

## 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 CO<sub>2</sub> emissions to 17% and 9%, respectively.

**Keywords:** heritage buildings; passive design; energy conservation; reduction in CO<sub>2</sub> emissions



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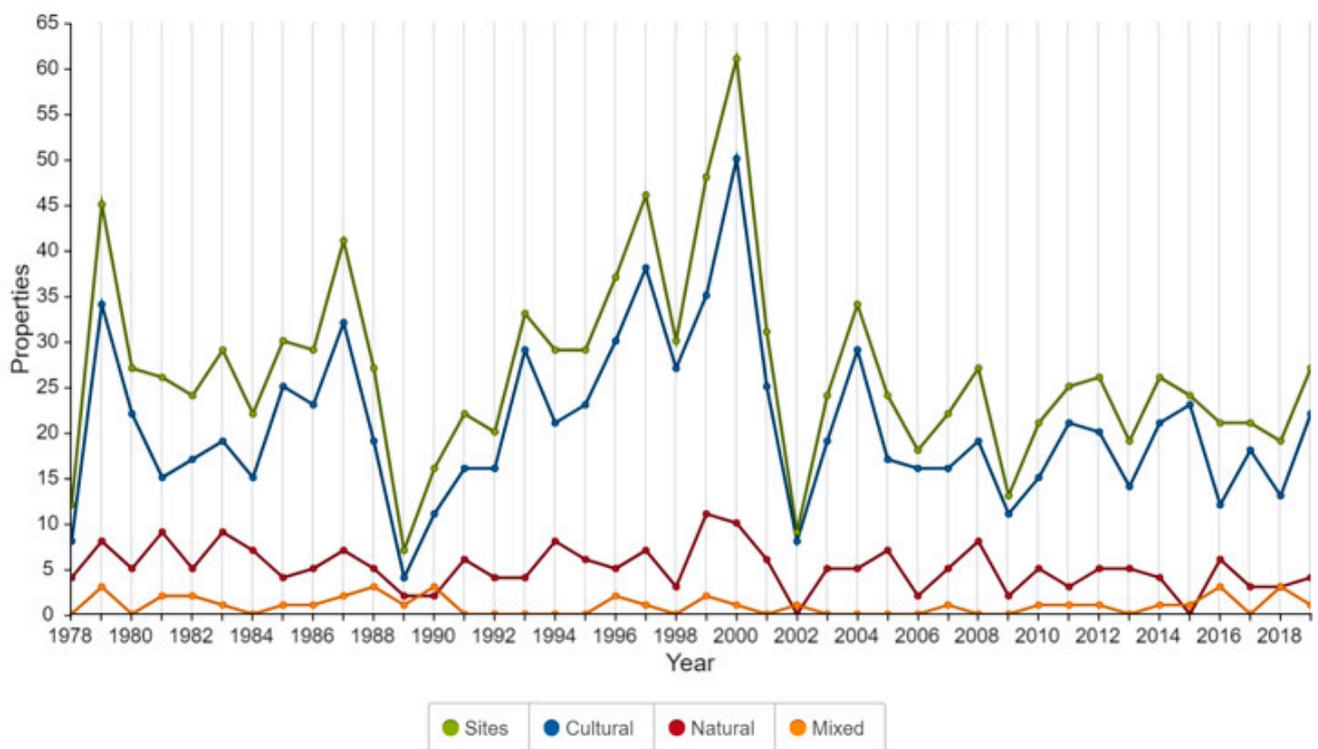
## 1. Introduction

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<sub>2</sub> 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].



**Figure 1.** The number of World Heritage properties inscribed each year per region [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 interims 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) Design-Builder 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 m<sup>2</sup> [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.

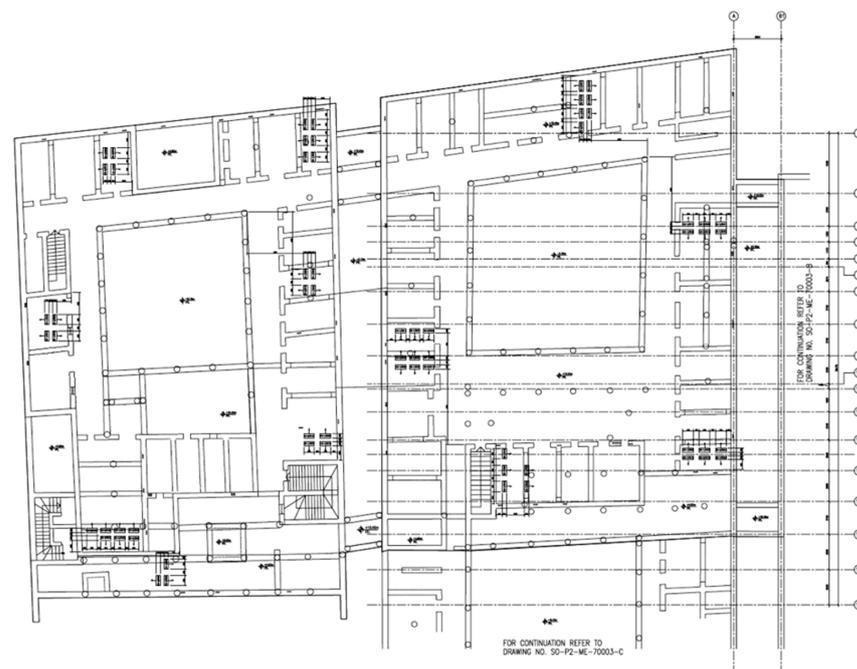


Figure 2. Murabba Palace architectural plan using AutoCAD® software.

