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Article

Thermally Future-Proofing Existing Libyan Housing Stock with Biobased Insulation Materials and Passive Measures: An Empirical and Numerical Study Using a Digital Twin

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Abstract: Thermal refurbishment and retrofitting building envelopes with passive measures such as the optimisation of opaque and transparent fabric performance may play a key role in reducing cooling and heating load and promoting building energy efficiency. Furthermore, to reduce the embodied carbon impact of the building, the refurbishment measures need to consider the use of low-carbon building materials. This paper investigates ways to thermally future-proof typical Libyan houses using biobased materials. Several typical Libyan houses were monitored for one year to investigate the heating and cooling energy use and to thermally retrofit the building envelope. A digital twin was created in the DesignBuilder software using the real building data of one building for digital model calibration. Finally, multi-objective optimisation was carried out with low-impact biobased materials for insulation, including camel hair, sheep wool, and date palm fibre as well as using other optimisation variables such as shading and glazing types. The study reveals that thermally upgrading the building roof and wall with insulation materials and upgrading the windows with energy-efficient glazing and local shadings can achieve a reduction in cooling load from 53.51 kWh/m^2/y to 40.8 kWh/m^2/y. Furthermore, the heating load reduces from 19.4 kW/m^2/y to 15 kW/m^2/y without compromising the standard annual discomfort hours.

Keywords: multi-objective optimisation; passive design; digital twin; biobased materials; future-proofing; sustainability; low carbon

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1. Introduction

Global warming is likely to make existing buildings increasingly thermally uncomfortable. As such, the heating load in buildings will plausibly increase in the future. Over 35% of global energy consumption and 40% of energy-related CO_2 emissions are attributed to the building and construction industries [1]. Eenergy use by the residential sector in Libya is the largest single contributor to energy demand. It makes up about 36% of total energy consumption [2] (Figure 1).

The existing residential buildings in Libya were built without considering their impact on residents and the environment. The adoption of Western architectural solutions originally designed for markedly different climatic conditions has caused significant thermal discomfort inside these buildings [3]. Nearly half of all energy used in residential buildings in Libya is consumed to provide cooling for the occupants [3–6]. Therefore, to thermally refurbish the existing housing stock, it is very important to identify the key building parameters that contribute to heat gain and loss and increase the need for cooling in summer and heating in winter. This paper investigates ways to thermally future-proof typical Libyan houses using low-impact biobased materials and passive measures.

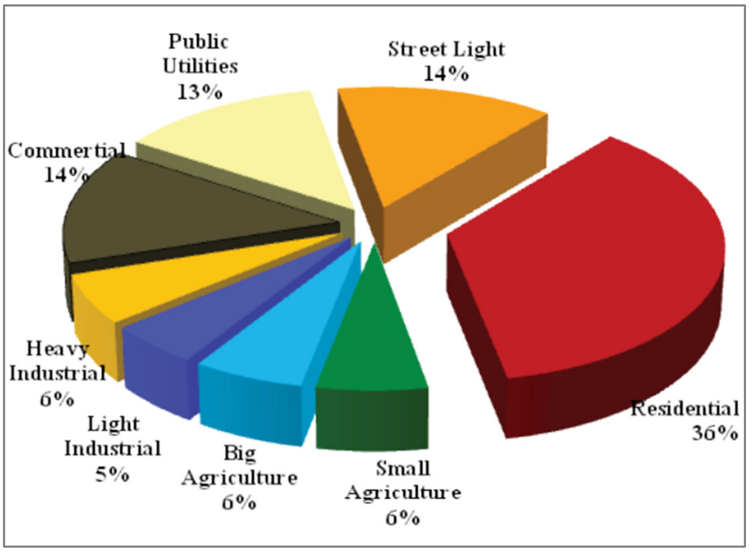


Figure 1. Electricity consumption by sector in Libya [2].

1.1. Building Parameters Affecting Energy Consumption in Residential Buildings in Libya and Neighbouring Countries

The external environment and design parameters are frequently identified as the main factors influencing building energy use in current research [7–10]. These factors influence energy consumption in different ways, although the increase in cooling loads is the most significant effect on residential buildings in Libya [3–6]. Recent studies have revealed that cooling load is significantly affected by the thermal characteristics of the building envelope [3,7,8]. Traditional dwellings in Libya utilise very thick walls and roofs with a high thermal mass. The envelope materials are locally available, such as sand, stone, mud, and sun-dried brick [9]. This means that, traditionally, outdoor conditions had limited influence on indoor temperatures and a reasonably acceptable level of thermal comfort could be maintained by providing cooling during the day in summer and heating during the night in winter. On the other hand, modern buildings' indoor temperature is affected more by outdoor conditions compared to traditional buildings [3,4], as little attention was given to thermal quality in the construction of these contemporary buildings [10]. The walls are usually made of 20 cm thick hollow concrete blocks or limestone blocks, and the roof is made of reinforced concrete leading to a rise in thermal transmittance.

Studies find that a significant amount of heat transmittance from the surrounding environment to interior spaces is caused by the absence of insulation materials in Libya [4,11,12], including Benghazi's residential buildings [3]. The absence of insulation materials from a building's roof and walls plausibly causes a considerable amount of heat to penetrate through them and thus leads to the consumption of a large amount of energy. Similar studies were conducted on residential buildings in neighbouring countries. For instance, a study was carried out on residential buildings located in Cairo, Egypt, using building performance simulation software (DesignBuilder) [13]. The study revealed that, in conventional buildings, a significant amount of heat between outdoor and indoor spaces is caused by the external wall construction, which needs to be treated to enhance the building's thermal and energy performance as well as reducing the associated impacts on the environment. A multi-objective genetic algorithm model for three major climates in Egypt (Mediterranean, semi-arid and arid) were developed to investigate the influence of different design variables on energy consumption [14]. According to the study's findings, wall and roof construction ranked as the optimum solutions for energy conservation in the three different climates. A model of residential buildings located in Saudi Arabia was created using computer-based simulation software (DesignBuilder) to propose possible measures for the reduction of CO_2 emissions and energy consumption in residential buildings located in hot climates [15]. According to the results, installing thermal insulation in the walls and roof can reduce overall energy consumption by approximately 45%. However, when combined with other energy-saving measures, a significant saving of 67% can be achieved. However, other studies have revealed that that glazing type and window shading have the highest impact in terms of controlling the amount of heat transfer and sunlight that reaches the building and have a significant impact on building energy use in Libya [5,16]. Therefore, based on the findings of previous studies, additional investigation is required to determine the hierarchy of design variables in terms of heat transfer and, consequently, the cooling and heating load. As a result of such a study, the optimum energy saving measures for upgrading existing residential buildings in Libya can be properly determined.

1.2. Biobased Building Materials and Their Availability in Libya

A variety of conventional insulating materials were used to improve a building's energy efficiency in most of previous research. However, the selection of insulating materials should consider not only their energy behaviour and the physical properties, but also their environmental footprint. Thermal insulations based on natural materials are anticipated to develop into an effective replacement for widely used man-made boards composed of polystyrene, polyurethane, or mineral wool [17]. Research findings reveal that sheep wool, for instance, has equivalent thermal insulation qualities to conventional materials such as mineral wool, fibreglass, rock mineral wool, and calcium silicate, and in certain cases, it even performs better in terms of cutting down the use of fuel for heating and cooling the household [17–19]. Based on previous studies, natural fibres, such as camel hair and palm fibres, are durable, renewable, environmentally friendly, and have low relative density and strong thermal properties [19,20]. Also, in contrast to conventional thermal insulation materials that contain chemical components and carry a potential risk of pollutant emissions and health issues [21], biobased insulation materials pose minimal or no risks to human health, causing no irritation to the eyes, skin, or lungs, and are capable of absorbing and releasing moisture without substantially affecting thermal performance [17].

In Libya, there are many raw materials from which insulation materials can be produced locally such as sheep wool, camel hair, and date palm fibres. In Libya, livestock represented the largest income-producing item in agricultural production, and sheep constitute the largest percentage of livestock [22]. Their number has grown from 2.8 heads in 1977 to around 6 million heads in 2011 [22,23]. In addition, more than 80% of the world's camel population is found in African countries, including Libya. There are a wide variety of camel breeds available in various locations in Libya such as Fakhreya in to the west of Benghazi, Tibisti in the southern areas of Libya, Kasabat in northwestern Libya, Oulad Bou Sayf in the western oasis of Libya, and Sirtawi found mainly in the Sirt area in the middle coastal zone in Libya [24]. Libya also has a long history of date palm farming, which has played an important role in the livelihoods of the desert and semidesert areas [25]. Date palm trees are currently grown in areas along the northern coast and the oasis in the south [22,25] and, according to the Ministry of Agriculture data, Libya has about ten million palm trees distributed across its territory, especially in the regions of Al-Jufra, Jalo, and Awjila. Hence, the potential for generating adequate insulating materials in Libya is promising because of the availability of these raw resources.

2. Materials and Methods

This study aims to determine the influence of optimizing different design variables on the cooling and heating load of terraced houses in Benghazi, Libya, by implementing biobased insulation materials and using other optimisation variables such as shading and glazing types. This aim is achieved by applying an approach that combines case study building monitoring and numerical simulations of a digital twin. The case study building was selected and monitored to acquire data on energy consumption, indoor and outdoor thermal conditions, and the U-value of the building envelope to calibrate the digital twin. The calibrated model was then used for simulation and optimisation studies. The study did not require ethical approval as it did not involve human participants and no one under the age of 18 was the resident of the house where sensors were installed.

2.1. The Case Study Building

The case study building was selected to serve as a representative of terraced houses in Benghazi for the following reasons:

- It was built with construction materials common in Benghazi;
- It has a design, layout, and floor area typical of most terraced houses in Benghazi;
- The number of occupants in this building represents the average Libyan household (5 people).

The Survey of the Case Study House

The two-storey terraced house is located in an urban residential area in the city of Benghazi. The contrast of sea and desert, between the humid Mediterranean coast and the arid desert areas, is the most striking characteristic of this city. The total built-up area of the house is about 300 m^2. The exterior walls of the terraced house are adjacent to and shared by the attached houses from the back and sides, while the front facade faces the open front yard. The house also contains two small courtyards between rooms to facilitate natural ventilation and daylight. Each floor consists of two bedrooms, a living area, a reception area, a kitchen, and a bathroom (Figure 2). The building adopts mixed ventilation strategies (natural and mechanical) for cooling the indoor spaces. Natural cooling in summer may be aided by the small courtyards. The floors also benefit from mechanical cooling via one split air conditioner on each floor. For heating in the winter, electric heaters are used. The ground floor (GF) of the house is 147 m^2 and was constructed in 1976 with a reinforced concrete ceiling and limestone brick walls covered by cement plaster on both sides.

