

## Research Article

# Optimum Building Design Variables in a Warm Saharan Mediterranean Climate Zone

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This research contributes to making residential buildings more efficient in the city of Azraq, Jordan, which is located in a warm climate zone in the Saharan Mediterranean region (classified as a hot desert climate according to the Köppen climate classification). It involved the optimisation of several envelope parameters with the aim of reducing the usage of energy within a normal structure occupying an area of 186 m<sup>2</sup> without the occupants' involvement in saving energy in the building to solely measure the building envelope's thermal performance. The DesignBuilder software was used for the sensitivity analysis using 12 design variables, which enabled their significance for both cooling and heating loads. The selected variables were separated into two categories based on their level of significance: a group with higher importance (window to wall %, local type of shading, ground floor building, natural rate of ventilation, rate of infiltration, kind of glazing, and flat roof structure) as well as a group with lower importance (partition construction, site position, construction of outside walls, kind of window blinds, and window shade control timetable); these variables will save a significant amount of heating and cooling energy.

## 1. Introduction

With the aim of reducing the consumption of energy, there has been increased focus on the construction of low-energy buildings and implementation of energy-efficient techniques. This is because achieving more efficient buildings along with efficient systems for cooling and heating as well as installation of renewable energy sources could help to resolve the global energy shortage crisis. The world is currently facing various different crises including global warming, pollution, an increasing population, and the growing energy demand accompanied by the exhaustion of the world's natural resources. Substantive ongoing efforts have been made to solve these problems, including the invention of electric cars, the utilisation of new renewable sources of energy, and the design of low-energy buildings. The energy consumed by residential buildings needs to be reduced as this constitutes a significant proportion of the energy profile of most countries.

Thus, numerous studies have been conducted to improve the thermal efficiency of buildings and enhance thermal comfort without increasing energy consumption. Scientists and researchers have therefore continued to develop new methods and materials to construct low/zero energy buildings.

In order for a building's thermal performance to be improved, an appropriate envelope design is required. This is determined by several factors, including geographical location, climate type, and building materials. It is also contingent on the building envelope's general performance. This means that its various components, such as the windows, openings, roof, and walls, need to function as a synergistic whole. Consequently, any alterations to the parameters of one or several of these elements will impact the efficiency of the others and, correspondingly, the overall performance of the building. Therefore, to substantially enhance thermal performance, the efficiency of the different parameters of these elements needs to be optimised.

There are numerous warm to hot climate regions around the world (both subtropical and tropical). These include harsh arid desert climates such as the Sahara and milder climates such as the Mediterranean. It is therefore important to differentiate adaptation solutions according to differences in the extremes and amplitudes of air temperatures, air humidity ratios, amounts of solar radiation and sun paths, and precipitation rates, for instance, the city of Azraq, Jordan, which is located in a warm climate zone in the Saharan Mediterranean region (classified as a hot desert climate according to the Köppen climate classification) [1].

Buildings intended for warm or hot climate regions are designed on the basis of either pragmatic contemporary or intuitive traditional principles. Current guidelines for building design that are both climate-sensitive and energy-saving encompass the following elements [2–4]:

- (i) Building form and orientation, building materials, and envelope construction (roof, façade, windows, walls, and floor)
- (ii) Site planning, including vegetation and landscape
- (iii) Control of climate features, including shading and daylight, solar access, and ventilation
- (iv) Specific optimisation of climate resources, including evaporative coolers, solar thermal, and wind catchers

Experimental and statistical research on housing in hot arid regions in Algeria has been performed for the purpose of evaluating the thermal comfort within modern and low-cost traditional buildings. Their aim was to ascertain whether it would be feasible to design houses offering effective thermal environments at a reasonable cost by ensuring effective thermal insulation of the outer envelope (including the roof). The use of such insulation implies that a building's shape is no longer a critical factor. It also makes sense to combine effective night ventilation with high interior thermal storage. According to the findings, it is suggested that firstly, south-facing windows occupying 15% of the floor area are effective if combined with good insulation. Second, movable shading devices are more effective than fixed shading devices. Third, it is vital to provide summer night ventilation and this is most effective when combined with high thermal storage [5].

Another study suggests that, for low-income houses in Jordan, a lower-cost, more effective solution is to minimise building infiltration. The researchers conducted analysis to compare the efficiency of insulation infiltration rate techniques implemented in such houses in different climate zones within Jordan. For the purpose of testing the efficiency of different infiltration rate and insulation scenarios (roof, wall, and roof and wall combined), they developed a simulation that represented the common configuration of buildings. The results indicated that in distinct climates, minimising the infiltration rate reduces energy demand better than the installation of 12.5 cm roof or wall insulation, while reducing infiltration by half (0.75 air changes per hour (ACH)) is as effective in lowering the demand for energy as 10 or 12.5 cm wall or roof insulation [6].

Another set of researchers employed numerical modelling and empirical measurements to explore methods for reducing the consumption of buildings in Mediterranean Jordan. Based on a numerical parametric study of Amman, an optimised building was devised with a south orientation, a window to floor ratio between 12% and 20% facing south, and thermal insulation of 0.5–0.7 W/m<sup>2</sup> K for the roof and walls. In comparison to a noninsulated base case, heating energy demand was reduced by 86% and cooling need by 26% [7].

Another study examined whether the passive house concept could be extended to southwest Europe. The findings showed that, with a few exceptions, the appropriate cooling energy demand was below 2 kWh/m<sup>2</sup> while the typical heating energy demand ranged between 10 and 15 kWh/m<sup>2</sup>. These gave rise to the following general guidelines: double low-e glazing, good movable exterior shading with preferably a south orientation, and robust thermal protection with approximately 10 to 20 cm of thermal insulation (lower than for mid-Europe). A compact shape also appeared to be advantageous in both hot and cold seasons. To avoid excessive insulation or provide active cooling and dehumidification, it is important to install an exhaust air ventilation system in conjunction with excellent tightness. To reduce cooling, night ventilation is as effective as good insulation. Thermal mass has less importance but is also beneficial. In the hottest climates, good solar reflectance of exterior surfaces is recommended, while insulation of the basement ceiling or floor slab should be avoided [8].

