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Sensitivity Analysis of Passive Design Strategies for Residential Buildings in Cold Semi-Arid Climates

Waqas Ahmed Mahar [1,2,]*[ID]**, Griet Verbeeck** [3]**, Sigrid Reiter** [4][ID] **and Shady Attia** [1][ID]

[1] Sustainable Building Design (SBD) Lab, Department of UEE, Faculty of Applied Sciences, Université de Liège, 4000 Liège, Belgium; shady.attia@uliege.be
[2] Department of Architecture, Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Airport Road, Baleli 87100, Quetta, Pakistan
[3] Faculty of Architecture and Arts, Hasselt University, 3590 Diepenbeek, Belgium; griet.verbeeck@uhasselt.be
[4] LEMA, Department of UEE, Faculty of Applied Sciences, Université de Liège, 4000 Liège, Belgium; sigrid.reiter@uliege.be
*   Correspondence: architectwaqas@hotmail.com

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Abstract: Buildings are significant drivers of greenhouse gas emissions and energy consumption. Improving the thermal comfort of occupants in free-running buildings and avoiding active and fossil fuel-based systems is the main challenge in many cities worldwide. However, the impacts of passive design measures on thermal comfort in cold semi-arid regions are seldom studied. With the rapid urbanization and the widespread use of personalised heating and cooling systems, there is a need to inform building designers and city authorities about passive design measures that can achieve nearly optimal conditions. Therefore, in this study, a global sensitivity analysis of the impact of passive design parameters on adaptive comfort in cold semi-arid climates was conducted. A representative residential building was simulated and calibrated in Quetta, Pakistan, to identify key design parameters for optimal thermal comfort. The results list and rank a set of passive design recommendations that can be used widely in similar climates. The results show that among the investigated 21 design variables, the insulation type of roof is the most influential design variable. Overall, the sensitivity analysis yielded new quantitative and qualitative knowledge about the passive design of buildings with personalised heating systems, but the used sensitivity analysis has some limitations. Finally, this study provides evidence-based and informed design recommendations that can serve architects and homeowners to integrate passive design measures at the earliest conceptual design phases in cold semi-arid climates.

Keywords: decision support; building simulation; personalised systems; adaptive comfort

1. Introduction

The urban populations in Asia and Africa are projected to become 64% and 56%, respectively, by 2050. Between 2010 and 2050, more than 60 percent of the expected urban population growth will occur in Asia [1]. Pakistan is among the Asian countries with high urbanization with 3 percent growth annually—one of the fastest growth rates in Asia [2]. According to the estimates of the United Nations Population Division, by 2025 almost 50 percent of the population will live in urban areas (more than one third do today) [3]. The real challenge of Pakistani cities is to provide affordable and sustainable housing for its rapidly growing urban agglomerations [4]. As in most Global South countries, medium-sized cities in Pakistan play a determinant role as a transitional pivot between rural and urban networks [5]. The rapid urban transformation process is impacting those medium-sized cities and affecting their urban centres and extending their peripheries.

Quetta City is an example of those important middle-sized cities that face rapid urban expansion in Pakistan. The city has an urban population of over one million, according to the Population and Housing Census of 2017 [6]. Quetta is located at 30°21′ North latitude, 67°02′ East longitude, at an elevation of 1680 m above sea level. Quetta has a cold semi-arid climate (Köppen BSk classification) with significant variations between winter and summer temperatures. The city is heating-dominated with 2511 Heating Degree Days (HDD) and 459 Cooling Degree Days (CDD), on average, over 30 years (1985–2015) [7]. Highest recorded summer temperature in Quetta was 42 °C and the lowest temperature in Quetta can reach close to −18.3 °C [8]. Compared to other easterly parts of Pakistan, Quetta does not receive heavy rainfall since it is located out of monsoon region [9]. The average annual rainfall is 244 mm. Quetta is situated on the western side of Pakistan, in the northern Balochistan Province, near the Pakistan–Afghanistan border. As a provincial capital, Quetta is a gateway for Afghanistan, Iran, and Central Asian States. Moreover, Balochistan Province is becoming the home to major infrastructure projects in China's Belt and Road Initiative (BRI) [10]. Therefore, it is important to develop the technical knowledge required to manage the city growth, urbanization, and building construction of middle-sized cities in a sustainable way.

In this era of climate change, it is crucial to inform local building designers and planners about passive and bioclimatic design. The climate emergency necessitates guidance and evidence-based recommendations that can be adapted to the specific needs for sustainable building construction in middle-sized cities. The city of Quetta is an excellent place for the implementation of sustainable building design measures due to its specific intermediary function between the city and countryside. On the urban governance scale, city authorities need to cut down on the speculative practices that lead to large amounts of valuable urban real estate being seized by investors [11] because this deprives people of the land and space needed to build houses with solar access [12]. On the building design scale, architects, urbanists, builders, and homeowners need to build sustainable and low-impact housing that takes into account the flow of materials, energy, and climate change.

Few studies investigated the implementation of bioclimatic and passive design strategies for new construction in cold semi-arid regions worldwide [13]. As shown in Figure 1, the cold semi-arid climate (Köppen BSk) regions of the world are limited. They can only be found in Europe, covering parts of Spain and Turkey; in Africa, covering part of Algeria, Morocco and South Africa; and in Asia, covering part of China, Iran, Mongolia, Nepal, and Pakistan. The study of Huang et al. (2016) evaluated climate-responsive design measures in the cold semi-arid regions of Tibet, China [14]. The study focused mainly on traditional passive designs addressing primarily thermal comfort. Similarly, Upadhyay et al. (2006) investigated climate-responsive building design in the Kathmandu Valley in Nepal [15]. Pourvahidi (2013) developed climate-responsive design recommendations using bioclimatic charts in Iran, including Shiraz, Yazd, and Isfahan [16]. Then Roshan et al. (2017 and 2019) investigated the impact of climate change on design recommendations for residential buildings falling in the cold semi-arid regions of Iran [17,18]. Bahria et al. (2016) investigated solar passive design principles in the cold semi-arid areas of Djelfa, Algeria [19]. Monge-Barrio et al. (2015) investigated the passive solar potential of building-attached sunspaces in the residential architecture in the cold semi-arid region of Spain [20]. Also, Molinar-Ruiz presented an interesting overview of passive architectural designs in cold semi-arid regions worldwide and tested a design case study in El Paso, Texas, U.S.A. [13]. More recently, Ameur et al. (2020) used sensitivity analysis to evaluate the impact of passive design features with a focus on natural ventilation in a free-running residential building in Morocco [21].
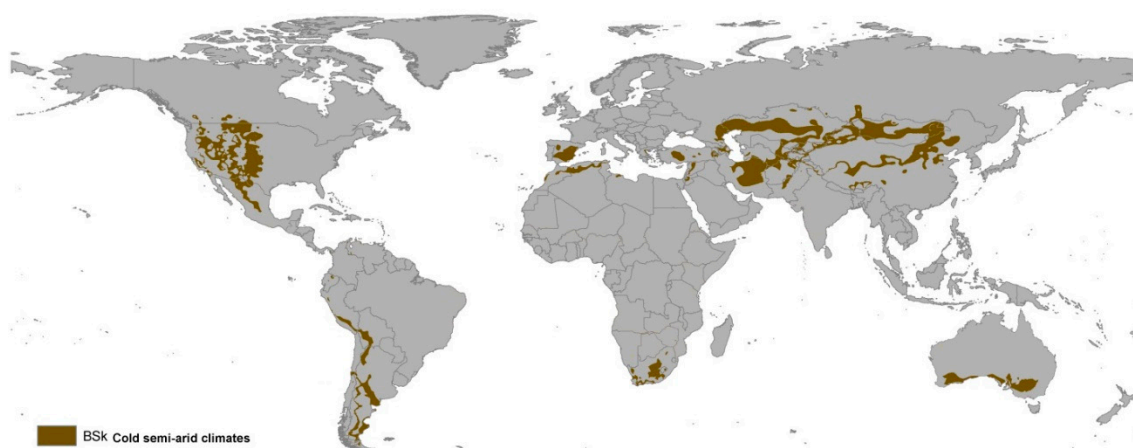
Figure 1. Cold semi-arid climate regions worldwide according to Köppen World Map (BSk) [22].