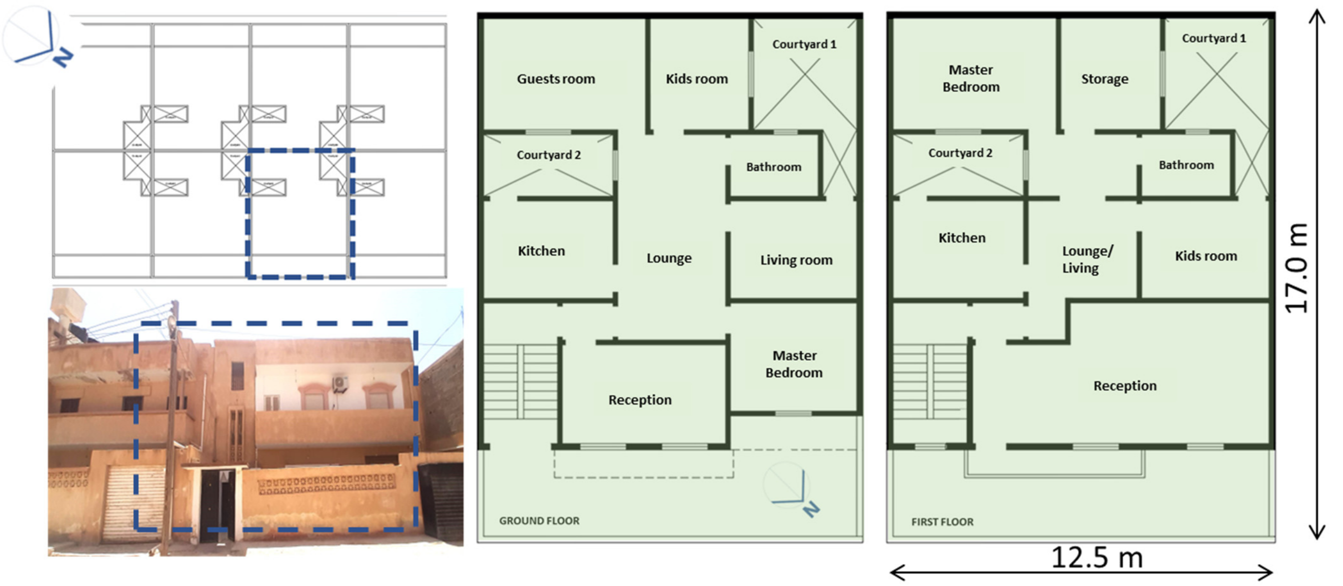


Figure 2. Case study building form and layout.

The first floor (FF) is 152 m^2 and was built in 2013, with a reinforced concrete roof and hollow concrete block walls covered by cement plaster on both sides. The building was constructed without any insulation in the envelopes; this practice is common in Benghazi's residential buildings [3]. More information on the building materials can be found in Table 1.

Table 1. Building construction materials.

	Material Description	Layer Order
GF Wall	10 mm cement mortar + 180 mm limestone block + 10 mm cement mortar + 5 mm gypsum plaster	External to internal
GF Celling	10 mm ceramic tiles + 10 mm cement mortar + 200 mm reinforced concrete slab + 10 mm cement mortar + 5 mm gypsum plaster	Top to bottom
GF Floor	10 mm ceramic tiles + 10 mm cement mortar +200 mm dense concrete + 500 mm sand and gravel	Top to bottom
FF Wall	20 mm cement mortar + 200 mm hollow concrete block+ 20 mm cement mortar + 5 mm gypsum plaster	External to internal
FF Roof	50 mm cement mortar + 200 mm reinforced concrete slab + 10 cement mortar + 5 gypsum plaster	Top to bottom

2.2. Monitoring Equipment and Data Acquisition

The following data were collected at 30 min intervals:

Outdoor weather data: A weather station was installed on the roof to collect data on outdoor weather variables including temperature, humidity, wind speed and direction, rain, and barometric pressure. A solar radiation detector was used every two hours during the daytime to measure the horizontal solar radiation. The data collected were used to create an EnergyPlus Weather (EPW) file for model settings to calibrate the building model and to obtain reliable simulation outputs. The solar radiation data in the EPW file were in good agreement with the data measured by the manual sensor. Therefore, solar radiation data of the EnergyPlus Weather file were left unchanged.

Indoor temperature data: Tempo bluetooth sensors were used to acquire indoor temperature data.

Heat flux: A heat flux sensor device was used to determine heat flux through the walls to determine the U-values.

Energy Consumption:

1. Current clamp meters were used to measure the building's energy use and AC unit energy use.
2. Socket energy meters were used to measure the energy consumed by the electrical water heaters. The data were useful for calibrating the total energy use of the selected building.

Equipment specifications and their measurement errors are presented in Table 2.

Table 2. Specifications for the monitoring equipment.

Equipment		Measurement Range	Accuracy	Resolution
Weather Station (Tempcon Instrumentation, West Sussex, UK)  EnviroTrack Weather Station and Data Logger	Temperature	−40 °C to 75 °C (−40 °F to 167 °F)	±0.21 °C from 0° to 50 °C (±0.38 °F from 32° to 122 °F); see Plot A	0.02 °C at 25 °C
	Relative humidity	0–100% RH at −40 °C to 75 °C	±2.5% from 10% to 90% RH	0.1% RH
	Wind speed	0 to 76 m/s (0 to 170 mph)	±1.1 m/s (±2 mph) or ±5% of reading, whichever is greater	0.5 m/s (1.1 mph)
	Wind direction	0 to 355 degrees	±7 degrees	1 degree (0 to 355 degrees)
	Rain	0.0 to 10.2 cm	±4.0%, between 0.2 and 50.0 mm ±5.0%, between 50.0 and 100.0 mm	0.2 mm

Table 2. *Cont.*

Equipment	Measurement Range	Accuracy	Resolution
Solar Radiation Detector (PCE Instruments UK Ltd., Manchester, UK) 	0 to 2000 W/m^2	1 W/m^2	±10 W/m^2 or ±5%
Temperature Sensor (Blue maestro, USA) Tempo disc bluetooth sensors 	−30 °C to +75 °C	0.4 °C at −10 °C to +75 °C	Maximum 4%
Heat Flux Sensor (greenTEG, Switzerland) gSKIN U-Value and Heat Flux Sensor 	±300	±0.5 (−10 to +65 °C)	<0.22
Current Clamp Meter (Gemini Data Loggers, UK) Tiny-Tag View 2 Current Logger 	0.15 to 200 A	0.5 A to 10 A (5% of reading +/−0.5 A) 10 A to 40 A (3% of reading +/−0.5 A) 40 A to 200 A (2% of reading +/−0.5 A	10 mA
Socket Energy Meter (RS, UK) 	0 kWh–9999 kWh		

The sensors were placed at representative points away from the effects of solar radiation and wind, and in all rooms, in order to acquire temperature and humidity data (Figure 3). Furthermore, the heat flux sensors and loggers were placed in the north wall and energy loggers were placed in the appropriate places.

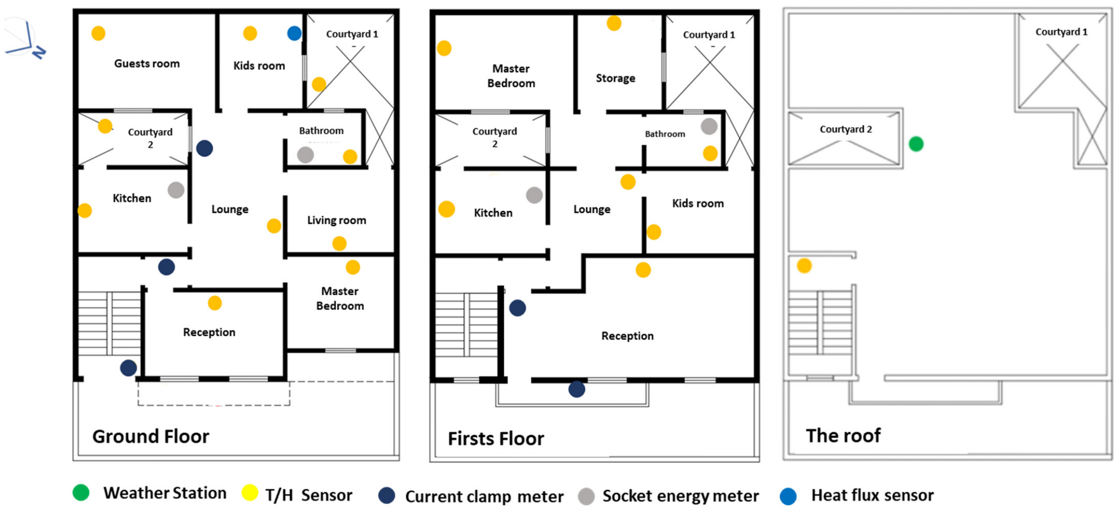


Figure 3. Sensor locations in the case study house.

2.3. Case Study Modelling and Calibration

DesignBuilder software v7.0.2. 6 was used to model the building for simulation and optimisation studies.

2.3.1. Case Study Modelling and Setting in DesignBuilder

The DesignBuilder model was based on the data collected during the monitoring period between the 8th of June 2022 and the 7th of June 2023. The building energy consumption and the weather data were measured for the whole period, while indoor temperature and relative humidity were monitored for the following three representative periods: a month in summer, a month in winter, and a month in the transitional season. The location of the base case digital twin was similar to the actual house (latitude: 32.094771 North; longitude: 20.187911 East; elevation: 132 m above sea level). Two-dimensional architectural drawings of the building were generated using AutoCAD software 2021 v R.47.0.0. The drawings were saved as a DXF file, and then exported to DesignBuilder to create the building model. The key data needed to run the simulation process, such as the orientation, weather file, building construction and materials, internal load, and HVAC systems, were entered into the system. The thermal zones were defined for each conditioned and unconditioned room. Information about the equipment schedule, window opening times, and the number of people in each room was also set to represent the real behaviour of the house users. The thermophysical characteristics (U-value and heat capacity) of the building materials were set based on real measurements for the wall constructions and from the DesignBuilder materials libraries for the floors and roof. The infiltration rate was set to 6.14 ach based on the average air leakage at 50 Pa of pressure difference for 20 tested dwellings located in the Mediterranean region [26], with comparable weather conditions and construction to dwellings in Benghazi. The surrounding buildings also were modelled as shading surfaces to achieve greater accuracy in terms of the simulation results (Figure 4).