Using simulations, another group of researchers monitored the air and surface temperatures of an unoccupied building with closed shutters during one hot summer week in a hot Mediterranean climate area. The results indicated that thermal insulation and thermal mass exerted a positive effect as the average indoor temperature was only 27°C when the outdoor temperature reached 38°C. A study compared simulated data for a noninsulated conventional construction and a prototype and found that in the former, the air temperature could reach 32°C. The indoor air temperature could be reduced further by combining night ventilation with horizontal overhangs used as shading devices. The researchers recommended that the dimensions of the fixed horizontal overhangs should be optimised, which appeared to be impractical due to their large size [9].

The adoption of an adaptive strategy encourages building occupants to implement more sustainable methods of obtaining thermal comfort including naturally ventilating spaces (opening/shutting windows), appropriate attire, and shading. When implemented in the context of standard housing modules, adaptive behaviours reduced the amount of mechanical cooling or heating needed by greater than 50% in comparison with typical occupants in similar climates [10–13]. The use and application of the adaptive thermal comfort model considerably lowered the time required by mechanical cooling and heating by in excess of 50% in comparison to the air-conditioning constant thermostat setting. Using wider ranges of air-conditioning thermostat setting lowers the operating energy by approximately 50% compared to operating temperatures that were fixed at a certain level. This can be accomplished via the application of a wider scope

of tolerable temperature thresholds as well as the use of methods that optimise energy consumption while sustaining the thermal comfort of occupants [14–16].

A comparative study was conducted on two styles of walls: one made from bricks and the other from stones. The chosen configurations included the possibility of constructing the walls with an insulating layer. The study was performed based on the climatic environment of the Tunisian city of Tunis. A mathematical technique founded on the Complex Finite Fourier Transform (CFFT) was developed to analyse the data. The findings revealed that the stone wall, including a sandwich comprising an insulation sheet of extended polystyrene, the thickness of which was optimised at 57 cm, offered a higher degree of indoor thermal comfort relative to its homologous bricks [17].

The impact of using light coloured paint and/or thermal insulation of a residential structure's thermal efficiency and energy usage was explored. According to the findings, the Overall Solar Reflectance (TSR) of the roof and other outer surfaces improved from 50% to 92%, which led to a decrease in the mean free-float indoor temperature of 2.0°C to 4.7°C in old buildings (without thermal insulation) and a decrease of 1.2°C to 3.0°C in new buildings (with thermal insulation). The fall in the mean inside temperature of as much as 1.5°C has a trade-off effect. The findings indicated that when cool paints were used, high savings of approximately 30% in annual cooling energy consumption were achieved [18]. A computational parametric analysis for an optimised building in the city of Amman, Jordan, was conducted, which had a thermal insulation of 0.5–0.7 W/m<sup>2</sup>·K for the walls and roof, a south orientation, and a window to floor ratio between 12% and 20% facing south. Compared to a noninsulated base case, the optimised solution reduced heating energy demand by 86% and cooling demand by 26% [19]. In various climatic zones, Baneshi et al. compared various pigments on white and black substrates used for rooftops with traditional paints. They found that the best results were obtained using CuO pigment coatings. Depending on the climatic zone, a reduction in the annual cooling load and an increase in annual heating load were observed. The improved heat gain in cold mountain regions did not induce any change in the building's energy performance. However, in desert climates, the overall annual energy saved for air conditioning was 1442 kWh, while in Mediterranean climates, the overall energy saved was 1148 kWh. Additionally, it was found that, in terms of a building's energy efficiency, the colour and pigments of the paint have a significant influence on the rooftop's *U* value [20].

A simulation-optimisation tool was generated and employed to improve building design and building envelope functionality. To reduce energy use in a residential building, the simulation-optimisation framework paired a GA with a building energy simulation program was used to choose optimal values from a detailed array of envelope-related parameters. When conducting the optimisation, different forms of buildings were explored, which included the rectangle, L, T, cross, U, H, and trapezoid. In addition, building envelope characteristics, such as the roof and wall designs, foundation styles, levels of insulation, and window dimensions and areas, were also considered. The optimisation findings showed that

buildings were trapezoidal and rectangular shapes regularly exhibit the highest efficiency (lowest cost of life cycle) in five distinct climate zones. Both displayed the lowest variability from best to worst within the design [21].

The researchers in [22] explored how informed decisions could be made in a multidimensional space. They performed a sensitivity analysis to evaluate the effect of window to wall ratio, U-Wall, U-Win, solar heat gain coefficient, and degree of side fin surface reflectance on the usage of energy, daylight, and over temperature.

In [23], the researchers compared the applicability of distinct sensitivity analysis approaches for evaluating the energy efficiency of structures. To that end, they compared the effectiveness of Standardised Regression Coefficient (SRC), Fourier Amplitude Sensitivity Testing (FAST), and Morris in determining the effect of aspect ratio, window to wall ratio, amount of storeys, position, general scale, *U* values (wall, roof, and window), solar heat gain coefficient, lighting peak density, and equipment peak density on heating energy use, cooling energy use, and electricity use. In [24], the researchers conducted a sensitivity analysis (Morris) to examine the effects of reflectance values. They performed measurements to determine the effects of surfaces: floor, wall, ceiling, ground, and frames, on total annual illumination, useful daylight illuminance, daylight autonomy, and the daylight factor.

The DesignBuilder programme was used in another research for the purpose of comparing the scenario involving a conventional residential apartment with dimensions of 100 m<sup>2</sup> situated on the top floor of a three-storey structure in Egypt that had wall and roof insulation installed to the situation where there was no form of heat insulation. The sensible cooling load, air-conditioner energy usage rate, energy usage charge, and CO<sub>2</sub> emitted by the power station, because of energy consumed in the two situations where the room temperature was set at 24°C, 22°C, and 20°C, respectively. The findings showed that the installation of thermal insulation in the form of a glass wool blanket with a thickness of 0.05 m in the roof and walls led to a 40% reduction in electricity consumption related to the air-conditioning system and therefore considerable cost savings in terms of operations. Moreover, the energy saved would reduce the power plant CO<sub>2</sub> emitted by 30% [25].