The type of studies presented above contribute to the need for providing informed decision-making for building designers and planners in those regions. The studies above prove that there is a need for an understanding of common design principles and strategies that best fit this climate [23]. There is a need for technological knowledge and perhaps even informed builders and developers to make sure that more houses are built quickly and sustainably. There is a knowledge gap in literature regarding bioclimatic and passive design measures in cold semi-arid climates.

This literature review is also focused on studies that have been conducted to perform sensitivity analysis and multi-objective optimization to inform the design decision-making for bioclimatic and climate-responsive design.

Sensitivity analysis can assist decision-makers in identifying the most relevant design variables [24]. A sensitivity analysis determines how different values of an independent variable in a given set of boundary conditions affect a particular dependent variable [25]. When we understand the relationships and the relative importance of design parameters, we can easily improve the performance of the building [26].

There have been many studies on the energy performance of residential buildings and the evaluation of the influence of energy conservation measures on passive design measures using sensitivity analysis techniques. Gustafsson (1998) conducted a sensitivity analysis for energy retrofit measures for a residential building in Sweden [27]. Lam et al. (2008) conducted a sensitivity analysis for energy conservation measure implications for office buildings in Hong Kong [28]. Similarly, Heiselberg et al. (2009) conducted a sensitivity analysis for an office building in Denmark [29]. Breesch et al. (2010) conducted a sensitivity analysis to evaluate passive cooling strategies in office buildings in Belgium [30]. Tian et al. (2011) conducted a sensitivity analysis of building performance using probabilistic climate projections for a case study in the United Kingdom [31]. Yildiz et al. (2011) conducted a sensitivity analysis to reduce the energy requirements of low-rise apartment buildings in Turkey [32]. Attia et al. (2012) conducted a sensitivity analysis for a zero-energy building in Egypt [33]. Huang et al. (2016) conducted a sensitivity analysis for passive adaptation measures to reduce cooling energy needs in a residential building in Taiwan [34]. Bre et al. (2016) investigated the potential of residential building design optimisation using sensitivity analysis in Paraná, Brazil [35]. Ascione et al. (2017) investigated the potential of large-scale energy retrofit measures on the building stock using sensitivity analysis techniques [36]. Chen et al. (2017) performed a sensitivity analysis of passive design strategies for a high-rise residential building in the hot and humid climate of China [37]. While those papers offer design recommendations on how to design energy efficient or sustainable buildings, none of those abovementioned studies caters to the cold semi-arid climate of Pakistan. More importantly, the studies above mainly focus on fully space-conditioned or free-running buildings. None of those

abovementioned studies focus on thermal comfort in buildings that are operated with personalised heating and cooling systems during different seasons of the year.

The above reviews indicate that sensitivity analysis has been applied in climates other than the cold semi-arid regions and to buildings that are fully space-conditioned or fully in free-running mode. At the same time, several papers have found the most positive attributes of sensitivity analysis [33,38], which are short computation time and modelling simplicity [39]. The sensitivity analysis can be performed by consulting architects at the early stage of the building design and project delivery process [40]. Its main advantages, compared to automated optimisation, is that its application decreases the calculation time and complexity [41].

While sensitivity analysis studies have been applied in residential and office buildings [33] to assess the impact of passive and active design measures on the energy performance of buildings, sensitivity analysis has not been rigorously exploited to evaluate the effects of passive design measures worldwide and, in particular, cold semi-arid climates. Therefore, we consider sensitivity analysis as an effective tool that has previously successfully fulfilled research objectives [42]. So far, sensitivity analysis has not been performed to assess thermal comfort in buildings with personalised heating and cooling systems. In particular, sensitivity analysis is a unique tool with powerful and straightforward methods that have not yet been explored to assess passive and bioclimatic architecture.

Given the above limitations to pursuing new knowledge on passive design measures for sustainable buildings, the current paper was motivated by the convergence of recent weather data and building energy modelling techniques, in particular, sensitivity analysis techniques. The objectives of this paper are: (1) to conduct a sensitivity analysis utilising an EnergyPlus-based simulation environment to assess the effects of thermal control, solar access, building mass, passive cooling on thermal comfort; (2) to generate new knowledge on bioclimatic passive design strategies in low-rise residential buildings in cold semi-arid climates concerning adaptive thermal comfort and occupants' comfort expectations; (3) to examine the relative autonomy of buildings from heating and cooling systems or to quantify their operation with personalised heating and cooling systems. The results of this study can inform architects, building designers, homeowners, city planners, and city authorities of the most effective passive design measures—according to the occupants' thermal comfort. There are relatively few experts in cities who have a background in, or knowledge of, passive design measures in cold semi-arid climates. In fact, few universities worldwide even offer courses in this field and this climate. Once you have building professionals who know the extent of the thermal comfort problem and how to deal with it, the situation can start to improve. Therefore, acting on the findings of this paper can also yield economic and environmental benefits to avoid the use of fossil-fuel and improve the energy efficiency of new constructions. Therefore, the research questions corresponding to the objectives are:

- How to model a typical residential building, considering the realistic operating conditions assumed for the initial calibration, and perform a sensitivity study in the cold semi-arid climate of Pakistan?
- How to achieve maximum comfort in a residential building with personalised heating and cooling systems based on an adaptive comfort model?
- What are the most effective passive design strategies for low-rise housing in the cold semi-arid climate of Quetta?

This paper applies building performance simulation and sensitivity analysis techniques to a representative Pakistani house to answer the above questions. It is structured as follows. Section 1 introduces the research problem, provides the background of the study and study area. It further presents sensitivity analysis for passive design strategies and provides a literature review of related studies that performed simulation-based parametric analysis for bioclimatic design measures. Then methods used to create the simulation model, calibrate it, and conduct the parametric simulations are provided in Section 2. Next, the results of the above questions are presented in Section 3. Section 4 discusses the limitations of the sensitivity analysis approach, and Section 5 concludes the paper.