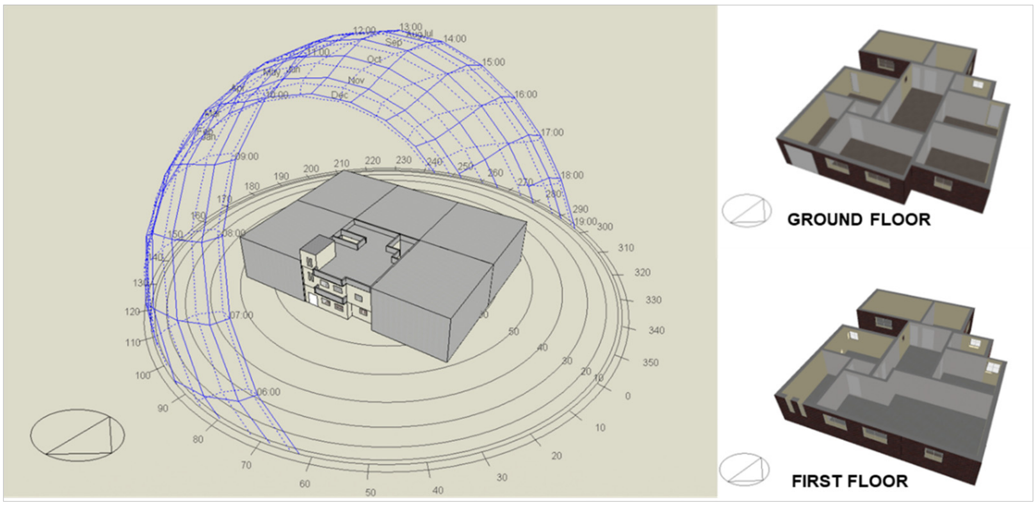


Figure 4. Terraced house modelling in DesignBuilder.

An EPW weather file for the city of Benghazi was used to conduct the simulation study. To accurately calibrate the building's digital twin, the weather file was first converted to a CSV file using the EnergyPlus Weather Statistics & Conversions tool and then modified by inserting actual weather data that was collected during the monitoring period. A new EPW file was then created using the same conversion tool. The schedule of occupancy and equipment use was set based on the data collected during the site visit, such as the window opening times, the number of people in each room, equipment use, and occupancy time, to represent the real behaviour of the house users. Table 3 summarises the settings and conditions adopted for the simulation process.

Table 3. Simulation settings for the case study model.

Parameters	Setting	Reference
External conditions	Mid-latitude steppe and desert climate "Bsh", Benghazi	Energy plus
Orientation	NE	Surveyed
Floor area m^2	GF 147 m^2 FF 152 m^2	Surveyed
Building materials	As defined in Table 1	
Occupants	5 people on each floor	Surveyed
Occupancy density **Ground floor** **First floor**	 0.034 people/m^2 0.033 people/m^2	 Calculated Calculated
Fabric parameters **Limestone block wall U-value** **Hollow concrete block wall U-value** **Roof U-value** **Floor U-value** **Window g-value** **Window U-value** **Window-to-wall ratio**	 2.27 W/m^2.K 2.61 W/m^2.K 3.09 W/m^2.K 1.5 W/m^2.K 0.8 5.78 15%	 Measured Measured Calculated Calculated Calculated Calculated Calculated
Lighting	LED	Surveyed
Heating setpoint/setback **Cooling setpoint/setback**	24 °C–20 °C 22 °C–24 °C	Surveyed Surveyed
Window glazing	6 mm single layer clear glass with no solar protection	Surveyed
Operation schedule	Weekdays 7:00–9:00 and 14:00–23:00 Weekends 09:00–23:00	Surveyed
Infiltration rate at 50 Pa	Average 6.14 ach @50 Pa	Estimated from the literature review

2.3.2. Case Study Model Calibration

Model calibration is an essential step in building simulations to ensure the agreement between the actual building and simulated building model and to ensure the reliability of the simulation results [27–30]. This can be achieved by matching simulation outputs with the monitored and measured data. To determine how closely the monitored data correlated to the DesignBuilder simulation, two indexes were assigned based on ASHRAE guideline 14-2002 [31] to calculate the difference between the measured (monitored) and simulated outputs: the coefficient of variation of the root mean squared error (CV(RMSE)) and normalized mean bias error (NMBE). Based on ASHRAE, the models are declared to be calibrated if they produce (NMBE)s within ±10%, and (CV(RMSE))s within ±30% when using hourly data, or ±5% to ±15%, respectively, with monthly data. The NMBE and CV(RMSE) indices are calculated through the following Formulas (1) and (2):

$$NMBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{N_i \sum_{i=1}^{N_i} M_i} \times 100 \quad (1)$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i}\left[\frac{[(M_i - S_i)]^2}{N_i}\right]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \times 100 \quad (2)$$

where M_i is the measured energy data point during the time interval, S_i is the simulated energy data point during the same time interval, and N_i is the count of the number of values used in the calculation.

The discrepancy between measured and simulated results was reduced by detecting and altering the design parameters that most affect the cooling and heating load. These parameters were identified by sensitivity analysis. In addition, both real energy consumption and zone temperature data were assigned to calibrate the building model. After verifying the validity of the simulation by obtaining a simple error rate, the model was utilised for running the simulation and optimisation study.

Sensitivity Analysis

A primary sensitivity test was conducted on 10 variables to assist the calibration stage by identifying the hierarchical order of the sensitive parameters. Once these parameters were determined, the values of the least influential parameters were removed from further consideration, and the most influential ones were tuned manually until an acceptable discrepancy between the monitored and simulated data was achieved. In this study, the selected objective function in the sensitivity analysis was cooling load and heating load. The method applied was regression, where the indicating factor was the standardised regression coefficient (SRC), and the number of random simulations was chosen as 100 times the number of design variables. Table 4 shows the variables that were chosen for sensitivity analysis.

Table 4. Selected variables for sensitivity analysis.

	Variable Type	Distribution Category	Distribution Curve	Distribution Summary	Target Objects
Flat roof construction	Flat roof construction	1-Discrete	20-Uniform (Discrete)	Prob:0.200; Options:5	Building
FF external wall construction	External wall construction	1-Discrete	20-Uniform (Discrete)	Prob:0.167; Options:6	1 Target selected
GF external wall construction	External wall construction	1-Discrete	20-Uniform (Discrete)	Prob:0.167; Options:6	1 Target selected
Glazing type	Glazing type	1-Discrete	20-Uniform (Discrete)	Prob:0.200; Options:5	Building
Local shading type	Local shading type	1-Discrete	20-Uniform (Discrete)	Prob:0.250; Options:4	Building
Window-to-wall ratio %	Window-to-wall ratio %	2-Continuous	Normal	Mean:40; StdDev:10	Building
Equipment power density (W/m^2)	Equipment power density (W/m^2)	2-Continuous	Normal	Mean:5; StdDev:1	Building
Occupancy (days/weeks)	Occupancy (Days/Weeks)	1-Discrete	20-Uniform (Discrete)	Min.Val:0.00; Step size:1.00; Step No:8.00	Building
Cooling system seasonal COP	Cooling system Seasonal COP	2-Continuous	Normal	Mean:2.5; Std Dev:0.5	Building
Cooling setpoint temperature (°C)	Cooling setpoint temperature (°C)	2-Continuous	Normal	Mean:25; Std Dev:2	Building

2.4. Case Study Model Optimisation

To investigate the influence of optimising the building envelope parameters on the thermal performance of the selected building, the thermal and energy performance of the base case digital twin was first assessed using DesignBuilder software. This essential step allows for a comparison of the building's thermal performance before and after optimising the different design parameters. Multi-objective optimisation was performed using a genetic algorithm (GA) technique. The set optimal trade-off solutions of the multi-objective problem form the Pareto front. The Pareto front bordering the region of feasible solutions defines the limit beyond which the design cannot be further improved. The genetic algorithm (GA) technique optimises the design variables identified by sensitivity analysis through setting the objectives of the optimisation. The two objective functions are 'minimising total site energy consumption' and 'minimising thermal discomfort'. Cooling and heating loads are additional outputs that are added in the optimisation setting.

3. Results and Discussion

3.1. Sensitivity Analysis Result

When the energy consumptions of the measured and simulated end-use of the summer and winter months were compared, there was a discrepancy in cooling and heating and energy use, while the other categories (lighting, DHW, and other equipment) showed good agreement. Sensitivity analysis was carried out to determine the most sensitive design variables that can be adjusted to reduce the discrepancy between the measured and simulated cooling and heating energy use. According to the sensitivity analysis report (Figure 5a,b), the standardised regression coefficient (SRC) of the cooling load shows that design variables are the most influential variables. The roof and the first floor wall constructions have the greatest influence on the cooling load where increasing the U-value of the roof increases the cooling load. Cooling load is moderately influenced by ground floor construction, local shading, and glazing type. The occupancy schedule, window-to-wall ratio, cooling system coefficient of performance (COP), cooling setpoint temperature, equipment power density, and infiltration rate do not have any notable impact on cooling load and can therefore be ignored in the parameter adjustment step. The heating load sensitivity analysis result illustrates that the roof and first floor wall constructions have the greatest influence on heating load. The ground floor walls have a moderate influence, while local shading and glazing type have a very limited influence on heating load. Consequently, adjusting these design parameters helps reduce the discrepancy between the actual and simulated model results. However, since the U-value specifications of the ground floor walls and first floor walls were set based on actual measurements, both were exempt from the parameter adjustment step. Consequently, only the design variable specifications of the roof and floor construction were tuned manually until an acceptable discrepancy between the monitored and simulated data was achieved.