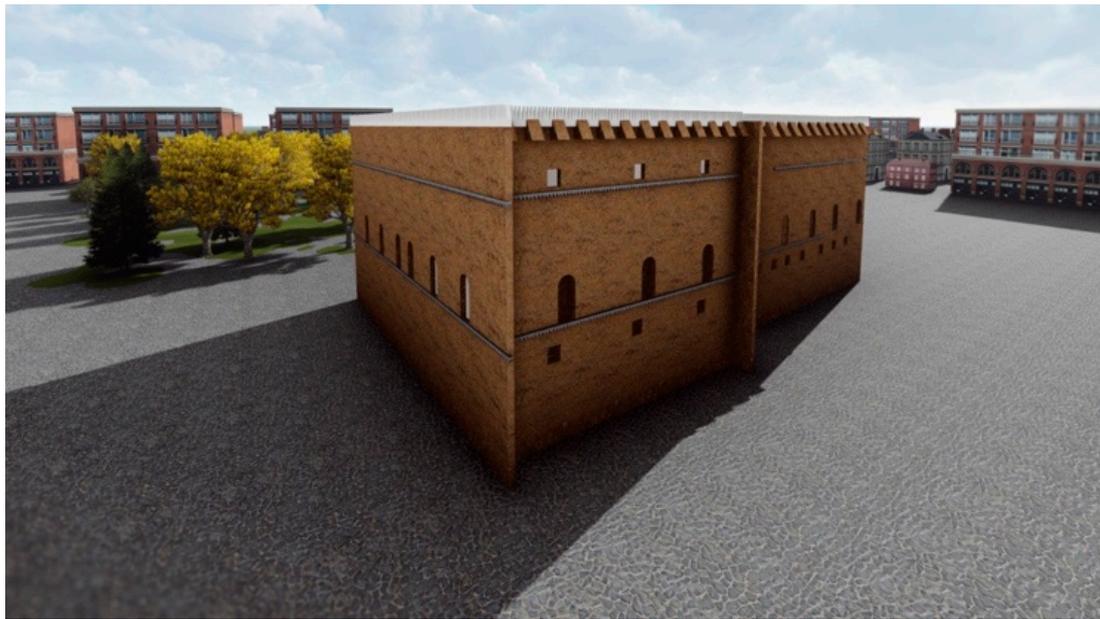


Figure 3. 3D model for Murabba Palace.

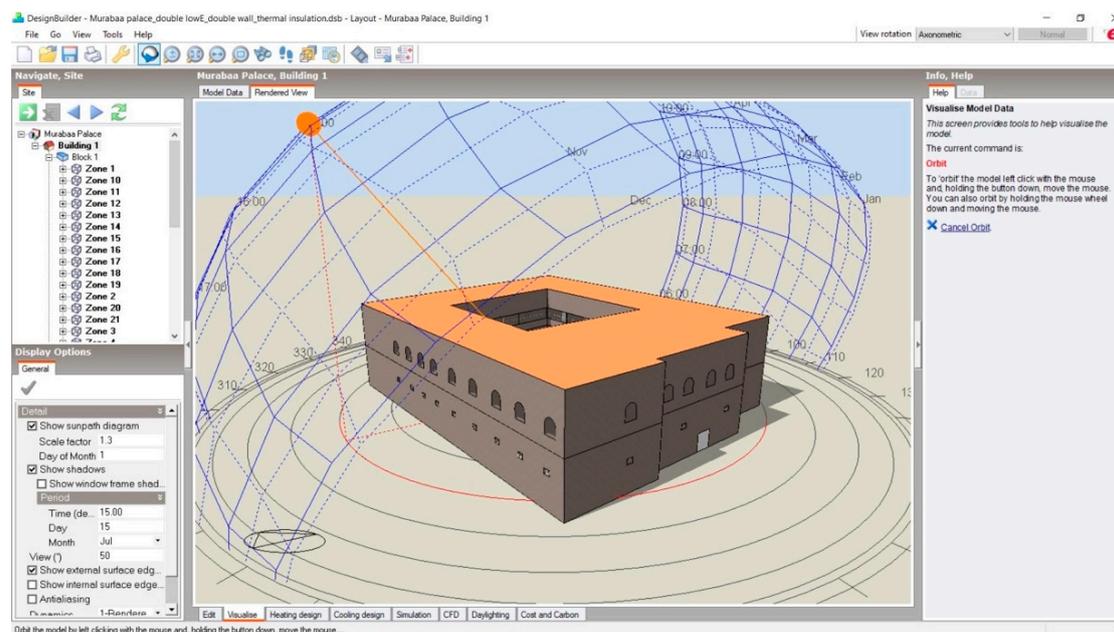


Figure 4. Simulation model of Murabba Palace using DesignBuilder® software.

### 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  $0.441 \text{ W/m}^2\cdot\text{K}$ ,  $0.779 \text{ W/m}^2\cdot\text{K}$ ,  $0.406 \text{ W/m}^2\cdot\text{K}$ , and  $1.737$  respectively.