2. Methodology

The conceptual study framework of this research illustrates the two major methodological steps (Figure 2) undertaken in this study: (1) model setting and selection of a representative model as a basecase for sensitivity analysis, and (2) sensitivity analysis to identify the influential passive design variables. A detailed description of the study methodology is described in the following sections.
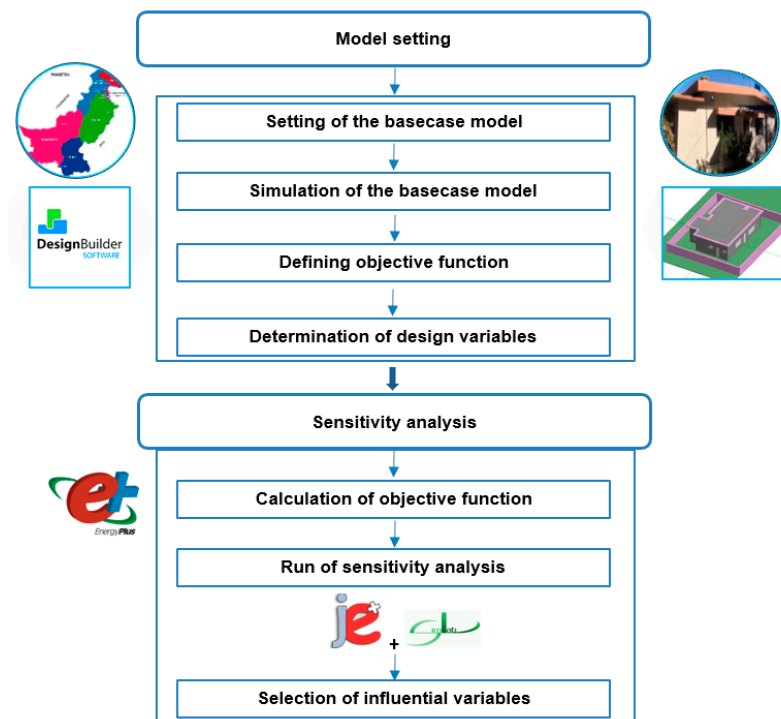

Figure 2. Conceptual study framework.

2.1. Model Setting

In the first step of model-setting, the basecase building model of the selected house in Quetta was created using DesignBuilder together with EnergyPlus. This model was then calibrated based on real-time monitored data. One objective function, namely comfort hours (CH), was defined as the indicator for the sensitivity analysis of annual indoor thermal comfort. In total, 21 design variables were initially selected based on screening the most common passive design principles and strategies in cold-arid climates (see literature review in Section 1) [43]. These design variables were supposed to be suitable solutions to improve indoor thermal comfort of the residential buildings in Quetta. The sensitivity analysis was performed aiming to identify the influential design variables that are significant to improve indoor thermal comfort.

2.1.1. Setting of the Basecase Model

The results of previous studies show that the majority of the residential buildings in Quetta consist of reinforced concrete frame (RCF) houses, having one to two storeys on average. Besides that, most of the houses constructed in Quetta are single-storey houses [44,45]. A representative basecase model of a single-storey house was selected for this study. This building model was considered to be a generic residential building example in Quetta, representing the most common construction techniques and buildings materials for walls, roofs, floors, openings, and architectural features.

The basecase house is a free-running building without air-conditioning and with personalised heating. The ceiling fans are installed in all rooms for ventilation during summer. In winter, only bedrooms, guest and living room are heated using personalised radiant gas heaters. As shown in

Figure 3, the basecase is a single-family house with a family size of eight members. The house has an area of 112.6 m^2 consisting of three bedrooms, a guest room, a living room, kitchen, and bathrooms. The plan and front view of the selected basecase are presented in Figure 3. The thermophysical properties of the building materials and construction details are summarised in Table 1, and the input parameters used for the simulation are detailed, in Table 2.

Figure 3. (**a**) Plan and (**b**) view of the selected basecase.

Table 1. Thermophysical properties of building elements of the base [23].

S. No	Building Element	Outermost to Innermost	Building Element Composition	Thickness (cm)	Conductivity (W/m K)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)
				E_p	λ	D	C_p
1	Walls	Layer 1	Plaster	0.95	0.431	1250	1088
		Layer 2	Brick	22.86	0.711	2000	836
		Layer 3	Plaster	0.95	0.431	1250	1088
2	Roof	Layer 1	Plaster	0.95	0.38	1150	840
		Layer 2	Bitumen	0.95	0.5	1700	1000
		Layer 3	RCC slab	10.16	0.753	2300	665.9
		Layer 4	Plaster	0.95	0.38	1150	840
3	Floor	Layer 1	Cement	0.95	0.72	1650	920
		Layer 2	Mortar	5.08	0.753	2000	656
		Layer 3	Concrete	7.62	1.8	2240	840
		Layer 4	Aggregate	10.16	1.74	2240	840
		Layer 5	Sand Earth/Soil	22.86	0.837	1300	1046
4	Windows	Layer 1	Single-glazed with clear glass	0.63	1.046	2300	836.8

Legend: RCC, reinforced cement concrete.

Table 2. The input parameters for the simulation.

Aspects	Description
Location	Quetta, Pakistan
Orientation	The long axis of the building is oriented to South
Building storeys	1
Height	3 m
Dimension	15 m × 11.2 m
Floor area	112.6 m^2

Table 2. *Cont.*

Aspects	Description	
Opaque envelope	Exterior walls	U-value = 1.4 (W/m^2 K)
	Roof	U-value = 2.9 (W/m^2 K)
	Floor	U-value = 1.8 (W/m^2 K)
Windows	Single-glazed	U-value = 5.7 (W/m^2 K)
	WWR (%)	8.08S, 10.1N, 0.9EW
	SHGC	0.81
Heating and ventilation	Heating system	Radiant gas heaters (individual units)
	Airflow	0.3 m/s
	Air tightness	2.5
DHW	Period 1 (October-March)	3.5 (L/m^2/day)
	Period 2 (April-September)	1.2 (L/m^2/day)
Occupancy	Household size	8 persons
	Density	0.07 (person/m^2)
Consumption	Average annual energy use	49 kWh/m^2
Clothing/activity	Summer	0.4 clo
	Winter	0.7 clo
	Metabolism level	0.9

Legend: WWR, window-to-wall ratio; SHGC, solar heat gain coefficient; DHW, domestic hot water.

2.1.2. Simulation of the Basecase Model

The selected basecase model was created based on high-quality data collected through monitoring, site visits, questionnaire, and semi-structured interviews. The monitoring of indoor air temperature and humidity was done in the selected house. The indoor air temperature of the simulated model was compared with the monitored indoor air temperature. The basecase model was then calibrated using two equations of normalised mean bias error (NMBE) and coefficient of variation of root square mean error (CV-RMSE), which are reliable measures for the validation of calibration [46–48]. The calibration was further validated using linear regression analysis to graphically represent the accuracy and correlation between simulated and monitored data. The investigation of indoor thermal comfort of the basecase model was performed together with parametric analysis to identify the possible passive and bioclimatic design strategies to optimise indoor thermal comfort [23].