3.2. Model Calibration Results

3.2.1. Monthly Energy Consumption Calibration

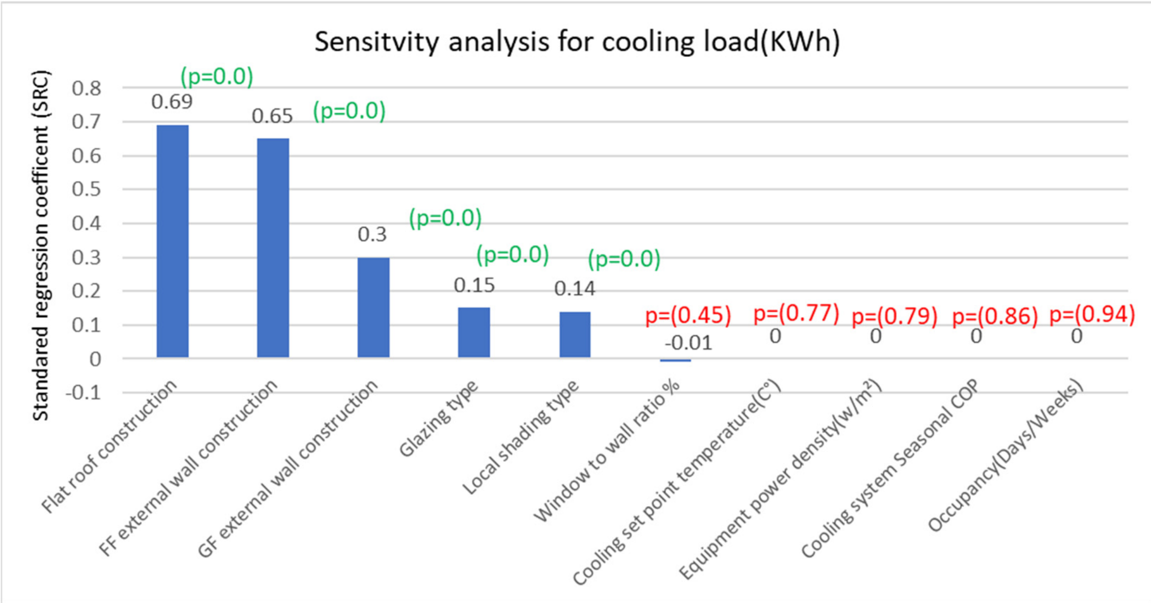
Figure 6 compares the monthly simulation results and the monitored data of electricity consumption and provides the key statistical error values. According to ASHRAE Guideline 14-2002, the monthly energy use profile was estimated with an acceptable degree of accuracy, i.e., CV (RMSE) $< 15\%$ and NMBE $<\pm 5\%$.

3.2.2. Hourly Energy Consumption Calibration

Initial checks confirmed that the measured and simulated energy consumption were correlated and in agreement to some extent. This can be seen when looking at the overall trends in measured and simulated energy consumption between 19th June and 22nd June 2022 (Figure 7).

However, an evaluation of the hourly NMBE and CV(RMSE) showed a discrepancy between monitored and simulated data (Figure 7). To investigate the reasons for the fluctuation in the actual energy consumption trend which caused the discrepancy, the actual energy use data of the AC unit was compared to the actual temperature trend of the lounge, where the AC is situated. It was found that the times when AC energy use was recorded as zero were the times when the indoor temperature reached the AC set point of 24 °C (Figure 8).

Due to the variability of the measured energy use, it was challenging to calibrate hourly energy consumption. For this reason, the running average of the measured data was used to help smooth its fluctuating pattern and then compared to the running average of the simulation outputs. When looking at the running average of the measured data against the running average of simulated data, it can be noticed that the general patterns of both are correlated very closely, which facilitates model calibration based on energy consumption using ASHRAE calibration criteria (Figure 9).



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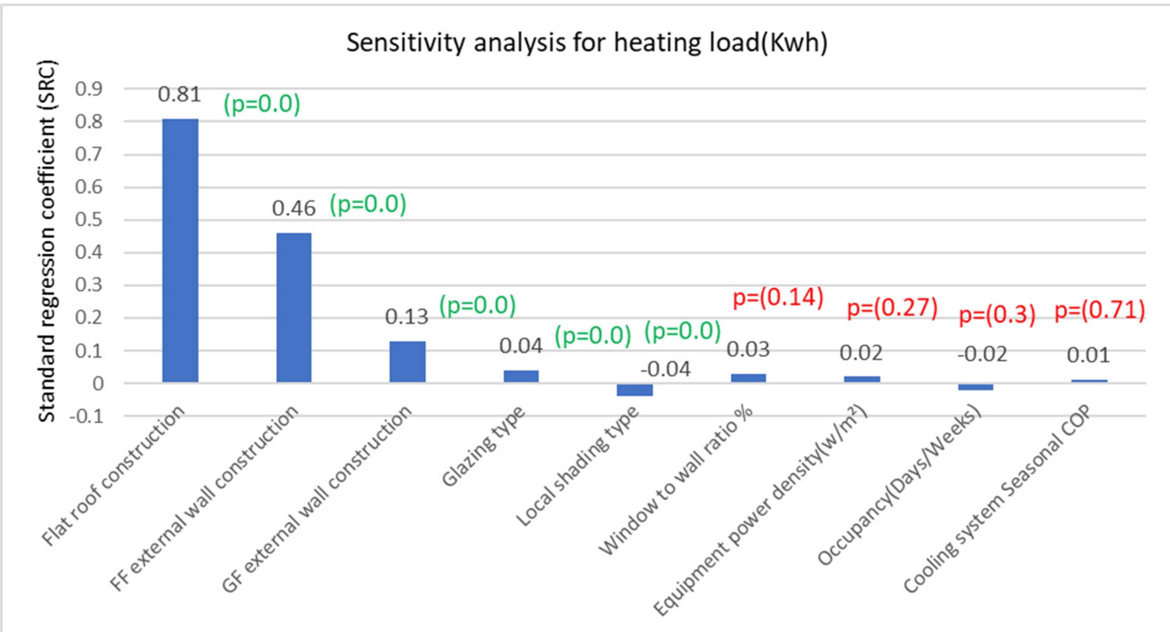

(**b**)

Figure 5. (**a**) Cooling load sensitivity analysis result, (**b**) heating load sensitivity analysis result.

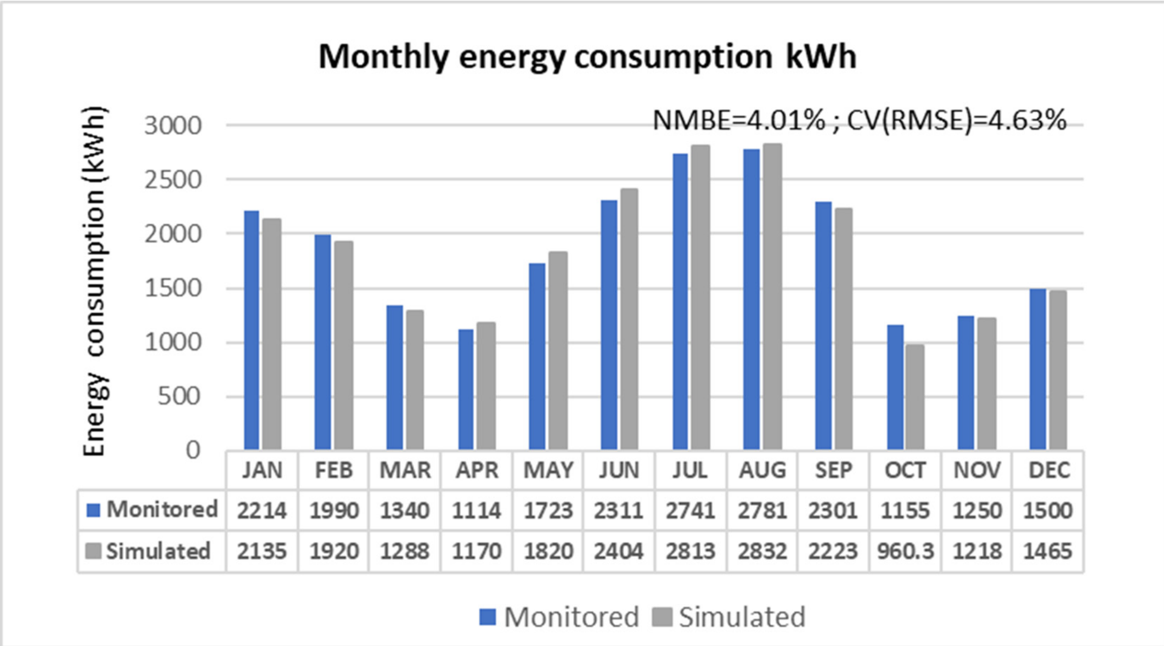

Figure 6. Monthly calibration results for the case study house.

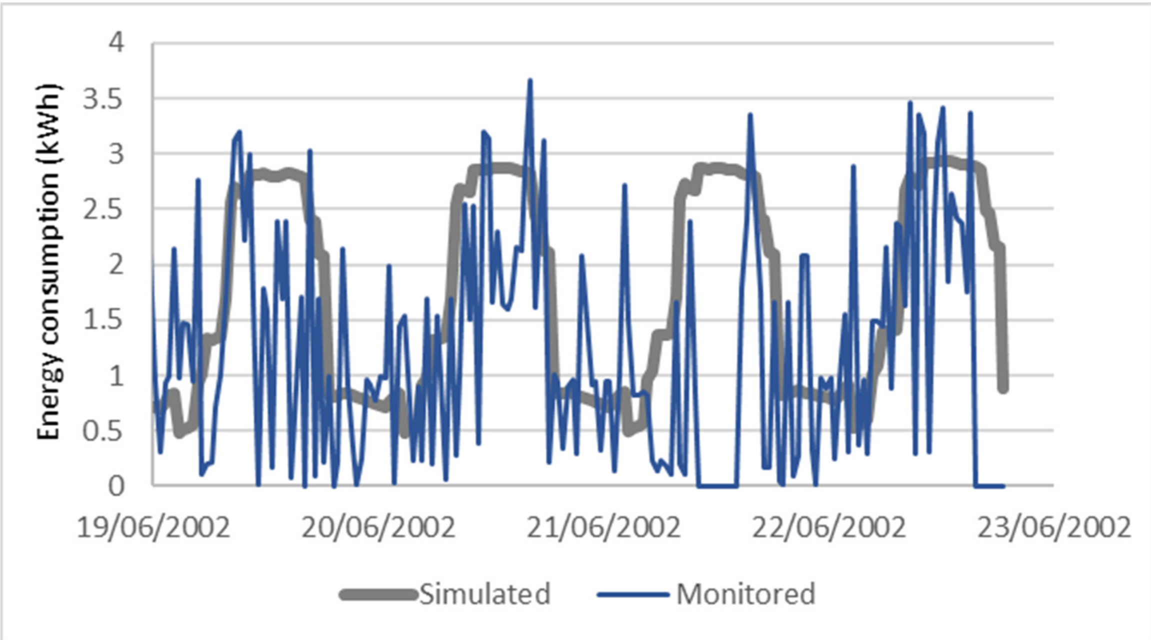

Figure 7. General trend in simulated versus monitored AC energy use data between 19th and 22nd of June.

