METHODOLOGY FOR THE DESIGN OF CLIMATE-RESPONSIVE HOUSES FOR IMPROVED THERMAL COMFORT IN COLD SEMI-ARID CLIMATES

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MAY 2021

UNIVERSITY OF LIÈGE
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Urban and Environmental Engineering

Methodology for the design of climate-responsive houses for improved thermal comfort in cold semi-arid climates

A thesis submitted in the fulfilment of the requirements for the degree of Doctor of Philosophy in Architecture and Urban Planning

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May 2021

The research presented in this thesis was financially supported by the Higher Education Commission (HEC) Pakistan under the HRDI-UESTP Program Batch-IV reference no. 50027882, and partly funded by Faculty of Applied Science, ULiège under '*FSA Fin de Thèse'* grant.

DOI: 10.13140/RG.2.2.23933.49120/1
D/2021/13.817/1
ISBN 978-2-930909-21-9
http://hdl.handle.net/2268/256478

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A thesis submitted in the fulfilment of the requirements for the degree of Doctor of Philosophy in Architecture and Urban Planning by Waqas Ahmed MAHAR

May 2021

To my family,

my country, my people,

and my profession.

Acknowledgements

Firstly, I would like to express my most profound appreciation to my supervisor, Prof. Dr. Shady ATTIA. I owe him a lot for making my PhD journey easier and for his support, assistance, and feedback during this PhD journey. I would also like to thank my PhD committee, Prof. Dr. Griet VERBEECK and Prof. Dr. Sigrid REITER, for the help and support they offered me throughout my PhD journey. Their feedback and guidance were helpful at the various stages of my PhD journey. I would also like to thank Dr. Elke KNAPEN, Senior Lecturer Hasselt University, for her guidance and assistance at the beginning of this PhD.

I am humbly grateful to all my family, friends and colleagues for their help and support; mainly I would like to thank my parents and brothers, Aijaz, Iqbal, Aftab, Sheeraz and Sajjad, who always kept me motivated and helped at various stages of my journey. I want to thank my former teacher and mentor, Ar. Abdul Waheed Memon for his help and support throughout my career. I would like to mention my friends and colleagues Sher M. Badini, Mamoon Ur Rashid, Jalal Faisal, Naveed Ur Rehman, Muzamil Hussain, Adeel Zahoor, Jahangeer Khan, Tahira Shaukat, Asif Iqbal, and Arshad Fahim, who helped me to complete various surveys during data collection in Quetta, Pakistan. It is necessary to mention Ar. Essa Khan, Ar. Nasser Ahmed Hijazi, Ar. Muhammad Naeem and Ar. Zain Kasi for providing required data and information during various stages of this PhD research.

I would also like to thank my friends Syed Hamid Akbar, Naveed Malik, Sheeraz Ahmed, Sjoerd Rommes, Kiarash Diba, Quan Manh Phung, Jui-Bon Man and my workmates Mohamed Amer, Guirec Ruellan, Samir Semahi, Ramin Rahif, and Muriel Diaz. Thanks for providing such a pleasant working environment and your company and friendship.

Funding: This PhD research was mainly funded by the Higher Education Commission (HEC) Pakistan, which provided the necessary funds and resources under the HRDI-UESTP Program Batch-IV reference no. 50027882. In addition to that Faculty of Applied Science, ULiège provided '*FSA Fin de Thèse'* grant for bridging the funding gap to complete this PhD research.

Abstract

Pakistan is facing a severe energy crisis which results in power cuts across the country. This situation seriously disturbs everyday life, business, and economic activities. The household sector in Pakistan is the primary consumer of electricity. A reasonable sum of this electricity is used for heating and cooling residential buildings, which can be reduced by adopting passive design strategies. This PhD research aims to provide informed decision support to design and construct climate-responsive houses in the cold semi-arid climate of Quetta, considering the appropriate and locally adapted low-tech solutions to improve residential buildings' indoor thermal comfort. Firstly, a literature review was done to understand the existing housing, comfort, and energy situation in Pakistan. An inventory of the current housing stock was then created to identify housing characteristics, construction types, and materials. The most common housing type was analysed for indoor climate, including monitoring indoor temperature and humidity, comfort perception and energy usage behaviour. Semi-structured interviews were conducted with the residents to get insights on their comfort perception, clothing, behavioural adaptations, lifestyle etc. Then a benchmark study was performed by selecting the most representative house. The representative house's virtual model was analysed using dynamic simulation and calibrated based on actual monitored data. Four comfort models were compared to identify the best fit-t-context model. A parametric analysis was done using passive design strategies to improve indoor thermal comfort. A sensitivity analysis of 21 design variables was performed to identify the most influential passive design strategies, which can be used in the climate of Quetta. A materialization survey was done to determine the locally available and manufactured materials. Based on this PhD research analysis and findings, a prescriptive guide was developed to provide informed decision support for architects to design comfortable and climate-responsive houses. The prescriptive guide was then tested and validated. A usability test was performed among the architects and architecture. The results show that the prescriptive guide provides enhanced decision support compared to the Building Code of Pakistan. In the end, recommendations are made for the regulators and further research.

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SUMMARY

In this thesis, the development and evaluation of a prescriptive guide (methodology) for decision support were explored. The thesis investigates the ability to achieve informed decision-making to improve residential buildings' indoor thermal comfort in cold semi-arid climates. This thesis is constituted of eleven chapters. The summary of the content of the chapters is described below:

Chapter 1: This chapter emphasises sustainability, thermal comfort and further presents the housing, energy and comfort situation in Pakistan. The aim of PhD study, research questions, research boundaries and thesis structure are also elaborated in this chapter.

Chapter 2: This chapter reports the state-of-the-art regarding building performance simulation, climate-responsive design, thermal comfort, and informed decision support. This chapter gives an idea of the general development and latest advancements in this research domain based on which the research methodology of this PhD is established.

Chapter 3: This chapter presents the essential research methods and approaches used in this PhD study. The research methodologies applied in this thesis are introduced along with the techniques used for data collection and analysis. The research ethics and quality criteria used in this study are also reported in this chapter.

Chapter 4: This chapter focuses on the housing and household characteristics of the existing houses in Quetta. It further discusses the climate of Quetta and housing-related facilities such as water, waste and energy systems. This chapter is based on field surveys and studies used for data collection.

Chapter 5: In this chapter, the indoor climate of the most common housing typology is discussed. It also focuses on HVAC and energy systems, lighting, occupants' adaptive and energy consumption behaviour and thermal comfort perception.

Chapter 6: In this chapter, the basecase house based on the most common housing typology is selected. The selected house's indoor thermal comfort is analysed, and parametric analysis was performed to improve the indoor thermal comfort. The essential passive design strategies for the climate of Quetta are evaluated.

Chapter 7: This chapter presents a sensitivity analysis of 21 design variables based on passive design strategies to identify the most influential design variables in the climate of Quetta. The basecase model was used to analyse 21 design variables.

Chapter 8: This chapter identifies the building materials for the application of the most influential design parameters specified in Chapter 7. The emphasis remains on locally manufactured and available materials. The feedback of architects and residents is reported who used/ applied such building materials.

Chapter 9: A decision support prescriptive guide to provide informed decision making for architects is presented in this chapter. The scoping study and development process of this prescriptive guide are also discussed.

Chapter 10: This chapter is based on the validation of the finding of this study. A usability test was performed with the architects and students of architecture to validate and compare the prescriptive guide and the Building Code of Pakistan (Energy Provisions-2011). The usability test results, critical feedback and recommendations considering the local climate and socioeconomic conditions are reported.

Chapter 11: This chapter summarises the findings of this PhD thesis. It also outlines the study implications, provides recommendations for regulators and possible future extensions of this thesis through new investigations.

List of publications

Peer-reviewed journal articles included in this thesis:

- Chapter 6 is based on:

1. ***Mahar, W.A.***, Verbeeck, G., Singh, M.K., Attia, S. (2019). An investigation of thermal comfort of houses in dry and semi-arid climates of Quetta, Pakistan. Sustainability, 11(19), 5203.

- Chapter 7 is based on:

2. ***Mahar, W.A.***, Verbeeck, G. Reiter, S., Attia, S. (2020). Sensitivity analysis of passive design strategies for residential buildings in cold semi-arid climates*.* *Sustainability*, 12(3), 1091.

Refereed Conference Proceedings

- Chapter 2 is partly based on:

3. ***Mahar, W.A.***, Anwar, N.U.R., Attia, S. (2019). Building energy efficiency policies and practices in Pakistan: A literature review*.* 5th International Conference on Energy, Environment and Sustainable Development (EESD) 2018. 14-16 Nov 2018. Jamshoro, Pakistan: Mehran University of Engineering and Technology (MUET). *AIP Conference proceedings 2119, 020005 (2019).*

- Chapter 4 is partly based on:

4. ***Mahar, W.A.***, Knapen, E., Verbeeck, G. (2017). Methodology to determine housing characteristics in less developed areas in developing countries: A case study of Quetta, Pakistan*. European Network for Housing Research (ENHR) Annual Conference 2017*. 4-6 Sep 2017. Tirana, Albania: Polis University.

- Chapter 5 is partly based on:

5. ***Mahar, W.A.***, Amer, M., Attia, S. (2018). Indoor thermal comfort assessment of residential building stock in Quetta, Pakistan. *European Network for Housing Research (ENHR) Annual Conference 2018*. 27-29 Jun 2018. Uppsala, Sweden: Uppsala University.

Scientific Reports

- Chapter 4 is partly based on:

6. ***Mahar, W.A.*** & Attia, S. (2018a). An overview of housing conditions, characteristics and existing infrastructure of energy, water & waste systems in Quetta, Pakistan. *SBD Lab, University of Liège.* 2 Apr 2018. ISBN 978-2-930909-11-0.

- Chapter 5 is partly based on:

7. ***Mahar, W.A.*** & Attia, S. (2018b). Indoor thermal comfort assessment in residential building stock: A study of RCC houses in Quetta, Pakistan. *SBD Lab, University of Liège.* 26 Dec 2018. ISBN 978-2-930909-14-1.

Posters and Briefs

8. ***Mahar, W.A.*** & Attia, S. (2018). Methodology for the design of climate-responsive houses for optimised thermal comfort in Quetta, Pakistan. *3rd Young Researchers Overseas Day (YROD)* 2018. 7 Dec 2018. Brussels, Belgium: Royal Academy of Overseas Sciences (RAOS), Belgium.

9. ***Mahar, W.A.*** & Attia, S. (2018). Thermal comfort in residential building stock of Quetta, Pakistan. *Doctoral Seminar on Sustainability Research in the Built Environment (DS²BE)*. 29-30 May 2018. Brussels, Belgium: Université Libre de Bruxelles, Belgium.

10. ***Mahar, W.A.***, Verbeeck, G. Knapen, E. (2017). Methodology for the design and development of a sustainable house concept for Quetta, Pakistan. *Doctoral Seminar on Sustainability Research in the Built Environment (DS²BE).* 26-27 Apr 2017. Liège, Belgium: Université de Liège.

Publications not included in this thesis

Journal Papers

11. Semahi, S., Benbouras, M.A, ***Mahar, W.A.***, Zemmouri, N., Attia, S. (2020). Development of spatial distribution maps for energy demand and thermal comfort estimation in Algeria. *Sustainability*, 12(15), 6066.

12. Bughio, M., Schuetze, T., ***Mahar, W.A.*** (2020). Comparative analysis of indoor environmental quality of architectural campus buildings' lecture halls and its' perception by building users, in Karachi, Pakistan. *Sustainability*, 12(7), 2995.

Conference Papers

13. Aleha, A., ***Mahar, W.A.***, Labdaoui, K. (2021). Urban green spaces and their role in making cities sustainable: revisiting Multan city from 1988 to 2020. *1st International Conference on Science, Engineering and Technology (ICSET-2021)*. 18 Mar 2021. Dera Ghazi Khan, Pakistan: Mir Chakar Khan Rind University of Technology (MCKRUT).

14. Amer, M., ***Mahar, W.A.***, Ruellan, G., Attia, S. (2019). Sensitivity analysis of glazing parameters and operational schedules on energy consumption and life cycle cost*. Proceedings of Building Simulation: 16th Conference of IBPSA.* 2-4 Sep 2019. Rome, Italy.

15. Anwar, N.U.R., ***Mahar, W.A.***, Khan, J.F. (2018). Renewable energy technologies in Balochistan: Practice, prospects and challenges*. Proceedings of the 5th International Conference on Energy, Environment and Sustainable Development (EESD) 2018*. 14-16 Nov 2018. Jamshoro, Pakistan: Mehran University of Engineering and Technology (MUET).

16. Kasi, Z.K., ***Mahar, W.A.***, Khan, J.F. (2018). Structural defects in residential buildings: A study of Quetta, Pakistan. *1st International Conference on Advances in Engineering & Technology (ICAET) 2018.* 2-3 Apr 2018. Quetta, Pakistan: Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS).

17. Mengal, M.U.R, & ***Mahar, W.A.*** (2018). Disaster mitigation strategies for adobe houses: A case study of District Awaran, Balochistan, Pakistan. *1st International Conference on Advances in Engineering & Technology (ICAET) 2018.* 2-3 Apr 2018. Quetta, Pakistan: Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS).

CHAPTER 1: INTRODUCTION

1.1 Sustainability and thermal comfort

The term sustainability has multidisciplinary use and meaning. It is generally described as the ability of a system to maintain and continue for a long time. The term might be used in various disciplines differently. Since the 1980s, sustainability is used primarily for human sustainability on earth, leading to sustainable development. In 1987, the Brundtland Commission of the United Nations defined sustainable development as follows:
"*Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*."

By involving human decision-making, sustainability achieves a substantial ethical aspect to change the social model on development, accomplishment, profit, and living standards. The reassessment of sustainability provides a more comprehensive and collaborative overview of several anthropological ecosystem factors, including science, technology, and architecture.

In the last few decades, sustainable development gained enough importance and became a central discussion point in several areas. The original 1987 report, “Our Common Future”, prepared by the World Commission on Environment and Development (over 300 pages) provided the guidelines for nations in devising their economic and political agenda (Brundtland, 1987).

In 2015, the United Nations set 17 interlinked goals (Figure 1.1) to achieve a better and more sustainable future for all. These goals are called Sustainable Development Goals (SDGs) or Global Goals, intended to be achieved by 2030. In SDGs, these goals, 3) Good Health and Well-being, 6) Clean Water and Sanitation, 7) Affordable and Clean Energy, 11) Sustainable Cities and Communities, 13) Climate Action, demands more attention of the architects and urbanists. Goal 11 focuses on making cities and human settlements inclusive, safe, resilient and sustainable (*UN SDG*, 2015).

Figure 1.1 UN Sustainable Development Goals 2015

In recent years, several studies and efforts been made regarding sustainable architecture to build sustainable residential projects. In 2018, the Union of International Architects (UIA) formed a committee named “the UIA Commission on UN Sustainable Development Goals”. The commission aimed to create a bridge between the UN17 SDGs and architects' practical activities by raising awareness, disseminating knowledge, and facilitating communication across its members worldwide. According to the UIA SDG Dhaka declaration, the architects can design and plan so that good acoustics, daylight and air quality are provided and healthy activity levels are promoted. The architects can design the buildings and settlements to reduce energy use, use alternative energy resources (where feasible), and adapt to climatic, geographic, and cultural conditions. The architects can also promote measures that help make cities more inclusive, safer and resilient, and adaptive to anticipated climate change. They can reduce or eliminate the climate-changing emissions associated with the buildings' construction and operation by designing climate-responsive buildings (*SDG Dhaka*, 2018).

In recent years, architects focused on eco-friendly designs and demonstrated special attention to sustainability. Sustainable architecture became an imperative movement rather than just a trend. It established a strong relationship with other fields of science to plan, design and develop sustainable buildings. The focus of sustainable architecture mainly remained on energy performance and building technologies (McMINN & Polo, 2005), which is primarily considered engineering. It has been noticed that architects may often lack the knowledge and skills of architectural and environmental sciences. There is a gap between sustainability and building designers, particularly for residential buildings. Architects mainly face more difficulty while combining sustainability aspects with other factors such as design requirements, bylaws etc.

The residential building's energy consumption is significantly increased due to active heating and cooling systems to provide a comfortable indoor environment. A trend of growing mechanical systems is observed due to modern architecture and lifestyle. The building sector consumes 36% of total energy, including 60% of electricity, contributing to 40% of carbon emissions globally. Buildings are the most significant contributor to carbon emissions after industries and transportation. The housing sector in Pakistan consumes a large amount of energy, which need more attention.

The key challenges in building performance are comfort, functionality, health, management and conservation of energy. The building materials and construction techniques need to be well supported, and sustainable development/ low carbon development principles need to be applied. The energy-saving measures must be implemented on the building envelope based on occupants' ability to adapt to the environment (Clements-Croome, 2021). The assessment of indoor thermal comfort must be performed before and after the renovation to ensure the thermal comfort is improved or optimised, shifting away from using active systems (Pagliano et al., 2016).

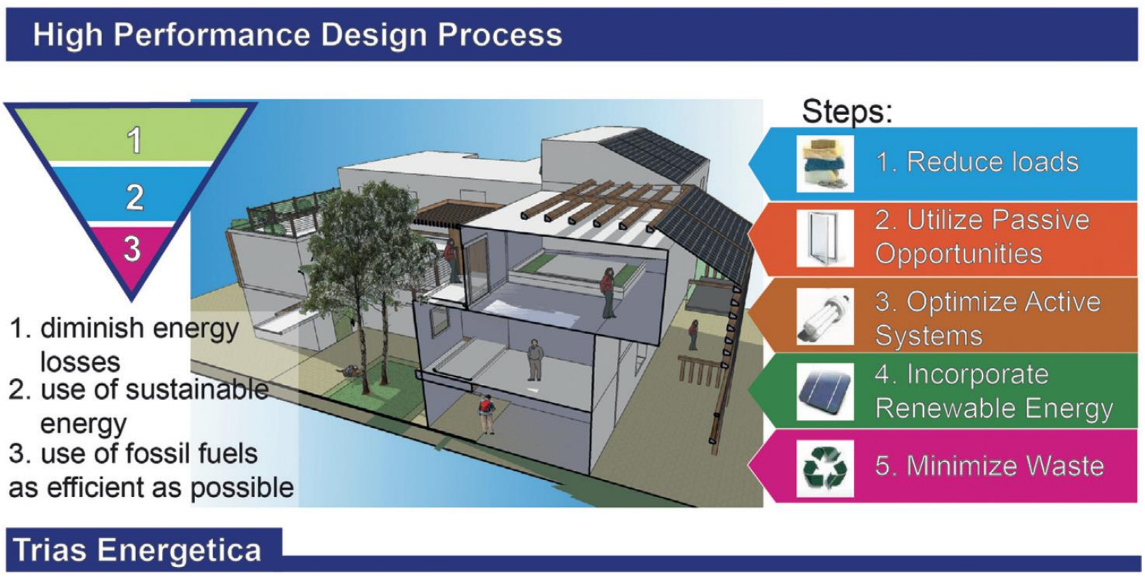


Figure 1.2 The fundamentals of nZEB design (Attia, 2018)

Trias Energetica is a three-step approach used to create an energy-efficient design. It was initially developed in 1979 at the Delft University of Technology. It has been widely used for sustainable building design. Attia discussed the design process for high-performance buildings (Figure 1.2) based on the fundamentals of nZEB buildings design. It focuses on three key aspects, i) diminishing energy loss, ii) using sustainable energy, and iii) using fossil fuels as efficiently as possible (Attia, 2018). This concept is suitable for developed countries; however, developing countries still lack adequate and decent housing facilities.

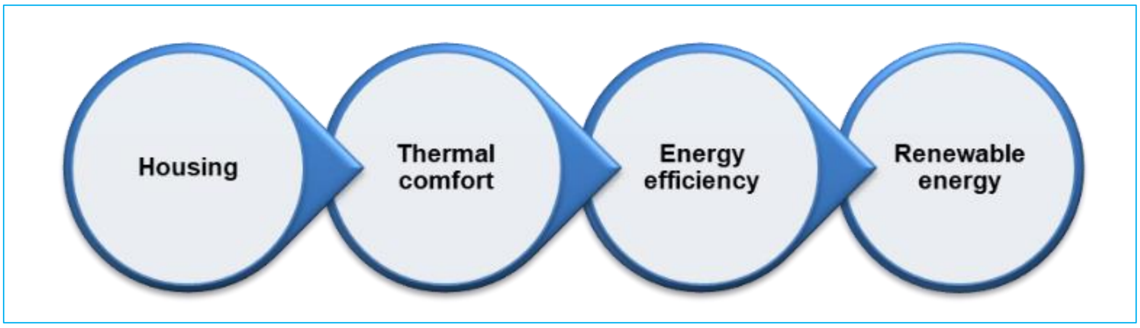


Figure 1.3 Housing paradigm shift model (Mahar et al., 2019)

A large number of population in the developing countries still live without proper shelter or in ill-designed and poorly constructed buildings. Pakistan is also facing a substantial problem of housing shortage, especially in the urban areas. Figure 1.3 presents a housing paradigm shift model, which was adopted in many countries. It emphasises providing housing for all, thermal comfort, energy efficiency, and renewable energy. Considering the context of Pakistan, comfort is the most important factor that needs to be achieved. In Figure 1.4, four priority steps to achieve energy-neutral buildings in Pakistan are proposed, including thermal comfort, indoor air quality, energy efficiency, and renewable energy.

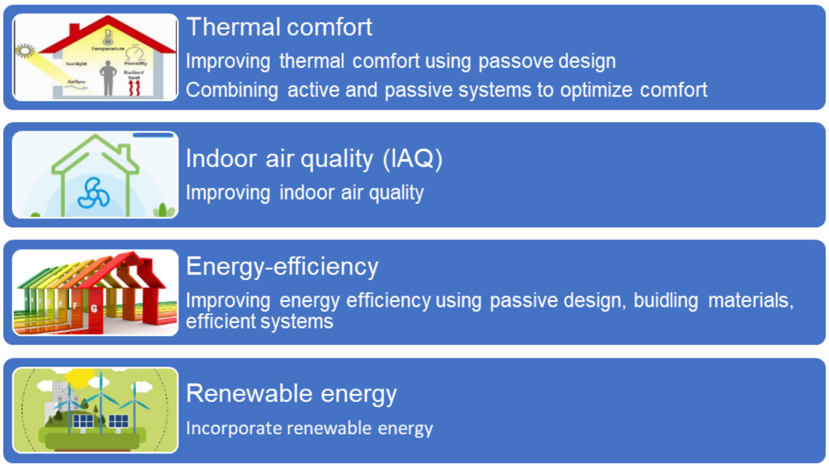


Figure 1.4 Steps toward energy-neutral buildings in Pakistan

The global aim of this PhD research is to improve indoor thermal comfort and quality of living conditions while ensuring acceptability of the occupants, considering locally available materials, and affordable cost. This study's focus remains on using passive and bioclimatic design solutions to minimise the building energy consumption by reducing the use of active systems. The research focuses on providing informed decision support for architects to design and construct new dwellings with improved thermal comfort. However, this study cannot cover all the aspects of sustainable housing and thermal comfort. Instead, it focuses on the most challenging part for architects and building professionals in cold semi-arid climates: a climate-responsive design for improving indoor thermal comfort in new dwellings.