2.1.3. Defining Objective Function

Only one objective function was used as an indicator for annual indoor thermal comfort, named Comfort Hours (CH), which is described in this section. There are several ways to evaluate indoor thermal comfort based on different comfort models, such as Predicted Mean Vote (PMV)—based on Fanger's model [49]—the European adaptive comfort model EN 16798–1 [50], Givoni's model [51], and ANSI/ASHRAE Standard 55 adaptive comfort model [52]. In this study, we used the ASHRAE 55 adaptive comfort model, considering 90% acceptability limits. In a previous study, Mahar et al. found that this model is the most suitable comfort model for the climate of Quetta, Pakistan [23]. The weather data used for simulation was a Typical Meteorological Year (TMY) weather file of Quetta. For the step of sensitivity analysis, comfort hours (CH) was used as an objective function.

2.1.4. Determination of Design Variables

Based on the calculation of the authors' previous work, passive and bioclimatic design strategies such as passive solar heating; thermal insulation; high thermal mass; and natural ventilation can increase indoor thermal comfort in the residential buildings of Quetta [23]. In total, 21 design variables were selected for sensitivity analysis. These variables were divided into six categories: building orientation, building envelope, thermal insulation, thermal mass, windows, and heating and ventilation. The variables include continuous uniform and discrete variable types ranging among different values, variation steps, and compositions of materials. Table 3 provides details of the selected design variables, their units, variable types, basecase values, interval ranges, and variation steps used for sensitivity analysis. The details and properties of the discrete design variables are presented in Tables 4–9.

Table 3. Input variables for sensitivity analysis.

Category	Design Variables	Unit	Variable Names	Variable Types	Min. and Max. Values	Variation Step	Basecase Values
Building orientation	Long axis azimuth	(°)	X_1	Continuous uniform	(0, 315)	45	180°
Building envelope	External walls construction	-	X_2	Discrete	[EW1, EW5]	Table 4	Table 1
	Roof construction	-	X_3	Discrete	[R1, R6]	Table 5	Table 1
	Floor construction	-	X_4	Discrete	[F1, F5]	Table 6	Table 1
Thermal insulation	Insulation type of external walls	-	X_5	Discrete	[I1, I4]	Table 7	-
	Insulation type of roof	-	X_6	Discrete	[I1, I4]	Table 7	-
	Insulation type of floor	-	X_7	Discrete	[I1, I4]	Table 7	-
	Insulation thickness of walls	(m)	X_8	Continuous uniform	[0, 0.06]	0.02	-
	Insulation thickness of roof	(m)	X_9	Continuous uniform	[0, 0.06]	0.02	-
	Insulation thickness of floor	(m)	X_{10}	Continuous uniform	[0, 0.06]	0.02	-
Thermal mass	Thickness of walls	(m)	X_{11}	Continuous uniform	[0.15, 0.45]	0.05	0.22
	Thickness of roof	(m)	X_{12}	Continuous uniform	[0.1, 0.25]	0.05	0.15
	Thickness of floor	(m)	X_{13}	Continuous uniform	[0.1, 0.25]	0.05	0.15
Windows	WWR	(%)	X_{14}	Continuous uniform	[10, 70]	-	15
	Window frame	-	X_{15}	Discrete	[WF1, WF4]	Table 8	Aluminium
	Window shading (overhang)	(m)	X_{16}	Discrete	[0, 0.15]	0.5	0.5
	Window opening	(%)	X_{17}	Continuous uniform	[0, 100]	-	50%
	Glazing type	-	X_{18}	Discrete	[W1, W10]	Table 9	Single glazed
Heating and ventilation	Cooling setpoint	(°C)	X_{19}	Continuous uniform	[25, 28]	-	-
	Heating setpoint	(°C)	X_{20}	Continuous uniform	[19, 22]	-	-
	Natural ventilation	(ac/h)	X_{21}	Continuous uniform	[1, 6]	1	4

Legend: WWR, window-to-wall ratio; WF, window frame; WS, window shading; W, window; R, roof; EW, exterior walls; F, floor.

Table 4. External walls construction.

S. No.	External Wall Material	Conductivity (W/m K)	Density (kg/m³)	Specific Heat Capacity (J/kg K)
		λ	D	C_p
EW1	Aerated concrete blocks	0.24	750	1000
EW2	Concrete hollow block	0.48	880	840
EW3	Sand-lime brick	0.75	1730	880
EW4	Burnt brick	0.85	1500	840
EW5	RCC walls	2.5	2400	1000

Legend: EW, external walls; RCC, reinforced cement concrete.

Table 5. Roof construction.

S. No.	Roof Material	Conductivity (W/m K)	Density (kg/m³)	Specific Heat Capacity (J/kg K)
		λ	D	C_p
R1	Fibreboard	0.06	300	1000
R2	Roof clay tiles	1.0	2000	800
R3	Gypsum plasterboard	0.65	1100	840
R4	Asphalt	0.7	2100	1000
R5	Concrete blocks	1.1	2100	840
R6	Reinforced cement concrete slab	2.5	2400	1000

Legend: R, roof.

Table 6. Floor construction.

S. No.	Floor Material	Conductivity (W/m K)	Density (kg/m³)	Specific Heat Capacity (J/kg K)
		λ	D	C_p
F1	Cork tiles	0.08	530	1800
F2	Timber flooring	0.14	650	1200
F3	Concrete blocks	0.51	1400	1000
F4	Plain cement concrete	0.75	2000	656
F5	Ceramic tiles	0.8	1700	850

Legend: F, floor.

Table 7. Type of insulation for external walls, roof, and floor.

S. No.	Building Element Composition	Conductivity (W/m K)	Density (kg/m³)	Specific Heat Capacity (J/kg K)
		λ	D	C_p
I1	Polyurethane foam	0.028	30	1470
I2	Expanded polystyrene (EPS)	0.04	15	1400
I3	Stone wool	0.038	40	840
I4	Glass–fibre batt insulation	0.043	12	840

Legend: I, insulation

Table 8. Window frame type.

S. No.	Window Frame Type	Frame Composition	Thickness (m)	Uf-Value (U frame) W/m² K
WF1 WF2 WF3 WF4	Aluminium window frame (no break) Aluminium window frame (with thermal break) Wooden window frame UPVC window frame	Aluminium Aluminium PVC Oak (radial) PVC	0.005 0.002 0.005 0.02 0.02	5.8 5 3.4 3.6

Legend: UPVC, Unplasticized polyvinyl chloride; PVC, Polyvinyl chloride; WF, window frame.

Table 9. Window glazing type.

S. No.	Window Glazing Type	SHGC	LT	Ug-Value (U glass) (W/m² K)
W1	Single clear (3 mm)	0.86	0.89	5.7
W2	Single LoE (e2 = 0.2) clear (3 mm)	0.76	0.82	3.8
W3	Double clear (3 mm/13 mm Air)	0.76	0.81	2.7
W4	Double clear (3 mm/13 mm Arg)	0.76	0.81	2.5
W5	Double Reflective-D (6 mm/13 mm Air)	0.42	0.3	2.6
W6	Double Reflective-D (6 mm/13 mm Arg)	0.42	0.3	2.4
W7	Double LoE (e2 = 0.1) clear (3 mm/13 mm Air)	0.59	0.76	1.7
W8	Double LoE (e2 = 0.1) clear (3 mm/13 mm Arg)	0.59	0.76	1.5
W9	Triple LoE (e2 = e5 = 0.1) clear (3 mm/13 mm Air)	0.47	0.66	0.9
W10	Triple LoE (e2 = e5 = 0.1) clear (3 mm/13 mm Arg)	0.47	0.66	0.78

Legend: W, window; SHGC, solar heat gain coefficient; LT, light transmission; LoE, low emissivity; Arg, argon.