Another study strived to increase levels of thermal comfort, reduce the electricity consumed, and promote natural ventilation within tall residential structures by employing air conditioning that contained a one-sided ventilation area (only one outside wall had windows). Their objective was to assess whether an air shaft located towards the rear of the room would magnify mean air velocity by increasing the pressure differential between the shaft's aperture on the roof and the window. The design of the room was intended to emulate a standard apartment in a 25-floor residential structure in Bangkok. The computational fluid dynamics functionality of DesignBuilder was utilised to evaluate the air velocities within predetermined occupied spaces in scenarios where an air shaft was and was not used (test and reference room, respectively). Once modified by the increased air velocity, the space's ambient temperature was used to determine the duration of comfort in each of the rooms in summer. The results suggested

that there was a significant increase in the mean air velocity within the test rooms, whereas in the reference room, it was not high enough to produce a cooling effect without the assistance of normal wind. The comfort duration in summer increased from 38% for the baseline space to 56% in the test space. This suggests that the proposed air shaft will lead to energy savings of approximately 2700 kWh due to the reduction in air-conditioning usage [26].

Several researchers have examined ways in which energy could be saved to create energy-efficient buildings by tailoring and combining design elements with effective air quality. A dynamic building simulation was therefore created for the purpose of modelling energy consumption in a standard two-floor terraced building in Kuala. The overall area of the building covered 676 square metres, which was separated into 11 zones that each had their own unique thermal properties [27].

Utilising Revit Architecture software, a case model was developed and then analysed using EnergyPlus software. Existing patterns of energy use were determined, and parts were replaced with new energy-efficient materials to calculate the optimum level of energy consumption. To determine the best combination of factors, a Design of Experiment (DOE) procedure was implemented. The results indicated that in these kinds of structures located in tropical regions, the material used in the ceiling had the most substantive effect on both energy usage and conservation. Wall structures also had a powerful impact on the consumption of energy. With regard to air quality, temperature was the most salient variable. Cooling loads were optimised by the effect of both temperature and a range of fabrics used in the walls and ceilings, specifically double-glazed windows with timber frames, suspended ceiling plaster insulation, a reverse brick veneer R20 for the walls, and a temperature of 26°C [28].

The design and construction of green buildings can be facilitated through forms of simulation software such as computational fluid dynamics (CFD), which can be utilised to construct a thermal model of a building and a virtual airflow to assess the design before construction begins. The ultimate aim is to design healthy, comfortable, and energy-efficient buildings. Prior to any renovation, CFD is able to evaluate the probable alterations to an existing building. This will make users aware of the benefits of altering design risks and avoid overpricing while allowing improvements and enhancements [29]. However, using CFD to perform a standard thermal simulation of buildings (up to one year) can be problematic; for example, there are difficulties in determining the correct sky temperature [30], peak temperature times can be inconsistent when prolonged CFD simulations are implemented [31], and warming issues can arise from an ongoing simulation [32], while problems also exist with the simulation and time step size [33] of wind effects on the thermal efficiency of structures [34].

This research presents an approach for optimally reducing the cooling and heating loads in structures situated in the country of Jordan, which is located in the Saharan Mediterranean warm climate zone. This approach is based on identifying the ideal configuration of the design for the envelope of the building (window to wall ratio, glazing type facades insulation, etc.). The designs obtained have minimal

energy consumption, while also ensuring that thermal comfort remains the same as for a typical residential building.

The research involved four separate stages:

- (i) First, the development of a residential building that complies with national Jordanian codes and assessment of its thermal performance using simulation software called "DesignBuilder-6.1." [35]
- (ii) Second, the establishment of a list of the most frequent design variables as well as the logical values these variables could have for the purpose of optimisation
- (iii) Third, determination of which of the identified variables significantly influences the thermal efficiency of the desired building
- (iv) Fourth, the use of a multiobjective numerical optimisation technique for determining the ideal configuration of the selected design variables that optimally reduces the energy consumption related to cooling and heating

In this study, there is a sensitivity analysis and optimisation for twelve building design variables in a warm Jordanian Saharan Mediterranean climate zone. These variables are rate of infiltration, shading, window-to-wall ratio, roof, floor, partition wall construction, types of window frame, window glazing, construction, rate of natural ventilation, orientation, outside wall construction, and window shading control schedule. DesignBuilder software was used to determine how they influence the general thermal efficiency. The main objective was to significantly minimise the need for cooling and heating while sustaining the occupant's thermal comfort, produced by utilising mechanical systems for cooling and heating.

## 2. Methodology

The following part offers in-depth information regarding the procedure followed to achieve an optimal configuration for the building envelope's design envelope and consequently maximise the reduction of the heating and cooling load needed to obtain the same thermal comfort levels as the baseline building.

*2.1. Location and Climate.* Jordan is situated between the Arabian Desert region and the Eastern Mediterranean region; therefore, its climate is distinguished by lengthy, warm, and arid summers, while winter is generally brief and cold. The coldest period of the year is between December and February where the average lowest/highest temperatures range between 10°C and 5°C, whereas the hottest time of the year is from July to September, when the average lowest/highest temperatures range between 35°C and 20°C. In the summer months, daytime temperatures can often be as high as 40°C or above, particularly when a hot, dry wind is blowing from the south-eastern direction. Winter often has considerable rainfall, with precipitation levels ranging from 200 to 400 mm, but this diminishes and largely ceases when

summer arrives. Jordan has various distinct climate regions, where some exhibit similarities to the climate in the Mediterranean area, whereas others are dominated by desert conditions. The Jordanian climate can be divided into four clearly delineated seasons, where optimal conditions for human comfort occur in spring and autumn.

The Saharan Mediterranean zone is warm with year-round sunshine, stable air, and high pressure. It is generally warm and dry throughout the year. The summer is hot to extremely hot with average temperatures of 35°C and peaks of 40°C during heat waves. In the colder winter months, temperatures can fall to freezing during the night; in general, the average high and low temperatures are shown in Figure 1. However, no major cities are located in this climate zone and there are only small towns such as Azraq.