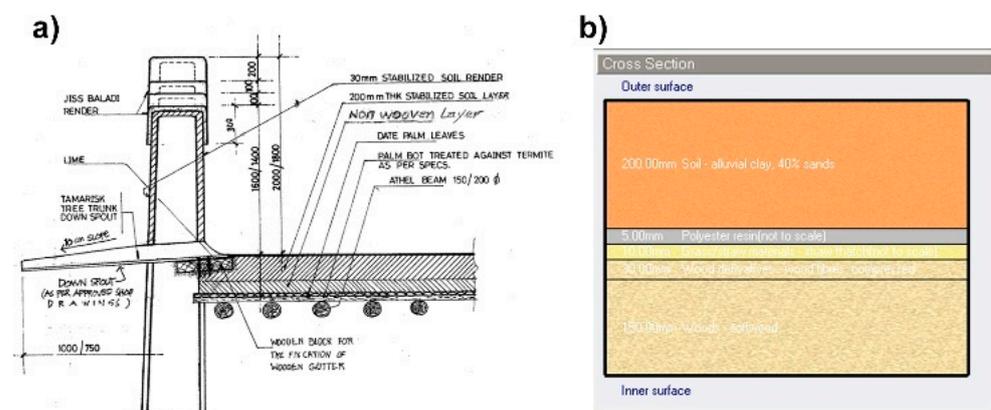


Figure 5. Roof floor layer: (a) as-built detail, (b) DesignBuilder data entry roof layer.

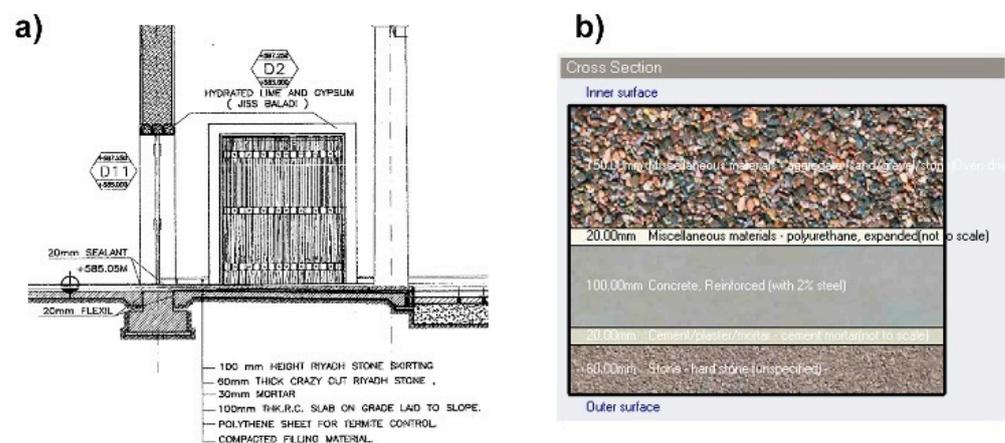


Figure 6. Ground floor layer: (a) as-built detail, (b) DesignBuilder data entry ground layer.

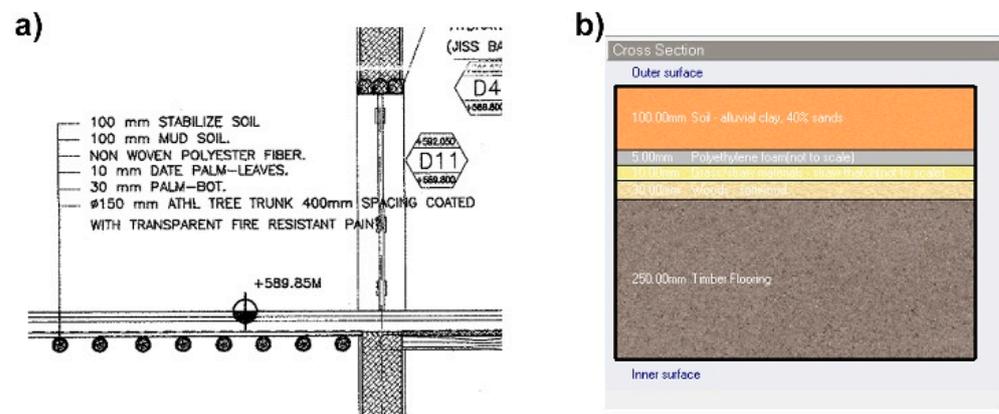


Figure 7. First-floor layer: (a) as-built detail, (b) DesignBuilder data entry ground layer.

### 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  $5.360 \text{ W/m}^2\cdot\text{K}$ , as in the base case, to  $1.622 \text{ W/m}^2\cdot\text{K}$ ; (2) replacing the existing single glass with double reflected glass with a 13 mm air gap that decreases the U-value from  $5.360 \text{ W/m}^2\cdot\text{K}$  to  $2.294 \text{ W/m}^2\cdot\text{K}$ ; (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  $1.614 \text{ W/m}^2\cdot\text{K}$ ; (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  $0.568 \text{ W/m}^2\cdot\text{K}$ ; (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  $0.626 \text{ W/m}^2\cdot\text{K}$ ; (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  $1.408 \text{ W/m}^2\cdot\text{K}$ ; (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  $1.614 \text{ W/m}^2\cdot\text{K}$ ; (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  $0.568 \text{ W/m}^2\cdot\text{K}$ ; (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  $0.626 \text{ W/m}^2\cdot\text{K}$ ; (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  $1.408 \text{ W/m}^2\cdot\text{K}$ .