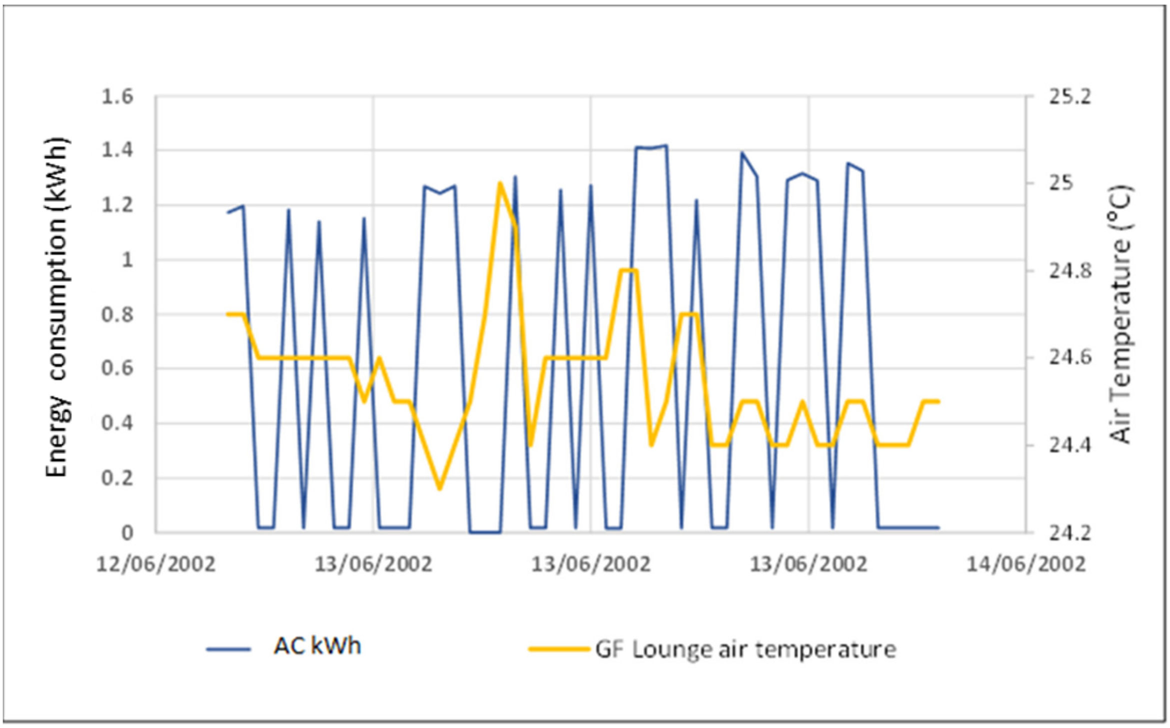

Figure 8. The air temperature of the ground-floor lounge against AC energy use.

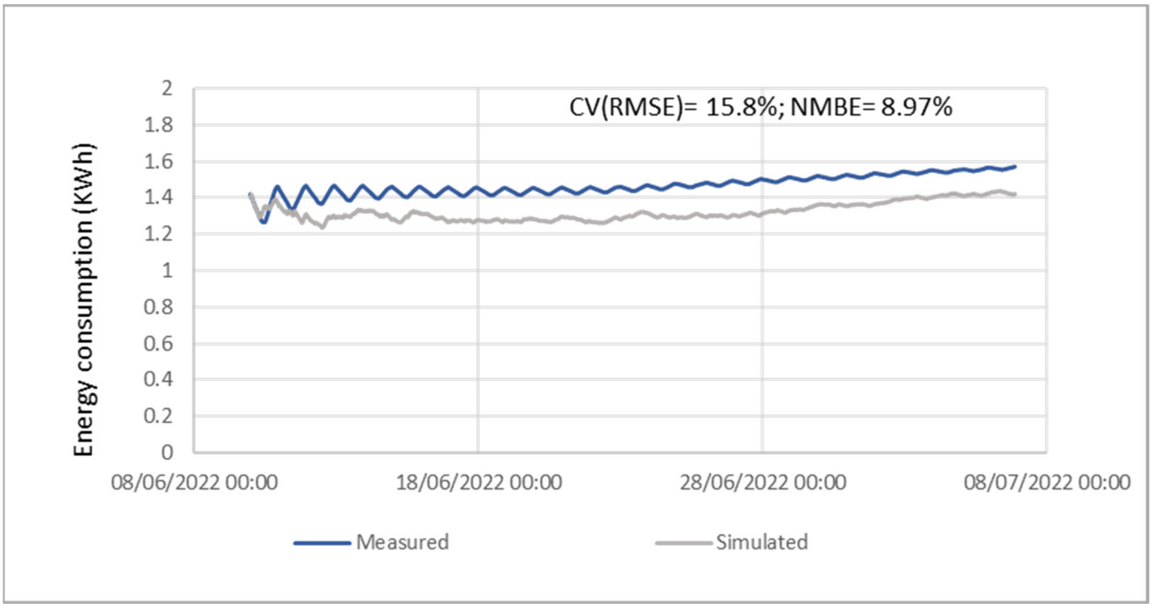

Figure 9. Running average of monitored and simulated building energy consumption between 8th of June 2022 and 6th of July 2022.

3.2.3. Monthly Zone Temperature Calibration

Zone temperature calibration is also adapted in this research to ensure that the calibrated model properly reflects the actual building's performance. Figures 10 and 11 show that the simulated average indoor temperature of randomly selected spaces on the ground floor and first floor closely follow the measured average indoor temperature. Moreover, an acceptable CV(RMSE), and NMBE are also achieved for all of the selected zones. Thus, the model is considered calibrated based on monthly zone temperature.

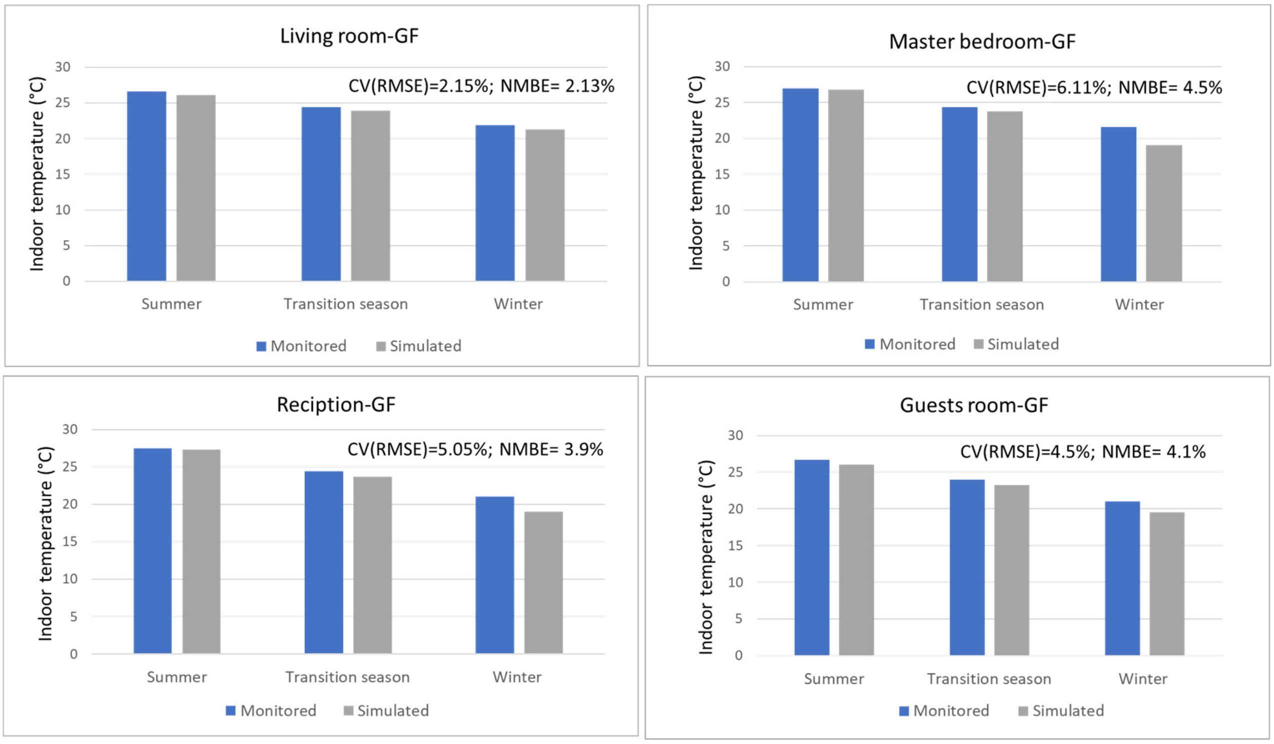

Figure 10. Monthly zone temperature calibration of ground floor spaces.