The common practice in the construction of RCF houses is to build reinforced cement concrete (RCC) columns, beams, frames (doors and windows), and roof slabs. Brick masonry using burnt bricks is the most common practice for wall construction. The cement plaster is then applied to both the inner and outer surfaces for the wall finishing. These houses are mainly constructed without any thermal insulation in walls, roofs, and floors [53–55]. Table 4 presents five different materials used for external wall construction type (X_2) to perform sensitivity analysis. The details of materials for roof construction (X_3) and floor construction (X_4), and their properties are mentioned in Tables 5 and 6, respectively. Four different types of thermal insulation were used in external walls, roof, and floor (X_5-X_7) as discrete variables, which are shown in Table 7. Description of window frames (X_{15}) are given in Table 8, while Table 9 sums up the details of the design variable window glazing type (X_{18}).

2.2. Sensitivity Analysis

In the second step of sensitivity analysis, initially the calculation method for the objective function was defined. For this study, the objective function of CH was evaluated based on ASHRAE 55 adaptive comfort model's 90% acceptability limits. Sensitivity analysis was performed using EnergyPlus to identify relatively influential passive and bioclimatic design variables for the climate of Quetta. SimLab 2.2 software was used to produce the datasets for sensitivity analysis [56]. The Latin Hypercube Sampling (LHS) was adopted, which is considered a powerful method for generating a small yet powerful representative of cases. A sample size of 1.5 to 10 times the number of input variables was suggested in the SimLab manual, a sample of 210 LHS cases was created for the second step of sensitivity analysis. To ensure the accuracy in the sensitivity analysis and its validation 1100 LHS cases were finally used.

The jEPlus software was used to reduce the simulation time of these 1100 LHS cases. The jEPlus is a powerful parametric analysis tool. It can automatically prepare the input files for EnergyPlus according to a job list file, launch EnergyPlus for parallel simulations, and collect the simulation results according to the specific setup. The job list file of jEPlus can be transformed from the sample file of SimLab after generating the LHS cases. The results of the simulation were then imported back into SimLab software to perform sensitivity analysis. The influential design variables were then identified based on this sensitivity analysis, considering a single objective function of comfort hours.

2.2.1. Calculation of Objective Function

A simulation was performed to investigate the annual comfort and discomfort hours in the selected basecase model. The results were calculated using the ASHRAE 55 adaptive thermal comfort model, using the following equations to identify discomfort houses. Where $f(T_{out})$ is the prevailing mean outdoor air temperature in ANSI/ASHRAE 55 for 2013 and 2017 and the mean monthly outdoor air temperature in ANSI/ASHRAE 55 for 2004 and 2010 [52,57]:

$$\text{Upper 80\% acceptability limit } (°C) = 0.31 f(T_{out}) + 21.3 \tag{1}$$

$$\text{Upper 90\% acceptability limit } (°C) = 0.31 f(T_{out}) + 20.3 \tag{2}$$

$$\text{Optimal comfort temperature } (°C) = 0.31 f(T_{out}) + 17.8 \tag{3}$$

$$\text{Lower 90\% acceptability limit } (°C) = 0.31 f(T_{out}) + 15.3 \tag{4}$$

$$\text{Lower 80\% acceptability limit } (°C) = 0.31 f(T_{out}) + 14.3 \tag{5}$$

Source: ANSI/ASHRAE Standard 55-2017 [52].

2.2.2. Run of Sensitivity Analysis

The sensitivity analysis performed for this study was global analysis, which is one of the major methods; the other one is called local analysis [26,58,59]. The global analysis method was selected as it can explore a vast space of the input factor around a basecase and the interaction between the factors, such as the shape of probability density function and the effect of range of a factor. The Monte Carlo analysis (MCA) method was used to perform this global sensitivity analysis. MCA was developed in the 1940s. It is a computer-based analysis method that uses statistical sampling techniques to solve a mathematical equation or model by obtaining probabilistic approximation [60].

As described in Section 2.2, SimLab 2.2 software was used to carry out sensitivity analysis. In total, 1100 cases were created using the Latin hypercube sampling (LHS) method. The simulation was performed using EnergyPlus, driven by a parametric analysis tool called jEPlus. The SimLab software provides different sampling indexes such as Partial Correlation Coefficient (PCC) and Standard Regression Coefficient (SRC) [58]. The SRC sampling indexes are widely used in building performance analysis [61–65], and the same method was used in this study.

2.2.3. Selection of Influential Design Variables

The calculated SRCs of 21 design variables for the objective function of CH were sorted based on their positive and negative influences on the objective function. These variables were arranged in order of the largest to the smallest absolute value. A variable with the higher SRC absolute value was considered more influential while a variable with the lower SRC absolute value was considered less influential. The positive value of the SRC indicated the direct relationship between a design variable and the objective function, while the negative value of the SRC indicated the inverse relationship between a design variable and the objective function.

3. Results

3.1. Sensitivity Analysis

3.1.1. Calculation of Objective Function

This study was based on a single objective function of comfort hours, calculated using the ASHRAE Standard 55 adaptive comfort model's 90% acceptability limits. As mentioned in Section 2.2.1, the results were calculated using Equations (1)–(5), provided in the standard to calculate the comfort acceptability limits. The result showed that the annual comfort hours in the basecase model were 3766 out of 8760, which was equal to 42.9% hours. It indicates higher discomfort throughout the year. Since the chosen model was a building representative of the most common residential building typology in Quetta, this reflected that the existing houses mostly provide an uncomfortable indoor environment. Passive and bioclimatic design strategies were recommended as essential measures to improve indoor thermal comfort and reduce the use of the active system. Figure 4 presents CH in the basecase model calculated for a whole year using hourly data.
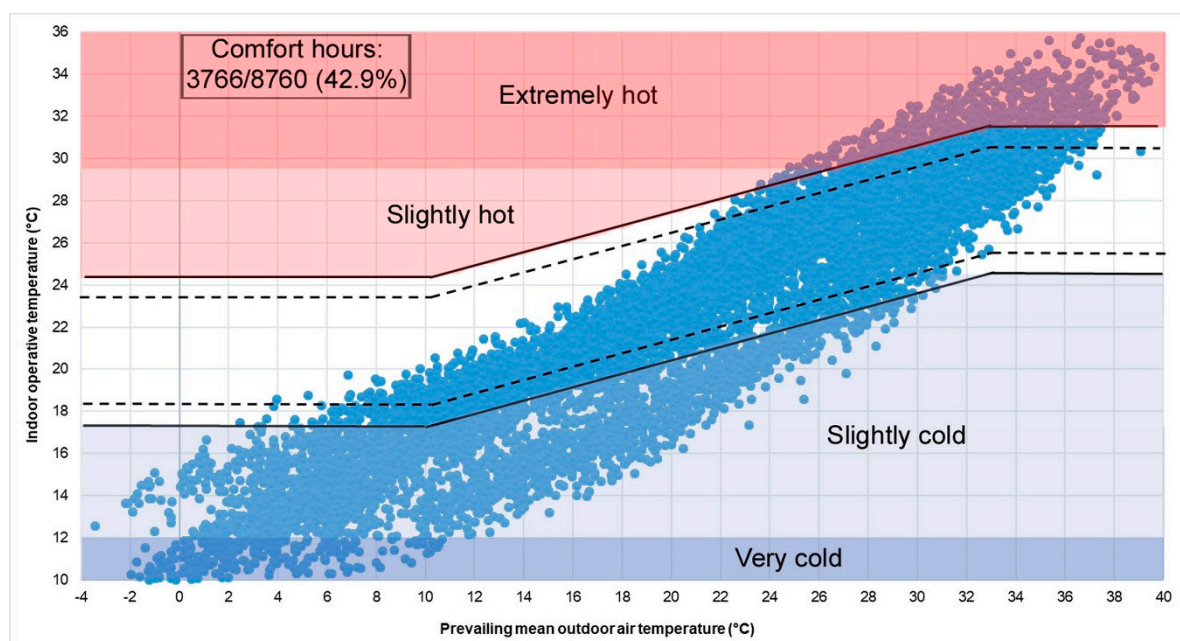
Figure 4. Calculation of objective function (comfort hours) in the basecase model.