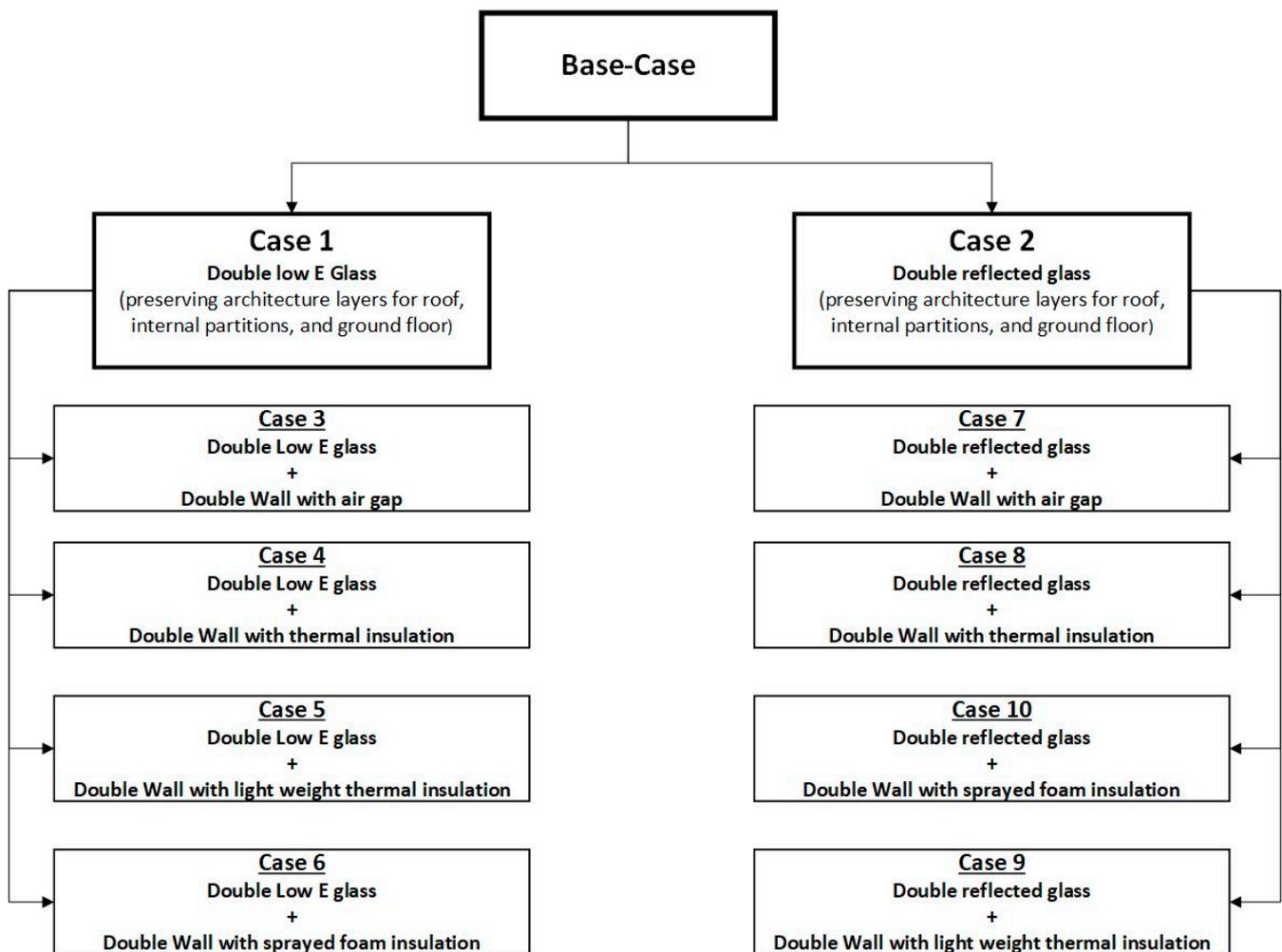


Figure 8. Proposed improvement alternatives.

#### 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<sup>2</sup> 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<sup>2</sup>, 479,941 Wh/m<sup>2</sup>, 478,284 Wh/m<sup>2</sup>, 445,552 Wh/m<sup>2</sup>, 472,506 Wh/m<sup>2</sup>, 437,958 Wh/m<sup>2</sup>, 435,721 Wh/m<sup>2</sup>, 437,086 Wh/m<sup>2</sup>, and 464,540 Wh/m<sup>2</sup>, 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<sub>2</sub> equ, representing a 2% reduction from the base case. Applying double reflective glass emits 290,844 Kg CO<sub>2</sub> 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<sub>2</sub> equ. Applying double low-E glass and a double wall with thermal insulation emits 268,663 Kg CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> equ, equal to a 2.3% reduction from the base case. Using double reflective glass possesses 265,402 Kg CO<sub>2</sub>