In fact, the town of Azraq was chosen to represent the climate zone as its latitude and longitude are 31.23 and 34.78, respectively, while the site elevation is 525 m above sea level.

The study will concentrate on the following:

- (i) Conducting a simulation of the thermal efficiency of a standard residential structure that is representative of a typical building in Jordan and satisfies the thermal specifications indicated in the country's building codes utilising the DesignBuilder programme [36]
- (ii) Identifying the parameters of the building envelope that require optimisation
- (iii) Performing sensitivity analysis to emphasise the specific parameters that are the most influential on the cooling and heating loads
- (iv) Optimising the design parameters through the implementation of an optimisation procedure in which multiple simulations will be conducted to determine the optimal solution taking into account any interface among distinct design parameters

**2.2. Building Baseline Specifications and Shape.** This representative structure consisted of a living space sitting room, kitchen, a room for storage, main bedrooms, and two further bedrooms and two bathrooms with a total footprint covering approximately 186 m<sup>2</sup>, where each room is differentiated as a distinct area, as illustrated in Figures 2 and 3. The building is/was oriented with the long axis positioned south-north. The building is not impacted by outside shading or wind obstacles, which means that a large volume of solar radiation is allowed to enter the structure.

The materials used in the building envelope as well as their specifications were obtained from standard architectural design plans in which the building codes of Jordan were followed, which were then implemented to the DesignBuilder programme as follows:

**2.2.1. External, Internal Walls, Roof, and Floor.** The specifications and configurations for the materials used in constructing the inside, outside, roof, and floor of the building are shown in Table 1.

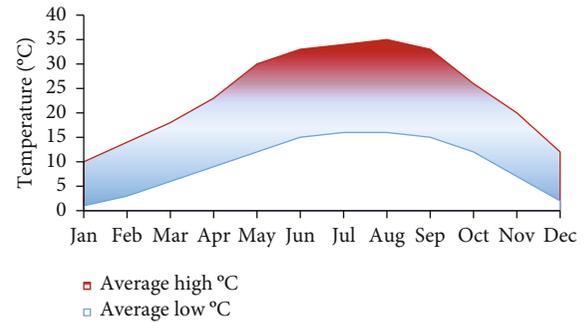


FIGURE 1: Monthly average maximum and minimum temperatures in Azraq, Jordan.

**2.2.2. External Window Glazing and Frame.** The specifications and configuration of the glazing materials used in the outside windows are shown in Table 2.

Thermally broken aluminium frames (polyvinyl chloride (PVC)) were used for the external windows with  $U$  value = 5.01 W/m<sup>2</sup>·K [37].

**2.3. Simulation Software.** DesignBuilder software (version 6.1) was employed for the purpose of simulating the building's energy performance. It is a software programme based on EnergyPlus that is used to analyse the building energy consumption, taking into account factors such as cooling, heating, ventilation, and illumination. Additionally, it is utilised for controlling and measuring a building's carbon, cost, and daylighting efficiency. This software offers an effective approach for simulating and optimising the envelope and environment of a building through the ability to quickly compare the performance of building components and to instantly deliver precise results. DesignBuilder enables users to investigate how altering the individual components of the building envelope impacts the building's energy efficiency and usage.

**2.4. Energy Retrofit Strategies.** Based on the objective of enhancing the general thermal performance within this climate zone, various design variables are taken into account.

**2.4.1. Temperature Set Point of Heating and Cooling.** The temperature set points for systems of cooling and heating in building significantly impact the amount of energy it uses. Therefore, the temperatures will be set at 24°C and 19°C for the cooling and system, respectively, in order to lower heating and cooling loads while sustaining occupant's thermal comfort.

**2.4.2. Building Orientation.** If the orientation of the building is optimised, that could reduce the amount of energy it consumes. To choose the orientation that offers the optimal energy efficiency, rotation of the base building design from 0° to 360° with 5° step from its original direction.

**2.4.3. External Walls and Roof Insulation Thickness.** The thermal conductivity ( $U$  value) of outside walls has a palpable impact on the total cooling and heating load within the building. Thus, it will be explored whether making the

Surface type	Floor area (m <sup>2</sup> )
Ground floor	186.96
Roof	186.96
Saloon/guest room	49.244
Kitchen	24.742
Living room	36.106
Bathroom 1	6.3
Bedroom 2	16.118
Bedroom 1	16.682
Master room	21.935
Master bathroom	8.405
Storage room	4.085
Bathroom 2	3.347

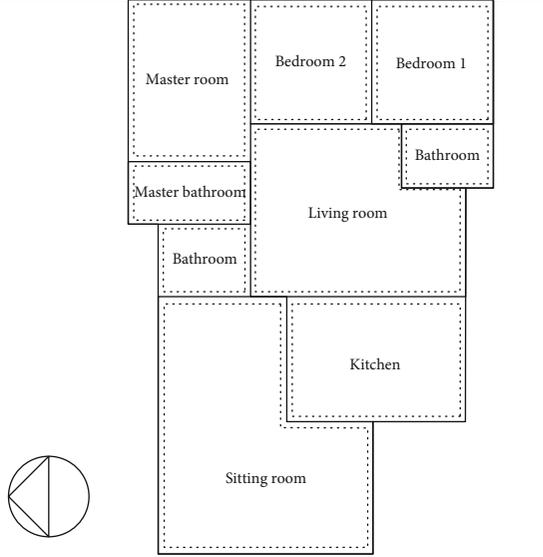


FIGURE 2: Building layout.



FIGURE 3: General view of the building.

insulation thicker will have an effect. Table 3 demonstrates the changes in the  $U$  value as the thickness of the insulation installed in the outside walls and roof increases.

**2.4.4. Internal Wall Thermal Mass.** The impact of altering the thermal mass of the inside walls will be investigated. Table 4 provides the thermal mass characteristics that will be examined for building the inside walls.

**2.4.5. Floor Insulation.** Tests will also be conducted to evaluate the impact of using thermal insulation layers of varying thicknesses. Table 5 illustrates how changing the thickness of the insulation affects the floor's  $U$  value.

**2.4.6. Glazing Type.** Energy performance is significantly affected by the specifications of the glazing material. Therefore, several glazing types from the DesignBuilder database have been tested to determine how they affect the building's cooling and heating loads.