3.1.2. Run of Sensitivity Analysis

The sensitivity analysis for this study was performed using EnergyPlus together with the jEPlus. The SimLab 2.2 software was used to present the results based on the SRC sampling method. The SRC of 21 design variables was determined based on a single objective function of comfort hours. The ranking of each design variable is presented in Figure 5 and Table 10.

The results of global sensitivity analysis showed that among the selected 21 design variables, the insulation type of roof was the most influential design variable. Some of the design variables showed a negative influence, such as heating set point, while two design variables showed no influence.
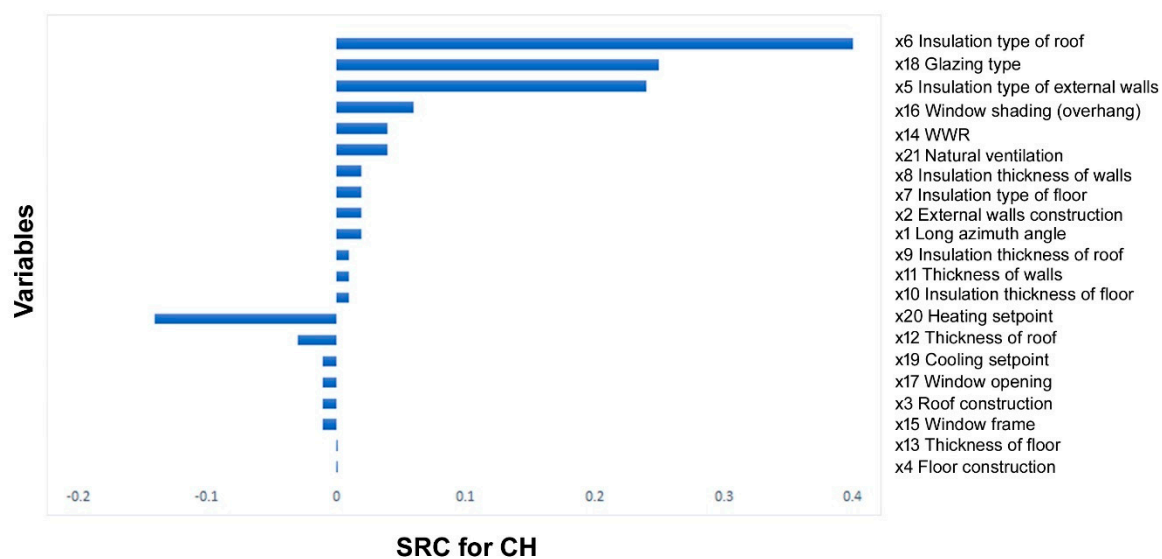
Figure 5. Sensitivity ranking of Standard Regression Coefficients (SRCs) for the comfort hours in the basecase model (relative threshold).

Table 10. Result of sensitivity analysis and SRC ranking for the discomfort hours in the basecase model. Legend: SRC, Standard Regression Coefficient; CH, comfort hours.

Design Variables	Variable Names	SRCs for CH (Ranking)
Long axis azimuth	X_1	0.02
External walls construction	X_2	0.02
Roof construction	X_3	−0.01
Floor construction	X_4	0
Insulation type of external walls	X_5	0.24
Insulation type of roof	X_6	0.4
Insulation type of floor	X_7	0.02
Insulation thickness of walls	X_8	0.02
Insulation thickness of roof	X_9	0.01
Insulation thickness of floor	X_{10}	0.01
Thickness of walls	X_{11}	0.01
Thickness of roof	X_{12}	−0.03
Thickness of floor	X_{13}	0
WWR	X_{14}	0.04
Window frame	X_{15}	−0.01
Window shading (overhang)	X_{16}	0.06
Window opening	X_{17}	−0.01
Glazing type	X_{18}	0.25
Cooling setpoint	X_{19}	−0.01
Heating setpoint	X_{20}	−0.14
Natural ventilation	X_{21}	0.04

3.1.3. Selection of Influential Design Variables

The results of this study showed that among the initially selected 21 design variables, only 13 showed positive influence, considering the objective function of CH. These variables were insulation type of roof (X_6), glazing type (X_{18}), insulation type of external walls (X_5), window shading (X_{16}), window-to-wall ratio (WWR) (X_{14}), natural ventilation (X_{21}), insulation thickness of walls (X_8), insulation type of floor (X_7), external wall construction (X_2), long axis azimuth (X_1), insulation thickness of roof (X_9), thickness of walls (X_{11}), and insulation thickness of floor (X_{10}), respectively. Among the 21 design variables six showed negative influence on the objective function of CH, namely heating setpoint (X_{20}), thickness of roof (X_{12}), cooling setpoint (X_{19}), window opening (X_{17}), roof construction

(X_3), and window frame (X_{15}). Two of the design variables showed no influence, i.e., the thickness of the floor (X_{13}) and floor construction (X_4).

According to the results presented in Figure 5 and Table 10, the thermal insulation of the building envelope is the most important passive design solution for the improvement of comfort hours in Quetta. The climate of Quetta is heating dominant, where more comfort is required in winter. The thermal insulation of the building envelope, including roof, walls, and floor, will increase the comfort hours. The existing roofs are mainly built with reinforced cement concrete (RCC) slabs, and bitumen is used for water-proofing, then a layer of lightweight cement plaster is applied to cover the surface. Such a roof creates more discomfort in summer due to increased solar absorptance. Additionally, the solar gain from the roof and walls during summer also creates discomfort. The provision of thermal insulation will prevent solar heat gain through the roof in summer. It is possible to reduce the discomfort by insulating floors. In many houses of Quetta, carpets are used in winter to cover the floor surface, mainly in bedrooms, which slightly reduces the discomfort.