1.2 Housing, energy situation and thermal comfort in Pakistan – Identifying problems

Pakistan is located in South Asia, at 30.3753° North latitude and 69.3451° East longitude. The territory of Pakistan covers 796,095 km^2 of land, which is slightly higher than the area of Turkey. It is comprised of four provinces: Balochistan, Khyber Pakhtunkhwa, Punjab and Sindh; and three administrative regions: Azad Jammu and Kashmir (AJK), Gilgit-Baltistan (GB), and Islamabad Capital Territory (ICT). There are 154 districts in Pakistan, including the provinces and administrative regions. The estimated population of Pakistan in 2019 was 211.17 million (*PES*, 2020)

Housing has a tremendous economic and social impact on human lives. It affects our lifestyle, health, environment, education and social life (Kasi et al., 2018). A faulty and defective house does not fulfil the residents' demands and needs, while a good house creates a good living and working environment. Housing became a rapidly growing industry due to technological advancement, increasing population and professional and skilled labour. The housing sector faces several challenges and problems, including housing shortage, poor planning and design, improper services and facilities, unaffordability, housing finance, etc. (Mahar, 2012). Several countries, including Pakistan, facing the problem of the housing shortage, which is increasing with its overgrowing population. According to the World Bank, the estimated housing shortage in Pakistan is up to 10 million units (*WB*, 2015), about 40 per cent of which is in urban areas (*IGC*, 2016). As per the 1998 census, the housing shortage was 4.3 million units. An additional annual requirement was a 0.57 million unit, while the yearly estimated production was 0.3 million units, creating a yearly recurring backlog of 0.27 million housing units (*PBS*, 1998). Another study mentioned that Pakistan's annual housing demand was 0.6 million units, while only 0.37 million units were being built annually and mostly in urban areas

(*NRPH*, 2015). The 6th Population and Housing Census were conducted in 2017; however, the housing indicators and complete census results are not available publicly (*PBS*, 2017).

Pakistan is also facing an energy crisis for the last several years. The current energy crisis started with a shortage of energy and an imbalance between demand and production. Besides, there are problems with energy transmission and distribution. The old and inefficient electricity distribution network causes line losses. During the fiscal year 2018–2019, distribution firms suffered 18.3 per cent of line losses (Dawn, 2019). Pakistan has an irrational and increasingly unaffordable electricity generation mix of 58.4% thermal, 30.9% hydroelectric, 8.2% nuclear, and only 2.4% renewables (*PES*, 2020). Subsidies in the energy sector have been reduced in recent months, which has created an immense burden of utility bills on the public (Kiani, 2019). On the other hand, Pakistan's housing sector remains the primary consumer of electricity by using 45% of its electricity, produced from July 2019 to March 2020 (*PES*, 2020).

A permanent house is the most significant investment of the many Pakistanis, which requires long-term saving and enormous efforts of the owners. The people in Pakistan mainly build their houses from their savings or often asking money from relatives or informal services at a very high rate. The banks in Pakistan were not interested in housing loan schemes till the 2nd quarter of 2020. Due to a legal issue faced by banks, for example, if the borrower became a defaulter of the loan, the banks could not sell the property to recover the loan. The recent legal and monetary policy changes will facilitate more banks to offer mortgage loans at lower interest rates for enabling people to construct their houses (Iqbal, 2020; *SBP*, 2020).

The majority of the buildings have poor building envelope and inefficient systems. The lack of awareness regarding energy consumption is also a key issue in Pakistan. When comfort is maintained at acceptable limits using active methods, it results in excessive energy use, especially in regions with extreme climatic conditions (Andris Auliciems & Szokolay, 2007). The residential buildings in Pakistan are mostly built without professional consultation and with a low investment. The large residential projects mainly aim to maximise investors' profit rather than the occupants' comfort and convenience. The houses in Pakistan are mainly constructed without considering the local climate and socio-cultural context. Reinforced concrete frame (RCF) houses are the leading and most widespread construction technology across the country. The houses mainly follow a typical design without ensuring passive design techniques and indoor thermal comfort. Having a shelter is a dream of millions of people living in developing countries. Hence, people may complain about building defects, building services and quality, whereas their perception of indoor thermal comfort and indoor environmental quality are ignored. Personalised active systems, such as radiant gas heaters and split air conditioners, are mainly used to provide comfortable indoor temperatures in houses, which increases energy usage and cost.

Occupant's thermal comfort studies are not very common in the context of Pakistan. The work of Nicol creates the basis of comfort studies in the country. Two surveys were performed in office buildings of five cities in Pakistan. The results of this study show a clear relationship between indoor thermal comfort and outdoor climatic conditions. Wide variations were observed in the selected office buildings' indoor temperature due to their layout, design, and limited ability to control indoor temperatures (Nicol et al., 1999). Kazmi studied occupant thermal comfort and energy efficiency in colonial and contemporary period public buildings. The results concluded that colonial buildings provide more comfort than contemporary buildings (Kazmi et al., 2011). Khan compared contemporary buildings with the traditional buildings in Peshawar, Pakistan. It was proved that traditional buildings provide more comfort and perform better, offering temperature variation in various building zones (Khan, 2016). A recent study was conducted to identify occupant comfort in Karachi's educational building (Bughio et al., 2020). However, the work done on indoor comfort in residential buildings remain limited, particularly in the cold semi-arid region of Pakistan. Based on the latest advancement of modern building science, technologies and assessment methods, it is expected that this PhD research will provide architects in Pakistan more opportunities to reach the target of sustainable housing by improving thermal comfort and providing informed decision support.

1.3 Aim and objectives

The global aim of this PhD research is to improve indoor thermal comfort using passive design strategies to design and construct climate-responsive residential buildings. The study further aims to provide informed decision support to architects to design and build comfortable dwellings (thermally) in Quetta. The provided solutions need to be adapted to Quetta's context for environmentally friendly, energy-efficient buildings at an affordable cost through effective use of construction materials, paying attention to passive and bioclimatic design and climate-responsive, and intelligent blend of modern building techniques.

To obtain the above-mentioned aim, the following objectives need to be achieved:

- The characterisation of the existing housing stock (inventory) to understand existing houses and households' characteristics. It will assist in identifying the common building materials, construction practices, and construction typologies.
- A better understanding of thermal comfort in residential buildings of Quetta, corresponding to climate conditions and building construction.
- The characterisation of building stock through benchmarking to test it through parametric analysis using different passive design strategies to improve indoor thermal comfort.
- Identification of the most influential passive design solutions in cold semi-arid climates and locally available and manufactured materials can be used to improve comfort.
- The development of a prescriptive guide (methodology) assists informed decision-making for architects to design climate responsive houses to improve indoor thermal comfort and the validation and application of the prescriptive guide.

Moreover, this study aims to provide valuable materials for research purposes and recommendations for the regulators and future researchers towards comfortable and sustainable housing in Pakistan.

1.4 Research questions

The main research question of this thesis is formulated considering the overall aim of this PhD study.

"How to achieve the maximum indoor thermal comfort using passive design solutions in the cold semi-arid climate of Quetta, Pakistan?".

The following research questions are formulated based on the main research question.

1. What are the characteristics of existing houses in Quetta?
2. What is the comfort situation in the existing houses and adaptive practices used in Quetta?
3. How to improve comfort using passive design strategies?
4. Which are the effective passive design solutions for the climate of Quetta?
5. How to provide informed decision making for designing climate-responsive houses?

1.5 Research boundaries

Sustainable housing is considered a large research domain. To ensure clarity and quality of this research, it needs to be focused on its specific aim of improving indoor thermal comfort in the new residential buildings in Quetta. The research study excluded some expects and will be limited to the following:

- Indoor thermal comfort is the main subject of this study. Hence, other comfort-related issues such as indoor air quality (IAQ), acoustic and visual comfort are assumed separate from thermal comfort and are not included in this research.
- This research only focuses on passive design strategies controlled by architects at the design phase by end-users at the occupancy phase. Active systems used in building design and operation, such as HVAC systems, remain out of research scope.
- Only residential buildings, particularly single-family houses, are the subject of this research, and other buildings types such as educational, office, commercial, industrial buildings are not included in this study.
- The study only conducts investigations on the building scale, e.g. the building design, the indoor microclimate. It carefully overlooks other urban-scale issues such as water and waste systems, energy and climate.
- The study aimed to provide informed decision making for architects to design and construct houses with better indoor thermal comfort. The construction of a real model or prototype is beyond the scope of this research.

It is observed that most of the residential buildings in Quetta are hybrid to favour the advantages of the cold and semi-arid climate. Therefore, the research will mainly focus on hybrid buildings, and those that use fans for cooling in summer and personalised gas heaters in winter. The buildings with personalised air conditioning units and HVAC systems remain out of the scope of this study.

1.6 Thesis structure

This thesis is constituted of eleven chapters. Chapter 1 focuses on the introduction, identification of the problem, aims and objectives of this study. The 2nd chapter provides state-of-the-art on building performance simulation, climate responsive design, thermal comfort, the complexity of the design, and informed decision support. Chapter 3 briefly discusses the research methods used at various stages of this PhD thesis. The housing and household characteristics of existing houses in Quetta are presented in Chapter 4, besides housing-related facilities. Chapter 5 aims to highlight the common housing typology's comfort situation, heating and cooling systems, and occupants' adaptive behaviour. A parametric analysis was done in Chapter 6. It further identifies the potential for comfort improvement based on passive design strategies. A sensitivity analysis was conducted in Chapter 7 to identify influential design variables in the selected climate. Chapter 8 explores the building materials which can be used for the improvement of indoor thermal comfort. A prescriptive guide for architects' decision support is presented in Chapter 9, then further validated and tested in Chapter 10. The last chapter provides a general conclusion and recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of the state-of-the-art related to the subject of this PhD thesis. It focuses on three keys subjects related to the domain of this PhD research. Section 2.2 discusses building performance simulation, its purpose and usage in building design, and validation methods. Section 2.3 looks at the climate responsive design and its importance. It further discusses thermal comfort, its parameters, recent trends and comfort models. Informing decision support, the complexity of design, types of decision support, and methods to inform decision-making for architects are reported in Section 2.4. The last section concludes the chapter (*Section 2.5*).

2.2 Building performance simulation

Building performance simulation (BPS) is a computer-based, mathematical model created using fundamental physical principles and sound engineering practices to analyse the various aspects of building performance. BPS programs were developed in the 80s to evaluate building performance during design using historical weather data (Bluyssen, 2013). These programs help quantify building performance related to design, construction, control, and buildings' operation (de Wilde, 2018). There are various sub-domains of building performance simulation; the most famous are thermal simulation, energy simulation, lighting simulation, airflow simulation and acoustic simulation. The field of building performance simulation falls within the broader scope of advanced scientific computing.

2.2.1 Importance of building performance simulation

BPS programs are an essential tool to investigate the effects of applying various retrofit strategies on building performance. However, searching for the best design strategies using energy simulation and obtaining the optimal solution is time-consuming due to a considerable decision space and numerous combinations (Asadi et al., 2012). Alternatively, a decision-making tool or guide can be used to achieve improved thermal comfort by applying effective passive design solutions. The importance of BPS programs is defined by focusing on four different aspects, which are discussed below.

Multi-zonal approach

Diving a building into multi zones for building performance simulation is the first degree of simplification. This approach was introduced in the 1990s (Bouia & Dalicieux, 1991; Wurtz, 1995). The approach provides a better way to detail buildings' indoor environment and assesses a zone's thermal comfort. The zonal simulation is an appropriate way to estimate the indoor thermal comfort in a room (Wurtz et al., 2006). The multizonal approach is also used to minimise the complexity of building performance simulation (Foucquier et al., 2013).

Dynamic simulation

Dynamic simulation is a powerful and extremely accurate tool for evaluating the environmental performance of buildings (Patidar et al., 2011). It can be used to model and analyse a range of factors typically arising from planning, design, construction and building regulations. These include the analysis of thermal comfort, heating and cooling demand, overheating, daylighting and carbon emission etc. (Nguyen et al., 2014). The dynamic simulations are based on numerical routines, and for balancing the unsteady process, partial differential equation systems are used. The dynamic simulation programs provide better analysis compared to steady-state programs (Hong et al., 2000; Van der Veken et al., 2004)

Weather data

A building simulation typically uses weather files such as typical meteorological year (TMY), Test Reference Year (TRY) or International Weather for Energy Calculation (IWEC). A TMY weather file is meteorological data containing hourly data values of a year for a given geographical location. The data is usually selected from hourly data for a more extended period (typically ten years or more) (Ledo, 2015). There are three types of TMY data sets. TMY1, derived from the meteorological data of 1948-1980. TMY2, which covers the period between 1961 and 1990, and TMY3 are hourly data sets of meteorological data between 1991-2005. The TRY weather file represents a 'typical' weather year, created from the composition of average months from a database of historical weather data. The IWEC weather files are derived from the data sets of up to 18 years of DATSAV3 hourly weather data originally archived at the National Centres for Environmental Information (NCEI) of the United States, formerly known as the National Climatic Data Centre (NCDC). The availability of validated weather data is essential for building performance simulation programs. The weather data of

48 weather locations in Pakistan is available online (*WMO*, 2020) and can also be obtained from the Pakistan Meteorological Department (PMD) for education and research purposes.

Computational power

The advances in computational power and numerical programs have facilitated rigorous simulation and optimisation techniques of significant problems related to design, operation, control and optimisation of energy systems (Lee et al., 2018). Computer-based simulations have become affordable and possible for buildings due to the rapid growth in the computer industry during the last decades (Wang & Zhai, 2016). The computational tools and techniques help to accelerate the design process and optimise building performance at a relatively low cost (Augenbroe, 2002).

2.2.2 Building performance simulation for building design decision support

Building performance simulation (BPS) programs achieved more importance in building design by providing performance evaluation of various design decisions and choices. Using BPS programs is more affordable and faster rather than creating an actual building. There are three common types of analyses performed using BPS programs to provide decision support for designing buildings.

Building Performance analysis

The building performance analysis evaluates the actual performance of a building. It is mainly used at the early stages of design. The building performance analyses are done for assessing thermal performance, energy performance, lighting, acoustic design etc. It involves an iterative process in which one continuously evaluates a building's performance and what is affecting the performance, what can be done to influence it. Wilde discussed the issues related to building performance analysis and explained why it is a complex activity (de Wilde, 2018, 2019). The annual performance analyses are commonly done, considering one or more performance criteria or parameters. Some of the studies that involve building performance analysis are mentioned here. Nguyen did the thermal performance analysis of a low-cost apartment building in Vietnam. The results showed that comfort could be improved using passive design strategies (Nguyen & Reiter, 2012). In another study, the potential passive solar heating and passive cooling were analysed for eight different Algerian cities. The results show that passive cooling and heating can be used to improve annual comfort (Semahi et al., 2019). Climate change consideration and long-term performance evaluations provide better design decision support guidance (Nguyen et al., 2021; Nurlybekova et al., 2021).

Parametric analysis

A parametric analysis allows studying the influence of various physical and geometrical parameters on the solution. In building performance simulation, the effects of various parameters can be analysed to identify their impact on the selected objective, such as energy performance, lighting etc. In parametric analysis, the variations of different parameters and their effect are determined by manual or automated simulation techniques. Several studies have been performed used parametric analysis. Shiel et al. performed a parametric analysis of energy performance at the design stage of building and discussed various studies regarding selecting parameters (Shiel et al., 2018). Najjar et al. discussed integrating parametric analysis with building information modelling to improve construction projects' energy performance (Najjar et al., 2019). Guarino et al. did a parametric analysis with the application of phase change materials to optimise buildings' cooling performance in the Mediterranean climate (Guarino et al., 2015).

Optimisation

Building performance simulation programs are also used for optimisation studies to identify the best possible solution(s) for the selected objective. The optimisation can be done for single or multiobjective(s). The optimisation helps to identify the most functional, effective or perfect solution for a design problem. The studies found that building performance optimisation using BPS is a useful method for assessing various design options to find the optimal or nearly optimal solution for the selected objective(s) while considering some limitations (Attia et al., 2015; Zhang et al., 2020). Hashempour presented a literature review on the optimisation of the energy performance of existing buildings. The results show a need to create a novel-decision making tool to reduce the computational time of optimisation (Hashempour et al., 2020). The optimisation techniques are primarily based on two types of algorithms, Single-Objective Genetic Algorithm (SOGA) and Non-dominated Sorting Genetic Algorithm (NSGA-II). Gou did multiobjective optimisation of newly-built residential buildings in Shanghai using NSGA-II algorithm coupled with Artificial Neural Network (ANN). The study produced passive design solutions that the architects can easily understand and adopt (Gou et al., 2018). In another study, a nearly zero-energy building was optimised to minimize the thermal and visual discomfort (Carlucci et al., 2015). In another study, a cost-optimal solution was assessed in a retrofitted building to reduce the primary energy used for cooling and indoor thermal discomfort (Ascione et al., 2015).

2.2.3 Validation of the simulation models and results

The building performance simulation programs have been developed to increase the validity of results by minimising the uncertainties. The BPS program's validity is mainly tested by applying the Building Energy Simulation Test (BESTEST) (Weytjens et al., 2012). While building performance simulation can be validated by modelling, calibration and sensitivity/ uncertainty analysis.

Modelling

The BPS programs allow modelling by creating virtual models of actual buildings. These models are feed based on the geometry, design, construction and materials used in the actual building. The schedules for occupancy, lighting, etc., can also be based on the real situation. The input data can also be assumed or set based on a standard or practice. However, the accuracy of a model is evaluated by the accuracy of data inputs.

Calibration

The calibration of building models is necessary to produce validated results. The calibration can be done by monitoring or analysis of some parameters of the real building. For example, the model can be calibrated using the weather or energy consumption data.

Table 2.1 Calibration criteria for NMBE and CV(RMSE) indices

Indices	Monthly data	Hourly data
NMBE	Not larger than 5%	Not larger than 10%
CV(RMSE)	Not larger than 15%	Not larger than 30%

The calibration is mainly performed by satisfying the criteria mentioned in the ASHRAE Guideline 14 using Normalised Mean Bias Error (NMBE) and Coefficient of Variation of Root Square Mean Error (CV(RMSE)) (*ASHRAE 14*, 2014). Table 2.1 presents the limitations of two indices to evaluate the calibration of a model. The linear regression analysis method is also used to check the correlation coefficient between the monitored and simulated data. The higher correlation coefficient value (R^2) represents better calibration of the model.

Sensitivity and uncertainty analysis

The identification of influential parameters cannot simply depend on a subjective parameter selected based on the knowledge of a modeller, but it should be based on a scientific process such as Sensitivity Analysis (SA). Sensitivity analysis is a generic concept. It plays a vital role in building energy analysis and can be used to find key variables influencing a building's thermal performance. Tian discussed various sensitivity analysis methods used for building energy analysis. The study identified that local sensitivity analysis is a simple and useful method for building performance analysis besides its shortcoming. However, the global sensitivity analysis method is widely accepted and used for building energy analysis. The selection of parameters and SA methods depends on the purpose of research, input variable, computational time and cost, and familiarity with SA methods (Tian, 2013). Another study identified that Latin Hypercube Sampling (LHS) provides better convergence of parameter space with relatively fewer samples (Hou et al., 2021). The Monte Carlo Analysis (MCA) is the common approach used for sensitivity analysis (Nguyen & Reiter, 2015). It is recommended to minimise the uncertainties of data variables and input. A few aspects should be considered for the uncertainty analysis, climate or weather file, occupancy, physical properties of building materials (envelope), internal heat gain and buildings systems. It is recommended for a suitable building design to evaluate the reliability of simulation results and uncertainty (Spitz et al., 2012; Tian & de Wilde, 2011).

2.3 Climate-responsive design and thermal comfort

Climate-responsive design is simply the application of bioclimatic and passive design strategies in building design practice. In recent years, climate-responsive design became a basis to achieve more sustainable buildings. It is, therefore, essential to consider climatic conditions while designing structures. The concept of 'organic architecture' was given by the American architect Frank Lloyd Wright in the 1930s. The philosophy of organic architecture is based on designing buildings in harmony with people and the surrounding environment. Aronin's work was probably the first academic work published on climate-responsive architecture (Aronin, 1953). However, Olgayay's work received a better reputation in academic research (Olgyay, 1963). In his book, Olgyay created the foundation of the bioclimatic design approach based on a bioclimatic chart invented for the United States. The climate of various regions in the U.S was analysed based on a bioclimatic chart, and the findings were made based on architectural design principles. Olgyay's most significant achievement was the systematic integration of human thermal comfort in building design and climate analysis. In 1969, Givoni developed an innovative design method based on bioclimatic design. Givoni developed a bioclimatic chart on the psychometric chart, which was then broadly used in building research. Using a similar approach, several researchers developed design guides for different climatic regions based on the recent developments in building research, experience, and available knowledge (Cofaigh et al., 1996; Givoni, 1998; Koenigsberger et al., 2010; Nguyen, 2013; Roaf et al., 2001; Szokolay, 2014). However, several questions related to climate responsive design in various climatic conditions are yet to be addressed. The application of local techniques and available materials to construct buildings with improved thermal comfort while considering local climate, social and cultural aspects is necessary.

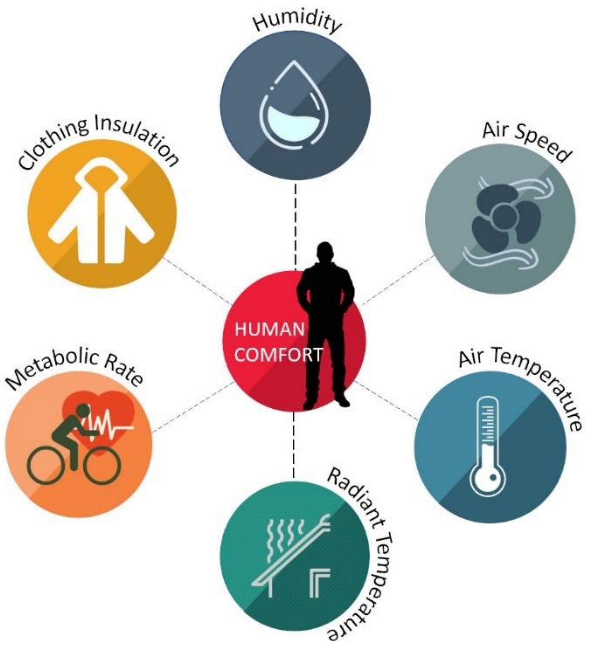


Figure 2.1 Comfort parameters

According to ANSI/ASHRAE Standard 55-2017, thermal comfort is defined as "the condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (*ASHRAE 55*, 2017). Thermal comfort significantly influences occupants' satisfaction and productivity (Freire et al., 2008). The first study on thermal comfort was conducted in 1905, which attempted to define design temperatures in England (Haldane, 1905). By the mid 20th century, people were able to adjust the indoor environment to their expectations. Only then, indoor thermal comfort was acknowledged as a primary concern in buildings rather than providing shelter from severe environmental conditions (Shove, 2004).

Thermal comfort is difficult to measure since it is very subjective and may change person to person and involves a contextual response (Attia & Carlucci, 2015; Auliciems, 1981; Rudge & Gilchrist, 2007; Singh et al., 2016). It depends on several factors such as air temperature, humidity, radiant temperature, air velocity, clothing, metabolic rate, shown in Figure 2.1. Every individual experience comfort a bit differently based on his/ her condition and physiology. Thermal comfort is also known as human comfort. The occupants' satisfaction level from surrounding thermal conditions is an essential factor to be considered while designing a building. Generally, thermal comfort indicates whether an individual does not feel too cold or too hot concerning certain thermal conditions. A cold sensation can be unpleasant when the body is cold but pleasant when the body is overheated. The skin temperature is also not uniform and varies with respect to weather, thermal conditions, activity, and clothing. It is essential to control the indoor climate since it affects human life, physical health, and well-being (Roshan et al., 2017). Previous studies show that indoor thermal comfort can be improved using passive design strategies. The comfort expectation is lower by the residents of developing countries, and the occupants may accept a broader range of thermal conditions (Nguyen, 2013).