**2.4.7. Window to Wall Ratio.** A feature of the envelope that has particular importance in terms of the building's cooling and heating loads is the windows, as they facilitate energy gain radiation from the sun while also potentially increasing

the rate of infiltration and thermal conductivity between the structure and the external environment. Thus, a window to wall ratio ranging between 0% and 100% with a step of 1 will be analysed.

**2.4.8. Infiltration Rate (Air Leakage).** The rate of infiltration is defined as air that enters the internal area of a building from the surrounding external environment via fissures, gaps, and doorways. Air change per hour (ac/h) is used to measure the infiltration rate. A range of infiltration rates from 0.25 (ac/h) to 1 will be tested.

**2.4.9. External Shading.** External shading can be provided through attaching fixtures to the outside surfaces of windows in the building envelope, including louvres, side fins, or overhangs as shown in Figure 4. Table 6 shows the various scenarios that were used, where the devices created were tested separately or when combined with each other.

**2.4.10. Window Shading Type and Schedule.** Devices used to provide shading for windows are instruments that shield the surface of the window glazing, which building occupants can open or close in order to prevent some or all of radiation from entering the building according to their transmittance and reflectance attributes.

**2.4.11. Natural Ventilation Rate and Schedule.** Naturally ventilating buildings can be a critical factor in reducing cooling and heating loads if appropriately managed due to the fact that it facilitates the exchange of heat between internal and external environments based on the temperature differential between the different areas.

Hence, testing for the natural ventilation rate will be performed for 0 (ac/h) to 5 (ac/h) with a step of 0.1 (ac/h) with a schedule determined according to the frequency at which the room is occupied.

TABLE 1: Thermal conductivity and thicknesses of outside walls.

Layer name	Thermal conductivity(W/mK)	Thickness (mm)
Internal wall		
Cement render	1.25	35
Concrete bricks	1.65	110
Cement render	1.25	35
$U$ value ( $W/m^2 \cdot k$ )	2.5	
Outside wall		
Stone	2.25	50
Concrete reinforced	2.55	100
Extruded polystyrene	0.035	50
Concrete bricks	1.65	100
Cement render	1.25	10
$U$ value ( $W/m^2 \cdot k$ )	0.55	
Roof		
Waterproofing bitumen roll	0.03	50
Miscellaneous materials-aggregate	1.3	100
Concrete reinforced	2.5	320
Cement plaster	1.2	20
$U$ value ( $W/m^2 \cdot k$ )	0.54	
Floor		
Ceramic tiling	1.05	8
Gravel and sand	0.3	70
Concrete reinforced	2.3	350
$U$ value ( $W/m^2 \cdot k$ )	2.5	

TABLE 2: Configuration and thicknesses of glazing layer materials.

Layer name	Layer thickness (mm)
Clear glass	5
Air gap	5
Clear glass	5
$U$ value ( $W/m^2 \cdot K$ )	3.15
Solar heat gain coefficient (SHGC)	0.49
Light transmission (%)	0.51

TABLE 3: Thickness of external wall and roof insulation and associated  $U$  values.

Wall insulation thickness	$U$ value ( $W/m^2 \cdot K$ )
50 mm (baseline)	0.65
75 mm	0.45
100 mm	0.35
125 mm	0.26
150 mm	0.22

In this analysis, we assume that the natural ventilation occurred for a short period every day (30 minutes) just to reduce carbon emissions and humidity. For many reasons, we did not include natural ventilation at night in the summer months including privacy, dust in the desert areas, opening the windows on opposite sides to create flow required the involvement of residents to open specific windows during specific periods of the day, and the precision of results intended to evaluate the thermal performance of buildings in the Saharan Mediterranean warm climate zone without interference from occupants. Although this could potentially save significant amounts of energy, including the occupants' adaptations and behaviours aimed at saving energy will have a considerable influence on the final results.

*2.5. Sensitivity Analysis.* As separate design variables could have a combined effect on the cooling and heating loads inside the building, testing each variable individually or utilising a local sensitivity analysis technique could prevent an optimum solution from being obtained. Therefore, it is necessary for the different variables to be optimised.

However, if there is a large amount of variables with high values, then the number of potential simulation combinations will be excessive and the process of running the simulations could be very lengthy.

Hence, it is necessary to conduct global uncertainty and sensitivity analysis, which will reveal which of the variables have the greatest and least effect on the targeted output and, according to these findings, the amount of variables included in the optimisation procedure will be diminished, which will subsequently accelerate the process of optimisation.

Conducting the sensitivity analysis enables the association between the building design parameters and the targeted objectives to be elaborated, and this can be achieved by employing different approaches including FAST (Fourier Amplitude Sensitivity Testing), Morris, and regression, among others.

In this study, the regression technique will be employed as it is included in the functionality of the DesignBuilder programme, which is an exhaustive approach utilised to obtain responses for complicated models; in such situations, a critical aspect of the sensitivity analysis is the Standardised Regression Coefficient, which enables the variables considered to have the highest and lowest importance to be identified.

Cooling and heating load are taken as the objectives, whereas the design variables are those described above.

*2.6. Energy Retrofit Strategies.* In order to increase the accuracy of the results provided by DesignBuilder, it is essential that various factors are taken into account:

- (i) It is generally recommended that the size of the samples used for random simulations is 1.5 to 10 times the amount of variables, whereas DesignBuilder guidelines indicate that it should be at least 10 times the amount of variables
- (ii) In this study, there are 12 primary variables, although some could have at least 16 potential values. Therefore, the size of the sample was set at

TABLE 4: Specifications of different thermal masses for inside walls.

Thickness (mm)	Material	Conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m <sup>3</sup> )
100	Heavy concrete cast	1.33	845	2050
200				
300				
50	Heavy concrete bricks	1.32	845	2245
100				
150				
200				
100	Light concrete cast	0.22	845	725
200				
300				
100	Light concrete	0.16	850	475
200				
300				
100	High density concrete	2	1000	2450
200				
300				

TABLE 5: Thickness of floor insulation and association  $U$  values.