The second most influential variable is glazing type (X_{18}). The existing windows used in Quetta are mainly single-glazed clear glass windows with a high U-Value of 5.7 (W/m^2 K) and a solar heat gain coefficient (SHGC) of 0.81. Double-glazed, low emissivity windows with a lower SHGC will increase the comfort hours. Two more influential factors related to windows are window shading (X_{16}), and WWR (X_{14}). Besides the cold winter, Quetta also experiences mild to extreme summer. With the better design of shading devices, better comfort can be achieved in both seasons. Window-to-wall ratio is also an important passive design solution to improve the solar gain in winter, which will improve comfort. The existing practice in Quetta is to provide an overhang above the windows for shading. The window in the basecase model has an overhang of 0.5 m. It is recommended to carefully design a window shading system that can be effectively used in both summer and winter seasons. The existing houses have lower WWR, i.e., 15% (in the basecase). Solar heat gain through windows can increase by adding larger windows on the south side to improve comfort in cold climates.

Natural ventilation (X_{21}) is an important passive design solution in the climate of Quetta to increase comfort. It was also found during the surveys and interviews with the residents. It is a common practice in Quetta to keep windows open in summer during the night and evening to increase indoor thermal comfort [54,55].

The consideration of building orientation is also important for comfort in houses. In a cold climate, the long axis azimuth (X_1) of a building should face towards the south for solar heat gain. The existing basecase building is south-facing and oriented at an angle of 165°, assuming that actual north is at 0°. Since the actual north is tilted to approximately 15° to north-northwest, the positioning of building at 180° to south-southeast will match it with the actual south direction. It will expose the whole front façade to the southern direction and improve comfort inside the building, especially in the winter season.

The thickness of walls (X_{11}) is also an influential variable. In old and vernacular housing construction techniques in Quetta, most of the houses were built with thick and massive load-bearing walls, which also supported the structure. These thick walls provided more comfort due to thermal mass and solar heat gain. This practice stopped after the introduction of reinforced concrete frame houses. Most of the external walls constructed nowadays are 0.22 m to 0.45 m thick, compared to the walls in old buildings, including the houses built during the British period where wall thickness was between 0.6 m and 0.76 m.

4. Discussion

The research findings are discussed further in the following sub-sections, along with main findings and recommendations, strengths and limitations of the study, and study implications and future research.

4.1. Main Findings and Recommendations

For this study, a basecase model was selected, which was simulated and calibrated based on actual monitored data. Sensitivity analysis of passive design strategies was performed to identify influential design variables for thermal comfort. In total, 21 input variables were selected for this study to perform sensitivity analysis. The study focused on only one objective function, i.e., comfort hours. ASHRAE Standard 55 was used to calculate the objective function of comfort hours. The results showed that indoor thermal comfort can be improved using solutions based on passive design principles and strategies. It was found that the most relevant passive design principles in the climate of Quetta are thermal control, passive solar heating, solar control, and passive cooling.

The study proved that thermal control is the most important passive design principle, which should be carefully adapted in buildings of Quetta. The results showed that passive design strategies based on the principle of thermal control, such as thermal insulation and high thermal mass, have a positive influence on thermal comfort. As shown in Figure 5 and Table 10, passive design solutions such as insulation type of roof (X_6), insulation type of external walls (X_5), insulation thickness of walls (X_8), insulation type of floor (X_7), insulation thickness of roof (X_9), thickness of walls (X_{11}), and insulation thickness of floor (X_{10}), had positive influences of 0.4, 0.24, 0.02, 0.02, 0.01, 0.01, and 0.01, respectively.

The second important passive design principle is passive solar heating. The influential strategies for passive solar heating, in this study, were WWR and orientation of building. The size of windows play an important role in the cold climate. The orientation of the azimuth angle of the long axis of building at an angle where building receives more benefit from sunlight can increase thermal comfort. The selected basecase building has small windows with low WWR (15%). It is vital to increase the WWR to get more benefit of passive solar heating in the winter season for the improvement of indoor thermal comfort. The long axis of the basecase building is facing south, yet it is not positioned on the actual south. Tilting the long axis of building to 15° south-southeast will match the angle to the actual south. The influence of design variables WWR (X_{14}) and long axis azimuth (X_1) were 0.04 and 0.02, respectively.

Solar control is the third important passive design principle in the context of Quetta, which shows a positive influence on thermal comfort. The design variables glazing type (X_{18}) and window shading (X_{16}) had positive influences of 0.26 and 0.06, respectively. The use of high-quality double-glazed and low emissivity windows, together with proper shading techniques and adequate size of shading overhangs, can improve comfort during summer.

Passive cooling is an important passive design solution which can be useful in the climate of Quetta. It plays a more vital role at night in warm summer to provide more comfortable indoors. The results show that natural ventilation (X_{21}) had a positive influence of 0.04.

In addition to these passive design strategies and solutions, thermal comfort can also be improved by changing construction techniques and material. The thermal properties of building materials such as U-value and heat capacity should be considered. The design variables of external wall construction (X_2) and the thickness of walls (X_{11}), showed positive influences of 0.02 and 0.01, respectively.

Besides the positive influence, the study also showed negative or no influence of some passive design variables. The heating setpoint (X_{20}), thickness of roof (X_{12}), cooling setpoint (X_{19}), window opening (X_{17}), roof construction (X_3), and window frame (X_{15}) showed a negative influence of −0.14, −0.03, −0.01, −0.01, −0.01 and −0.01, respectively. Two of the design variables showed no influence, i.e., the thickness of the floor (X_{13}) and floor construction (X_4). The heating and cooling setpoint temperatures used for this study were based on the values provided in the Building Code of Pakistan (Energy Porvisions-2011). These temperatures are mainly for the buildings with HVAC systems. We used this data as there is no such standard for the residential buildings in Pakistan [53,66]. There is a need to identify the suitable indoor temperatures for the buildings in different climatic zones of Pakistan.

Based on the results of this study, recommendations are made for the architects to construct better houses using solutions based on passive design principles and strategies. These recommendations are divided into four parts, covering building envelope, glazing, shading and building orientation.

- Thermal control using insulation of walls, roof, and floor, and high thermal mass of walls are recommended. The average insulation thickness of 60 mm for walls, roof, and floor is essential to provide thermal control. It will reduce the U-values of walls (1.43 W/m^2 K to 0.45 W/m^2 K), roof (2.9 W/m^2 K to 0.54 W/m^2 K), and floor (1.5 W/m^2 K to 0.46 W/m^2 K), respectively. The thickness of 0.6 m is recommended for walls. It will decrease the U-value of the existing external walls from 1.43 W/m^2 K to 0.9 W/m^2 K.
- Use of single-glazed windows is very common in Quetta. In recent years, double-glazed windows were introduced in the local market. The U-value of existing single-glazed clear glass windows is 5.7 W/m^2 K, with light transmission (LT) 0.88, and solar heat gain coefficient (SHGC) of 0.81. It can be reduced to the U-Value = 1.7 W/m^2 K, with LT 0.76, and SHGC 0.59 by using low emissivity double-glazed windows.
- In practice, overhang is used on the doors and windows of houses in Quetta for solar control. These overhangs can also limit the solar heat gain and light in winter. It is recommended to design adjustable, flexible shading devices which can be beneficial in both summer and winter.
- In a cold climate, passive solar heating is recommended to achieve more comfort in winter. The long axes of buildings in Quetta should be placed to the southern direction (at 180°, assuming north is located at 0°) to get the maximum benefit of solar light and heat gain. For natural ventilation, the placement of windows and their size are important. Natural ventilation can improve indoor thermal comfort at night in summer. On average, five to six air changes per hour (ac/h) are recommended for bedrooms and living room.