2.3.1 Current trends and parameters related to the thermal performance of buildings

In recent years, most of the research focuses on the design, construction, operation and control of energy-neutral buildings. However, the issue of occupants' thermal comfort is not yet resolved in many parts of the world. In developing countries, such as Pakistan, achieving improved comfortable temperature in buildings remain a challenge for designers and researchers. Table 2.2 compares the comfort parameters related to buildings and their importance concerning high-tech and low-tech buildings. The table focuses on three aspects, including building envelope, opaque and transparent surfaces. It can be seen that airtightness is more important in high-tech buildings for controlling the indoor environment. However, the airtightness level or values in low-tech buildings are usually high due to inappropriate sealants, air leakages take place through building elements such as doors and windows frames

Table 2.2 Comfort parameters related to building

Types of surface	Comfort parameter	Low-tech buildings	High-tech buildings
Envelope	Airtightness	High range/ value	Narrow range/ value
Opaque	Thermal conductivity	High	Low
	Specific heat capacity	High	Low
	Reflectivity/ absorptance	Low	High
Transparent	Thermal conductivity	High	Low
	Specific heat capacity	High	Low
	WWR	Low	High
	G-value	Low	High
	Shading Coefficient	High	Low

Legend: WWR, window-to-wall ratio

2.3.2 Methods of comfort analysis

The thermal comfort is perceived by using two sets of ideas. The first one was established in a developed country by Fanger in a climate chamber, which is based on the globally accepted predicted mean vote (PMV). This approach is called the static approach and is mainly based on laboratory-based or controlled experimental studies (Fanger, 1970). The PMV neglected the transient conditions of real-life scenarios and was governed by controlled indoor conditions. The PMV model consists of a 7-point thermal sensation scale that ranges from (+3) Hot to (-3) Cold. The model was later adopted as ISO standard.

On the other hand, a group of people acknowledged that humans are not passive recipients of the environment but tend to interact with it (Roaf et al., 2010). This approach is adaptive and is based on occupants' measures related to behavioural adaptations to its environment. The method was founded by field studies carried out in 'real' buildings during 'real' environmental conditions, without marginalising the subjects' pragmatic activities and actions. It consists of three categories, physiological adaptation, behavioural adaptation and psychological adaptation (Yau & Chew, 2014). In this model, the occupants adapt the surrounding environment to suit their expectations by changing their metabolic rate (activity), clothing (rate of heat loss) or using control systems (windows, fans, blinds, doors) (Nicol & Humphreys, 2002). Most of these studies were mainly guided by the investigation and formation of criteria, standards and thresholds to identify the range of conditions that people are satisfied by their thermal environment. It is found that the static models have a low range for comfort parameters such as temperature, humidity, airspeed etc. while adaptive models include a wider range.

Thermal comfort is usually analysed using comfort models. Four comfort models are mainly used, namely Fanger's model adopted in ISO 77300 (Fanger, 1970; *ISO 7730*, 1994), Givoni's bioclimatic model (Givoni, 1969), EN 16798-1 European comfort model (*EN*, 2019), and American adaptive comfort model (*ASHRAE 55*, 2017). These models are compared in Table 2.3, providing an overview and limitations of each model.

Table 2.3 Comparision of four comfort models

S.No.	Comfort models	Description
1	Fanger - ISO 7730 model	- Static model/ steady-state - Based on laboratory-based experiments (controlled chamber - Controlled/ fixed operative temperature - Constant indoor temperature - Acceptability to a narrow range of temperatures - PMV/ PPD method - Suitable for conditioned buildings
2	Givoni Bioclimatic model	- Based on expected indoor temperature - Presents boundaries of comfort zones - Based on outdoor air temperature and humidity level - Includes zones where specific passive design strategies are effective - Inaccurate boundary conditions and lack of diurnal and seasonal variations
3	EN 16798-1: 2019 model	- Comfort acceptability depends on the type of system - If cooling is provided using an active system, then indoor temperature respect the range defined in Fanger's model - If cooling is provided using passive strategies, then the upper-temperature limit is set by an adaptive model - The optimal operative comfort temperature is calculated by knowing the daily mean outdoor dry-bulb air temperature of previous days
4	ASHRAE 55 Adaptive comfort model	- Changing operative temperature - Indoor temperature changes based on outdoor temperature - Acceptability to a broader range of temperatures - Includes adaptive measures and behaviour - Includes clothing and metabolism factor - Upper and lower acceptability limits for 80% and 90% occupancy comfort - Suitable for free-running and hybrid buildings

Legend: PMV, predicted mean vote; PPD, predicted percentage of dissatisfied

2.4 Informing decision-support

Designing comfortable buildings using passive design and climate-responsive strategies is a challenging and complex problem. Choices at the early stage of a design are important in decision making and the long term effects of buildings. Taking advantage of passive design solutions can reduce the use of active systems and provide a better combination for optimal thermal comfort. The failure or success of a project depends on the decisions taken at the early stage of design; therefore, it is essential to assure informed decision support at this phase. This includes incorporating building performance simulation tools (BPS) at an early stage of the design process (Attia et al., 2012; Han et al., 2018; Shaviv, 1999).

Architectural design is complex, ill-defined, uncertain, and exploratory. The outcome is based on the inclusion of better research, experience, and inclusion of advanced knowledge in building science. A multidisciplinary approach is mandatory for decision making at the early stage of design by architects. Support at the early design phase is more important since small scale projects lack the budget and resources. At the early design stage, 20 per cent of the decisions taken subsequently influence 80 per cent of all design decisions (Bogenstätter, 2000).

The concept of informed decision support is based on providing knowledge and guidance before decision making to influence the decision approach. Decision aids, tools or guides have been developed in many parts of the world. Building codes and bylaws are also guiding decision making to make better decisions at the early-design stage. However, these tools or guides are not widely available for many developing countries and specific climatic conditions. Some of the guides and tools are based on architectural principles and passive design strategies and others are based on local knowledge and construction practices. By adopting building performance simulation tools, validated results can be achieved by reducing uncertainty and improving the robustness of the design.

2.4.1 Complexity of design

Design is a complex phenomenon. For every design decision, there is a consequence. Designing residential buildings while considering the occupants' requirements, building code and bylaws, construction techniques and materials, and climatic factors is a challenge for architects and building professionals. In Pakistan, most houses are constructed with

Reinforced Concrete frame (RCF) structures and a typical layout plan without considering their geographical location and climatic factors. Indoor thermal comfort is mainly ignored, and the focus remains on the quality of materials and construction. Previous studies related to indoor thermal comfort in Pakistan prove that the existing buildings do not provide better thermal comfort to their occupants (Bughio et al., 2020; Khan, 2016; Mahar et al., 2018; Mahar et al., 2019; Nicol et al., 1999). Designing buildings in the cold climate is a significant challenge for architects, particularly in the cities with high-temperature variations between day and night temperatures and between two long seasons, i.e. summer and winter.

In recent years, several tools have been developed for climate analysis and building design. However, these tools are not easy to use by architects in building design due to their complexity. Some tools require specific conditions of thermal comfort, which can be easily applied in developed countries. However, their application is inappropriate in many developing countries due to a lack of resources, technology, and differences in climate, socio-cultural aspects, and lifestyle. The people living in developing countries also have lower expectations for thermal comfort due to their adaptive behaviour. Building simulation tools gained significant importance in recent years for the design and analysis of buildings. These tools provide better understanding and validated results for designing and improving comfort, energy efficiency, and buildings' environmental impact. Hyde discussed new methods and ideas to apply simulation in building design (Hyde, 2008). Building simulation is a complex process, not readily available and requires specific skills, knowledge level and equipment, such as high-performance computers. The situation makes it difficult for the architects to practice in developing countries and design residential buildings using simulation tools due to limited resources, time and projects. In such a situation, a design guide can provide firsthand information to architects for designing houses with improved thermal comfort without spending a lot of time and effort.

2.4.2 Types of decision-support

While designing buildings, architects make a series of decisions to evaluate their design and its outcomes. These design decisions follow a set of steps based on design practice, principles or guidelines from an idea, to the creation of bubble diagrams, sketches, planning, elevations, sections, and the selection of materials and specifications. Cuff discussed the various aspects related to the professional practice of architects (Cuff, 1992). In general, architects practising around the world need to follow some bylaws, guidelines, or standards to evaluate their design or assess the quality of design. However, in many parts of the world, these rules and guidelines are either not available, in-process of formulation, or lack implementation. In such a situation, the researchers and building professionals are creating the knowledge to assist the design decisions at the local level. However, providing a robust and factual understanding of design, climatic conditions and building problems is essential, and a scientific basis and validation must support the decision. It is also necessary to provide decision support that should not affect architects' creativity (Looman, 2017). There are several methods of informing decision-support to architects. Table 2.4 enlists the most common types of informing decision support.

Table 2.4 Types of informing decision-support

Type of decision-support	Description
Charts	A sheet of information in the form of a table, graph or diagram
Guidelines	A set of rules, principles or pieces of advice
Standard	A norm or requirement to achieve a level of quality
Decision support system	Interactive software-based tool to inform decision making
Simple (steady-state) simulation	Provide analysis for a specific period
Dynamic (multizonal) simulation	Provides better understanding, estimation and future forecasts
Decision support tool	Software developed to support analysis and decision making
Prescriptive guide	A guide provides exact instructions, directions or rules telling people what they should do, rather than simply giving suggestion

2.4.3 Informing decision support to architects

The decision support methods and tools have been evolved over time. These methods are mainly based on three systems, data-based, model-based and knowledge-based (Larsson et al., 2014). The use of building performance simulation for informing decision making is found an effective method. A better decision-support method should include a strong database, a good knowledge base with expert knowledge and best practices, and a validated building simulation model (Erbas & Dijk, 2012). However, architects face challenges in learning and adopting building simulation tools and techniques (Weytjens et al., 2012). Previous studies discussed the importance and incorporation of building performance simulation into the early stages of the design process (Attia et al., 2012; Ellis & Mathews, 2002). Looman proposed a framework to provide decision-support for climate-responsive design, consisting of three factors: performance, process, and architectural consequences. The performance relates to the thermal comfort and energy performance of a design solution. The process refers to the application of energy function, its effects on collaborators and design principles. The architectural consequence factor is related to the effects of a design solution on the appearance of the design (Looman, 2017).

The building performance simulation programs come with their complexity and limitations. It is not easy for architects and building professionals to adapt to these tools while designing various buildings and systems. BPS programs need precise data, a variety of input variables and are time-consuming. There is a need to provide a better solution for architects, which includes expert knowledge, best practices, validated simulation results, specific context-based actions, and comparative alternatives to design buildings. Such a solution also needs to reduce the complexity of design and various design solutions. It needs to provide decision making in a simple way yet using advanced methods and techniques for the higher accuracy of the results and actions.

2.5 Conclusion of the chapter

This chapter provides state-of-the-art related to three main aspects: building performance simulation, climate-responsive design and thermal comfort, and informed decision support. The review focuses on the global aim of this PhD thesis and the most important themes. This PhD research aims to provide informed decision-making using passive design solution for designing houses with improved thermal comfort in Pakistan's cold and semi-arid climates. The issues related to thermal comfort, building performance simulation and informing decision making been studied globally. The research on the built environment, including architecture, planning, housing, is relatively limited in Pakistan compared to its neighbouring countries. It is also reflected in the ill-planning of cities, lack of innovation in design and construction, lack of skilled labour and workforce, and inadequate housing design.

In total, there are 33 architectural schools in Pakistan; however, the number of PhD faculty is lower than 20. Most of them are working in universities located in major cities—currently, only four universities offer PhD programs in architecture, most of which were started in the last decade. On the other hand, the total number of registered architects in Pakistan are 6028, while the ratio of architects per 1000 population is 0.028. This shows an indicative shortfall of 90530 architects compared with the OECD average. The existing 33 architecture schools in the country representing a ratio of 0.16 schools per million (*PCATP*, 2020). These figures show an urgent need to emphasise this profession for the sustainable development of the country. The studies related to thermal comfort are limited, as discussed in *Chapter 1 (Section*

1.2). There is a knowledge gap regarding sustainable housing design, construction, indoor thermal comfort, energy efficiency, and climate sensitivity.

The existing regulatory framework doesn’t provide better support for the goal of sustainable development. The Building Energy Code of Pakistan (BECP) was developed in 1990 (*ENERCON*, 1990). Since there have been several technological developments in the last 20 years that changed people's lifestyles and increased energy consumption at the domestic level, it became essential to revise and update this energy code to cater to recent developments. In 2011, Energy Provisions were developed to be included in the Building Code of Pakistan. The Building Code of Pakistan (Energy Provisions-2011): BCP(EP-2011), is mainly adopted from the ASHRAE Standard 90.1-2004. While its section-4, “Building Envelope” was developed based on the local environment and the Energy Codes of regional countries (*BEC*, 2011). These provisions mainly focus on active systems in buildings and code implementation at the national and local levels. The BCP doesn’t apply to residential buildings, and its scope is limited to commercial buildings and large structures.

The housing sector in Pakistan is the largest consumer of energy, i.e. 45% (*PES*, 2020). The use of active systems is common for comfort improvement, which increases the spendings of a household on energy consumption and creates fuel poverty. The existing energy mix of Pakistan mainly relies on fossil fuels, and the percentage of renewable energy remains very low, i.e. 3.9% (*PES*, 2020). In such a situation, there is an urgent need to focus on residential buildings' energy consumption. By applying passive design strategies, indoor thermal comfort can be improved, and reliance on active systems can be reduced. However, the proposed solutions should be based on a strong knowledge base, scientific methods, and best practices. These solutions need to focus on the design process and decisions made at the early stages of design. Therefore, it is necessary to simplify the complexity of design and provide validated, applicable solutions for architects to inform decision support.

CHAPTER 3: RESEARCH METHODS

3.1 Introduction

A methodology chapter aims to provide necessary information on research methods used in a study and their reproducibility. The current chapter presents the essential methods and approaches which were applied in this PhD study. It further discusses the research types and techniques used *(Section 3.2)*, data collection *(Section 3.3)*, data analysis *(Section 3.4)*, research ethics *(Section 3.5)*, and the quality criteria *(Section 3.6)*. During this PhD research, the selected city was visited five times for data collection, surveys, monitoring of indoor climate, and performing a usability test to validate the developed prescriptive guide.

A conceptual study framework of this PhD research is illustrated in Figure 3.1. It shows the main steps of research workflow, including characterisation of housing stock, selection of common typology and monitoring of indoor climate *(Chapter 4 and 5)*, comfort and parametric analysis *(Chapter 6)*, sensitivity analysis *(Chapter 7)*, materialization *(Chapter 8)*, and development of the decision-support prescriptive guide *(Chapter 9 and 10)*.

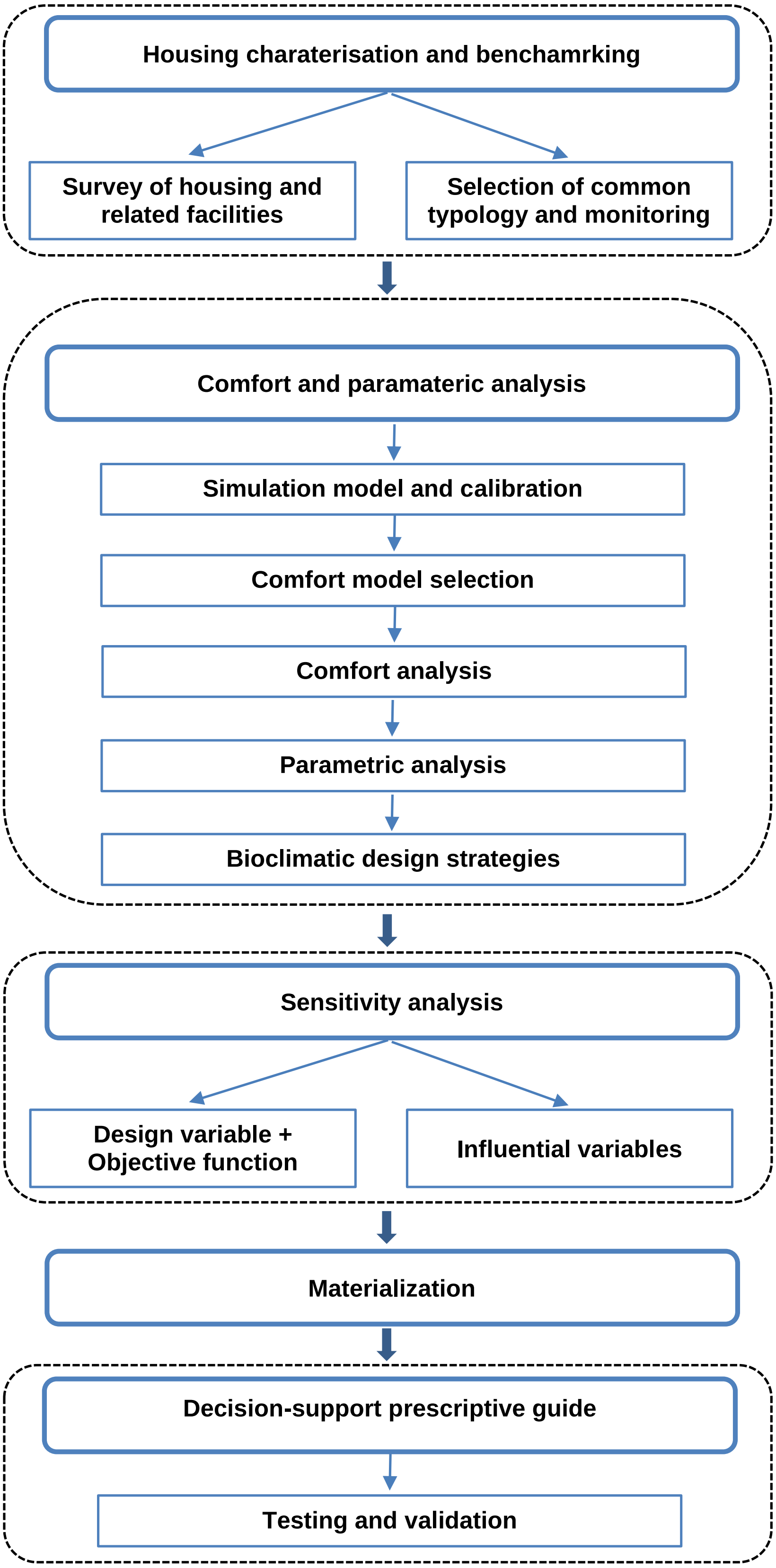


Figure 3.1 Study conceptual framework of PhD research

3.2 Research methodology

This PhD study is based on mixed-mode research methodology, which combines quantitative, qualitative, observational and modelling methods. Figure 3.2 illustrates the details of each research methodology and its purpose. Combining different research approaches was essential for this study to ensure a systemic data collection process, analysis, results, and validation. The selected research methodologies are further elaborated in the data collection *(Section 3.3)*.

The quantitative methods used throughout this research gave insights into several factors, including people's perception of residential areas and neighbourhoods' safety for housing survey and data collection—the characteristics of housing and households, construction methods, materials and techniques—behavioural adaptations and energy consumption behaviour—a materialization survey to identify building materials that can be used to improve indoor thermal comfort. Additionally, the usability test participants answered a self-reported questionnaire to access validation of the developed prescriptive guide. The total sample size(s) for each study are also mentioned in Figure 3.2; the incomplete questionnaires were not included in the total sample size.

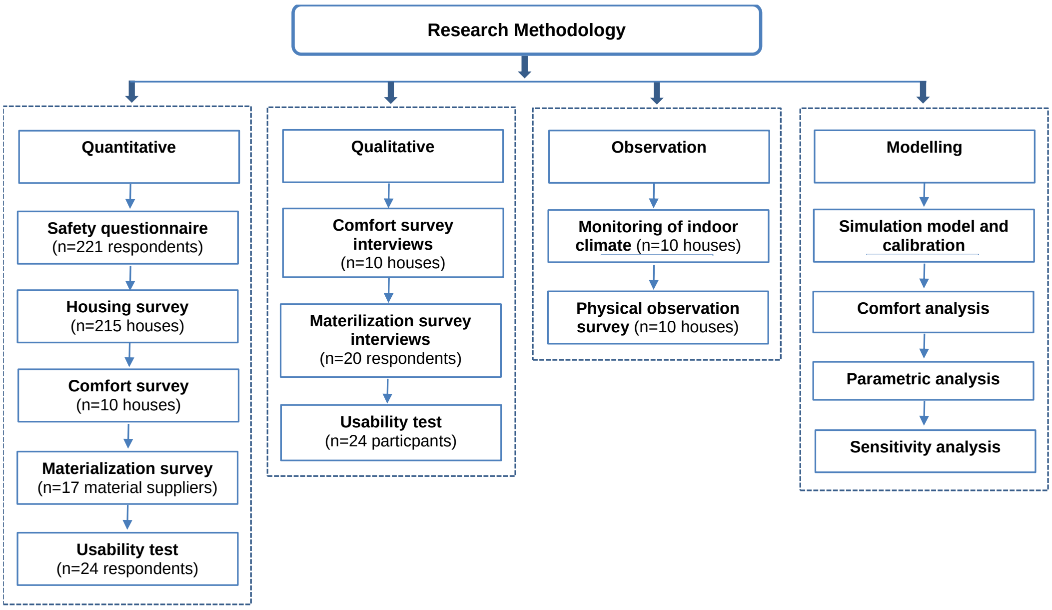


Figure 3.2 Research methodology used in this PhD research

During this PhD, the qualitative data collection includes semi-structured interviews conducted from the occupants during comfort and materialization surveys; and from practising architects regarding the locally available and manufactured materials. A usability test was conducted to validate the prescriptive guide. It involves discussion with the participants to report their experience and opinion regarding the usability test and informed decision making provided by the Building Code of Pakistan and the prescriptive guide.

In observational methodology includes two main aspects, i) monitoring indoor climate using data loggers performed in ten houses, and ii) physical observation survey. The monitoring was done in both long seasons, i.e. summer and winter. Additionally, outdoor air temperature and humidity were also monitored for a whole year. The physical observation survey included visiting actual houses, measuring spaces to draw plans, and observing construction techniques and materials (Mahar & Attia, 2018c).

The study also includes modelling using a virtual model of basecase, which was calibrated based on monitored data in the actual building. A comfort analysis was done, and parametric analysis was conducted to improve indoor thermal comfort using passive design strategies. The last step in modelling was a sensitivity analysis to identify the most influential design variables related with indoor thermal comfort.

3.3 Data Collection

The data collected in this PhD research are divided into primary and secondary data. Most of the data used in this study are primary data; collected using questionnaires, interviews, physical observations, and indoor climate monitoring. The secondary data were obtained from development authorities and public/ private sector organisations; and a comprehensive literature review of scientific articles, books, reports and documents. The following sections further describe the data collection process for primary data.

3.3.1 Survey of housing and related facilities

This PhD research focuses on improving the residential buildings' indoor thermal comfort in cold semi-arid climates of Pakistan, and Quetta city was selected for this purpose. The available data on housing and household characteristics, construction typology and practices, and housing-related facilities in Quetta was limited or outdated (*PBS*, 1998). For this reason, it was necessary to conduct a housing survey to create a starting point for this research. Two questionnaire-based surveys were performed for the housing survey. Firstly a safety questionnaire was distributed online to identify the safe areas to conduct a housing survey (due to the unsatisfactory law and order situation in Quetta). Secondly, a housing survey of 215 houses was conducted in 32 neighbourhoods of Quetta.