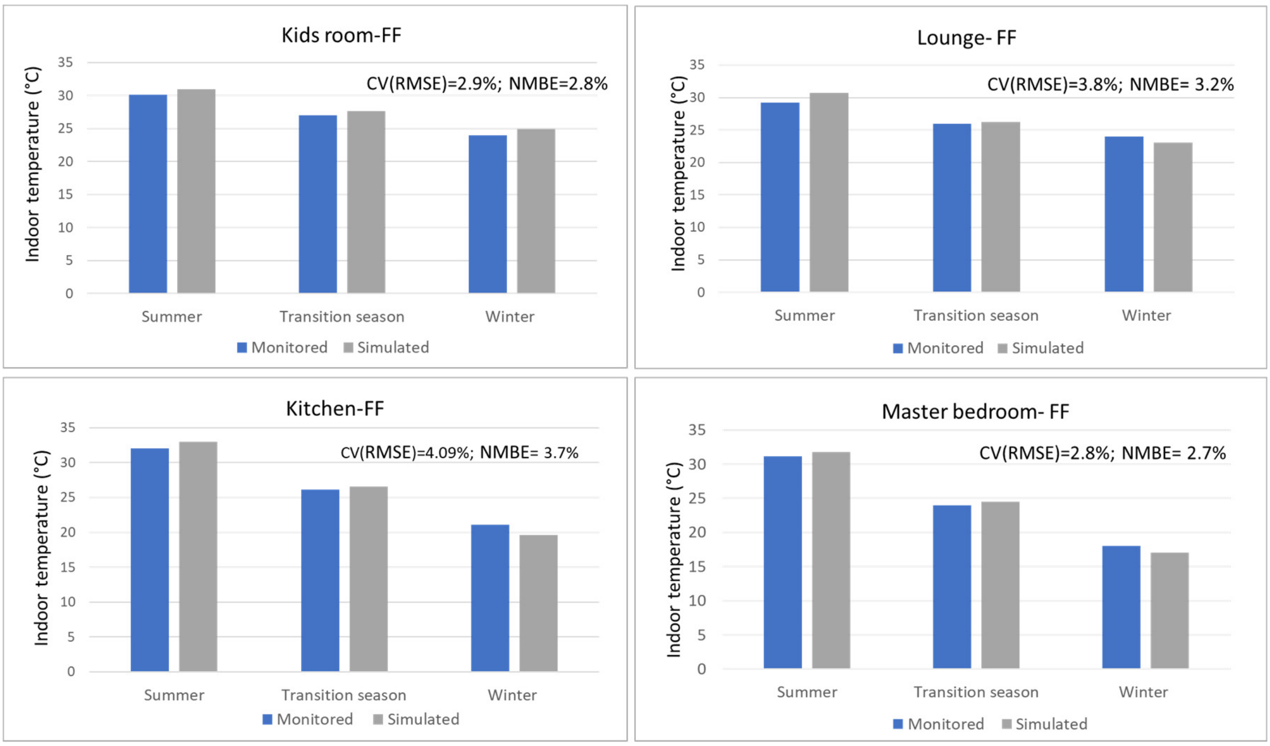

Figure 11. Monthly zone temperature calibration of first floor spaces.

3.2.4. Hourly Zone Temperature Calibration

To ensure that the calibrated model reasonably reflected the actual building's performance, the hourly zone temperature calibration of the summer months was carried out. The monitored indoor temperature data for the ground floor and first floor spaces were also compared to the simulated data. The simulated temperatures closely follow the measured air temperature as shown in Figures 12 and 13. Moreover, an acceptable hourly NMBE and CV(RMSE) were also achieved for all of the selected zones. As a result, the calibrated model reflects the actual building's performance and is validated for the simulation study.

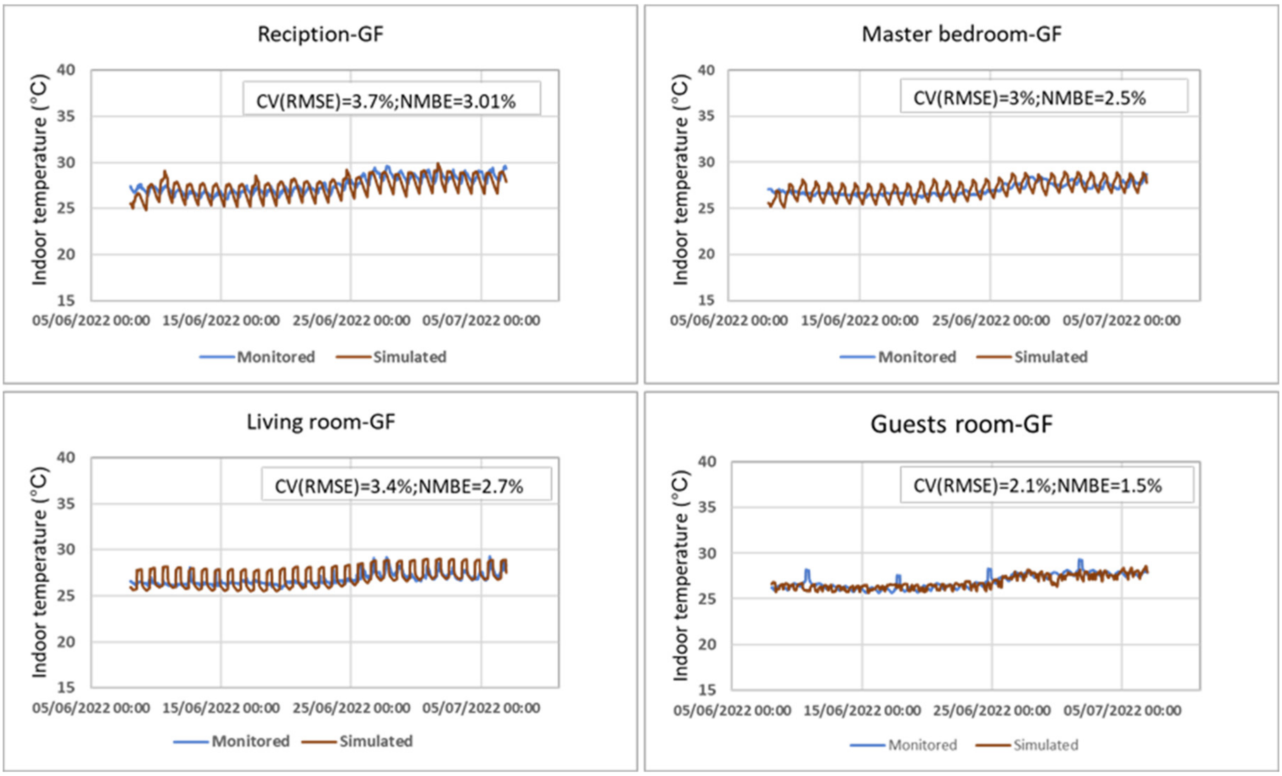

Figure 12. Hourly zone temperature calibration of ground floor spaces.

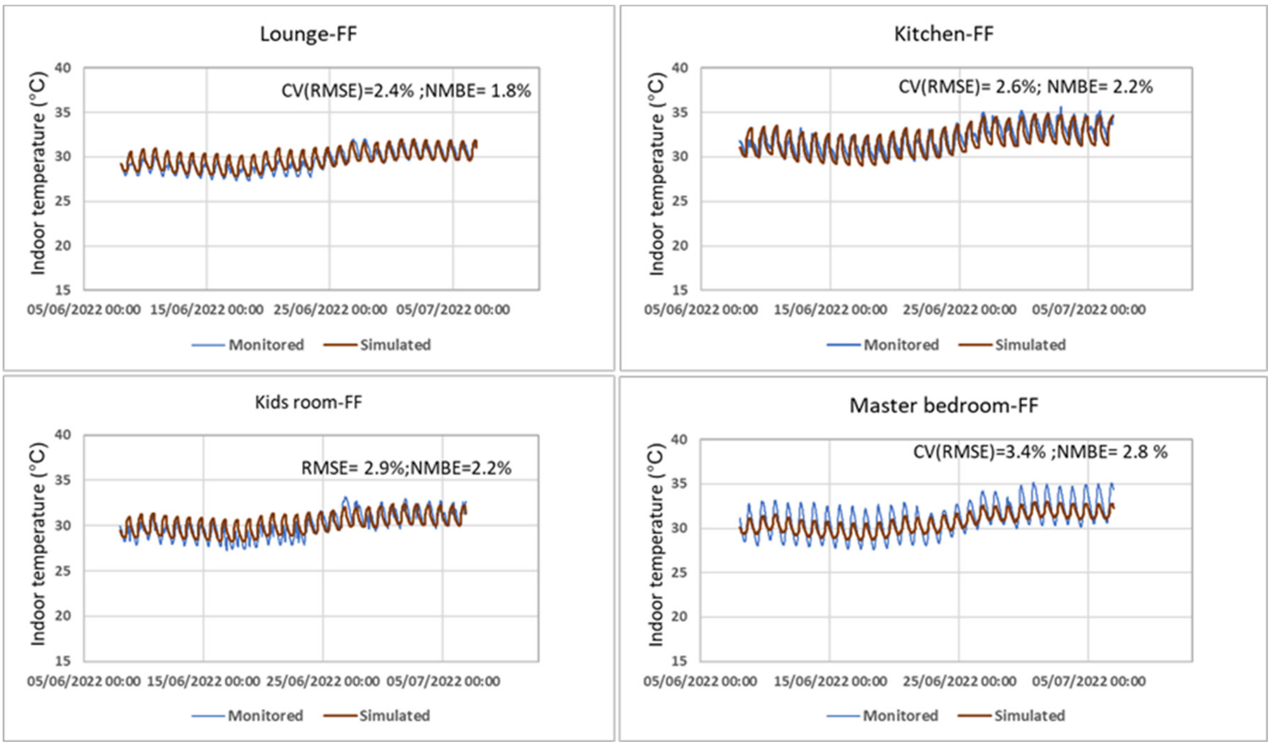

Figure 13. Hourly zone temperature calibration of first floor spaces.

3.3. Building Simulation Results

The building simulation results show that a typical terraced house located in Benghazi, Libya consumes 24,660.97 kWh/year of energy. The annual primary energy demand was 209 kWh/m^2, which is above the 120 kWh/m^2 passive house target. The house consumes 13,198.00 kWh/y of cooling energy and 4801.78 kWh/y of heating energy which make up 53.51 kwh/m^2/y and 19.4 kwh/m^2/y of unit energy, respectively. The combined annual heating and cooling energy demand is about five times higher than the 15 kWh/m^2 target of passive house buildings. These data serve as a reference to compare them with the building energy optimisation results. The annual fuel breakdown in Figure 14 shows that building cooling and heating constituted the most consumed energy.