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<sub>2</sub> equ. Applying double reflective glass and a double wall with thermal insulation emits 264,047 Kg CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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 <sup>2</sup>	Case 2 Wh/m <sup>2</sup>	Case 3 Wh/m <sup>2</sup>	Case 4 Wh/m <sup>2</sup>	Case 5 Wh/m <sup>2</sup>	Case 6 Wh/m <sup>2</sup>	Case 7 Wh/m <sup>2</sup>	Case 8 Wh/m <sup>2</sup>	Case 9 Wh/m <sup>2</sup>	Case 10 Wh/m <sup>2</sup>
<b>January</b>	20,353	20,341	20,391	20,540	20,647	20,638	20,548	20,527	20,538	20,522	20,475
<b>February</b>	18,776	18,718	18,886	19,036	19,226	19,212	19,061	18,953	18,966	18,942	18,839
<b>March</b>	22,194	22,088	22,465	22,648	22,993	22,969	22,696	22,429	22,448	22,399	22,222
<b>April</b>	34,426	33,924	34,695	34,825	33,794	33,857	34,643	32,856	32,807	32,785	33,671
<b>May</b>	54,472	53,246	54,010	53,751	48,784	49,090	52,903	48,167	47,827	48,025	51,882
<b>June</b>	55,578	54,082	54,713	54,256	48,245	48,616	53,234	47,892	47,506	47,776	52,416
<b>July</b>	66,064	64,174	64,867	64,321	56,892	57,364	63,074	56,579	56,127	56,418	62,147
<b>August</b>	64,214	62,465	62,991	62,401	54,985	55,464	61,159	54,879	54,392	54,726	60,418
<b>September</b>	55,200	53,926	54,563	54,092	48,385	48,771	53,181	47,976	47,603	47,890	52,348
<b>October</b>	44,792	43,983	44,827	44,633	41,633	41,816	44,198	40,789	40,620	40,736	43,095
<b>November</b>	27,098	26,841	27,356	27,462	27,287	27,301	27,468	26,606	26,576	26,571	26,803
<b>December</b>	20,106	20,088	20,178	20,318	20,467	20,454	20,341	20,303	20,311	20,295	20,225
<b>Total</b>	483,273	473,875	479,941	478,284	443,338	445,552	472,506	437,958	435,721	437,086	464,540