The research questionnaire used in this study were carefully designed. It was inspired by the English Housing Survey and an inventory used in a PhD research conducted in Shikarpur, Pakistan (*EHS*, 2016; Naeem, 2009). The questionnaire was then modified with the consultation of experts. This survey created the basis of this study. It provided valuable insights into the existing houses and housing-related facilities. The details of the housing survey are reported in Chapter 4. The safety questionnaire is presented in Annexure A, and the housing survey questionnaire can be found in Annexure B.

3.3.2 Selection of common typology and monitoring

The housing survey facilitated identifying the most common construction typology in Quetta, i.e. reinforced concrete frame (RCF) houses. Ten RCF houses were carefully selected to further understand the housing and household characteristics, behavioural adaptations, comfort perception, energy consumption behaviour, clothing, and activity. The study was based on self-reported questions, physical observations, semi-structured interviews and monitoring of indoor climate. Further details of this study are presented in Chapter 5. The questionnaire used for data collection is reported in Annexure C.

Physical measurements

The physical measurements include monitoring of microclimate in ten selected houses to understand the comfort situation of existing houses. In addition to that, the activity level was estimated, and clothing insulation was calculated based on the occupants' responses. The monitoring was focused on measuring two essential parameters, indoor air temperature and humidity, in each house. The outdoor air temperature and humidity were also monitored for a whole year. The monitoring was done using HOBO U12-012 data loggers, which were also used in previous studies (García et al., 2019; Kumar & Singh, 2019; Soebarto et al., 2019). Besides, airflow and carbon dioxide concentration was also monitored as a part of this field study. A Testo-405 thermal anemometer was used to measure air velocity, and a Testo 160 IAQ was used to measure carbon dioxide concentration. However, this study does not focus on indoor air quality. Table 3.1 presents the details of monitoring equipments.

Table 3.1 Details of the instrument used for measurements

Parameter	Instrument	Make	Range	Accuracy
Temperature	HOBO U12-012	Onset USA	-20 ºC to 70 ºC	± 0.35 °C (0-50 °C)
Humidity	HOBO U12-012	Onset USA	0 to 95% RH	± 2.5% (10-90%)
Air velocity	Testo 405	Germany	0 to 5 m/s (-20-0 °C) 0 to 10 m/s (0-50 °C)	± 0.1 m/s

Monitoring of human behaviour

Occupants take particular behavioural actions to overcome thermal discomfort, which is also reported in previous studies (Feriadi & Wong, 2004; Wong et al., 2002). In this research, the human behaviour monitoring includes occupants' adaptations to adjust comfort situations by adjustments such as opening/ closing windows, turning/ off on a fan or changing clothes. It further focuses on the energy consumption behaviour of the residents. Three approaches were used to monitor human behaviour, i) participants' responses to a questionnaire, ii) structured interviews, iii) and formal observations made by the researcher. The questionnaire was designed to mainly explore the occupants' subjective responses and attitudes in each house during different seasons and situations, such as actions taken during electricity outage hours. No sensors or monitoring devices were used for monitoring occupancy and behavioural adaptations. The input data was created based on the responses of occupants.

3.3.3 Materialization

The selection of building materials influences the construction methods, cost, maintenance and performance of buildings. Studies show that indoor thermal comfort can be improved by changing building materials (Hall, 2010; Latha et al., 2015). The knowledge and availability of materials used for thermal comfort and energy efficiency in Pakistan are limited. The study aimed to identify the available and locally manufactured building materials which can be used to improve indoor thermal comfort. This study is based on a market survey of various building materials, semi-structured interviews with practising architects and residents. Chapter 8 includes more details on the materialisation survey. The questionnaire used for the materialization survey is listed in Annexure D.

3.4 Data analysis

3.4.1 Analysis of the housing and comfort survey

The data collection in housing and comfort surveys include quantitative and qualitative data. It includes questionnaires, semi-structured interviews and monitoring. The results were analysed using the statistical approach and qualitative analysis of semi-structured interviews to report important facts, observations and results.

3.4.2 Comfort and parametric analysis using building performance simulation

The Building Performance Simulation (BPS) has emerged as a unique approach to analyze the complex problems related to building design and satisfy standard or regulation requirements. These problems vary from improving indoor thermal comfort, calculating heating and cooling energy demand, designing HVAC systems to constructing high-performance and net-zero energy buildings.

Building simulation techniques are used in this study to perform comfort, parametric and sensitivity analyses. Based on housing characterisation and monitoring, a virtual model of the representative house was created in DesignBuilder. EnergyPlus was used as a simulation engine, which is a validated tool for building performance simulation. The virtual model was created based on actual data, specification and construction details and was calibrated using monitoring of indoor climate in the real house. Three methods were used for calibration; Normalised Mean Bias Error (NMBE), Coefficient of Variation of Root Square Mean Error (CV(RMSE)) (*ASHRAE 14*, 2014), and linear regression analysis of monitored and simulated data. Four different comfort models were compared to identify the best fit-to-context model. The thermal performance of the selected basecase was tested, and a parametric study was performed to improve indoor thermal comfort using passive design strategies. The important bioclimatic design strategies for the selected climate were identified using DeKay and Brwon's chart (DeKay & Brown, 2014). Chapter 6 covers more details of this comfort and parametric analysis. The thermophysical properties of building materials are listed in Annexure E, and the schedules of occupancy, lighting and domestic hot water are displayed in Annexure F.

3.4.3 Sensitivity analysis

Sensitivity analysis is an effective method to identify the significant design variables to assist decision-making (Lomas & Eppel, 1992). It also helps to understand the importance of various design variables, which can be used to improve a building's performance (Nguyen & Reiter, 2015). A global sensitivity analysis of 21 design parameters based on passive design strategies was performed to identify the influential design variables for the climate of Quetta. DesignBuilder was used coupled with EnergyPlus, SimLab 2.2 and jEPlus for the analysis and outputs. A single objective function of comfort hours (CH) was used for the sensitivity analysis, based on the 90% acceptability limits of the ASHRAE Standard 55 adaptive comfort model (*ASHRAE 55*, 2017).

There are two main methods used for sensitivity analysis, local analysis and global analysis. This study is based on Monte Carlo Analysis (MCA) which uses a statistical sampling technique to perform the global sensitivity analysis (Christian, 2004). In total, 1100 cases were analyzed using Latin Hypercube Sampling (LHS) method. The results of sensitivity analysis are presented using Standard Regression Coefficient (SRC) index, which is widely used in building performance analysis. Chapter 7 presents the detailed methodology, analysis and results of sensitivity analysis.

3.4.4 Materialization survey

The materialization survey is based on a questionnaire used for data collection from the material suppliers and semi-structured interviews conducted with practising architects and residents. The results of the interviews were qualitatively analysed to establish the conclusions. Chapter 8 reports the results of the materialization survey.

3.4.5 Usability testing

A prescriptive guide was developed to provided informed decision support for architects at the early design stage to design and construct residential buildings with improved thermal comfort in the cold semi-arid climate of Quetta. The guide concludes with different studies performed in this PhD research, including surveys, empirical analysis, interviews, building simulation, sensitivity analysis and materialisation. A scoping study of six variables; insulation, openings, windows shading, natural ventilation, construction of external walls and building orientation was conducted. The scoping study and developed perspective guide are presented in Chapter 9. A usability test was conducted among the architects and architecture students to validate and test the prescriptive guide's ability to inform decision-making. The results of the usability test are documented in Chapter 10.

3.5 Research Ethics

In recent years, ethical concern gained more attention. In 2018, the General Data Protection Regulation (GPDR) was implemented in the European Union (EU) and the European Economic Area (EEA). According to the regulation, no data can be processed without considering six legal bases, including consent, contract, public task, vital interest, legitimate interest or legal requirement (*EU GDPR*, 2016). In Pakistan, the Personal Data Protection Bill (PDPB) was drafted in 2018 and has been revised four times. The revised bill, namely Personal Data Protection Bill 2020, is under deliberation for the parliament's final approval (*PDPB*, 2020). During this PhD, the candidate also attended two courses; i) ethics in design, ii) ethics and quality in research.

It is essential to consider the ethical implications of a research study. Two factors need to be justified in this regard; i) creating a balance between the benefits of research towards society and the risk concerned to the participants, ii) the confidentiality of the collected and monitored data. The participants involved in this PhD research were informed about the study's purpose, data collection methods, data confidentiality and anonymity. If the participant wanted to know more about the research and its results, they were told that the published results would be shared in future.

All participants who took part in this PhD research provided prior approval. They were also told that they could skip one or more part(s) of the questionnaires, interview or leave it incomplete. No living being was harmed during this study. The monitoring devices used in this PhD study were carefully tested, validated, and possessed no risk to the occupants.

3.6 Quality criteria

There is a continuous debate on the standard for research quality within the scientific community (Yokuş & Akdağ, 2019). The standard and strategies for validating research quality depend on the methods, evidence, and tools used for performing scientific research. There are different methods of research, such as quantitative, qualitative, and mixed-mode studies. All methods have distinct understanding and criteria to access the quality in research. It is essential to explain a study focusing on validated methods for data collection, analysis and results to ensure the research quality. The quality of research is important since it provides a rich source of information to understand the pressing and complex issues related to various topics and issues (Heale & Twycross, 2018). This PhD research is based on validated and tested methods used at various stages of this PhD thesis.

- The basecase (benchmark) model was selected after a housing survey of 215 houses in 32 residential areas of Quetta.
- The virtual model was created using actual input parameters, material specifications and construction details.
- This model was calibrated using monitored data in the selected building.
- The calibration was validated using the NMBE, CVRMSE and correlation coefficient methods.
- The simulation was performed using validated software and tools such as DesignBuilder, EnergyPlus, jEPlus and SimLab.
- The comfort hours are calculated using the ASHRAE 55 Standard adaptive comfort model.
- The sensitivity analysis of passive design strategies was performed using Monte Carlo based global analysis, and the Latin Hypercube Sampling method.
- The ranking of sensitivity analysis is created using Standard Regression Coefficient (SRC) index.
- The materialization study is based on an actual survey conducted in Quetta. The semi-structured interviews were conducted with the residents and practising architects.
- The developed prescriptive guide was tested and validated with the architects and architecture students.
- The metrics defined in the ISO Standard were used to verify the usability test (*ISO 9241-11*, 2018).

3.7 Conclusion of the chapter

A sound research methodology includes the tools and techniques which can be tried, tested, validated, and similar results can be reproduced. The research approach used and presented in this PhD study is based on mixed-mode methodology. Two key factors were considered in this study to increase its validity and reproducibility, i) the validation of methods and results by decreasing the uncertainty, ii) and repetition of the methods.

This research focuses on improving indoor thermal comfort by using passive design strategies. The developed prescriptive guide will help improve the thermal performance of residential buildings in cold semi-arid climates. There are limitations to the generalizability of the results since the building usage, design, construction, and microclimate differ. However, the methods used in this study can be considered for developing design strategies and improving indoor thermal comfort in a similar climate.

Despite using a mixed-mode methodology in this PhD thesis, it was realised that building performance simulation, parametric analysis, and sensitivity analysis provided significant insights into indoor thermal comfort by identifying effective passive design strategies and measures in the selected climate.

CHAPTER 4: AN INVENTORY OF HOUSING CONDITIONS AND RELATED FACILITIES

4.1 Introduction

Quetta is the 10th largest city of Pakistan with over one million urban population and the provincial capital of Balochistan (*PBS*, 2017). However, the province of Balochistan is one of the most deprived and less developed areas of Pakistan. The city of Quetta emerged from a small garrison city (in the British period) to a metropolitan. Due to its unique climatic, geographical, and topographical position, Quetta remains one of the country's most important cities.

Similar to other major cities of Pakistan, the available housing data in Quetta was very limited or outdated. As a starting point of this PhD, it was necessary to understand the characteristics, materials, construction, and typologies of existing houses in Quetta. Furthermore, the information on the climate and housing-related facilities such as available energy, water, and waste disposal is also included in this chapter. A housing survey was conducted for data collection using a survey questionnaire to identify housing and households' characteristics. The data on related facilities were collected from literature, visiting the concerned departments using questionnaires and semi-structured interviews. The following objectives were set for this study: i) the classification of common construction type(s) of houses in Quetta. Ii) the identification of existing materials and construction techniques; iii) understanding the existing housing conditions and their related facilities; and iv) the documentation of housing and household characteristics. This chapter presents the study area's introduction, the methods used for this study, its results and conclusion. The results of this Chapter were also presented in previous studies (Mahar et al., 2017; Mahar & Attia, 2018a).

4.1.1 The study area

Quetta is located in the North-West of Balochistan province near the Pakistan-Afghanistan border (Figure 4.1), and it is a trade and communication centre between the two countries. According to the Quetta District Development Profile (QDDP), the total area of the Quetta district is 2653 km^2. The terrain of the Quetta district varies from 1390 m to 3455 m above sea level. It is located in an earthquake zone and approx. Sixty thousand people died during the earthquake of 1935. The climate of Quetta is cold, dry, and semi-arid: mild to extreme cold in winter and hot in summer. Quetta lies out of the monsoon range, and it receives snowfall mainly in December, January and February (*QDDP*, 2011). The climate of Quetta has significant variations during winter and summer. The average recorded temperature in summer was 28.6 ºC, and winter 5 ºC between 2011-2020.

Figure 4.1 Location of Quetta

The energy crisis in Pakistan also affected the residents of Quetta. The urban population faces 4-6h per day of electricity outage (load shedding) in winter and 6-8h per day in summer (*QESCO*, 2019). The studies show that the city and its surrounding areas have great potential for renewable energy generation (*NREL*, 2007a; *NREL*, 2007b).

4.2 Methodology

A housing survey was conducted to identify the housing and household characteristics in Quetta. Due to the unsatisfactory law and order situation (*QDDP*, 2011), it was essential to know more about the safety level of housing areas for the students and staff before visiting and conducting the survey. The methodology included two steps, i) identifying the safe areas and ii) inventory of the housing stock to determine housing characteristics.

In recent years, several areas of Quetta have been affected due to terrorist attacks and activities. The opinion of local authorities and the local population vary on the safety of areas and localities. It was decided to seek the local people's opinion on the residential areas' safety rather than local authorities, to get the point of view of a diverse and large group. For the housing stock inventory, both primary and secondary data sources were used to complete this study. The preliminary data were obtained using a structured household questionnaire which was filled during the housing survey. Secondary data was collected and reviewed from literature, and information provided by Quetta Development Authority (QDA), Water & Power Development Authority (WAPDA), Quetta Electric Supply Company (QESCO), and Water & Sewerage Authority (WASA).

4.2.1 Safety questionnaire

The city of Quetta was divided into 11 areas concerning the local population's familiarity with the major roads and links (Figure 4.2). It was then confirmed with the map provided by the Quetta Development Authority (QDA), which shows the distribution of areas with road networks' connection. Less populated places and neighbourhoods were not included in this survey. Quetta Cantonment area was also not included since it is difficult to get permission for a visit. The cantonment authority does not follow the same bylaws and regulations as Quetta city. The selected 11 areas were further divided into several sub-areas based on the major neighbourhood and housing located in each area. A safety questionnaire was developed and distributed online via email and social apps, i.e. Facebook, WhatsApp. It was possible to fill the questionnaire using a computer, mobile phone or tablet. The survey period was two weeks, from 19/9/2016 to 4/10/2016. In total, 497 participants were invited from various walks of life, including academics, medical professionals, lawyers, media personnel, civil servants, students, social workers, traders and businessman, etc. In total, 242 people attempted the online survey and 221 completed it. The 21 partly filled questionnaires were not included in the results. The questionnaire consists of questions on the respondent's demographic information and his/her familiarity with specific areas and sub-areas of Quetta city. Once the respondents consider any area familiar, then a question about sub-areas appears to select familiar sub-areas. After the selection of sub-area(s), the respondent had to mark sub-area(s) “safe”, “unsafe” or “I don’t know”. The participants were then asked if they visited or lived in the marked sub-areas. The residential areas which were more familiar and marked safe by most of the respondents who lived and visited those areas were considered safe.

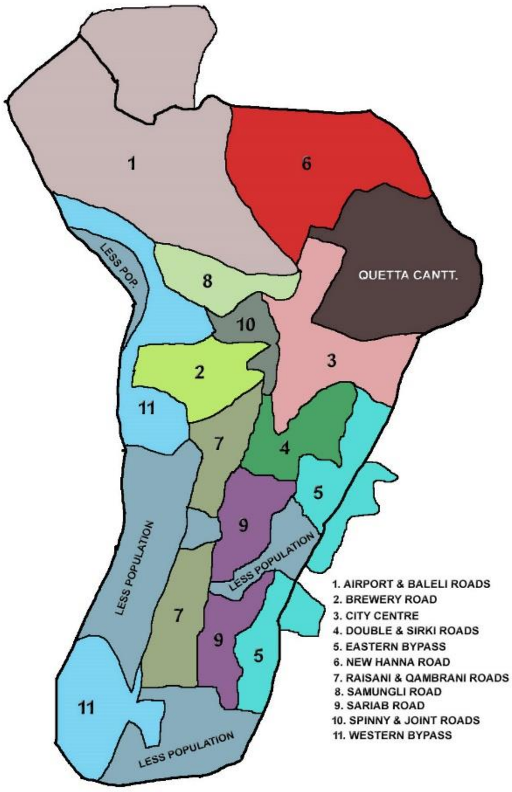


Figure 4.2 Map of Quetta city with the classification of areas for safety questionnaire

4.2.2 Housing survey

Initially, 12 out of 14 (safely marked) areas were selected for the housing survey. However, to get a more representative sample of Quetta, 18 additional housing areas were included to represent various housing typologies (public, slum, real-estate etc.), old and new housing developments, and areas with different ethnic, religious and income groups. The residential areas' classification in some studies was based on rent and amenity value (*TMD*, 2003; Osumano, 2007). In the case of Quetta, it was not possible to classify housing based on rent, amenity value or income level due to lack of available information. Two master plans prepared for Quetta identify the slums, informal settlements, old neighbourhoods and proposed future developments in the city (*MPQ*, 1980; *NESPAK*, 1985). The details of new and planned developments are also discussed in a report by AlHasan systems private limited (*PESA*, 2015). Based on that information, additional areas were selected and classified to focus on various housing areas. The classification of all 32 residential areas selected for the housing survey is given in Table 4.1.

Table 4.1 Classification of residential areas for a housing survey

S. No.	Reason/ Housing type	No. of areas
1.	Safe areas	12
2.	Public housing	3
3.	Real estate developments	3
4.	Slums and squatter settlements	4
5.	Old neighbourhoods	3
6.	New developments	2
7.	Middle-high income areas	3
8.	Low-income areas	2
Total		**32**

A structured survey questionnaire was designed inspired by the English Housing Survey (EHS) and a housing inventory used in PhD research conducted in Pakistan (*EHS*, 2015; Naeem, 2009). The questionnaire was further modified after discussion with the experts from architecture, economics, and social sciences background. Initially, the survey was conducted in 5 residential areas by students who live in the same area as a pilot study to determine the residents' response and if there is any need to change/ skip any question in the questionnaire. The response was good, and no change was needed in the questionnaire. Later on, the survey was conducted in the remaining 27 residential areas.

Multiple criteria were used for the selection of houses within a specific area. Clear instructions were given to the survey team and verified after the survey. In public or planned housing schemes, every 5th house on each side from a selected landmark was surveyed (Yakubu et al., 2014); in case of more than one sector or residential block, a representative number of houses from each sector/ block were selected; if the residents were not willing to participate, then the next house or household willing to participate in the survey from the same street/ area was selected; in areas with mixed or multiple construction types, a representative number of houses in terms of architectural layout/ construction type (Tunçoku et al., 2015) were selected. Finally, the representation of major ethnic, religious and income groups was also one of the selection criteria.

According to the World Food Programme (WFP), the wealth index is usually used as a proxy indicator to know more about household-level wealth and key assets (*WFP*, 2008). For Demographic and Health Surveys (DHS), USAID developed wealth indices for many countries, including Pakistan (*DHS*, 2013). The wealth index was also used in scientific studies to assess the household physical assets and endowments (Tipple et al., 1997; Yakubu et al., 2014). Since questions on household income are always delicate and might result in inaccurate answers, the household wealth was also validated through the availability of assets besides asking a question on household income. The purpose was to determine the availability of various utility and luxury items and appliances being used by the residents. Initially, 31 assets/ items were enlisted, which were then modified after discussion with experts and, finally, 22 assets were selected. These assets were then divided based on their importance and usage (what assets/ service people would prefer to buy/ get when they can afford) into Need and Luxury assets or items (Table 4.2). However, the assets mentioned in the wealth level were given no score since it is hard to define a price or value of the items in the context of Quetta; for example, there are also markets in Quetta where people can buy used products and cars which are brought into the country through informal ways.

Table 4.2 Wealth level assets for Quetta

S. No.	Assets	
	NEED	LUXURY
1	Electricity	Charpai (local bed)
2	Natural gas	Bed
3	Fan/ Air Cooler	Dining table
4	Press Iron	Sofa
5	Room heater	Microwave oven
6	Mobile phone	Vacuum cleaner
7	Television	Air-conditioner
8	Washing machine	Computer
9	Water geyser/ boiler	Internet connection
10	Refrigerator	Car
11	Motorcycle or scooter	Domestic servant in the household

Employing literate community members for socioeconomic data collection is an effective method (Barry & Ruther, 2005). Therefore, the survey was conducted with the help of local contact persons who also possess specific knowledge about housing and construction and who can speak the local language(s) for friendly communication with the residents. The survey team includes 3rd year onward students of the architecture department, staff members of civil engineering and architecture departments of the Balochistan University of Information Technology, Engineering & Management Sciences (BUITEMS) Quetta, practising architects and the members of non-government organisations (NGOs). The number of houses surveyed per survey team can be seen in Table 4.3.

In total, 224 questionnaires were filled, and after sorting, 215 questionnaires were included for the result of this survey. The excluded nine questionnaires were partly filled, or several questions were skipped or left blank, which provided incomplete information.

Table 4.3 Details of the survey team

S. No.	The survey is done by	No. of houses
1.	Students	125
2.	Architects	33
3.	University staff	27
4.	NGOs	30
Total		215

4.3 Urban housing and its characteristics

In Pakistan, the plot size or area of a house is usually measured in square feet (sq. ft.). The average area of a house in the housing survey was 423 m^2 (4555 sq. ft.). Most of the houses were constructed during the last 40 years. Out of which, the maximum were even built in the previous two decades: 37% of houses were built during 1997-2006, and 26% of houses were constructed during 2007-2016 (Figure 4.3). The situation could be related to the refugees, internal migration, and the development of the new housing schemes during the last two decades, mainly in the northern part of Quetta city.