4.2. Strengths and Limitations of the Study

The strength of this study relates to the selection of a real basecase model and combining it with building performance simulation techniques including sensitivity analysis. The study is helpful to applying passive design principles and strategies to reduce discomfort in the indoor climate of buildings with personalised heating systems located in a cold semi-arid climate. By using passive design strategies, comfort can be significantly improved without using fossil-fuel-dependent active systems. The building construction solutions and technologies based on passive design measures can be integrated in future buildings to reduce the carbon footprint and decrease building energy use intensity. In Pakistan, electricity is mainly produced using fossil fuels (62.1%), while the household sector is the major consumer of electricity (48%) produced in the country [67]. Passive design solutions can decrease the reliance on active systems, which will reduce the household energy consumption.

Also, the study is based on an advanced method of sensitivity analysis of various design variables. EnergyPlus was used for simulation and modelling, and jEPlus was used to create input data sets for EnergyPlus, while results were simplified using SimLab 2.2. The LHS sampling was used for sensitivity analysis, and the results were ranked based on SRC ranking. Initially, the simulation was run using DesignBuilder together with EnergyPlus. Each iteration took around 3 m and 40 s to minimise the time jEPlus was used together with EnergyPlus for simulation. In total, 100 LHS cases were created using SimLab 2.2. The total simulation time of these 1100 cases was reduced to 21 h using an Intel Core i7 CPU workstation with the speed of 2.9 GHz. The simple use of sensitivity analysis tools helped to identify influential design variables for the climate of Quetta. The study provides informed decision support and saves time for local architects and practitioners to identify better passive design solutions for the construction of houses in Quetta, and perhaps in other cold semi-arid areas worldwide (See Figure 1).

On the other hand, this study has some limitations. The most important limitation is the use of global sensitivity analysis. In fact, we did a global sensitivity analysis for the 21 design variables

collectively. A local or single-factor sensitivity analysis may have provided the best value(s) for each design variable, individually. This would have required the use of a single objective function, i.e., CH for sensitivity analysis, and increased the computation time and simulation complexity significantly. The same situation would apply if we had followed an automated optimisation approach. Also, the use of one specific housing typology has its limitations. Even though the selected residential typology represents the dominant household typology of Quetta Pakistan, other typologies such as apartment buildings would be also interesting to investigate. However, we need to remind the reader that this is the first study to conduct an evaluation of passive design measures in hybrid buildings (only with personalised heating systems) in Pakistan. Therefore, it is recommended to explore other building typologies (offices, schools, hospitals, etc.) and climate-responsive prototypes in the future.

4.3. Study Implications and Future Research

The climate of Quetta and its geographical location make it different, compared to other cities of Pakistan. Although the climate of Quetta is heating-dominated, it has a mild to extreme summer. For the residents of Quetta, comfort is more important than energy efficiency, especially during winter. Table 1 shows that the materials used in existing houses have no thermal insulation. The existing houses do not provide comfortable indoor temperatures throughout the year. Figure 3 shows that the basecase building only provides up to 43% comfort hours throughout a year. This situation creates huge discomfort, causing reliance on mechanical systems to improve indoor thermal comfort.

This study highlights the importance of passive design principles and strategies for indoor thermal comfort. The solutions based on passive design are explored, which should be applied to construct future buildings in Quetta. The study can be helpful to create a building design or energy efficiency code for Quetta. It further highlights the importance of the creation of industrial infrastructure to locally manufacture high-quality energy efficient materials. There is a need to consider the cost of materials and taxes. Currently, most of the available materials in Pakistan are either imported from abroad, which are not affordable for most of the people. There is a need to set up local industries to manufacture high-performance and affordable building construction materials. The training of labour and the workforce is necessary to build better houses and to adapt modern construction techniques.

The study provides informed design decision support for the architects and designers regarding influential design variables in the context of Quetta for the improvement of thermal comfort in houses. It is difficult for many designers and builders to use building performance simulation and benefit from the power of sensitivity analysis techniques. Therefore, the study findings can be used to increase the awareness of builders regarding the influential design variables of building elements, materials, and construction. By using solutions based on passive design principles and strategies, and using energy efficient construction techniques and materials, comfort can be significantly improved while avoiding fully air or hydronic space-conditioning systems.

There is a need to explore the best possible design solutions and to integrate the influential design variables in the construction of new houses according to the local climate conditions [68]. Therefore, the materialisation of passive design solutions into real architectural and technological building elements and components must be the next step. Future studies may identify (i) the materials and solutions that are locally available and can be implemented in the local context to design and construct better houses with improved indoor thermal comfort, and (ii) identification of methods and solutions for the refurbishment of existing houses.

5. Conclusions

The study aimed to identify the most influential design variables for indoor thermal comfort by sensitivity analysis of passive and bioclimatic design strategies. The findings of this study can be used not only for the improvement of indoor thermal comfort, but also as informed design decision support for the architects and designers to design and construct future houses. The study findings will also

help the material suppliers to come up with materials with better energy performance in the climate of Quetta, which will reduce energy consumption and improve comfort without using active systems.

The results confirm that by using passive design principles such as thermal control, passive solar heating, solar control, and passive cooling, comfort can be improved without adding mechanical solutions. The potential of active systems and their performance can be explored later to achieve more comfort throughout the year.

The following recommendations are given based on the findings of this study:

(1) The passive design principles such as thermal control, passive solar heating, solar control, and passive cooling are important in the climate of Quetta. The thermal insulation of walls, roof, and floor is essential to improve comfort. High thermal mass, passive solar heating, shading devices, natural ventilation, and use of low emissivity double-glazed windows is recommended for the construction of houses in Quetta.

(2) There is a need for education and awareness of comfort, energy efficiency, passive design solutions, and construction techniques that can be adopted in Quetta. The training of labour and the workforce is recommended to build future houses that provide more comfort using less energy.

(3) It is recommended to explore the existing building materials and to identify the suitable materials to achieve indoor thermal comfort.

(4) There is a need for research at the national and local level to manufacture advanced, energy efficient building construction materials at low cost.

Nomenclature

The following abbreviations are used in this manuscript

ANSI	American national standard institute
Arg	Argon
ASHRAE	American society of heating, refrigeration, and air conditioning engineers
BRI	Belt and Road Initiative
CDD	Cooling degree days
CH	Comfort hours
CV(RMSE)	Coefficient of variation of root square mean error
DHW	Domestic hot water
EPS	Expanded polystyrene
EW	Exterior wall

F	Floor
HDD	Heating degree days
LHS	Latin hypercube sampling
LoE	Low emissivity
LT	Light transmission
MCA	Monte carlo analysis
MW	Mineral wool
NMBE	Normalised mean bias error
NNW	North north-west
PCC	Partial correlation coefficient
PMV	Predicted mean vote
PVC	Polyvinyl chloride
R	Roof
RCC	Reinforced concrete cement
RCF	Reinforced concrete frame
SHGC	Solar heat gain coefficient
SRC	Standard regression coefficient
SSE	South south-east
TMY	Typical meteorological year
UPVC	Unplasticized polyvinyl chloride
W	Window
WF	Window frame
WS	Window shading
WWR	Window-to-wall ratio

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