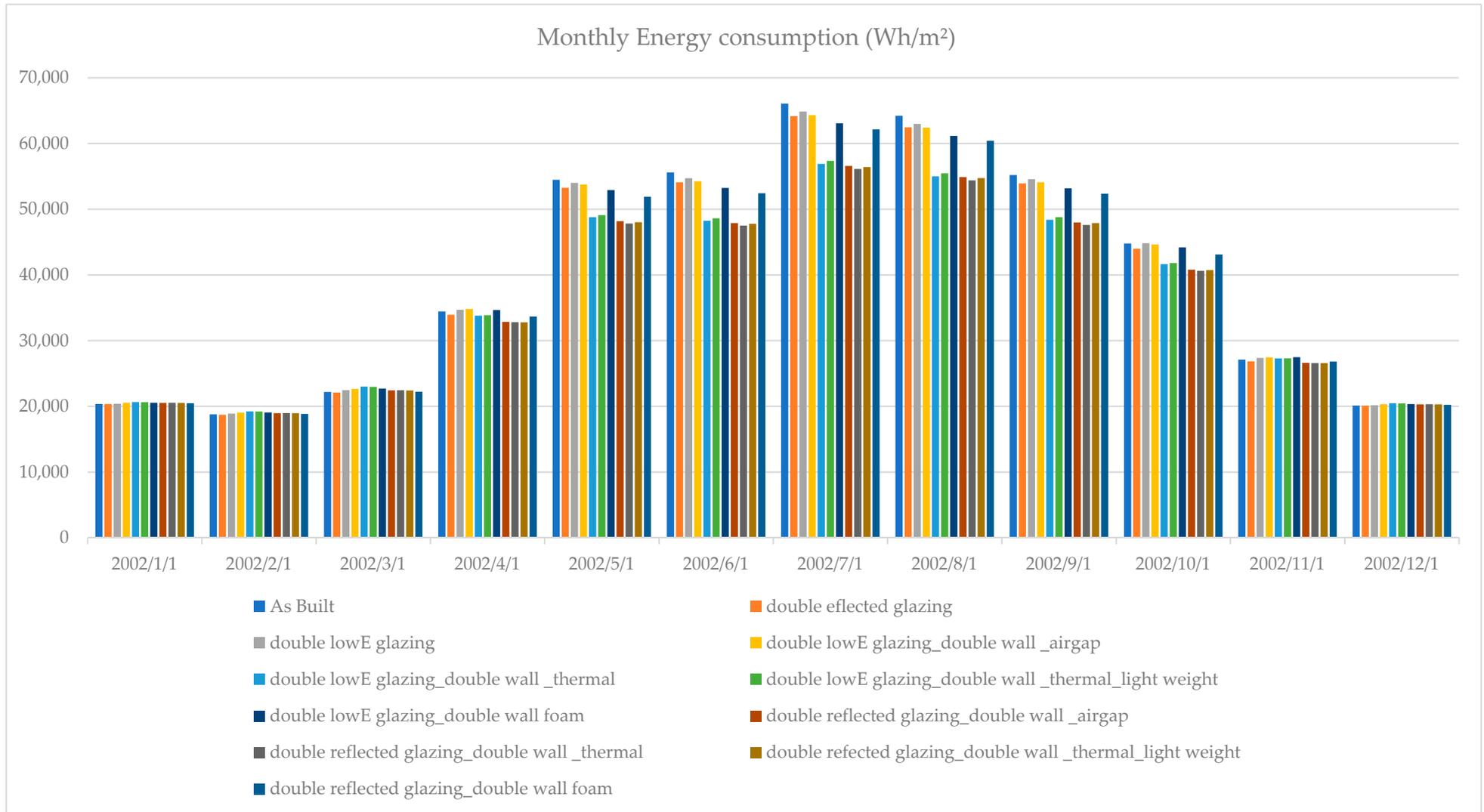


Figure 9. Monthly total energy.

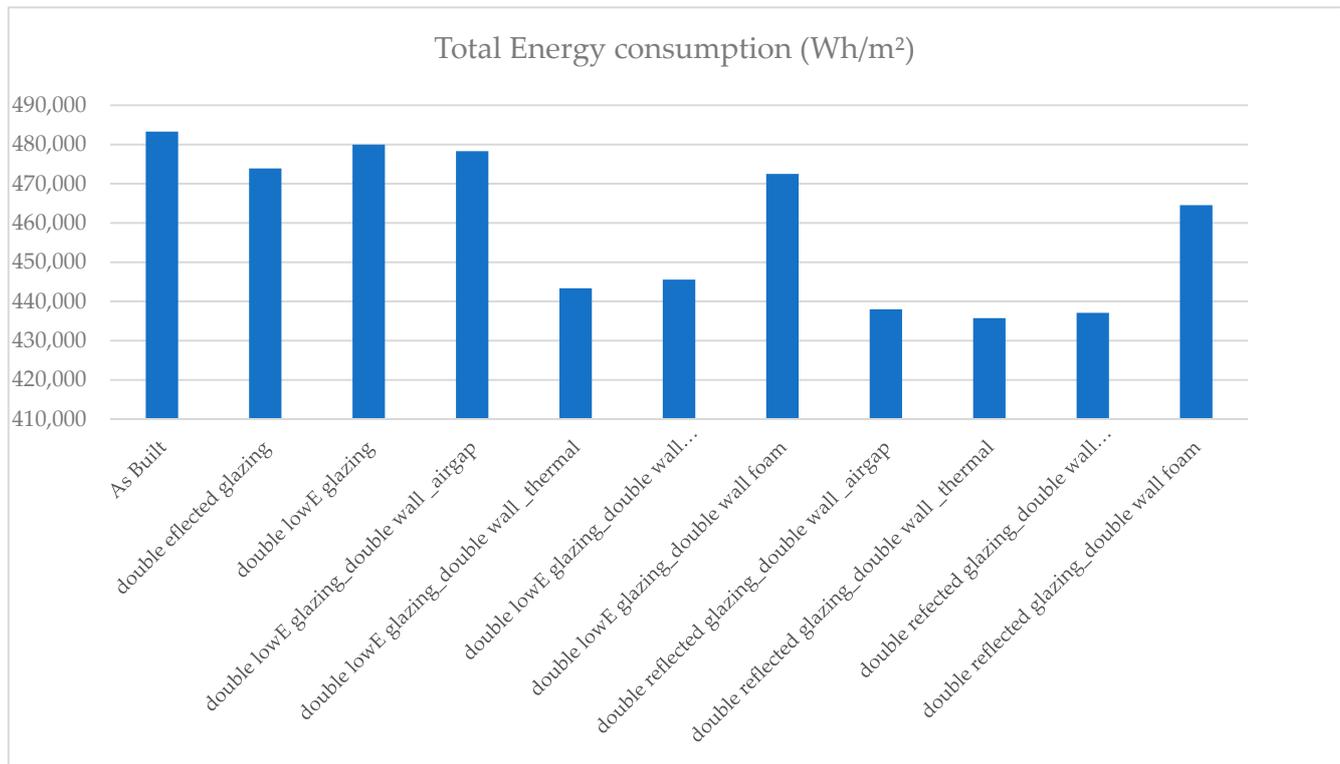


Figure 10. Annual total energy.