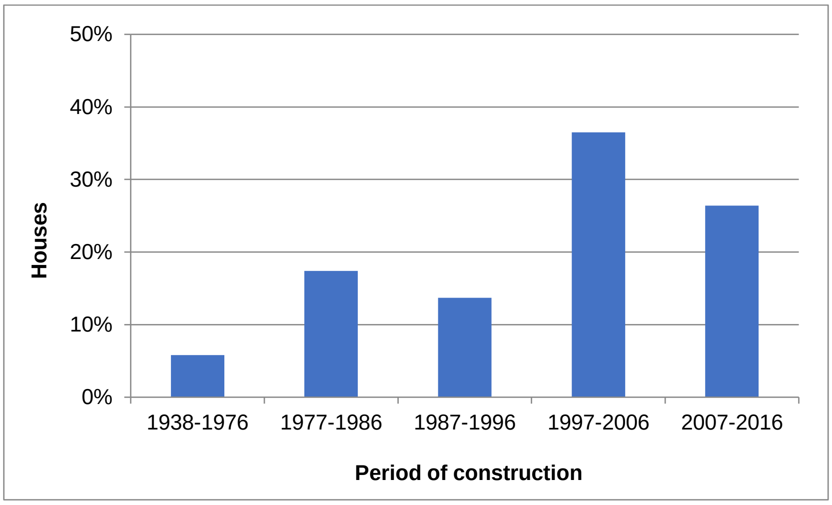


Figure 4.3 Period of construction of houses [n=189]

Most of the houses only consisted of a ground floor (48%), 36% of the houses consist of a ground floor, and the first floor, whereas 12% had more than two floors. The average room occupancy was 2.18 persons per bedroom, which are slightly higher than the tolerably crowding level proposed by the United Nations; 1.4 to 2.0 persons per habitable room (Haq, 2011). The majority of the houses (64%) were constructed of the reinforced concrete frame (RCF) structure, 31% of brick masonry construction and 5% of sundried bricks. According to the 1998 census, 44,249 (50.81%) houses out of 87,091 in Quetta were Pucca houses (*PBS*, 1998). The word Pucca means 'solid' and 'permanent'. This term is applied to housing in South Asia built of substantial material such as stone, brick, cement, concrete, or timber (Qadeer, 2006).

The results show that only 25% of the houses out of 215 were designed by a building professional. The external walls' thickness is mainly 22.8 cm, while internal and partition walls were 11.4 cm thick. The insulation of building envelope is not common practice in Quetta. Only in 5% of houses insulated walls, while 3% insulated roof and floor respectively.

4.3.1 Housing characteristics of the most common housing types

The reinforced concrete frame (RCF) and brick masonry houses were mainly built during the last four decades, with more units have been constructed during 1997-2006. The average plot size of houses varies from larger in RCF houses (434 m^2) to smaller (205 m^2) in houses built with sundried bricks. The RCF houses also had more bedrooms, where 21 houses with six bedrooms; in brick masonry houses, 13 houses had four bedrooms, while three houses had 2-3 bedrooms in sundried brick houses. Direct heating was common in all housing types, and fewer houses use the central heating system. Table 4.4. presents the characteristics of these houses.

Table 4.4 Housing characteristics of common housing types in the housing survey

Housing characteristics	**RCF (units)**	**Brick masonry (units)**	**Sundried brick (units)**
Year of construction			
1938-1976	5	7	
1977-1986	22	9	1
1987-1996	14	9	1
1997-2006	43	21	6
2007-2016	39	11	
Bedrooms			
1		1	1
2	26	12	3
3	28	10	3
4	23	13	2
5	19	11	1
6	21	7	
7	5	5	1
8	9	1	
above 8	7	7	
	R.C.C frame	Brick masonry	Sundried
Plot size (mean)	434 m^2	344 m^2	205 m^2
Heating system			
Direct heating (%)	90	97	100
Central heating (%)	10	3	

4.3.2 Construction materials and methods

The housing in Quetta can be divided into three main construction types, i.e. RCF houses, brick masonry houses and sundried brick houses. The materials composition for all these three structural types is stated in Table 4.5. In RCF houses, walls were constructed of baked bricks (98%) and concrete blocks (2%), with the cemented floor (96%) and RCC roof (100%). Many houses (68%) used single glazed windows, and 32% of houses had double glazed windows. In brick masonry houses, the walls were filled with baked bricks (97%) and concrete blocks (3%), the floor was mainly cemented (85%), roofs constructed of 4 different compositions, and 81% of the houses had single glazed windows. In sundried brick houses, walls were built of sundried bricks (73%) and rammed earth (27%), floors were earthen (45%), bricks (36%) and cemented (19%) as well. Roofs were girder/t-iron (46%), wooden beams with bamboos (45%) and wooden beams with girders (9%).

Table 4.5 The material composition of housing units in the housing survey

Building part/ material	RCF (%)	Brick masonry (%)	Sundried brick (%)
Construction of walls			
Baked brick	98	97	
Concrete blocks	2	3	
Sundried brick			73
Rammed earth			27
Flooring material			
Cement	96	85	19
Baked brick	1	5	36
Earth/ sand/ mud	2	10	45
Wood	1		
Roofing material			
RCC roof	100	52	
Girder/ T-iron		31	46
Wooden beams with		9	45
bamboos		8	9
Wooden beams with girder			
Insulation	4	7	
Walls	2	3	
Floor	3	4	
Roof			
Windows glazing	68	81	82
Single glazed	32	19	18
Double glazed			

4.4 The characteristics of households

Most of the respondents speak Pashto (34%) as their mother tongue. The average household size was 9.9 persons. In total, 30% of the households earned between €143-402 per month, and 27% of households make between €411-€715 per month, while 6% of the households earn less than €134 (PKR 15,000).

*Converted from PKR to EUR for better understanding, assuming 1EUR= 111.42 PKR (as per the applicable rates in 2017).

4.4.1 Household wealth

To evaluate the household wealth, a wealth level table was created consisting of 22 items and asking the respondents whether they have/ use that item/ facility in their house or not. It was further divided based on luxury and comfort, consisting of 11 items in each. Figure 4.4a,b presents the items of wealth level table based on need and luxury. All 215 houses had electricity connection while 210 houses were connected to the gas supply line. 98% of the households had a fan and mobile phone. Television was available in 93% of the households as families with more religious and radical background do not prefer to have a TV in their houses.

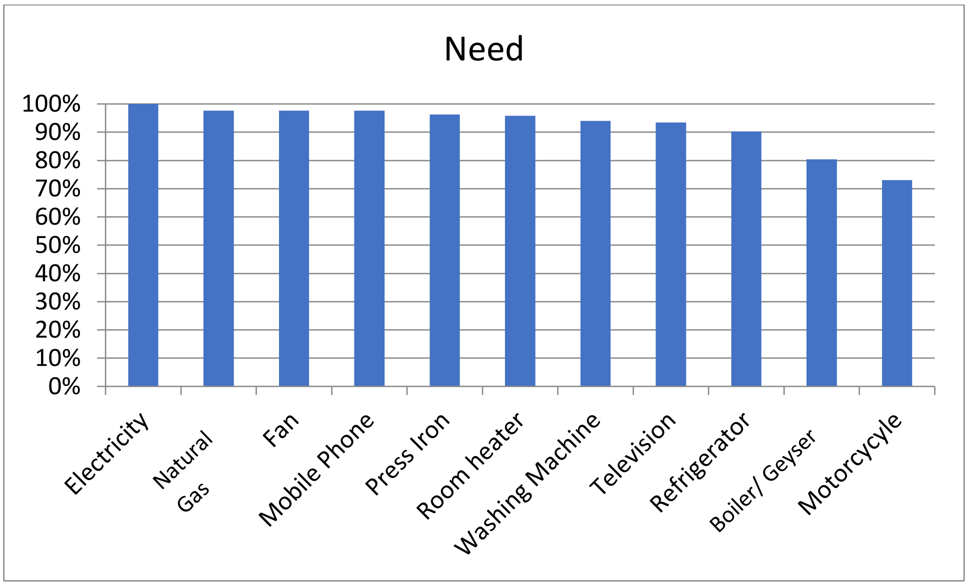


Figure 4.4(a) Wealth level index (Need)

More houses had computer 80% than internet connection 72%. Sofa or couch was available in half of the houses (50%), but only 32% of houses own a dining table. One reason could be that there is a tradition in Quetta that people take their meals while sitting on the ground, which is why they do not prefer a dining table. They use very nice rugs and carpet for sitting on in their houses.

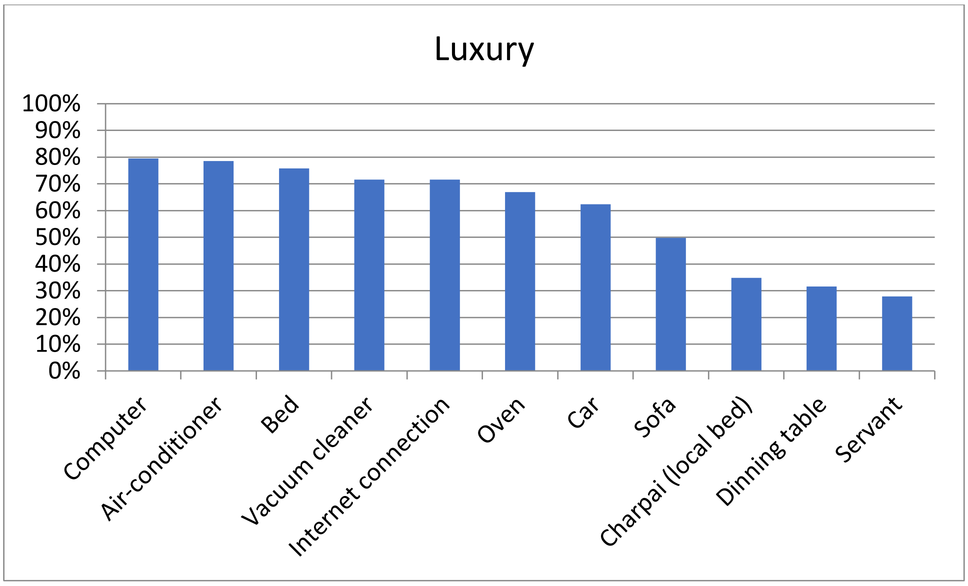


Figure 4.4(b) Wealth level index (Luxury)

4.5 The climate of Quetta and climate data

Quetta has a cold and semi-arid climate with hot summer and mild to extreme cold in winter. The city of Quetta lies out of the monsoon region; however, it receives snowfall mostly during December, January, and February (*QDDP*, 2011). It is important to add that the climate of Quetta has significant variations during winter and summer (Mahar et al., 2017). Between 2009-2016, the average recorded temperature in summer was 31 ºC and in winter at 7 ºC. The extreme recorded temperatures in Quetta are -18.3 ºC in 1970 and 42 ºC in 1998 (*PMD*, 2019). It is observed that there is a reasonably high demand for heating and cooling the buildings in harsh climates. Figures 4.5a,b,c,d provide more information about the climate of Quetta; the results are based on a TMY file of the years 1981-2016.

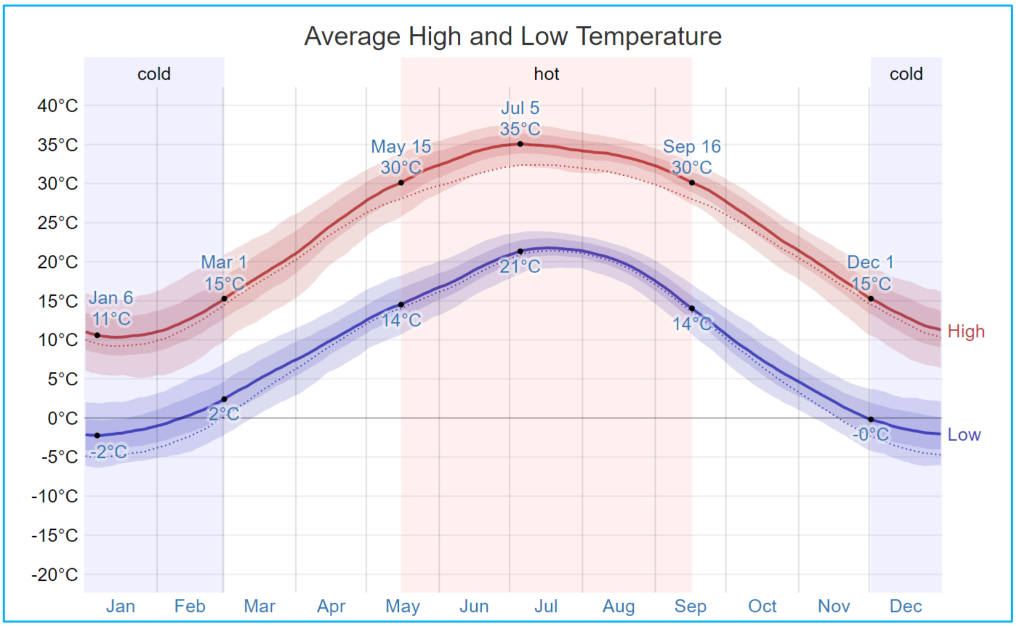


Figure 4.5(a) Average high and low temperature
Source: Weather spark

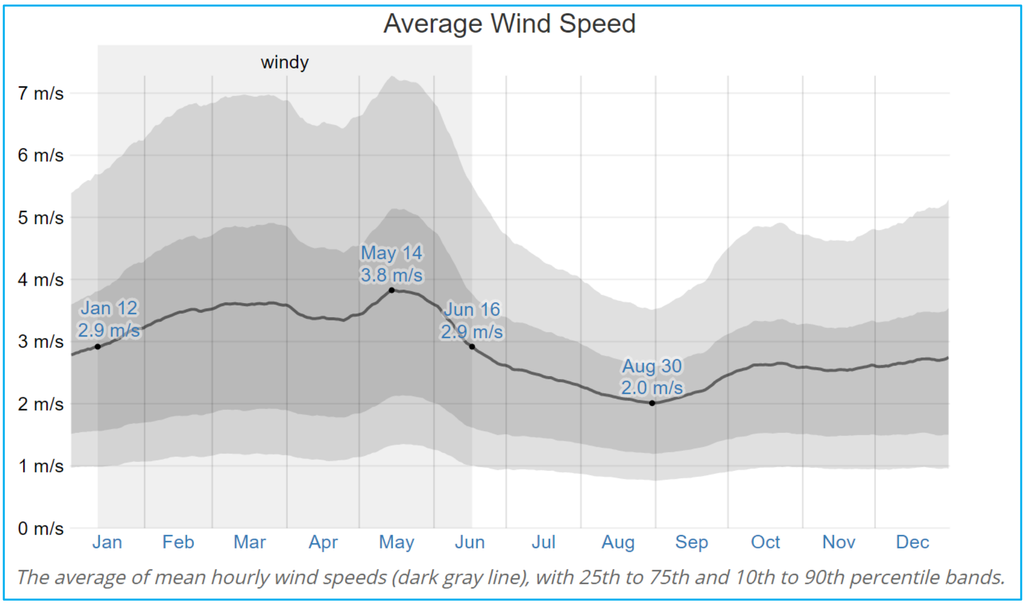


Figure 4.5(b) Average wind speed
Source: Weather spark

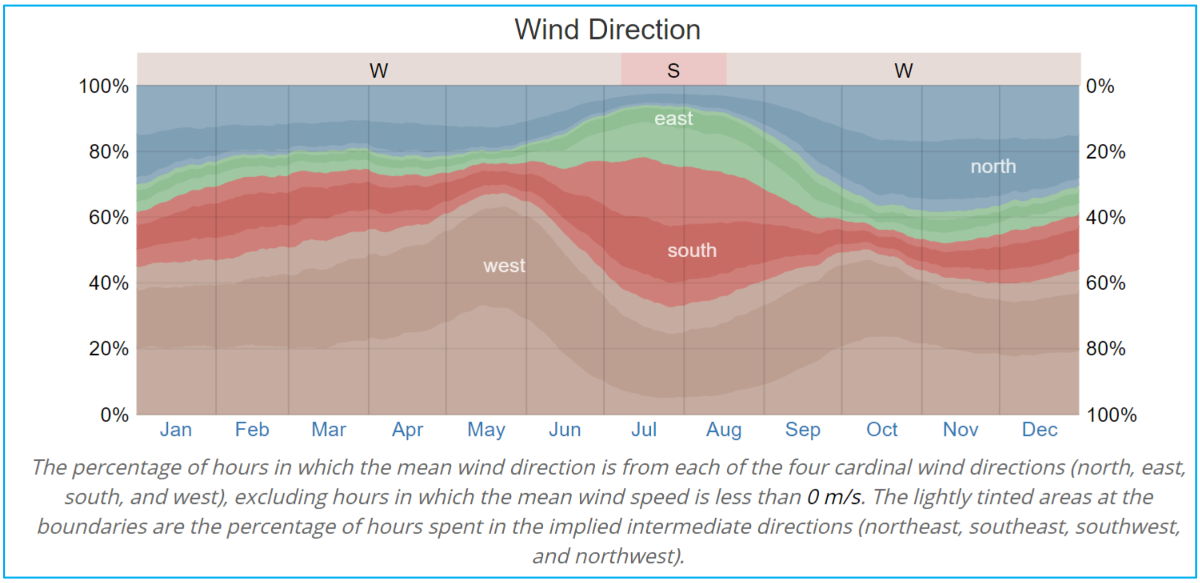


Figure 4.5(c) Wind direction
Source: Weather spark

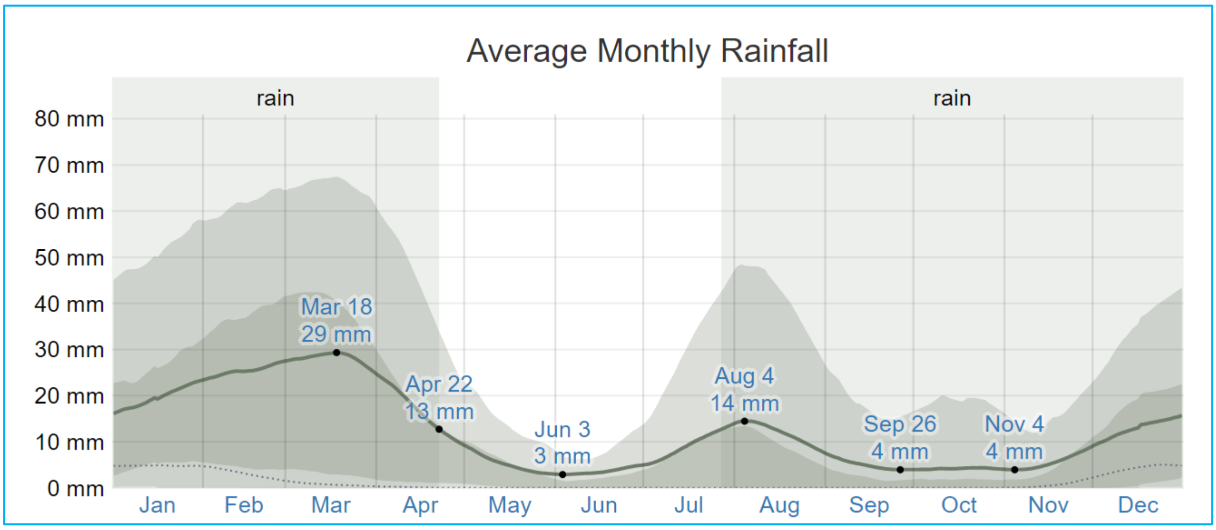


Figure 4.5(d) Average monthly rainfall
Source: Weather spark

4.6 Water, sewage and energy systems

Water, sewage and energy systems are essential needs of a household. This section will provide an overview of the existing situation of the available water, sewage, and energy systems in Quetta. The energy section is further divided into electricity and natural gas.

4.6.1 Water

This section covers the existing water supply system in Quetta and the water shortage problem in Quetta Valley.

Water Supply

Water & Sanitation Authority (WASA) Quetta was established in 1986 to provide water and sanitation services to the urban areas of Balochistan, having a population of more than 100, 000. Its mandate was revised in 2004-5 and only limited to providing water and sanitation services to the urban areas of Quetta. WASA is responsible for the water storage, filtration, treatment, distribution and water supply in Quetta city. It uses both water sources, i.e. ground and surface water, and serves around 62 thousand domestic consumers. It covers 70% of the city and serving 1.5 million people (*PWON*, 2012). The sewage coverage was12.5% in 2012, which is also due to seasonal water channels to drain off the sewerage. Some additional facts about WASA Quetta are stated in Table 4.6.

Table 4.6 Fact and figures of WASA Quetta

Description	Details
Average monthly water consumption per household	49.6 m^3
Per capita consumption	59 litres/ day
Average unit production cost	RS. 0.75/ m^3
Annual water production	1, 204.75 million m^3
Water bill per month	Rs. 125-Rs. 250 (€1.1-€2.2)
New connection charges (residential)	Rs. 1000 (€8.9)
Average availability of water	1 hour/ day
Total distribution pipes (water supply)	1900 km
Total sewer pipes	82 km

*1EUR= 111.42 PKR (as of 2017)

As of 2015, 95% of households have access to tap water (*PESA*, 2015). During the housing survey, it is observed that still, a large number of households use Tube well/ Borehole or Water tankers to fulfil their water demand. One of the reasons is the interruption of water supply in many areas of the city.

Water shortage

Quetta is located in the arid region, and water sources are limited. Groundwater depletion is rapid due to indiscriminate water mining, mismanagement, unplanned and inefficient water sources. The water shortage occurred due to increased population, refugee migration from Afghanistan, increased number of orchards, vegetable and crop cultivation, and substantially reduced recharge due to de-vegetation, deforestation, and housing construction on recharge areas. According to the International Union for Conservation of Nature (IUCN), the city of Quetta is growing rapidly, while the water resources are limited and cannot sustain the demand of the existing population, agriculture, industry, and nature for long (*IUCN*, 2011). Quetta falls in Pishin Lora Basin (PLB), located at the border region of Balochistan province, Pakistan and Kandahar province, Afghanistan (Sagintayev et al., 2008).

The water supply pipelines system of water supply is inefficient, and line losses due to leaky pipes are around 40 per cent. Galvanized iron (GI) and steel pipes are sensitive to corrosion, freezing and thawing in the cold winter season (*IUCN*, 2011). During 2010-11, WASA Quetta received 14 400 complaints related to water and sewerage services and 6, 480 broken water supply pipes were repaired (*PWON*, 2012).

Due to interruption in water supply, more tube well/ borehole connections were set up in many areas of Quetta, which also increased water use. This interruption made access to drinking water more challenging, and in many areas, households fulfil their water demands by calling water tanker, which cost extra expenses. The water connections are provided without the installation of water meters, and billing is based on the water pipe's size rather than actual usage/ consumption of water.

There are two aquifers in the Quetta Valley: A bedrock aquifer and an unconsolidated alluvial aquifer (Kazmi et al., 2005). The first one contains the limestone of the Chiltan and Shirinab formations and conglomerates of the Urak formation. It is recharged in the surrounding mountain areas where these formations are exposed. The second one (alluvial aquifer) contains sand, gravel, and silt deposits. It is also the main aquifer and recharged from infiltration of precipitation, inflow, and runoff from the bedrock aquifer.

Groundwater decline in Quetta was first noticed in 1989 when a drop of 0.25m per year was observed (*WAPDA*, 2001). The groundwater monitoring system was expanded in 1987, and at present, WASA maintains ten automatic level recorders and several dozen monitoring wells. During the 1990s decline of water level around 0.23-1.09 m per year was recorded in some parts of Quetta (Nguyen et al., 2007).

4.6.2 Sewage systems

Besides water supply, WASA Quetta is also responsible for initiating and maintaining the continuous planning and development process of sewerage and sanitation in Quetta (*GoB*, 2017). The main purpose of sewage disposal is the sanitary removal of human and industrial waste. A sewage system includes collecting, treatment, and disposal, collecting wastewater and purifying reduce the pollution effects and transfer of waste effluent back to the ecological cycle (*MPQ*, 1980).

The problem of sewage disposal became more severe due to the increasing population. The existing sewage pipelines are insufficient to handle the current and growing flow of waste due to increased water consumption and the installation of plumbing fixtures. There is no regulation in Quetta, which involves permission for the installations of plumbing units and fixtures. In some areas, the wastewater is drained in a seasonal water channel, locally known as '*Lora*'.