Floor insulation thickness (mm)	$U$ value (W/m <sup>2</sup> ·K)
0 (baseline)	1.88
50	0.5
75	0.37
100	0.29
125	0.24
150	0.2

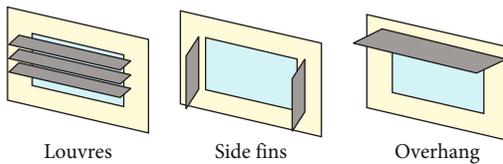


FIGURE 4: External shading techniques.

100 times the amount of variables, which meant that 1,200 random simulations were conducted

- (iii) When the variables are being defined, DesignBuilder suggests that that variables' values should be listed in ascending or descending order; for example, the outside wall could be ordered by raising or lowering the associated  $U$  value
- (iv) Also, DesignBuilder recommends that when sensitivity analysis is being conducted, options with identical values should not be used

**2.7. Optimisation.** The design parameters will be grouped into categories based on their significance for the heating and cooling load.

Then, the variables will be separated into two different groups: those with higher importance (comprising all variables apart from those whose importance on cooling and heating loads is low) and those with low importance.

This will be followed by the optimisation process, which will enable design options to be effectively scanned and then selected in order for the objective of enhanced core efficiency of the product to be achieved.

Genetic algorithms (GA) in DesignBuilder are employed for searching for optimal design parameters. Furthermore, it also permits the inclusion of two objectives within the analysis, which are "minimising heating load" and "minimising cooling load" in this study.

Each generation evaluates the level of fit of the variables in the population; in the context of the optimisation problem, the level of fit is normally overcome using the objective function value.

The individuals from the extant population that have better fit are selected stochastically, and then, the genome of each individual (recombined and likely spontaneously mutated) is transformed into another generation. The following iteration of the algorithm utilises the most up-to-date generation of potential solutions. The algorithm generally terminates after generating a specific amount of generations or when the population has reached an adequate level of fitness.

Graphical illustrations will be used to present the study outcomes, where heating and cooling are depicted on opposite sides, and the results of every variable combination analysed when running the simulations will be presented in the form of graphs. In terms of cooling/heating loads, the lowest values represent the "Pareto Front" of optimal configurations at the left bottom of the cloud data-point.

The optimisation of the set of variables deemed to have higher importance will be conducted using a random sample

TABLE 6: External window shading scenarios.

Scenarios	Characteristic
Baseline	Zero shading
First	Overhangs (500 mm)
Second	Overhangs (1000 mm)
Third	Overhangs (1500 mm)
Fourth	Overhangs (2000 mm)
Fifth	Louvres (500 m)
Sixth	Louvres (1000 mm)
Seventh	Louvres (1500 mm)
Eighth	Overhang (500 mm) + louvre (500 mm) + side fins
Ninth	Overhang (1000 mm) + louvre (1000 mm) + side fins
Tenth	Overhang (500 mm) + side fins
Eleventh	Overhang (1000 mm) + side fins

comprising 6,000 simulations, whereas 2,000 simulations will be run for the other group of variables with lower importance.

Once the optimisation has been completed, the solution of the pair of groups that offers the minimal total combined heating and cooling load will be chosen for the purpose of combining it together and running a simulation to determine the design variables to minimise heating and cooling energy further.

### 3. Results and Discussion

In this study, there is a sensitivity analysis and optimisation for twelve building design variables in a warm Jordanian Saharan Mediterranean climate zone. These variables are rate of infiltration, shading, window-to-wall ratio, roof, floor, partition wall construction, types of window frame, window glazing, construction, rate of natural ventilation, orientation, outside wall construction, and window shading control schedule. DesignBuilder software was used to determine how they influence the general thermal efficiency. The main objective was to significantly minimise the need for cooling and heating while sustaining the occupant's thermal comfort, produced by utilising mechanical systems for cooling and heating.

**3.1. Baseline Building.** To evaluate certain configurations of the building envelope's design parameters, the thermal performance of a conventional structure had to be acquired to serve as a baseline. Therefore, based on Jordanian national codes, a reference building was developed in order to investigate its thermal efficiency. The simulation demonstrated for warm climate zones in the Saharan Mediterranean (Azraq, Jordan), the yearly usage of energy in the reference building is 3194.66 kWh/year divided into 1771 kWh/year for heating load and 3195 kWh/year for cooling load.

**3.2. Sensitivity Analysis.** An excessive number of input variables in an optimisation process might generate billions of possible solutions. Therefore, conducting a sensitivity analy-

sis prior to the optimisation can significantly minimise the amount of simulations required. To that end, a regression technique in the sensitivity analysis used a random sample of twelve hundred (hundred times the number of variables) was implemented.

The Standardised Regression Coefficient (SRC) for the cooling load shown in Figure 5 indicated that the window to wall ratio has the maximum effect followed by external shading type, construction on the ground floor, rate of natural ventilation, and flat roof construction. Other variables including construction on the outside walls, infiltration (ac/h), type of window blinds, type of glazing, building orientation, window shading control timetable, and the construction of partitions have no tangible impact on the cooling load. Consequently, these inputs can be disregarded when conducting additional analysis of the cooling load using this model.

The heating load's SRC shown in Figure 6 indicates that the variable that has the strongest influence is infiltration (ac/h) which causes the heating load to rise followed by the type of glazing, window to wall ratio, local shading type, and flat roof construction that are moderate. Site orientation, ground floor building, window blind, construction of partitions, shading control schedule, natural ventilation rate, and outside wall construction have no discernible effect on the heating load. Thus, these inputs can be disregarded when further analysing the heating load in this model.

Based on the findings of the sensitivity analysis using SRC, two groups of design variables were formed:

- (i) A high importance group (local shading, window to wall %, natural ventilation rate, ground floor construction, glazing type, flat roof construction, and infiltration rate (ac/h))

Among the high importance group, window to wall ratio, local shading type, and type of glazing are the variables with the highest probability of having an interaction effect on both cooling and heating variables due to the fact that such variables determine the extent of solar heat gain absorbed as radiation, which causes the temperature within the building to rise. This solar heat gain positively impacts the heat load while massively increasing the cooling load, particularly in Saharan zones where ambient temperatures can reach exceptionally high values.