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

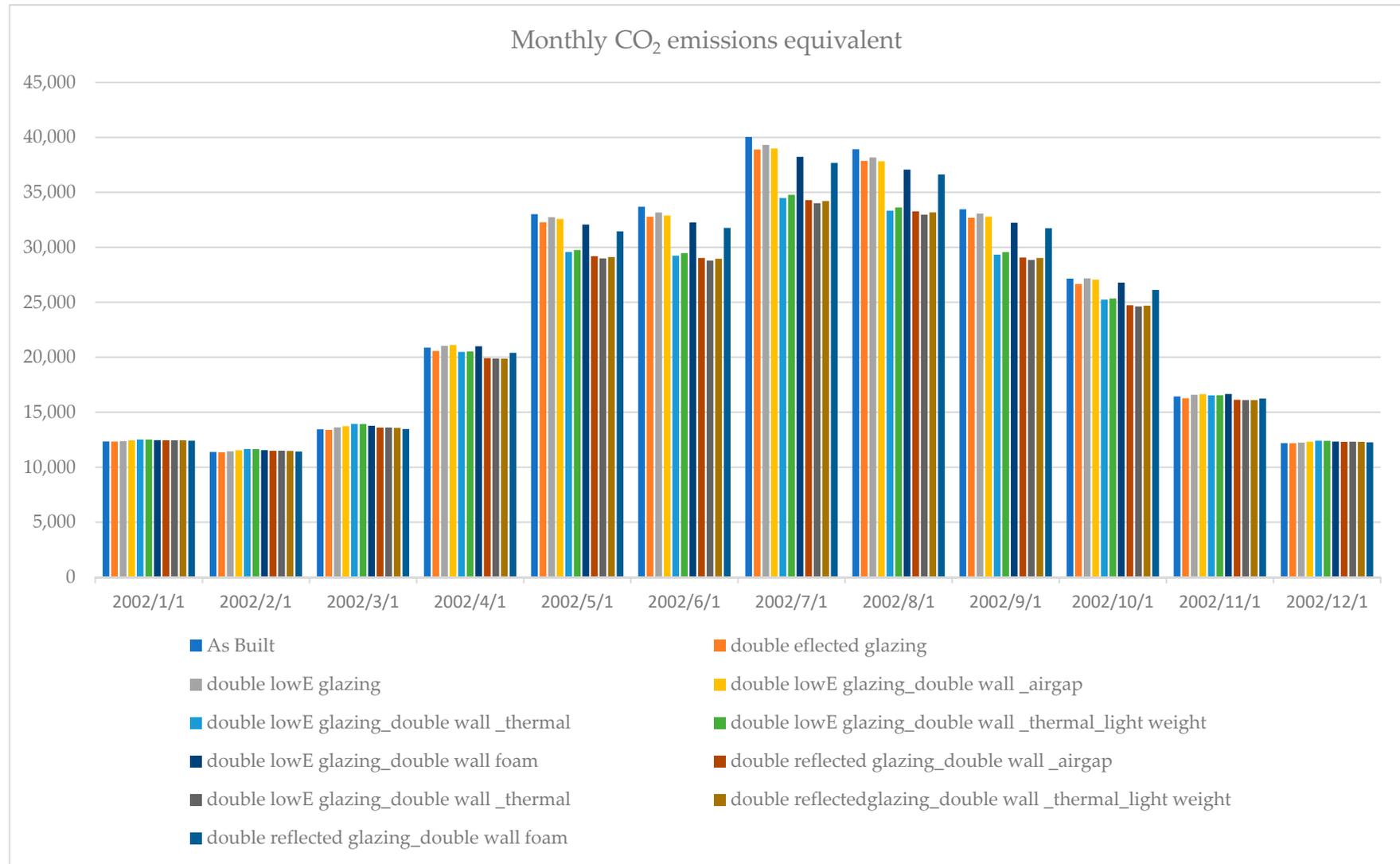


Figure 11. Monthly CO<sub>2</sub> emissions.