The existing situation of sewerage and sanitation is very poor (*BP*, 2017). The situation gets worst after rainfall and snowfall when wastewater overflow on the streets and roads of the city—making it difficult for people to walk and drive on roads and increasing the risk for spreading several diseases. Many city areas look flooded after continuous or heavy rain, and the water enters into houses, shops, and markets that make every business more challenging (Baloch, 2015).

4.6.3 Electricity

Quetta Electric Supply Company (QESCO) is the only electricity distribution company in Quetta. The company also supplies electricity to the whole Balochistan province except few Lasbela district areas, which are covered by K-Electric ('K-Electric', 2020). QESCO get the electricity from the national grid, generated in power plants around the country except in 3 districts of the Makran division where electricity is supplied/ imported from Iran (Riaz, 2017).
The electricity price per kWh depends on the usage of electricity, i.e. consumer uses up to 50 units (kWh) per month pay 4 rupees (Rs.) per kWh, and if consumption exceeds 50 units; 1-100 units/ per month then they need to pay Rs. 12.5 per kWh (*QESCO*, 2015). Similarly, the tariff increases for the users with higher consumption of electricity. These prices are not fixed and can vary depending on the charges/ cost of fuel.

According to data provided in 2016 by Management Information System (MIS) department QESCO (Table 4.7), there are 181861 domestic consumers in Quetta, and load shedding hours vary from 4-6h/day in winter to 6-8h/day in summer. The household sector in Quetta also consumed the most significant part of electricity (74%). The consumption of commercial, agriculture, industrial and sectors was 19%, 5% and 1% respectively.

Table 4.7 Overview of electricity in Quetta

Description	Details
No. of domestic consumers in Quetta	181, 861
Source of electricity	11KV transmission line
Alternative energy source	Solar
Average load shedding hours in winter	4-6 hours/day (2160 hours/year)
Average load shedding hours in summer	6-8 hours/day (2880 hours/year)
Average demand of domestic consumers	429, 529 MW per month
---	5, 154, 348 MW per year
Usage of domestic consumers	342, 850 MW per month
---	4, 114, 200 MW per year
Short fall and gap between demand & supply	9, 705.06 MW per month

Electric power plants in Quetta

Currently, there are two power generation stations in Quetta, and both are operational. Both power stations use natural gas to produce electricity.

- Quetta Thermal Power Plant: This plant was commission by Mitsubishi Japan in 1994. The total capacity of this plant is 35 MW, and it consists of 1 unit. The project was an initiative of WAPDA (Water & Power Development Authority), and it is currently being operated by PEPCO (Pakistan Electric Power Company) (*GEO*, 2011).

- Habibullah Coastal Power Company (HCPC) Private Limited: This power plant is located near Killi Almas, Shaikh Manda, Airport Road, Quetta. The plant started its operations in September 1999. This plant's total capacity is 140 MW, and it consists of 4 units (*GEO*, 2010; *PSS*, 2018).

Future electricity generation projects in Quetta

Inter-teck Kuwait Investment Authority and the provincial government of Balochistan signed MoU to set up a solar energy power plant in Quetta, Balochistan, to meet the provincial capital's energy demands. The plant will be started at 50 MW and gradually upgraded to 500 MW (Jabri, 2016).

On 15th December 2013, the Government of Balochistan (GoB) and Mutual Agreement with CK Solar, Korea, established a 300 MW Solar Power Plant at Quetta. The project would cost USD 700 Million, and GoB allocated 1500 acres of land for the project near Kuchlak, District Quetta. According to the agreement, the project will be started in December 2014 and completed in 2017 (*GoB*, 2013).

Renewable energy potential

According to the American National Renewable Energy Laboratory (NREL), Quetta and its neighbouring areas receive average solar global isolation of 6.5-7.5 kWh/m^2/day (Figure 4.6). It shows that there is an excellent potential for solar energy in Quetta and its neighbouring areas. The provincial government installed solar streetlights, which are mostly not functioning due to battery fault or stolen. However, solar PV usage is increasing in the city, especially during load shedding hours, and some people prefer to use solar energy instead of installing an Uninterrupted Power Supply (UPS).

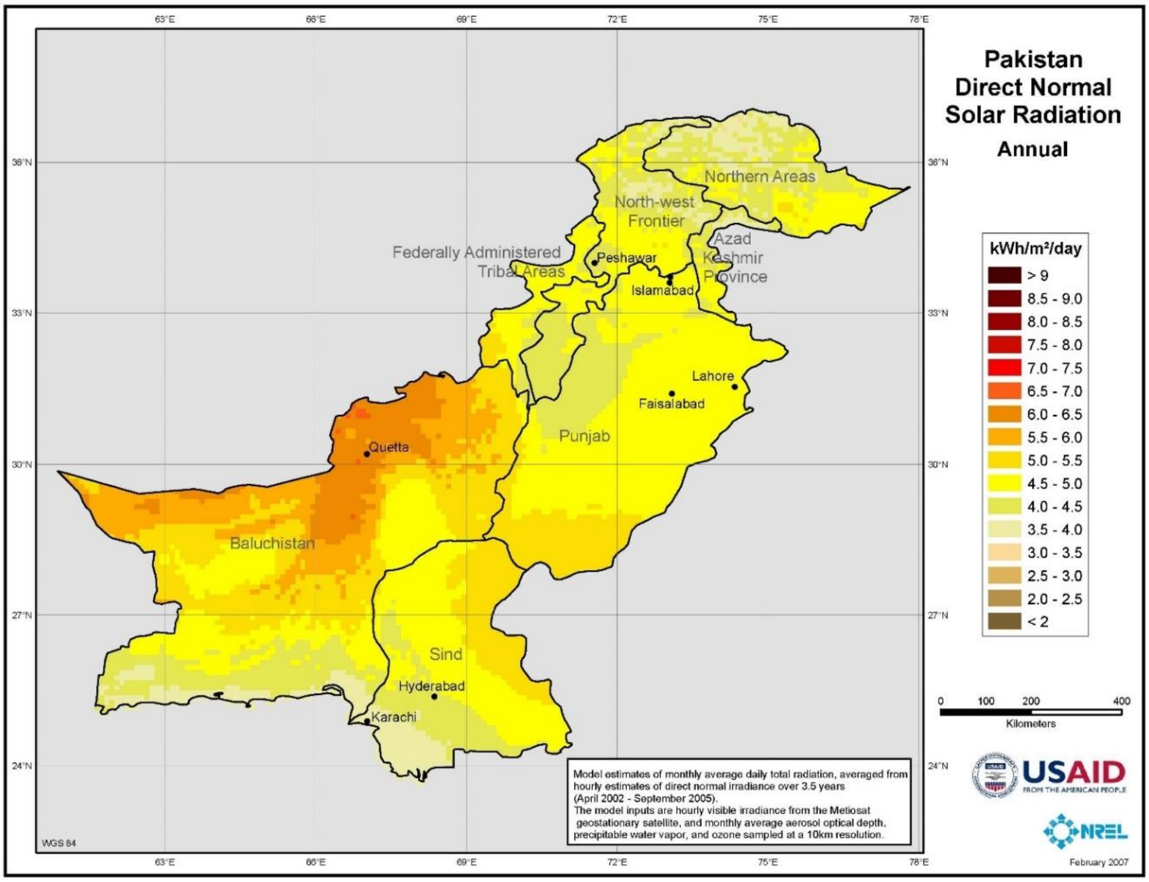


Figure 4.6 Direct Normal Solar Radiation (Annual) Map of Pakistan
Source: (*NREL*, 2007a)

There is fair potential to generate wind power in Quetta and its neighbouring areas, and the wind power density at 50m is 300-400 W/m^2 with a wind speed of 6.2-6.9 m/s (*NREL*, 2007a). Institute for Development Studies & Practices (IDSP), a non-government organisation (NGO), installed a windmill, solar panels, solar water heaters and biogas plant to fulfil the energy demand of IDSP University of Community Development (UCD) campus located at Hanna road, Quetta. Balochistan University of Information Technology, Engineering & Management Sciences (BUITEMS) Quetta installed a wind tunnel on Takatu Mountain to generate wind power; the project was stopped due to a change of the university administration. Windmill (fans) were also installed on the roof of the Department of Architecture's Building (Hall-I), which were operational in the beginning and was considered a success. Batteries and installations are still present, but the project is no more functional due to lack of maintenance (Anwar et al., 2018).

4.6.4 Natural Gas

Sui Southern Gas Company (SSGC) is responsible for distributing natural gas in Pakistan's southern part, including Balochistan and Sindh province. SSGC is also engaged in the installation of high-pressure transmission and low-pressure distribution system. The billing tariff for domestic consumers is listed in Table 4.8 (*SSGC*, 2016).

Table 4.8 Billing tariff of SSGC for domestic consumers

Usage	Sale price in Rs./ MMBTU
Up to 100 m^3 per month	110
Up to 300 m^3 per month	220
Over 300 m^3 per month	600
Minimum charges: Rs. 148.50 per month	

Source: (SSGC, 2016)

Natural gas is mainly used for cooking, heating (rooms+ water) and lighting in some houses (during load shedding hours). According to the 1998 population census, 77.53% of housing units in Quetta use gas for cooking (*PBS*, 1998). Quetta and Balochistan citizens experience very low gas pressure, especially in winter, a gas suspension in different city areas, which affects life during cold weather (*TN*, 2015; Reki, 2016). The overall consumption of gas in Balochistan (7%), which is lower than the production (19%) during 2012-16 (*PES*, 2015). A large part of the province has no distribution line of natural gas (*ET*, 2014).

4.7 Conclusion of the chapter

Housing and residential facilities play an essential role in our lives. Adequate housing and living facility improves our mental and physical health and well-being. The provision of better houses and housing facility remains a challenge in many developing countries, including Pakistan. There is a shortage of millions of houses in Pakistan; on the other hand, the existing houses do not provide comfortable living conditions. The climatic conditions cannot be ignored while designing a house, especially in the context of Quetta.

The results show that majority of the houses in Quetta are not designed by any qualified professional. The use of single-glazed windows and active systems for heating and cooling is not efficient and affordable. Insulation is not commonly used, and people have insufficient knowledge about the benefits of insulation and its usage. The electricity crisis severely disturbs everyday life, and residents cannot enjoy their time and sleep in their houses for several hours. There is a need to properly design the houses to gain more use of passive design techniques and acquire comfort by natural ventilation in summer and solar gain by winter to reduce energy usage and effectively achieve thermal comfort in the houses. Using alternative materials and insulation may also help to improve comfort and reduce discomfort hours. The energy, water, and sewage system need to be enhanced and upgraded according to the residents' overgrowing demands and changing lifestyle.

CHAPTER 5: MONITORING AND ANALYSIS OF COMMON TYPOLOGY

5.1 Introduction

The monitoring of the current housing stock's indoor climate in Quetta will provide valuable information for further improvements. This study explores the occupants' indoor thermal comfort, comfort perception, satisfaction, and behavioural adaptations. This chapter presents the methodology of monitoring indoor climate, climate monitoring results, and the conclusion of the interviews from the residents of ten houses. This study will help understand the existing dwellings, indoor climate, comfort perception, and residents' opinions about comfort, indoor environment, behavioural adaptations, HVAC and energy systems, lighting, and renewable energy. The common housing typology in Quetta, i.e. reinforced concrete frame (RCF) houses, was selected for this purpose. In total, the monitoring of indoor climate and a comfort survey was done in ten houses. The results of this chapter were also presented in the previous studies (Mahar et al., 2018; Mahar & Attia, 2018b, 2018c).

5.2 Methodology

Similar to the work of (Singh et al., 2016) and (Attia et al., 2012), this study is based on two steps; i) selection of houses and ii) the monitoring of indoor climate and comfort survey. Both steps are discussed in detail.

5.2.1 Selection of houses

In total, ten houses of various sizes, from large to small, were selected for this study. Table 5.1 provides more information regarding the selected houses. The selection criteria were based on the layout of the house, construction materials, location of the house, the household's income level, construction typology, and the residents' willingness to participate in the monitoring and comfort survey. All ten houses represent the same structural system, i.e. RCF structure, climate, and are geographically located in different neighbourhoods of Quetta. The houses may represent a different combination of construction and finishing materials, heating and cooling systems/ devices and housing typology, i.e. attached, semiattached etc. The houses may also differ regarding household size and their cultural, ethnic, religious, economic, and educational background (Mahar et al., 2018).

Table 5.1 List of selected houses

S. No.	Area of the house (m^2)	Household size	Monitoring period	Year & season
I.	650	11	Four weeks (2+2)	Summer 2017, Winter 2017-18
II.	408	12	Four weeks (2+2)	Summer 2017, Winter 2017-18
III.	307	8	One year	27 Jul ’17- 26 Jul ‘18
IV.	278	8	Four weeks (2+2)	Summer 2017, Winter 2017-18
V.	213.6	7	One year	27 Jul ’17- 26 Jul ‘18
VI.	148	12	Four weeks (2+2)	Summer 2017, Winter 2017-18
VII.	130	6	One year	27 Jul ’17- 26 Jul ‘18
VIII.	130	7	Four weeks (2+2)	Summer 2017, Winter 2017-18
IX.	140	6	One year	27 Jul ’17- 26 Jul ‘18
X.	63	7	One year	27 Jul ’17- 26 Jul ‘18

5.2.2 Monitoring of indoor climate and comfort survey

A field survey was conducted to understand the indoor climate. Fields surveys provide “first-hand” data to understand the residents' thermal comfort and the actual daily environment. Usually, two types of data are required for such field surveys: objective and subjective measurement data (Wong et al., 2016).

Indoor air temperature and relative humidity were monitored in all ten houses for objective measurement. The monitoring was started simultaneously in all houses; however, due to some on-site issues, the monitoring was done for four weeks in five houses, i.e. two weeks in summer and two weeks in winter. In summer, the monitoring took place from 27/07/2017 to 9/08/2017 and in winter from 27/12/2017 to 9/01/2018. This period was selected to monitor extreme hot and cold temperatures. While monitoring was continuously done round the year in the rest of the five houses. Details of the monitoring period for each house is mentioned in Table 5.1. Two data loggers were placed in each house at a position where sunlight, heating and cooling devices don’t affect them. One data logger was placed in the master bedroom and one in the living room/ lounge. The loggers were activated for a delayed start, and all loggers were placed in the houses before their launching time. The loggers were set to measure indoor air temperature and humidity in all ten houses with an interval of every 10 minutes.

The measured data were then compared between the internal and external environment. The ceiling fan remained on during occupancy hours, and windows were mostly open during summer for cross ventilation. In winter, heating was on during the occupancy hours while doors and windows were kept closed to avoid the entrance of cold air. However, during winter, the residents sometimes open a small door, window or ventilator for the fresh air during heating hours. This is to avoid the suffocation and lack of oxygen due to the use of radiant gas heaters.

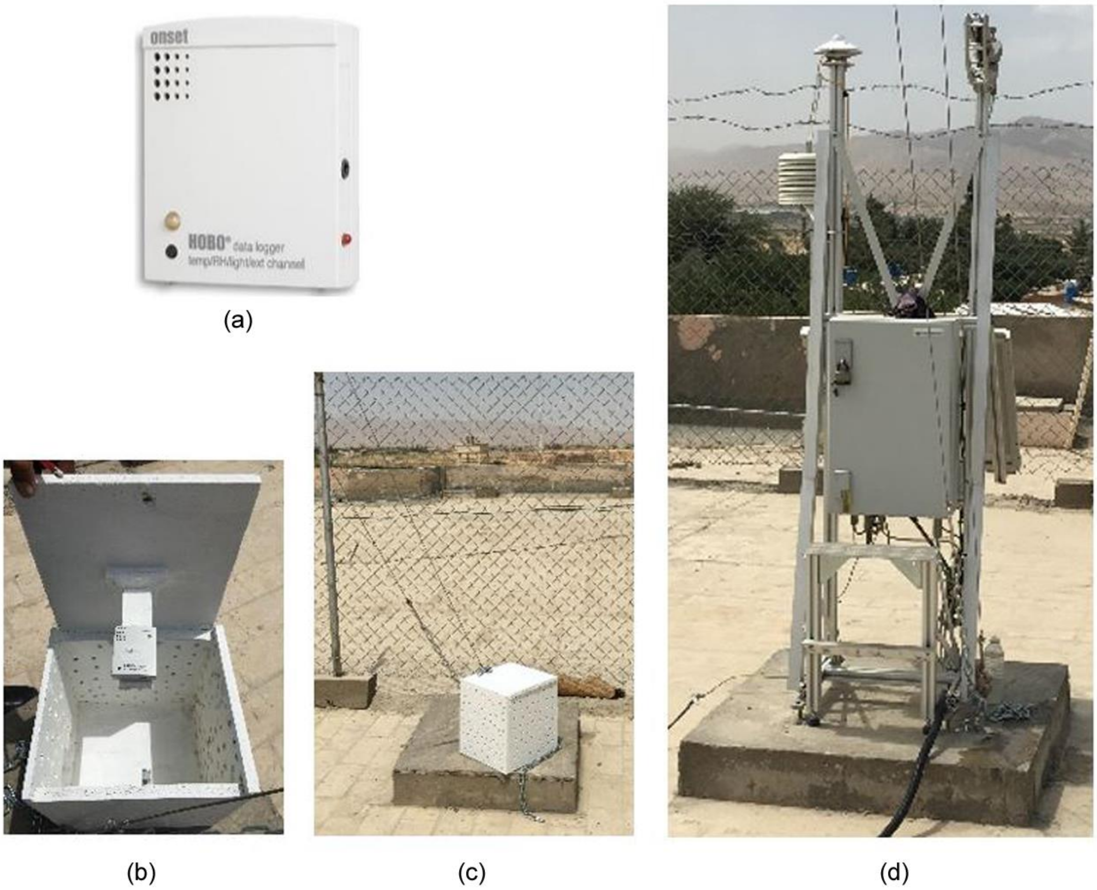


Figure 5.1 HOBO U12-012 data logger, weatherproof box and weather station

The outdoor air temperature and humidity were also monitored for a whole year by placing a data logger in a well ventilated weather-proof box (see Fig. 4.1). The box was then placed on a building rooftop at the Balochistan University of Information Technology, Engineering & Management Sciences (BUITEMS) Takatu campus Quetta. The weather data was also taken from the Pakistan Meteorological Department (PMD) and a weather station at the same campus of BUITEMS University maintained by the Alternative Energy Development Board (AEDB), Government of Pakistan, together with the National Renewable Energy Laboratory (NREL) of United States. The HOBO U12-012 data loggers were used to monitor air temperature and relative humidity inside the houses. Figure 5.1(a) shows the data logger,

Figure 5.1(b), and Figure 5.1(c) shows the weatherproof box used for outdoor monitoring. The outdoor weather station at BUITEMS Takatu campus Quetta is shown in Figure 5.1(d).

A short questionnaire was filled, and semi-structured interviews were conducted with the residents for the subjective measurement and understanding their comfort perception, behavioural adaptations etc. Follow-up questions were asked, and respondents were encouraged to provide their input on a specific question to understand the responses clearly. The plans of all ten houses were drawn as per the actual measurements and construction. The questionnaire and semi-structured interview comprise the questions related to socio-demographic information, building and architectural aspects, energy problem and prices, heating and cooling systems/ devices, lighting, comfort, clothing, behavioural insights and renewable energy.

The semi-structured interview questions were devised and later on revised and updated after discussion with local architects and building professionals practising in Quetta. The interviews were conducted with the head of the household and some family members (if possible). Due to cultural, societal differences, and time limitations, the researcher couldn't meet all ten households' family members. In that case, the household head collected the responses from family members and then conveyed them to the researcher. The semi-structured interviews were recorded and transcribed. The essential findings and of the interviews are presented in this study. Appendix C illustrates the structure of the questions used in the semi-structured interview.

5.3 Monitoring of climate

The monitoring of indoor and outdoor climate was also done for this study. Only air temperature and relative humidity were monitored. The result of four weeks of monitoring, two weeks each in summer and winter, are presented here. Figure 5.2(a) and 5.2(b) presents the data of the summer period, while Figure 5.2(c) and 5.2(d) showing the data measured in the winter period.