Decreasing the  $U$  value of the ground floor and flat roof construction reduces heating and cooling loads. The design variable that most strongly affects the heating load is the infiltration rate, as high infiltration rates easily leak all the heat retained inside the building to the external environment. Furthermore, natural ventilation plays a major role in reducing the cooling load when controlled properly. The process of minimising infiltration rate and controlling the rate of natural ventilation is simple and cost-effective. Window glazing strongly influences the heating load as it is reliant on the transparent characteristics of the glass, which permits sunlight to enter the structure during winter months and requires reduced thermal conductivity for the temperature within the building to be maintained.

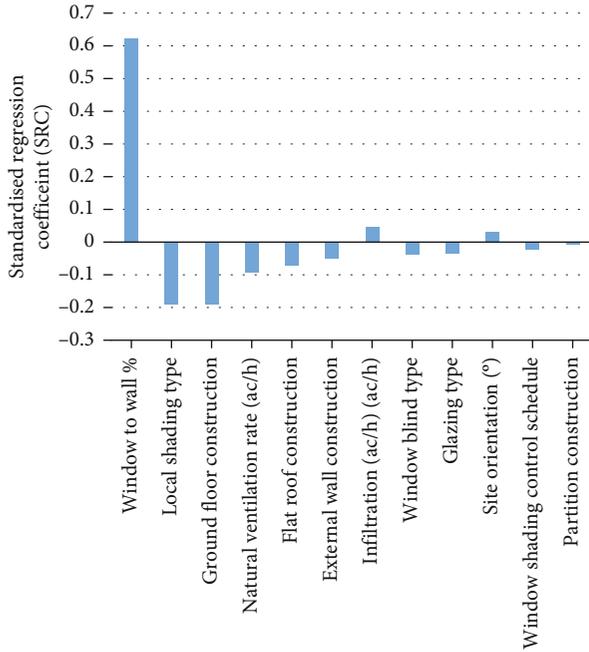


FIGURE 5: Cooling load sensitivity analysis.

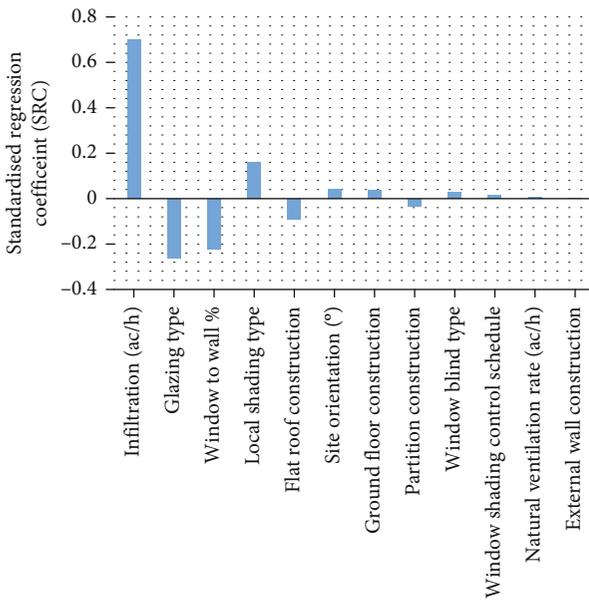


FIGURE 6: Heating load sensitivity analysis.

- (ii) A low importance group (site orientation, window shading control schedule, partition construction, window blind type, and external wall construction)

The construction of both partitions and outside walls was among the least effective design variables according to their input values, and increasing the insulation or thermal mass of these walls is extremely costly. Although these would usually be ignored in further analysis, they were retained to find the optimum solution. Modifying the orientation can be inexpensive in cases where the proprietor is not constrained

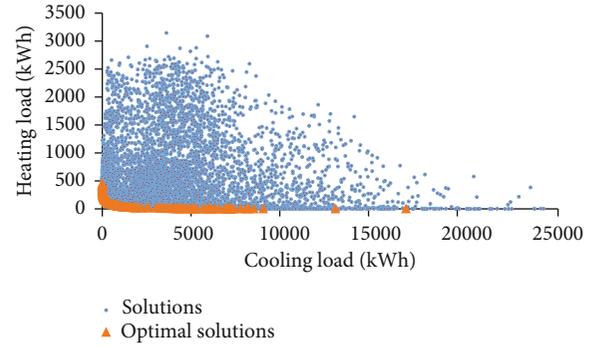


FIGURE 7: Optimisation of high importance variables.

by the shape of the land. Finally, although the effect of the type of blinds and associated control schedule on cooling and heating loads is not strong, they are not expensive, and if they are applied correctly, there is a strong likelihood that this will produce a cost-effective solution.

3.3. *Optimisation.* After conducting the sensitivity analysis, the two categories of design variables acquired then underwent an optimisation process (separately for each group) using the GA technique embedded within the DesignBuilder programme. Overall, a total of 6,000 random simulations were run for the variables with high importance, whereas 2,000 random simulations were run for the other group with the aim of minimising both cooling and heating loads.

3.3.1. *High Importance Variables.* Figure 7 shows the cloud for the high importance variables (solution) as well as the optimum solutions (Pareto Front).

The Pareto Front (optimal solutions) in this optimisation consisted of 200 out of 6000 solutions, three of which were investigated:

- (i) Minimising cooling load

There were 16 optimal solutions where the cooling load was under 1 kWh/year, and for these solutions, the heating load ranged from 339.4 to 461.2 kWh/year. In the solution that had the least energy consumption, the design variables had a cooling load of 0.77 kWh/year (negligible) and heating load of 339.4 kWh/year. Table 7 shows how the design variables in this solution are configured.

The design variables in the 16 optimal solutions were largely the same apart from the window to wall ratio, which ranged between 0 and 10%, and the type of local shading, which varied in almost all its input values.

- (ii) Minimising heating load

There were 22 optimal solutions with a heating load under 1 kWh/year. The solution in which the heating load is 0.72 kWh/year was chosen as optimal as it had the lowest cooling load of 5715.07 kWh/year (cooling load for all solutions ranging between 5715.07 and 16665.02 kWh/year). Some design parameters are presented in Table 8.