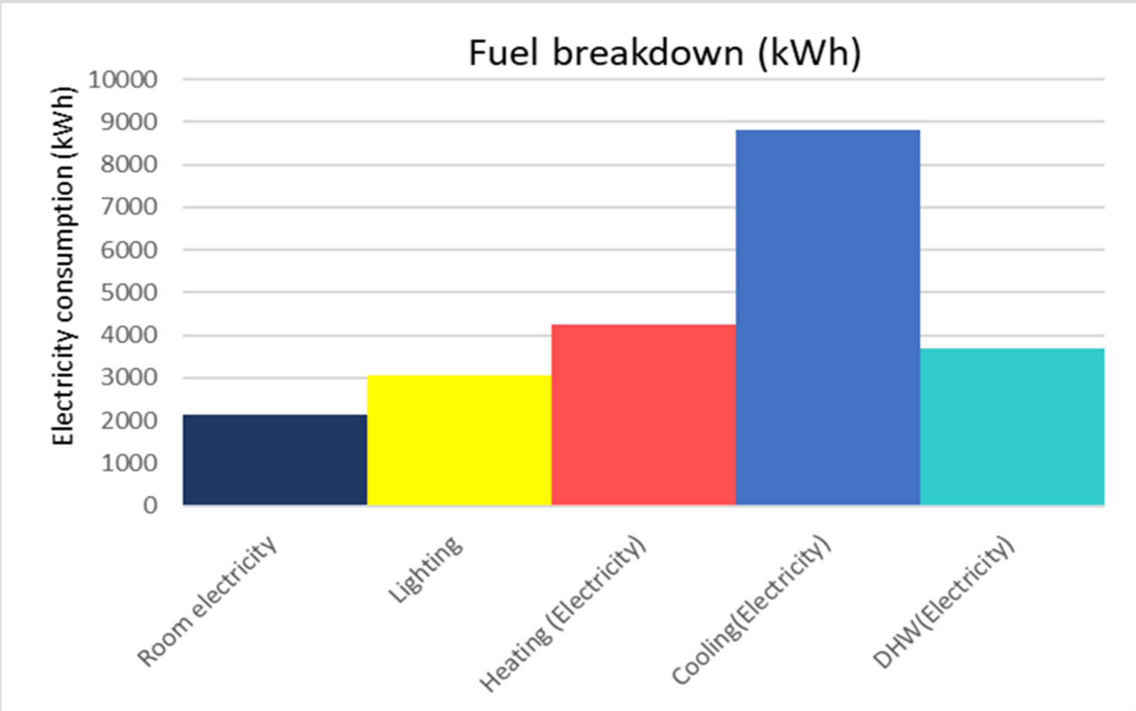

Figure 14. Fuel breakdown of the case study house.

The summer heat balance graph for the case study building shows that the highest heat gains are through the roof, followed by the walls and solar gain from exterior windows with heat gain contributions of 51.48% 17.4%, and 19.12%, respectively. The internal heat gain from the occupants, electrical lighting, appliances, as well as infiltration rate is limited (Figure 15). Similarly, the winter heat balance graph illustrates that the roof and walls are the most influential parameters on heating load (Figure 16). This is consistent with the sensitivity analysis results which show that the building envelope parameters, including the roof, walls, and windows, are the most influential parameters on cooling load in summer and heating load in winter. Therefore, thermal refurbishment of the building envelope parameters could plausibly lead to a reduction in building energy use and its associated influence on the environment.

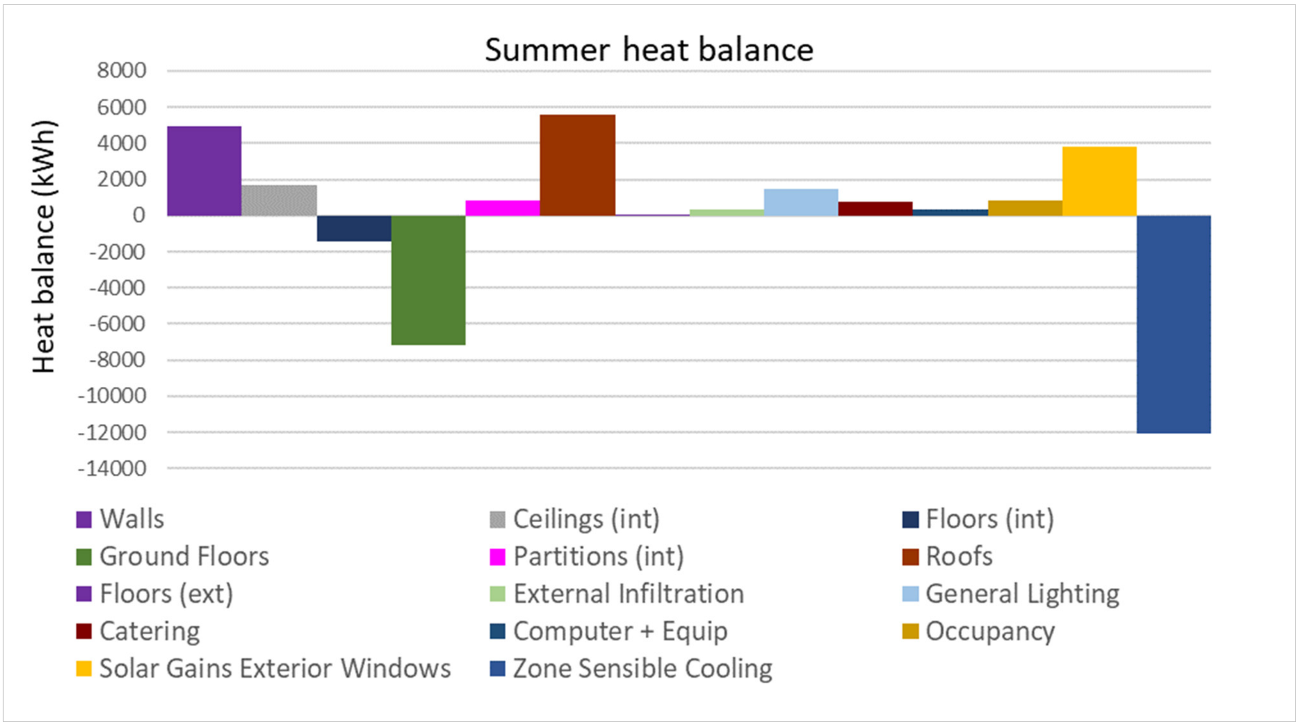

Figure 15. Heat balance report for summer.

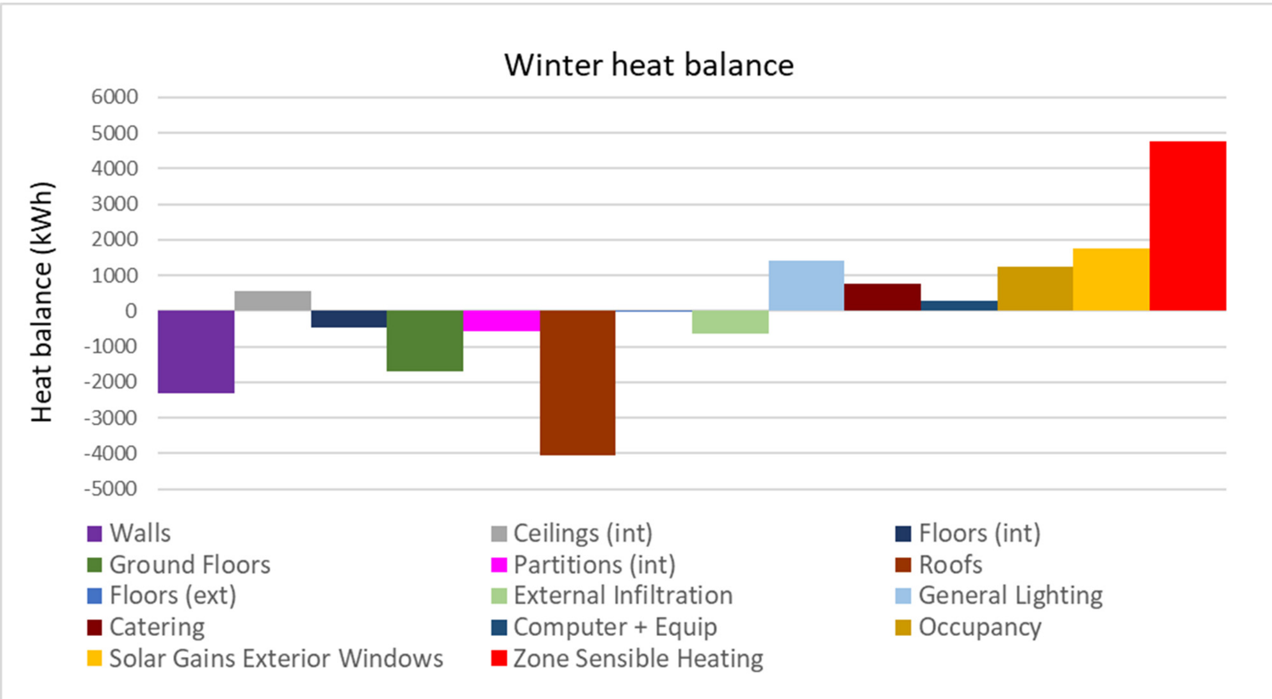

Figure 16. Heat balance report for winter.

3.4. Building Energy Optimisation Results

The standardised regression coefficient (SRC) indicates that cooling load and heating load are most strongly influenced by flat roof construction, external wall construction, and moderately by glazing type and local shading type, agreeing with the findings of the sensitivity analysis (Figure 5). Other variables do not have any notable impact on cooling and heating loads and can, consequently, be ignored in further studies of cooling and heating loads for this model. The design variables for optimising the building envelope parameters are presented in Tables 5–7. The thermal properties of the insulation materials are gathered from previous published research, and manufacturers' websites [32] and presented in Table 8.

Table 5. Specifications of insulation materials for roof and walls optimisation.

Element	Parameters			
	Base Case U-Value W/m^2.K	Insulation Position	Material	U-Value Range W/m^2.K
Roof	3.09	Internal	Sheep wool, camel hair, date palm fibres	0.5–0.1 @ 0.1 decrement
Ground floor wall	2.27	External/internal	Sheep wool, camel hair, date palm fibres	0.5–0.1 @ 0.1 decrement
First floor wall	2.61	External/internal	Sheep wool, camel hair, date palm fibres	0.5–0.1 @ 0.1 decrement

Table 6. Glazing type used for windows optimisation.