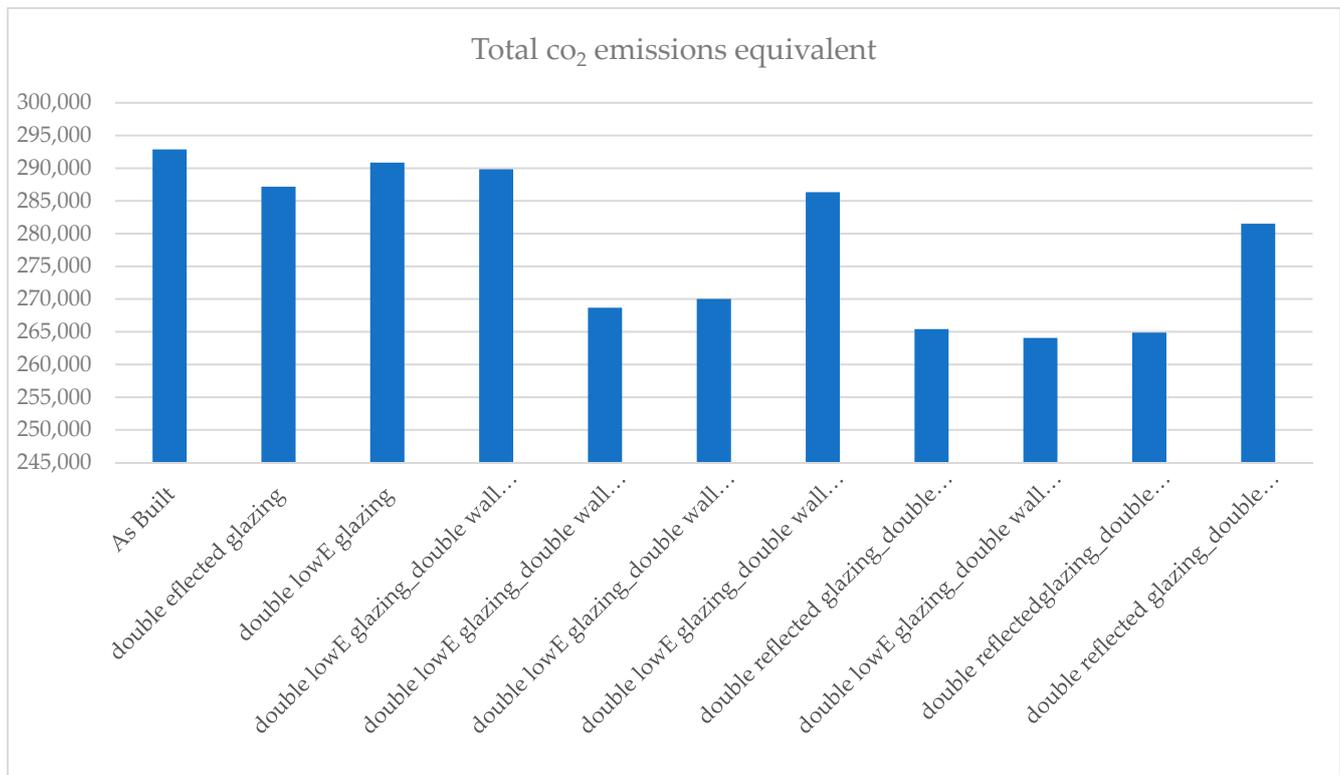


Figure 12. Annual CO<sub>2</sub> emissions.

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	-0.34	-0.29	-0.41	-0.42	-0.42	-0.36
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

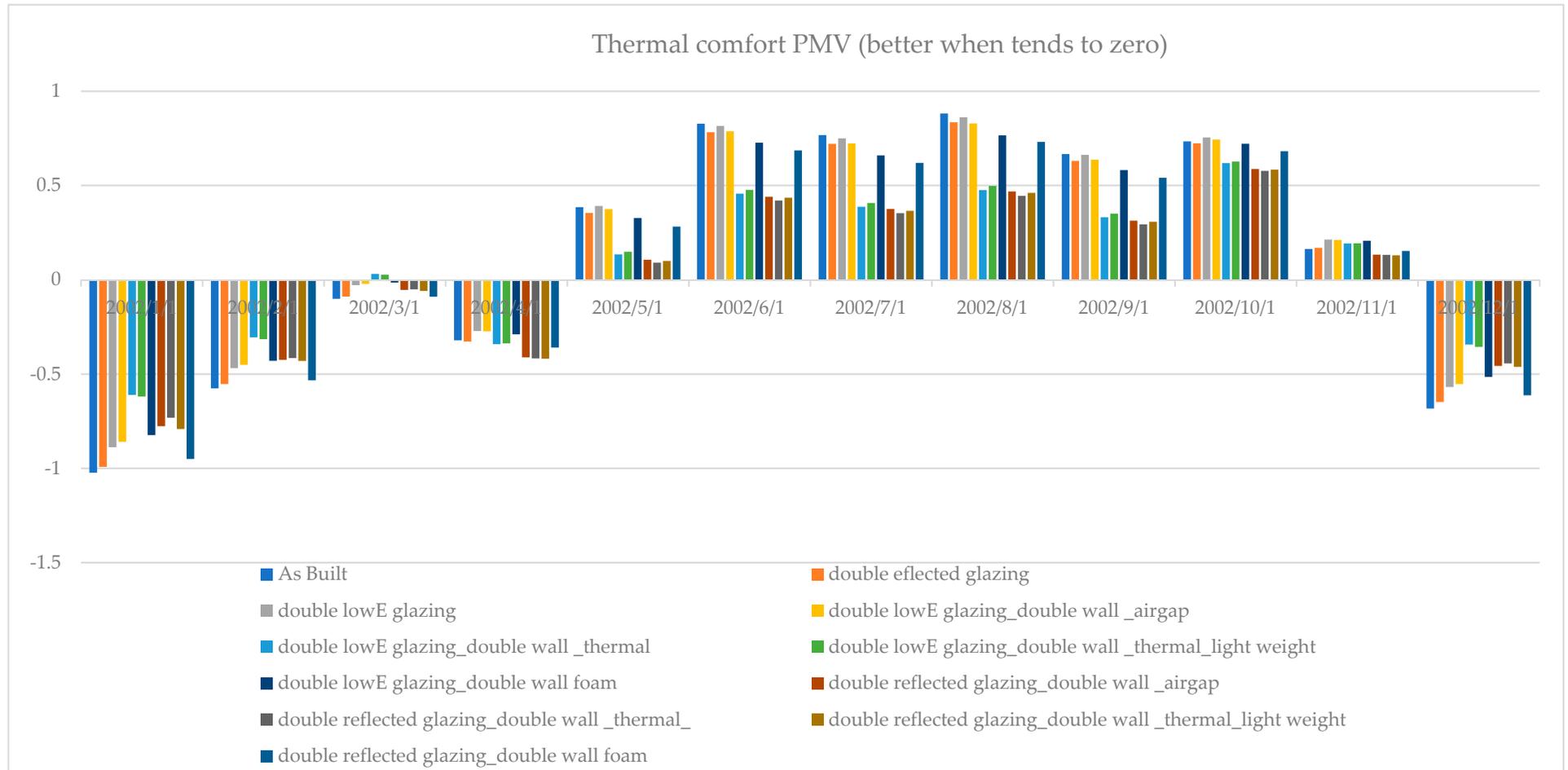


Figure 13. Fanger PMV thermal comfort.

## 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 CO<sub>2</sub> 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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