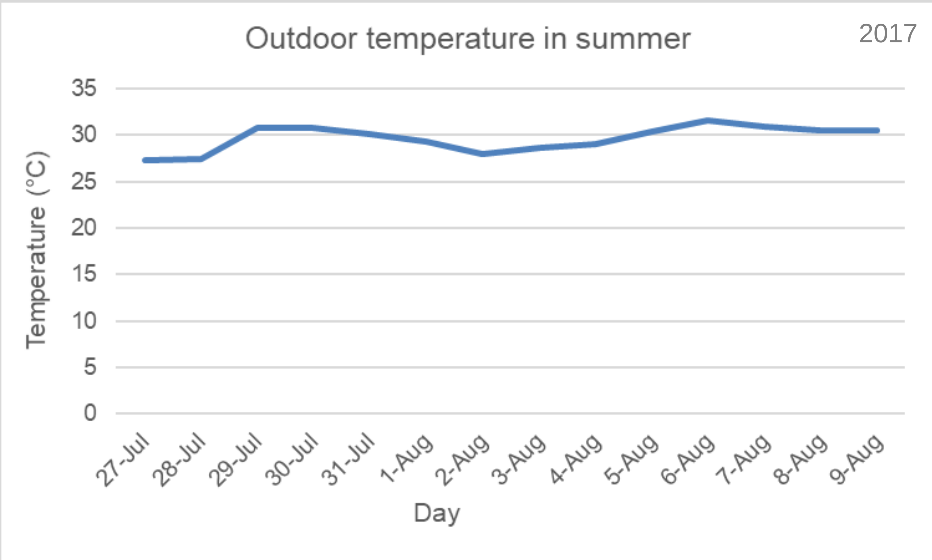


Figure 5.2(a) Outdoor temperature in summer

2017

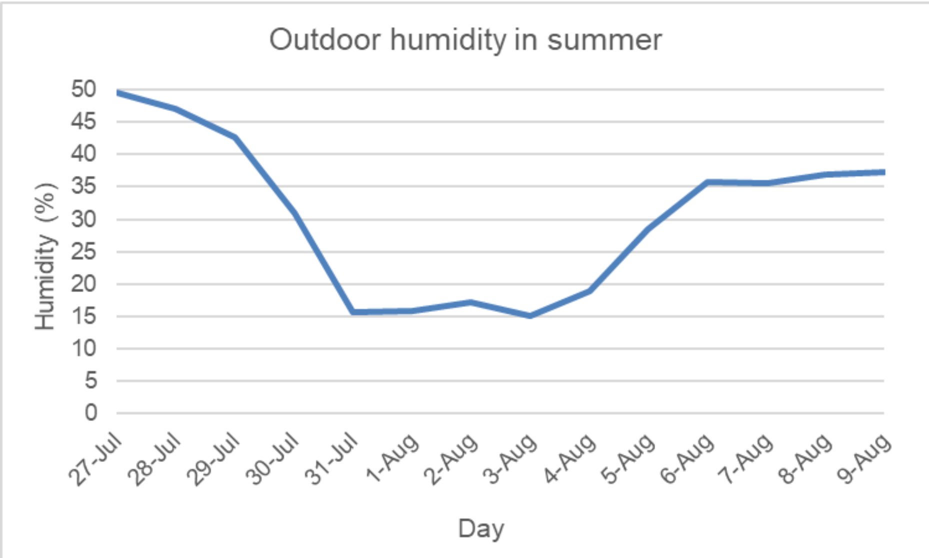


Figure 5.2(b) Outdoor humidity in summer

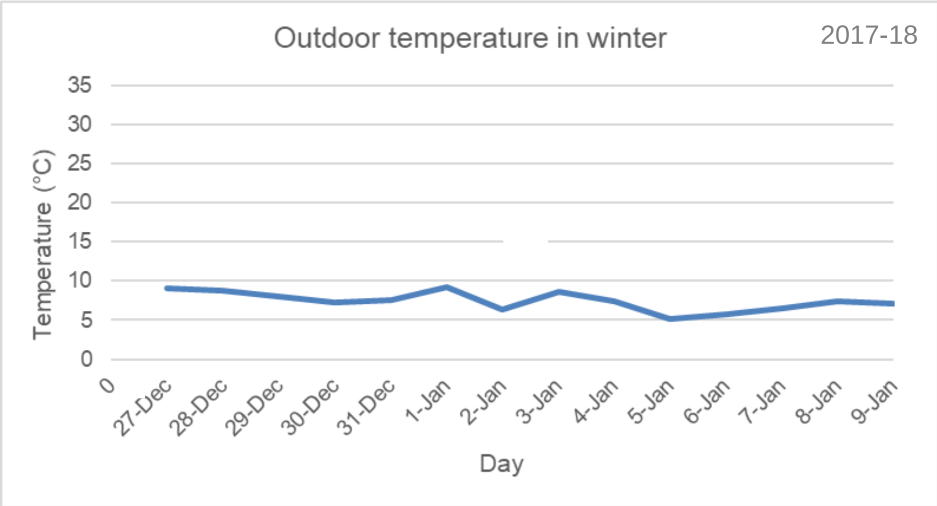


Figure 5.2(c) Outdoor temperature in winter

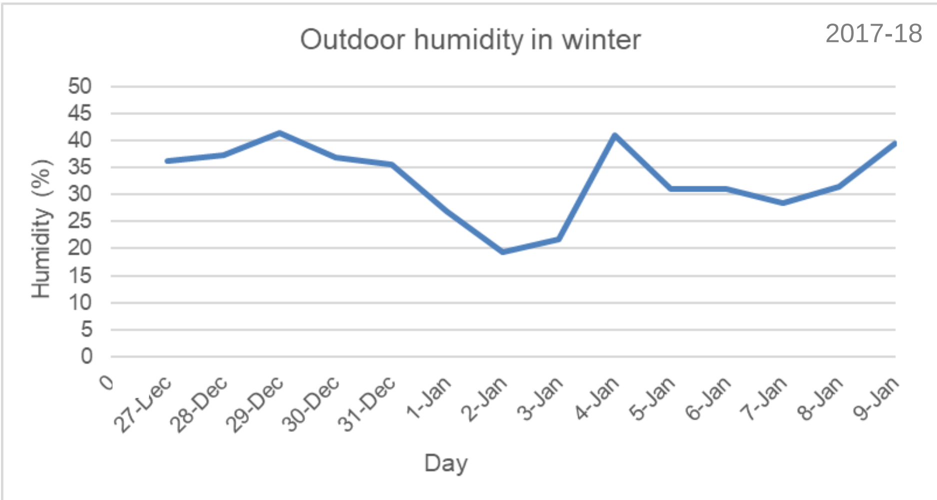


Figure 5.2(d) Outdoor humidity in winter

Figure 5.2 Outdoor climate conditions (daily) during summer and winter

Figures 5.3a,b,c,d presents the air temperature (℃) and humidity data measured in all ten houses (living rooms only) during the monitoring periods in summer and winter. Typically, the indoor air temperature relies on outdoor air temperature. If the outdoor air temperature decreased, the indoor air temperature drops as well. Similarly, when the outdoor air temperature increases, the indoor temperature increases.

The variations in indoor air temperature were recorded in all ten houses in summer. There was a temperature variation between 29.5℃ to 34.4℃ during the monitoring period, which shows that the indoor climate was very uncomfortable. In general, houses II, IV, and VII remained warmer during most of the days, while comparatively lower temperatures were recorded in house VI and IX.

In summer, the indoor humidity level remained lower as compared to winter. The variation in humidity level was between 15.5% to 43.5%. The humidity level in house IV and VII comparatively remained low while it was better in house VI and IX during the summer monitoring period. It has been noticed that at a higher temperature, the humidity level decreases. That's why the humidity level inside the houses in winter is better than the humidity level in summer. In house II, the humidity level remained better in summer and winter and showed no relation to temperature differences. It might occur due to the presence of an underground water tank underneath the floor of the room.

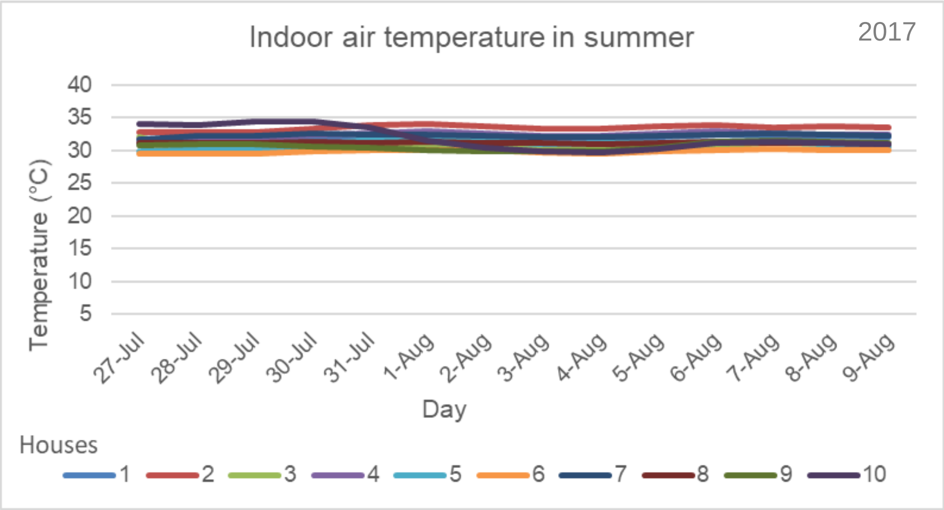


Figure 5.3(a) Indoor air temperature in summer

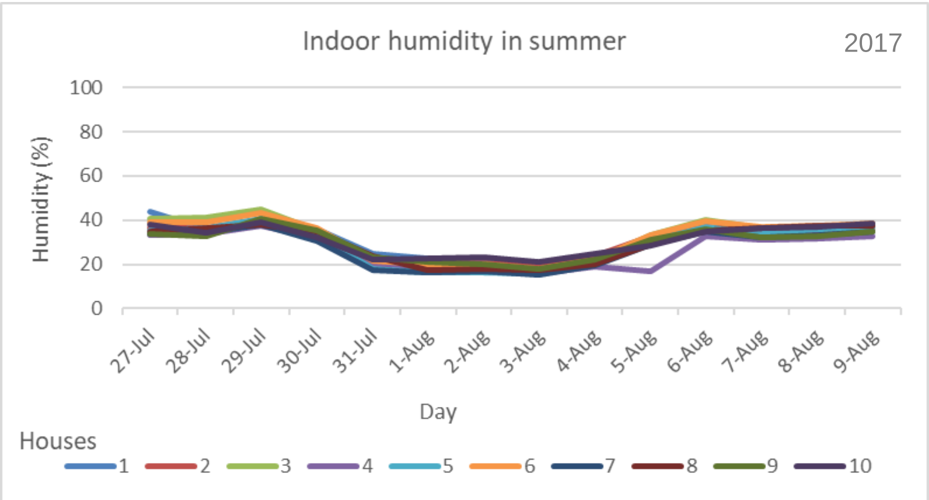


Figure 5.3(b) Indoor humidity in summer

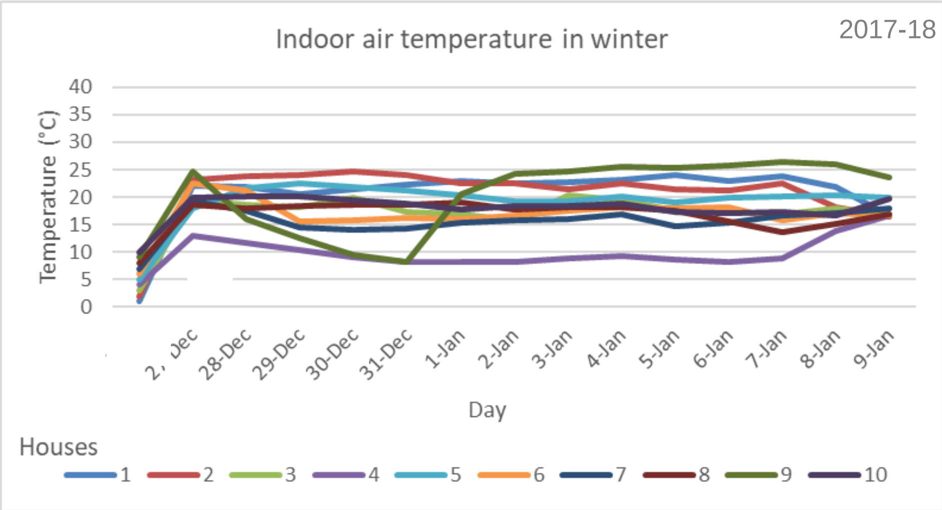


Figure 5.3(c) Indoor air temperature in winter

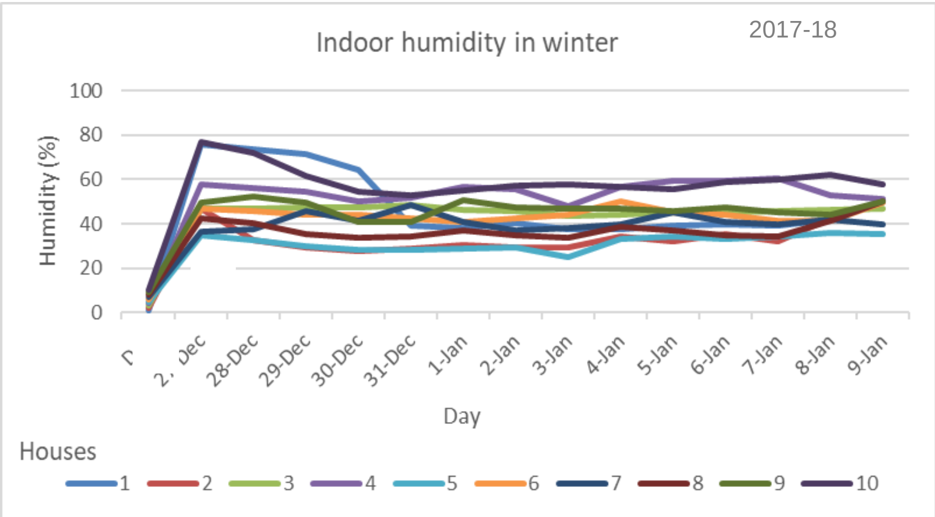


Figure 5.3(d) Indoor humidity in winter

Figure 5.3 Indoor climate conditions during summer and winter

Significant variations were noticed between indoor temperature and humidity in winter and in summer. The variation of indoor temperature was between 8.1℃ to 26.3℃ during the monitored periods. Higher temperatures were observed in Houses II and V compared to the rest, while lower temperatures were observed in house IV. The humidity level in winter varied from 25% to 76.9%. Higher humidity levels were recorded in house I, IV, and X while remaining low in V and VIII.

5.4 Control systems

The control systems enable occupants to modify the indoor climate as per their needs. Windows, ventilators and doors are used in naturally ventilated buildings to control the internal temperatures in buildings. While fans, evaporative coolers, air-conditioners and heaters are used in extreme conditions to maintain indoor temperatures. These systems are essential to get a comfortable environment inside any building and are discussed in detail based on the responses of the occupants of the houses included in this study.

5.4.1 Windows

The openings such as windows and ventilators are essential to control the indoor climate in a house. Occupants open and close windows to get fresh air or maintain the indoor temperatures depending on the weather and seasons. It was noticed that the opening of windows depends on weather conditions as well as seasons and other factors such as avoiding dust particles, mosquitoes, flies, electricity outage hours and use of space. Windows are opened in the majority of the houses in the evening or nights of summer and remain closed in winter.

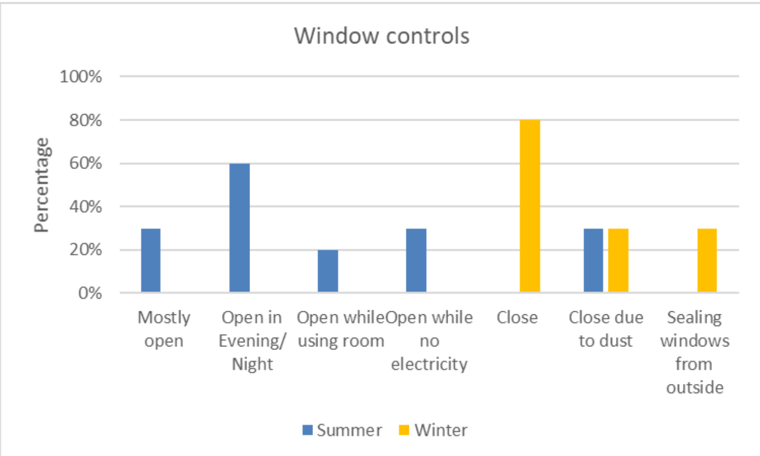


Figure 5.4 Window controls in summer and winter

It is also a common practice in Quetta to seal the windows during winter to avoid cold air entering the house due to air leakages from window frame/ fixing. For this purpose, first, a thick cloth/ fabric is fixed by nails over the surface area of the window (from outside), and then a plastic sheet is placed over the cloth and sealed by using masking tape. This plastic sheet protects the fabric from rainwater and snow and blocks the entrance of air. Figure 5.4 presents the result of window control in the selected houses.

5.4.2 Cooling

The climate of Quetta is heating dominant, yet there is a bit of cooling demand as well since there is a significant temperature difference between summer and winter. Ceiling fans are commonly used in all buildings, including houses, to improve indoor comfort during summer occupancy hours. Evaporative coolers which are locally known as air coolers are also used during hot summer months. The following table (Table 5.2) presents the available cooling devices in all ten houses selected for this study. It was found that all bedrooms, living and dining rooms were equipped with ceiling fans except in house X, where a wall-mounted or bracket fan was used in the living room. These ceiling fans are used between 8-12h per day during the summer period depending on occupancy and weather conditions.

In some rooms, exhaust fans are used to remove the warm air and continuous flow of fresh air. In comparison, these exhaust fans are used in the kitchen and toilets to draw the smoke and smell. Evaporative or air coolers are used in rooms or parts of the house that are warmer than the rest of the house's rooms. These air coolers are mainly fixed in a window and are used for 2-3 months during the hot summer. Air-conditioners are used in house III and VI bedrooms during summer for 8-12h per day. However, the air-conditioner in house VIII was not in use even it was in working condition.

Table 5.2 Fans and cooling devices used in the houses

House No.	Ceiling Fan	Bracket Fan	Pedestal Fan	Exhaust Fan	Air cooler (Evaporative)	Air conditioner
I.	All rooms	2	2	4	1	-
II.	All rooms	-	-	3	2	-
III.	All rooms	-	-	3	-	3
IV.	All rooms	1	-	4	-	-
V.	All rooms	-	1	5	2	-
VI.	All rooms	-	-	4	-	2
VII.	All rooms	-	-	2	-	-
VIII.	All rooms	-	-	3	-	1
IX.	All rooms	-	-	3	1	-
X.	3	1	-	1	1	-

5.4.3 Heating

During winter, the outdoor temperatures in Quetta remain low, which tends to use heating for creating a comfortable indoor climate. The use of direct heating is a common practice in Quetta. The heaters are placed in each room or space of the house, which is used between 6-12h per day depends on the occupancy of the residents and weather conditions.

Radiant gas heaters are commonly used in Quetta; see Figure 5.5(a). These heaters follow the combustion principle, which increases the CO^2 level inside the rooms and affects the indoor air quality (IAQ). Usually, a small portion of the door or window is kept open for fresh air and avoiding suffocation due to the increasing level of carbon. The residents prefer radiant gas heaters since the per-unit cost or price of gas heaters is lower than other heating devices.

On the other hand, the convector gas heaters, Figure 5.5(b), use gas and electricity. These heaters can not be operated during the electricity outage hours since there is 4-6h per day load-shedding or electricity outage in many parts of Quetta, making it challenging to use gas convector heaters. However, the use of convector gas heaters is growing in recent years as these heaters are safer to use inside houses. Considering the electricity outage hours in mind, the residents keep both types of heaters in their houses and use radiant gas heaters to warm the indoor spaces in the event of no electricity. Both types of heaters were used in house IX and X to heat the indoor spaces. The convector gas heaters are kept on during cold nights to maintain a comfortable indoor temperature.

Figure 5.5(a) Radiant gas heater

Figure 5.5(b) Convector gas heater

5.4.4 Clothing

Clothing is one of the essential factors in thermal comfort studies. The occupants wear clothes according to the season and activity to adapt to the comfort level. Clothing is also based on cultural and social aspects of society. In this study, the questions were asked about the occupants' clothing and the average clothing insulation values are calculated based on the responses. In winter, the average clothing insulation is 0.7 clo while it is 0.4 clo in summer. In summer, people mostly wear clothes with dynamic dimensions and loose-fitting and the clothing insulation of such clothes are only taken as indicative.

According to a previous study done in five different climate zones of Pakistan, the change of about 3.5- 4 °C occurs in comfort temperature with a change of clothing insulation of 0.5 clo (Nicol et al., 1999).

5.5 Comfort perception

To understand the residents' comfort level, the questions were asked from all household members of 10 houses. The sample size is 84, which is the total population of the selected ten houses. The responses of the residents regarding their comfort level in houses are presented in Figure 5.6. It was found that the existing houses do not provide optimal thermal comfort to the residents. The houses remain cold in winter and warm in summer, which leads the occupants to use active heating and cooling systems to achieve comfortable indoor temperature.

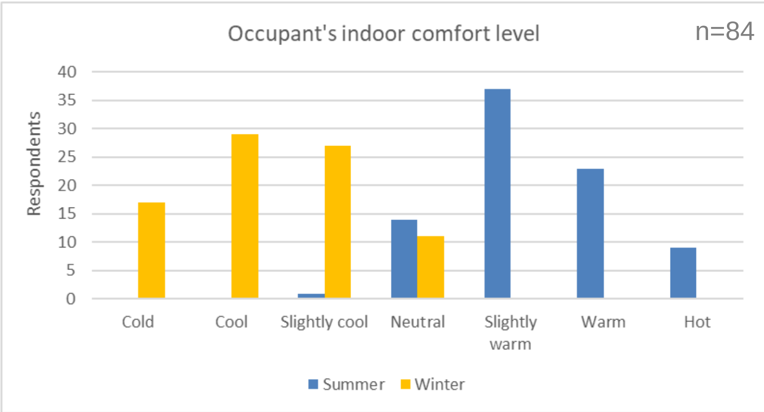


Figure 5.6 Indoor thermal comfort level of occupants

4.6 Energy

In recent years, the energy sector of Pakistan is going through major challenges and changes. Initially, the country was facing an energy shortage, and later there are problems of line losses, energy supply and distribution (Mahar et al., 2018). The existing distribution network is unable to supply enough energy as per the demand of the consumers. However, Pakistan's energy sector heavily relies on the use of fossil fuels for energy production, and as of February 2018, only 2% of the total electricity is produced on renewable sources. While the share of thermal power was 64%, hydropower was 27%, and nuclear power was 7% (Anwar et al., 2018).

The power sector remained the second-largest consumer of oil during the Fiscal Year (FY) 2016-17 by consuming 33% of the oil for electricity generation. On the other hand, between Jul 2017-Feb 2018, the power sector consumed 936 million cubic feet per day (MMCFD) of natural gas and remained the largest gas consumer. During the same period, the household sector remained second, with a total consumption of 860 MMCFD of natural gas (PES, 2018). The use of fossil fuels for electricity generation increases the cost, and energy prices, not environment-friendly.

It was found that the use of solar energy is getting familiar in Balochistan and particularly in Quetta. Our survey found that house III and IV use solar panels backed by rechargeable batteries to fulfil the electricity demand of their household during electricity outage hours. The residents of some other houses included in this study were also interested in using renewable energy sources; however, they preferred subsidy or reduction of the initial cost for installing solar panels. There is great potential in the province of Balochistan for the generation of renewable energy at various locations, including Quetta. (NREL, 2007a) (NREL, 2007b).

4.6.1 Energy prices

In this study, questions were asked from the residents to understand their satisfaction level with the prices of energy products, i.e. domestic gas and electricity. According to the results, the residents were less satisfied with electricity prices than natural gas. The satisfaction of the residents from energy prices is shown in Figure 5.7. It is essential to mention that the survey was conducted in 2018 and does not include the current situation of electricity and gas prices in Pakistan.

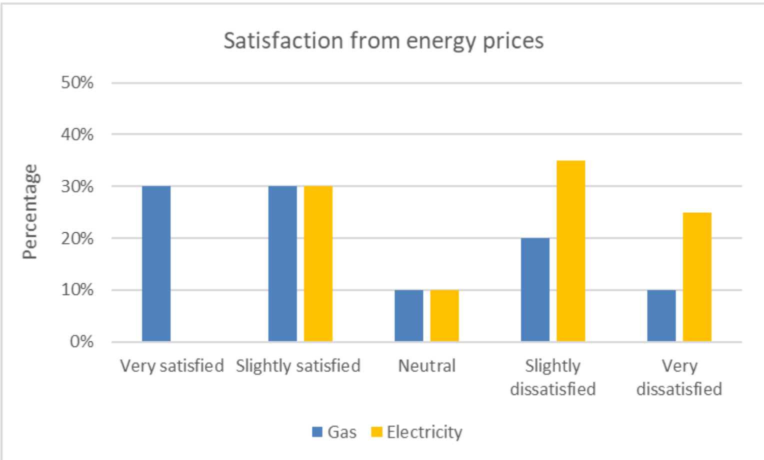


Figure 5.7 Occupants' Satisfaction from energy prices

4.6.2 Energy consumption behaviour

It was found that the residents make a complaint about the energy crisis and increasing energy prices. In contrast, their energy consumption behaviour shows that only 1-2 persons in a house were concerned about the overall energy consumption. Most of the family members, i.e. 67% out of 84, were not so cautious about the energy consumption, and they leave the lights, heating and cooling devices on while leaving the rooms. Since the houses can get very cold so that in some houses the residents need to turn on the heating devices 1-2 hours before the use of any room during winter. Heaters also remain on if the rooms are not in use up to 2h during the day, as the rooms get cold very fast and take more time to get warm again. This shows that houses are not properly designed and are climate-sensitive as the outdoor temperature increase or decreases; it directly affects the comfort level inside the houses. This might occur due to lack of thermal mass, insulation, improper design of the house and air leakages etc.

5.7 Conclusion of the chapter

The study provides valuable insights into the climate of Quetta and its effect on the indoor climate of the houses. The indoor temperature is usually dependent on the outdoor temperature and follows similar increase and temperature decrease trends. The selected RCF houses use active systems for cooling and heating in both seasons to achieve a comfortable environment. This shows that houses are poorly designed and failed to deal with various ranges of temperature. During high temperature, the humidity level decreases, which causes more discomfort. It was observed that, in summer, the air is mostly dry, and it contains dust particles. This dust causes several health problems and contaminates the indoor spaces.