	Glazing Type	U-Value W/m^2.K	Solar Transmission SHGC	Light Transmission
Base case	Sgl Clr 6 mm	5.78	0.8	0.88
Optimisation case	DblClr/6 mm/13 mmArg	2.5	0.7	0.78
	Dbl LoE (e2 = 0.1) Clr 6 mm/13 mm Arg	1.5	0.56	0.75
	Trp Clr 3 mm/13 mm Arg	1.6	0.68	0.74
	Trp LoE (e2 = e5 = 0.1) Clr 3 mm/13 mm Arg	0.78	0.47	0.66

Table 7. Shading optimisation parameters.

Base Case	No Shading				
Optimisation case	Overhangs, Depth m	Side Fins + overhangs, Depth m	Louvers, Depth m	Louvers, Vertical spacing m	Louvers, Angle
Shading	0.5	0.5	0.5	0.3	15°

Table 8. Specifications biobased insulation materials used for optimizing the roof and walls.

Material	Thermal Conductivity W/m.K	Density kg/m^3	Specific Heat Capacity J/kg.K
Sheep wool/camel hair	0.039	19	1700
Date palm fibres	0.051	254	1356

The most influential parameters on cooling and heating load, as identified by the sensitivity analysis and the heat balance graph, are optimised using multi-objective optimisation method based on genetic algorithm (GA). Two multi-objective optimisation runs were carried out, one with external wall insulation and another with internal wall insulation, both along with other optimisation variables such as shading variables and glazing U-value variables (see Tables 5–7).

The first simulation included 1277 iterations, of which the Pareto front produced 112 optimal solutions (Figure 17). The range of the site energy consumption for the optimal solutions was 17,675.1 to 19,433.21 kWh/y. The second simulation included 1370 iterations, of which the Pareto front produced 94 optimal solutions (Figure 18). The range of the site energy consumption for the optimal solutions was 17,701 to 19,596 kWh/y. Accordingly, the position of the insulation material, whether internally or externally, does not differ substantially in terms of energy use reduction. In addition, all the provided optimal solutions do not compromise thermal comfort.

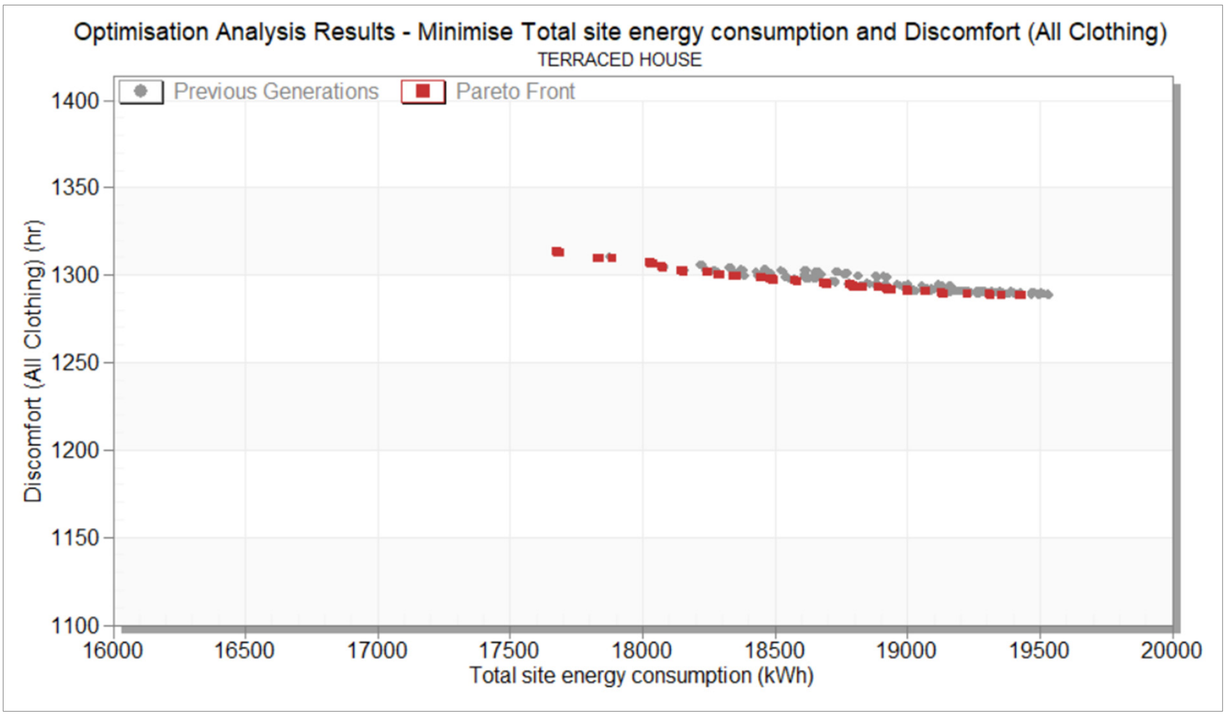

Figure 17. Multi-objective optimisation result 1.

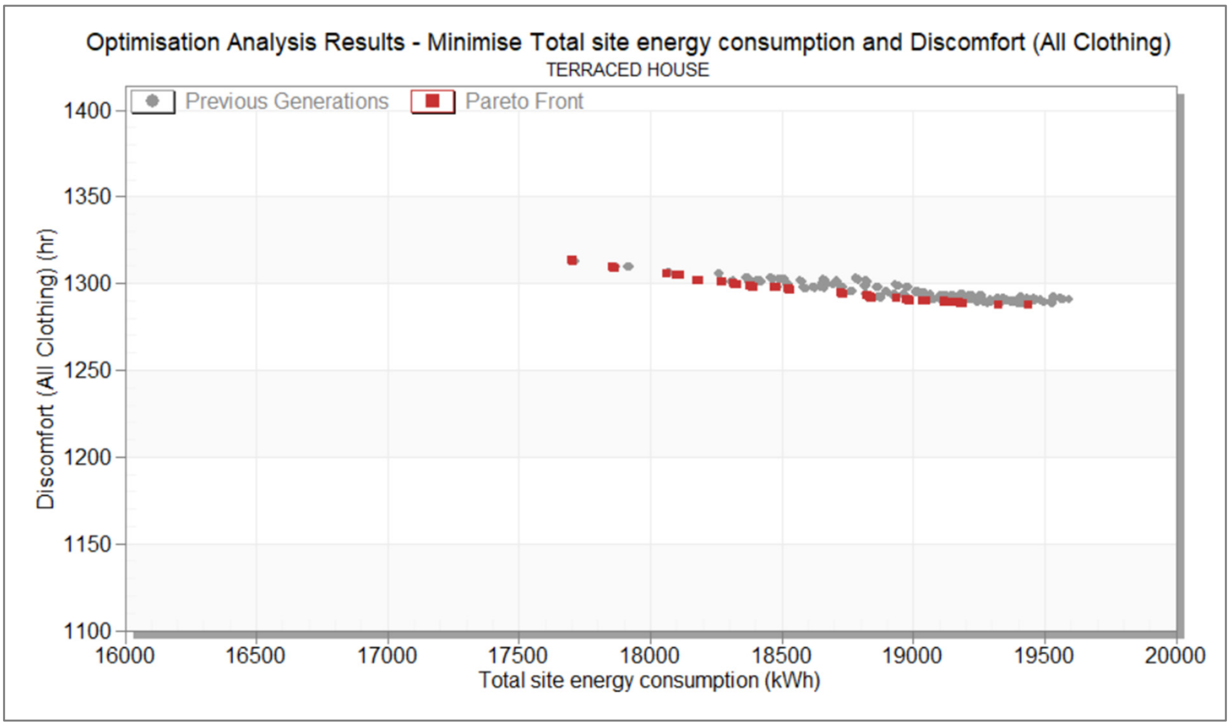

Figure 18. Multi-objective optimisation result 2.

The most optimal design solution that produced the lowest site energy consumption, with an acceptable range of 15% annual discomfort hour, includes the following design parameters,

- The roof with internal sheep wool or camel hair insulation with a U-value 0.3 W/m^2.K;
- The walls with external palm fibre with a U-value of 0.1 W/m^2.K;
- 'Trp LoE Clr 3 mm/13 mm Arg' glazing with a U-value of 0.78 W/m^2.K and SHGC of 0.47;
- Side fins 0.5 m + 0.5 overhang.

The primary energy consumption was 150 kWh/m^2/y which is a 28.33% reduction from the energy use of the base case building. The site cooling energy reduced from 53.51 kwh/m^2/y to 40.8 kwh/m^2/y, while the site heating energy reduced from 19.4 kWh/m^2/y to15 kWh/m^2/y. It can be observed that a combination of moderate and extreme values of different parameters helped reduce the energy demand.

4. Conclusions

In existing buildings, determining the key contributors to energy consumption is essential to identify the most appropriate strategy to reduce energy demand and carbon emissions. This study focused on a typical terraced house located in Benghazi, Libya, with a view to reducing energy demand. Having acquired all relevant thermophysical data from the case study building through a monitoring regime, a digital twin was created for thermal optimisation of the base case building. A sensitivity analysis was performed using the regression method. The results, also supported by heat balance data, indicated that the building envelope parameters including roof, walls, and windows are the most influential parameters on building energy consumption. The baseline simulation result also shows that cooling and heating loads are attributed the most to heat gain and loss through the roof, walls, and windows. As a result, these three elements were optimised, using the multi-objective optimisation method, with different energy saving measures including the application of biobased insulation material on the roof and external walls with a range of U-values and corresponding volumetric heat capacities. Different energy-efficient glazing types with a range of U-values and various local shading types were also incorporated in the optimisation process. The optimisation results indicate that upgrading the building roof with internal sheep wool or camel hair insulation with a U-value of 0.3 W/m^2.K, the walls with external palm fibres insulation with a value of 0.1 W/m^2.K, and upgrading the windows with energy efficient glazing (Trp LoE Clr 3 mm/13 mm Arg) and side fins 0.5 m + 0.5 overhang for shading could achieve a reduction in cooling energy demand from 53.51 kWh/m^2/y to 40.8 kWh/m^2/y. Heating energy demand was reduced from 19.4 kWh/m^2/y to 15 kWh/m^2/y without compromising the standard annual discomfort hours.

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