICE-02), Victoria, BC, Canada, 24–26 August 2020.
3. Dawoud, M.M.; Elgizawy, E.M. The correlation between art and architecture to promote social interaction in public space. In Cities’ Identity through Architecture and Art; CRC Press: Boca Raton, FL, USA, 2018.
4. Jokilehto, J. Considerations on authenticity and integrity in world heritage context. City Time 2006, 2, 1–16.
5. Mansfield, J.R. Sustainable refurbishment: The potential of the legacy stock in the UK commercial real estate sector. Struct. Surv. 2009, 27, 274–286. [CrossRef]
6. International Energy Agency. Global Energy & CO₂ Status Report. 2018. Available online: https://iea.blob.core.windows.net/assets/239eb39-7493-4722-accd-61433cbbfe10/Global_Energy_and_CO₂_Status_Report_2018.pdf (accessed on 1 October 2021).
7. Pérez-Lombard, L.; Ortiz, J.; Pout, C. A review on buildings energy consumption information. Energy Build. 2008, 40, 394–398. [CrossRef]
8. Lidelöw, S.; Örn, T.; Luciani, A.; Rizzo, A. Energy-efficiency measures for heritage buildings: A literature review. Sustain. Cities Soc. 2019, 45, 231–242. [CrossRef]
9. Loli, A.; Bertolin, C. Towards zero-emission refurbishment of historic buildings: A literature review. Buildings 2018, 8, 22. [CrossRef]
10. Bottero, M.; D’Alpaos, C.; Oppio, A. Ranking of adaptive reuse strategies for abandoned industrial heritage in vulnerable contexts: A multiple criteria decision aiding approach. Sustainability 2019, 11, 785. [CrossRef]
11. Fahmy, M.; Mahdy, M.; Nikolopoulos, M. Prediction of future energy consumption reduction using GRCenvelope optimization for residential buildings in Egypt. Energy Build. 2014, 70, 186–193. [CrossRef]

12. Mahmoud, S.; Fahmy, M.; Mahdy, M.; Elwy, I.; Abdelalim, M. Comparative energy performance simulation for passive and conventional design: A case study in Cairo, Egypt. Energy Rep. 2020, 6, 699–704. [CrossRef]

13. UNESCO. World Heritage Statistic; UNESCO: Paris, France, 2018.

14. Central Public Works Department. Handbook of Conservation of Heritage Buildings; Central Public Works Department: New Delhi, India, 2013; p. 104.

15. Al-Sakkaf, A.; Zayed, T.; Bagchi, A. A sustainability based framework for evaluating the heritage buildings. Int. J. Energy Optim. Eng. 2020, 9, 49–73. [CrossRef]

16. Mohammed Abdelkader, E.; Al-Sakkaf, A.; Ahmed, R. A comprehensive comparative analysis of machine learning models for predicting heating and cooling loads. Decis. Sci. Lett. 2020, 9, 409–420. [CrossRef]

17. Mirrahimi, S.; Mohamed, M.F.; Haw, L.C.; Ibrahim, N.L.N.; Yusoff, W.F.M.; Aflaki, A. The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate. Renew. Sustain. Energy Rev. 2016, 53, 1508–1519. [CrossRef]

18. Ruiz-Jaramillo, J.; Muñoz-González, C.; Joyanes-Díaz, M.D.; Jiménez-Morales, E.; López-Osorio, J.M.; Barrios-Pérez, R.; Rosajiménez, C. Heritage risk index: A multi-criteria decision-making tool to prioritize municipal historic preservation projects. Front. Arch. Res. 2020, 9, 403–418. [CrossRef]

19. Fiore, P.; Sicignano, E.; Donnarumma, G. An ahp-based methodology for the evaluation and choice of integrated interventions on historic buildings. Sustainability 2020, 12, 5795. [CrossRef]

20. Abdelrazik, H.; Marzouk, M. Investigating parameters affecting maintenance of heritage buildings in Egypt. Int. J. Build. Pathol. Adapt. 2020, 1–22. [CrossRef]

21. SoDangi, M.; Kazmi, Z.A.; Hassan Bakri, M.; Anwar, F. Protection of buildings with historic, architectural cultural values: The case of Royal Museum of Seri Menanti. In Proceedings of the 2nd International Sustainability and Resilience Conference: Technology and Innovation in Building Designs, online, 11–12 November 2020; pp. 1–6.