TABLE 7: High importance variables-optimum solution for cooling load.

Design variable	Value
Glazing type	Triple no tint
Ground floor construction	Baseline ground floor
Infiltration rate	0.26 (ac/h)
Flat roof construction	15 cm layer of insulation
Window to wall ratio	8%
Local shading type	500 mm overhang
Natural ventilation rate	4.6 (ac/h)

TABLE 8: High importance variables-optimum solution for heating load.

Design variable	Value
Flat roof construction	12.5 cm layer of insulation
Glazing type	Triple SageGlass no tint
Infiltration rate	0.26 (ac/h)
Natural ventilation rate	4.7 (ac/h)
Local shading type	No shading
Window to wall ratio	72%
Ground floor construction	Ground floor with 10 cm layer of insulation

The variables shared by the 22 optimal solutions were rate of infiltration, glazing type, and roof construction. Natural ventilation ranged between 1.1 and 4.7 ac/h, window to wall ratio ranged between 72 and 100%, the type of local shading was either zero shading or shading with minimal exposure, and the ground floor construction shared an insulation thickness ranging from 7.5 to 15 cm.

### (iii) Minimising heating and cooling loads together

The total cooling and heating energy consumption was the lowest which was 270.08 kWh/year divided into 43.71 kWh/year with regard to the cooling load and 226.37 kWh/year with regard to the heating load.

Based on the comparison of the design variables with high importance for the cooling load separately, the heating load separately, and cooling and heating load combined, it became clear that optimising heating load individually is the least cost-effective solution and the least energy efficient. The solution in which cooling load is minimised individually yields a relatively similar level of overall energy consumption to the solution in which cooling and heating and loads are optimised concurrently. However, the latter offers the highest cost-effectiveness and energy efficiency as it does not require any kind of shading and promotes a better light index.

**3.3.2. Low Importance Variables.** Figure 8 shows the cloud for the low importance variables (solution) as well as the optimal solutions (Pareto Front).

From the 2,000 solutions, Pareto Front (optimal solutions) consisted of 16 optimal solutions where the cooling load varied between 2175.35 and 2836.5 kWh/year while the

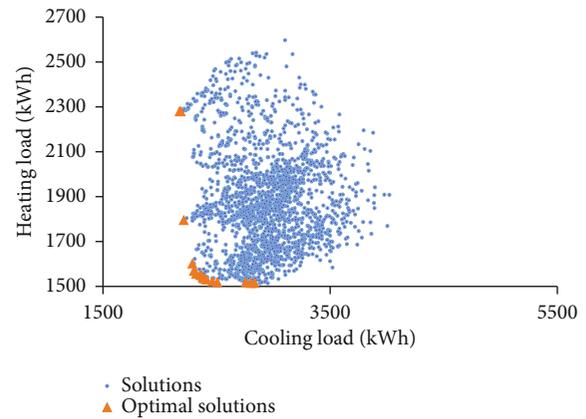


FIGURE 8: Optimisation of low importance variables.

heating load varied between 1514.37 and the number of optimal solutions was low and both heating and cooling loads were within a small range, the only solution selected was the one in which the summation of heating and cooling was lowest. For this solution, the overall energy usage is 3868.65 kWh/year (1587 kWh/year for heating and 2300 kWh/year for the cooling).

**3.3.3. Optimal Solution.** Subsequent to the selection of the optimum solution for groups of variables with both low and high importance, the design variables in these two solutions were amalgamated in order to create a solution for the building's cooling and heating load. The total energy was further lowered to 80.81 kWh/year divided into 0.19 kWh/year for the cooling load and 81 kWh/year for the heating load. However, reducing the consumption of energy by applying the changes recommended by optimising the design variables with low importance does not seem to produce a cost-effective solution, particularly the construction of outside walls and partitions.

## 4. Conclusion

This study portrayed an optimisation for several design variables for a structure in Azraq, Jordan, a country located in the Saharan Mediterranean warm climate zone. The objective was to lower the heating and cooling energy consumption while maintaining the thermal comfort.

A simulation was performed to determine the thermal efficiency of a reference building. This showed that the consumption of the reference building was 4966 kWh/year (3195 kWh/year for cooling and 1771 kWh/year for the heating). Sensitivity analysis using regression methods to find the design then the results was divided into two groups: a high importance group combined of seven variables and a low importance group comprised of five variables.

Both groups of variables then underwent an optimisation process using a GA. A comparison was made between three solutions when optimising the high importance design variables: minimising cooling load individually, minimising heating load individually, and minimising cooling and heating loads concurrently according to the lowest summation

of the different loads. The comparison indicated that the solution in which cooling and heating loads are optimised concurrently offers the highest cost-effectiveness and reduces overall energy usage by 94.56%, 98.63%, and 87.22% for overall energy usage, cooling load, and heating load, respectively. The total energy consumption saved by the optimisation was 270 kWh/year (226 kWh/year for heating and 44 kWh/year for cooling).

The selection of the optimum solution for the group of variables with low importance was made according to the lowest summation of the cooling and heating loads only due to the fact that the optimisation produced only 16 optimal solutions (Pareto Front) where the consumption of energy was not significantly changed and the design variables had close values. The chosen solution reduced energy consumption by 22%, 28%, and 11.4% for total energy consumption, cooling load, and heating load, respectively. The overall consumption of energy acquired from the optimisation was 3869 kWh/year divided into 2300 kWh/year for the cooling load and 1569 kWh/year for the heating load. However, the cost-effectiveness of this solution could be lower as the energy consumption is only minimally reduced even though the associated costs are high, particularly for the construction of outside walls and partitions.

The results showed that the overall consumption of energy was 81 kWh/year divided into 0.19 kWh/year for the cooling load and 81 kWh/year for the heating load. This was compared with 4966 kWh/year of energy (3195 kWh/year for cooling and 1771 kWh/year for heating). Thus, the reduction in energy consumption was 98% of overall energy consumption. Although the goal of minimising/eliminating the cooling and heating loads was achieved, some of the variables chosen might not be applicable or realistic in real world. Further work is therefore needed in this area.

## Data Availability

The [input data used in the simulation software] used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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