22. Mushtha, E.; Shamsuzzaman, M.; Abdouli, S.A.; Hamdan, S.; Soares, T.G. Application of the analytic hierarchy process to developing sustainability criteria and assessing heritage and modern buildings in the UAE. Arch. Eng. Des. Manag. 2020, 16, 329–355. [CrossRef]

23. Ismail, Z.A. Developing a maintenance index framework for heritage concrete buildings. Int. J. Build. Pathol. Adapt. 2019, 37, 510–527. [CrossRef]

24. Prieto, A.J.; Macías-Bernal, J.M.; Chávez, M.-J.; Alejandro, F.J.; Silva, A. Impact of maintenance, rehabilitation, and other interventions on functionality of heritage buildings. J. Perform. Constr. Facil. 2019, 33, 04019011. [CrossRef]

25. Pavlovskis, M.; Miglinskas, D.; Antucheviciene, J.; Kutūt, V. Ranking of heritage building conversion alternatives by applying BIM and MCDM: A case of Sapieha Palace in Vilnius. Symmetry 2019, 11, 973. [CrossRef]

26. Haroun, H.-A.A.F.; Bakr, A.F.; Hasan, A.E.-S. Multi-criteria decision making for adaptive reuse of heritage buildings: Aziza Fahmy Palace, Alexandria, Egypt. Alex. Eng. J. 2019, 58, 467–478. [CrossRef]

27. Kayan, B.A. Green maintenance for heritage buildings: Paint repair appraisal. Int. J. Build. Pathol. Adapt. 2017, 35, 63–89. [CrossRef]

28. Dyson, K.; Matthews, J.; Love, P. Critical success factors of adapting heritage buildings: An exploratory study. Built Environ. Proj. Asset Manag. 2016, 6, 44–57. [CrossRef]

29. Kutūt, V.; Žavadskas, E.K.; Lazauskas, M. Assessment of priority alternatives for preservation of historic buildings using model based on ARAS and AHP methods. Arch. Civ. Mech. Eng. 2014, 14, 287–294. [CrossRef]

30. Al-Sakkaf, A.; Bagchi, A.; Zayed, T.; Mahmoud, S. Sustainability assessment model for heritage buildings. Smart Sustain. Built Environ. 2021. [CrossRef]

31. Al-Sakkaf, A.; Mahmoud, S.A.; Abdelkader, E.M. Improving energy performance and thermal comfort for heritage buildings: A case study Murabba Palace. In Proceedings of the International Conference on Innovations in Energy Engineering & Cleaner Production (IEECP’21), San Francisco, CA, USA, 29–30 July 2021.

32. Ismail, A.M.; Abo Elela, M.M.; Ahmed, E.B. Calibration of Design Builder program. J. Am. Sci. 2015, 11, 96–102.

33. Baharvand, M.; Ahmad, M.H.B.; Safikhani, T.; Majid, R.B.A. DesignBuilder verification and validation for indoor natural Ventilation. J. Basic Appl. Sci. Res. 2016, 6, 58–73. [CrossRef]

34. Design Builder. LEED and ASHRAE 90.1 2007 and 2010 App G PRM—User Guide, Design Builder Manual Version V6.1

35. DesignBuilder Software Ltd.: Stroud, UK, 2019.

36. Towu, P.M.; Sambou, V.; Faye, M.; Thiam, A. Mechanical and thermal characterization of stabilized earth bricks. Energy Procedia 2017, 139, 676–681. [CrossRef]

37. Munthorah, A.S. Engineering characteristics of the compressed-stabilized earth brick. Constr. Build. Mater. 2011, 25, 4215–4220. [CrossRef]
39. Abdullah, E.S.R.; Mirasa, A.K.; Asrah, H.; Lim, C.H. Review on interlocking compressed earth brick. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *476*, 012029. [CrossRef]

40. Chen, R. Mechanical and thermal behaviors of cement stabilized compressed earth bricks. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *474*, 072090. [CrossRef]

41. Asman, A.N.S.; Bolong, N.; Mirasa, A.K.; Asrah, H.; Saad, I. Interlocking compressed earth bricks as low carbon footprint building material. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *476*, 012086. [CrossRef]