The energy crisis has badly affected everyday life, and people are looking for an alternate and reasonable measure to deal with this issue. However, renewable sources such as solar PV installation are not affordable for most families. The residents are interested in installing solar PV if they get some subsidy or reduction in the initial cost. On the other hand, low gas pressure is the main problem in cold winter. The residents' turn off heaters during low gas pressure or use gas cylinders for cooking their meals. The increasing fuel and energy prices are a big issue to be resolved. Yet, well-off families prefer to use air-conditioning and heating most of the time to achieve a controlled environment and thermal comfort. Gas heaters used in indoor spaces increase the level of carbon which affect the indoor air quality. The residents are generally dissatisfied with the thermal comfort level and thermal performance of the houses.

There is a lack of legislation at the provincial and local level regarding housing. The existing by-laws are not adequately enforced in many parts of the city. People can build a house without getting planning permission from the authority. The current by-laws of Quetta Development Authority (QDA) have no energy provisions or considerations that should be included. Due to the high land cost, the residents try to construct most plot areas, leaving significantly fewer and insufficient openings for natural light and ventilation.

CHAPTER 6: BENCHMARK STUDY[1]

In Pakistan, reinforced concrete frame houses are the most widely used and common construction technology. In a country that experiences extreme hot and cold seasons throughout the year, buildings need to be adaptable to the climate to improve the inhabitants' thermal comfort. Therefore, this study aimed to improve thermal comfort in reinforced concrete frame houses using passive design and energy efficiency measures in Quetta, Pakistan. The thermal comfort of a representative house was investigated using a building performance simulation. The building model created in EnergyPlus was validated by comparing it with on-site monitored data in both summer and winter seasons. The model was calibrated using statistical methods. Then, the calibrated model was used to perform a whole year simulation in which various orientations, ventilation, passive design, and energy efficiency strategies were applied to perform parametric analysis for the improvement of thermal comfort. The best fit-to-context thermal comfort model was selected, and the potential of bioclimatic design strategies was quantified. The results indicate that comfort hours can be increased from 43% to 59% by adopting passive design strategies. The study results revealed many findings that could be useful for architects and building engineers to set a future direction for improving indoor comfort in Quetta and many other areas of Balochistan Province in Pakistan.

[1] This chapter is based on a the following journal publication.

Mahar, W.A., Verbeeck, G., Singh, M.K., Attia, S. (2019). An investigation of thermal comfort of houses in dry and semi-arid climates of Quetta, Pakistan. *Sustainability*, 11(19), 5203.

6.1. Introduction

Pakistan is a large country with a rapidly growing population of more than 207 million in 2017 (*PBS*, 2017). The annual rate of rural-urban migration is 3%, which is the highest in South Asia. According to the United Nations Population Division's estimates, by 2025, nearly half of the country's population, currently 38 per cent, will live in urban areas (Kugelman, 2013). This increasing population has brought several challenges and socio-economic problems. The provision of adequate housing remains a challenge in Pakistan. The total backlog of housing units is between 9–10 million units (*WB*, 2015), and the housing backlog in urban areas is 3.5 to 4 million units (*IGC*, 2016). The gap is increasing by 0.4 million units per year (*WB*, 2017).

Climate is another important factor in Pakistan because it impacts to water, health, energy, agriculture, biodiversity, socio-economic factors, and the building sector. Pakistan has a wide range of climatic conditions; Simultaneously, the highlands of Balochistan are arid and cold, the coastal areas in Sindh and Balochistan are warm and humid, and Northern Sindh and Central Punjab are extremely hot and semi-arid. In contrast, the climate in the Northern and North-Western parts of Pakistan can be cold (Nicol et al., 1999). The global climate is continuously evolving, and in the last two centuries, environmental issues and climate change have become emerging problems.

Pakistan has also faced an energy crisis for the last several years. The crisis started with a shortage of energy and an imbalance between demand and production. In addition, there are problems with energy transmission and distribution. The old and inefficient electricity distribution network causes line losses. During the fiscal year (FY) 2018–2019, distribution firms suffered 18.3 per cent of line losses ('Dawn', 2019; Mahar et al., 2019). Pakistan has an irrational and increasingly unaffordable electricity generation mix of 62.1% thermal, 25.8% hydroelectric, 8.2% nuclear, and only 3.9% renewables (*PES*, 2019). Subsidies in the energy sector have been reduced in recent months, which has created an immense burden of utility bills on the public (Kiani, 2019).

On the other hand, Pakistan's housing sector is the main consumer of electricity and used nearly half of the country's electricity, i.e. 48%, produced during the period July 2018 to March 2019 (*PES*, 2019). Houses in Pakistan are mainly constructed without considering the local climate and socio-cultural context. Reinforced concrete frame houses are the main and most widespread construction technology across the nation. Personalized active systems, such as radiant gas heaters and split air conditioners are used to provide comfortable temperatures inside houses which increase energy usage and cost.

In this study, we focus mainly on houses of Quetta as a representative of Balochistan Province. Quetta is the tenth-largest city of Pakistan and the provincial capital of Balochistan, with an urban population of more than 1 million. The city of Quetta is densely populated, and the average population growth rate during the period 1998–2017 was 3.05% per annum (*PBS*, 2017). According to the Köppen-Geiger climate classification, Quetta lies in a cold semi-arid climate zone (BSk). It has a semi-arid and dry climate with low humidity, mild to extremely cold winters, and hot summers. Quetta is situated outside of the monsoon range, but the city receives snowfall mostly in December, January, and February. The city is also located at a high altitude with an average elevation of 1680 m (*QDDP*, 2011). It has extreme weather conditions, with recorded temperatures of 42 °C in summer and –18.3 °C in winter (*PMD*, 2019), which requires context and climate-based design recommendations for best practices.

In the context of the above-stated facts, there is a need to investigate the thermal performance of existing houses and provide updated recommendations on designing housing to achieve maximum indoor thermal comfort in hybrid buildings. Hybrid buildings fall between free-running and fully space-conditioned buildings. A literature review shows that there are insufficient studies that address the above-mentioned issue and provide recent weather data-based design recommendations using building performance simulations (BPS). In Pakistan, some previous studies have investigated the relationship between the occupants' thermal comfort and climate in residential and office buildings. Nicol et al. performed two surveys in office buildings of five different Pakistani cities. They found a definite relationship between outdoor climatic conditions and indoor comfort in line with an adaptive thermal comfort approach. The research also revealed wide variations in indoor temperatures in the buildings in Pakistan due to specific building designs, layout, and a limited ability to control indoor temperatures (Nicol et al., 1999). Another study focused on the residential buildings in Quetta, Pakistan and the effects of climate on residential buildings' indoor thermal comfort. Results concluded that the houses were designed and built without considering climatic conditions and were unable to withstand extreme temperatures. As a consequence, this created discomfort for the occupants (Mahar et al., 2018; Mahar & Attia, 2018c). Khan compared the traditional building designs with modern residential building designs in Pakistan. The results determined that traditional buildings performed better concerning temperature variations, reducing the ambient temperature and offering various comfort zones to the occupants during the hot summer (Khan, 2016).

In Asia, various studies have been conducted focusing on the comfort and thermal performance of buildings. However, thermal comfort studies are significantly rare in South Asia (Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka). Ahmad et al. investigated a traditional house's thermal performance in Dhaka (Ahmad & Rashid, 2010). Singh et al. evaluated the thermal performance and comfort temperatures in India's vernacular buildings (Singh et al., 2010). A simulation-based study was conducted to improve a traditional residential house's thermal performance in Assam, India (Singh et al., 2016a). In another study, the effect of a cool roof on the built environment was explored in composite and hot and dry climates of India (Singh et al., 2016b). Some of the important studies conducted on thermal comfort in Southeast Asia are presented here. Nguyen et al. proposed an adaptive thermal comfort model for Southeast Asia's hot, humid climate (Nguyen et al., 2012). Nguyen and Reuter investigated the thermal performance of a low-cost apartment in Danang, Vietnam (Nguyen & Reiter, 2012). Toe investigated passive cooling to optimize thermal comfort in houses in Malaysia (Doris, 2014). Nughoro et al. did a preliminary study of thermal comfort in single-storey terraced houses in Malaysia (Nugroho et al., 2007). Jamaludin et al. investigated the thermal comfort of residential buildings in Malaysia at different microclimates (Jamaludin et al., 2015). Feriadi et al. investigated thermal comfort in naturally ventilated houses in Indonesia (Feriadi & Wong, 2004). Wong et al. evaluated thermal comfort in naturally ventilated public housing in Singapore (Wong et al., 2002). Bhikhoo et al. explored passive design strategies to improve thermal comfort in low-income housing in Thailand. The study concluded that comfort could be increased by insulating roofs and adding balconies (Bhikhoo et al., 2017).

The above literature shows that there is a wide knowledge gap regarding housing and comfort in Pakistan. Hence, this study aims to improve indoor thermal comfort in common buildings in Quetta and raise awareness of climate sensitivity. The following objectives are set for this study: (1) investigation of indoor thermal comfort in existing houses and (2) identification of possible measures for the improvement of indoor thermal comfort. The paper presents the background of the study and an introduction of the study area and highlights the aim, objectives, and impact of this study. It further focuses on a literature review, reference case selection, measurements, building modelling and calibration to validate the measured and simulated data as well as parametric simulation and analysis. A comparison of four different comfort models was made to select the best fit-to-context comfort model for the climate of Quetta. The potential of bioclimatic design strategies is analyzed, and the results of each strategy with the percentage of comfort improvement are presented. Finally, recommendations for future work are outlined.

With the improvement of socioeconomic conditions, it is expected that awareness regarding comfort and the need for active cooling and heating demand will increase. In this context, this study provides unique guidance for designers, builders, and owners to design and operate healthy and energy-efficient buildings. The added value of this work is not only to address issues in Quetta but to extend the results to several cities of Balochistan Province since Pakistan has a variety of climatic conditions from its north to its south; the proposed strategies are context-specific and cannot be used in other regions of the country without further investigation.

6.2. Methodology

A conceptual framework of the study was developed that summarizes and visualizes the research methodology of this paper. As shown in Figure 6.1, the conceptual study framework is based on six axes which will be described in the following sections.

6.2.1. Reference Case Selection

A housing survey was conducted to identify the characteristics of existing housing in Quetta. The survey included questions on household characteristics (socio-demographic and household size, etc.), housing characteristics, main materials and construction type, energy, water, waste profiling, etc. In total, 215 houses were surveyed in 32 residential areas of Quetta. Questionnaires were filled, and plans were drawn by the survey team. It was found that the majority of the houses (64%) were constructed using the same building materials and construction techniques. This type of house is generally called a reinforced concrete frame (RCF) house (Mahar & Attia, 2018a; Mahar et al., 2017). RCF houses are widespread and the most acceptable typology in Quetta and other areas of Pakistan. The survey also identified that most of the houses (48%) are single-storey houses with one or more families living in the same house. It was observed that passive design measures and the use of insulation for comfort are uncommon in Quetta. The residents mainly rely on fans and personalized heating and cooling units for indoor thermal comfort. Considering this situation, a representative single-storey RCF house was selected for this study based on the most common typology, construction techniques, building materials, and household characteristics.

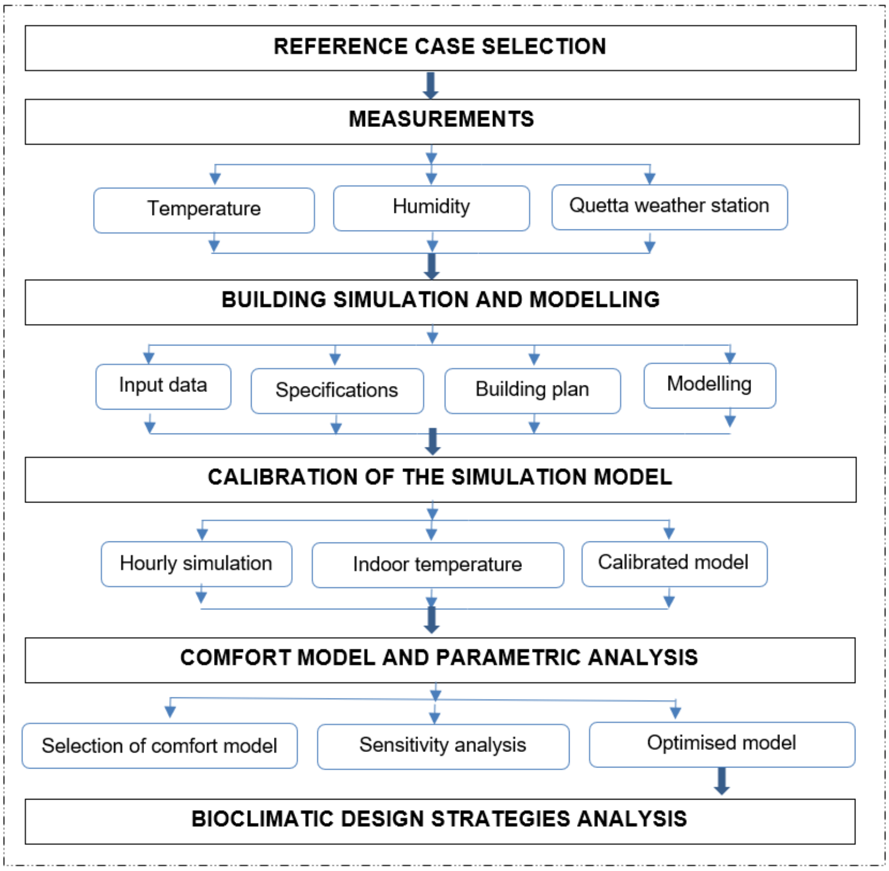


Figure 6.1. Conceptual study framework

The selected reference case house is a detached single-storey house located in the north of Quetta city. This house was constructed in the late 1980s and renovated in 2017. The family consists of eight members, and the house was occupied during the monitoring period. The house's covered area is 112.6 m^2 and consists of three bedrooms, a living room, a guest room, bathrooms, and a kitchen. The plan and the front view of the selected house are presented in Figure 6.2a,b. The selected reference case is a hybrid building, where radiant gas heaters are used for personalized heating, and only the bedrooms and living room are heated. The reference case uses single glazed windows, a reinforced cement concrete (RCC) roof, and a plain cement concrete (PCC) floor, which is similar to the majority of the houses which use the RCF system (Mahar et al., 2017; Mahar & Attia, 2018a). Further descriptions of the reference case are given in Subsection 6.2.3 and Table 6.2.

Figure 6.2 (a) Plan and (b) view of the reference case.

6.2.2. Measurements

For this study, indoor air temperature and relative humidity were monitored simultaneously in one bedroom and the living room. Previous studies confirm that a house's living room or bedroom can be selected as representative of the whole building. Colton et al. used the measurements taken in an apartment's main living space as representative of the whole apartment (Colton et al., 2014). In another study, the measurements taken in the living and bedrooms of apartments were considered representative for each apartment's assessment (Lai et al., 2009). Therefore, the measurements done in the living room of the reference case were considered representative and were used for calibration purposes. The weather data of Quetta Weather Station was initially obtained from the Pakistan Meteorological Department (PMD). Later, this data was found inappropriate to be used for simulation. Therefore, an extrapolated weather file of Quetta was used for simulation. The temperature and humidity were monitored using a HOBO U12-012 data logger. This was a four-channel data logger with a 12-bit resolution. The same equipment has been used in scientific studies performed previously (Jack et al., 2019; Kumar & Singh, 2019; Pathan, 2017; Pingel, 2019). The monitoring was done in summer and winter for four weeks each season, i.e. from 27th July to 23rd August 2017 and 28th December 2017 to 24th January 2018. The data loggers were kept at the centre of the spaces and at the height of 1.4 m to avoid any errors in measurements due to radiation from the floor and surrounding surfaces.

In addition, airflow and carbon dioxide concentration was also monitored as a part of our field study. A Testo-405 thermal anemometer was used to measure air velocity, and a Testo 160 IAQ was used to measure carbon dioxide concentration. The average measured airflow was always below 0.3 m/sec, which we found significant. Hence, we included an airspeed of 0.3 m/sec in all our calculations. However, this study does not focus on indoor air quality.

Table 6.1. The average clothing and metabolism values observed during the field study

	Age ≤ 30		**31 ≤ age ≤ 50**		**51≤**	
Clothing	Male	Female	Male	Female	Male	Female
Summer	0.3 clo	0.5 clo	0.5 clo	0.5 clo	0.5 clo	0.6 clo
Winter	0.8 clo	0.8 clo	0.8 clo	0.8 clo	0.8 clo	0.9 clo
Metabolism	3		2.6		2	

Table 6.1 presents the clothing and metabolism values calculated based on the field study. For simplification, we used clothing levels of 0.4 clo for summer, 0.7 clo for winter, and a metabolism value of 0.9, rather than specifying separate values based on age and gender. Besides, local discomfort was not identified during this study due to the use of personalized heating or cooling equipment. The influence of clothing and level of metabolism did not affect the comfort calculations significantly.

6.2.3. Building Simulation and Modelling

A survey questionnaire was filled to collect the input data from the occupants of the house and a semi-structured interview was conducted with the head of the household to obtain more details of the various necessary inputs, such as household size; actual drawings; details of construction techniques; materials, their thermo-physical properties; and various schedules based on the occupants' behaviour and occupancy, etc. The data collection included specific information related to comfort during summer and winter (clothing, activity, food type and adaptive behaviour). Input data and schedules used for the building simulation and modelling are presented in Table 6.2 and appendices A and B. A few of the thermal properties of building materials used in the simulation model are based on the previous work (Saeed et al., 2013; Shaheen et al., 2015). The value of airtightness is based on estimation. The EnergyPlus simulation program developed by the Department of Energy of the United States was used for building simulation given its suitability and robustness (Weytjens et al., 2012). A virtual model of the actual house (reference case) was created based on the actual measurements, sizes, schedules, and specification of materials which reflects the reality.

Table 6.2. Building description of the reference case (simulation model)

Category	Model Input Measures	Value/Parameter(s)
Envelope	Window-to-wall ratio (WWR) = (%)	8.08S, 10.1N, 0.9EW
	Openings (W/m^2 K)	U = 5.7
	Shading coefficient of glass (SC)	0.7
	Solar heat gain coefficient (SHGC)	0.81
	Light transmission (LT)	0.88
	LSGR (LT/SHGC)	1.08
	Overhangs, projection factor (PF) (S, N, EW)	0.65, 0.81, 1.6
	Wall = W/(m^2 K)	U = 1.4
	Wall surface absorptance, CCF	0.6
	Roof = W/(m^2 K)	U = 2.9
	Roof surface absorptance, CCF	0.7
Heating and ventilation	Airtightness (ACH)	2.5
	Coefficient of performance (COP)	0.85
	Heating temperature setpoint (°C)	23
	Mechanical ventilation system	Not applicable
	Heating system (individual heaters)	Radiant gas heaters
	Heating fuel	Natural gas
	Daily operative hours for ventilation/heating	12 h/day
	Airflow	0.3 m/s
Lighting	Installation power density (W/m^2) living rooms	20
	Lighting schedule	See Figures B1 and B2
DHW	Period 1 (October–March) (l/m^2/day)	3.5
	Period 2 (April–September) (l/m^2/day)	1.2
	Domestic Hot Water (DHW) schedule	See Figure B3
Occupancy	Household size	8 persons
	Area of the building	112.6 m^2
	Density (persons/m^2)	0.07
	Occupancy schedule	See Figures B4 and B5
Total consumption	Average annual energy use	49 kWh/m^2
Clothing/activity	Summer	0.4 clo/1.2
	Winter	0.7 clo/1.0
	Metabolism level	0.9

Legend: LSGR, light to solar gain ratio; CCF, cent (100) cubic feet

6.2.4. Calibration of the Simulation Model

The simulated data was calibrated by comparing it with the measured data to create the most suitable conditions for the actual measurements. The calibration method included several steps based on the ASHRAE Guideline 14 and in line with previously published studies (*ASHRAE 14*, 2014; Fabrizio & Monetti, 2015; Nguyen & Reiter, 2012; Pagliano et al., 2016). Firstly, to create a suitable weather input, site-specific hourly data from a baseline period had to be collected. Secondly, weather data were joined into a single data file for use with the EnergyPlus simulation program. However, the weather data obtained from the Pakistan Meteorological Department (PMD) was found inappropriate to be used for the simulation. Therefore, an extrapolated weather file of Quetta was used. Thirdly, all the construction and architectural details collected during the site visit were carefully entered into the simulation program. Then, the simulation was performed, and the results were extracted and compared with measured values. A graphical representation of the calibrated data was used to analyze the difference between measured and simulated data, and some appropriate modifications to the model were applied. A manual calibration method was used together with statistical approaches and methods, such as the normalized mean bias error (NMBE) and coefficient of variation of root square mean error (CV(RMSE)), as reliable measures to verify the calibration. Another method used for the calibration, linear regression analysis, was used to graphically assess the accuracy and correlation; this is presented in Subsection 6.3.1.

Normalized Mean Bias Error

$$NMBE = \frac{\sum_{i=1}^{Np}(M_i - S_i)}{\sum_{i=1}^{Np} M_i} (\%) \qquad (1)$$

Coefficient of Variation of Root Square Mean Error

$$CV(RMSE) = \frac{1}{\bar{M}} \sqrt{\frac{\sum_{i=1}^{Np}(M_i - S_i)^2}{Np}} \qquad (2)$$

In the above equations, Equations (1) and (2), *Np* is the total number of data values, *Mi* (where *i* = 1, 2 … *Np*) represents the measured data, and *Si* (where *i* = 1, 2 … *Np*) represents the simulated data. Using these equations, a simulated model is considered calibrated when NMBE is not larger than 10%, and CV(RMSE) is not larger than 30% when hourly data are used for the calibration. In this research, hourly data were used for the calibration of the simulation model.

6.2.5 Comfort model and parametric analysis

Three actions took place at this stage: (1) selection of the comfort model, (2) sensitivity analysis, and (3) an optimized simulation model based on the results of the parametric analysis. Four comfort models were compared using the climate of Quetta, namely Fanger's model (Fanger, 1970) as implemented in ISO 7730 (*ISO 7730*, 1994), the American adaptive comfort model as mentioned in ASHRAE 55 (*ASHRAE 55*, 2017), the European adaptive comfort model as reported in EN 16798-1 (*EN 16798-1*, 2009), and Givoni's model (Givoni, 1969). Similar to the work of Attia et al. [46], the results of the comparison allowed for the selection of the best fit-to-context model.

Firstly, the steady-state models were avoided since they neglect the effect of humidity adaptation by people and because residential and hybrid buildings are often not in a steady-state condition. Secondly, Givoni's model was reviewed; the model proposes 30 °C and 90% relative humidity and up to 32 °C and 93% relative humidity (Givoni, 1969). It was found that in the dry semi-arid climate of Quetta, the percentage of relative humidity remains lower than the proposed limits. Nevertheless, this study is based on small scale field surveys to justify the proposed comfort zone limits. Therefore, the ASHRAE Standard 55 adaptive comfort model was selected as it focuses on temperature rather than relative humidity. It was also found that Pakistan follows ASHRAE standards and that the existing Building Code of Pakistan (Energy Provisions-2011) is also based on ASHRAE standards (*ENERCON*, 1990; Mahar, Anwar, et al., 2019).

Then, a whole year simulation was performed considering heating and without heating scenarios. In the first scenario, the existing heating units were kept on in the living room and bedrooms during the winter. In the second scenario, heating units were kept off in all zones around the year. The most suitable comfort model was used to classify comfort hours in the reference case. Furthermore, all possible orientations were analyzed to determine the ideal building orientation for the reference case. Lastly, a parametric analysis was performed by applying architectural strategies to improve comfort hours in the selected house.

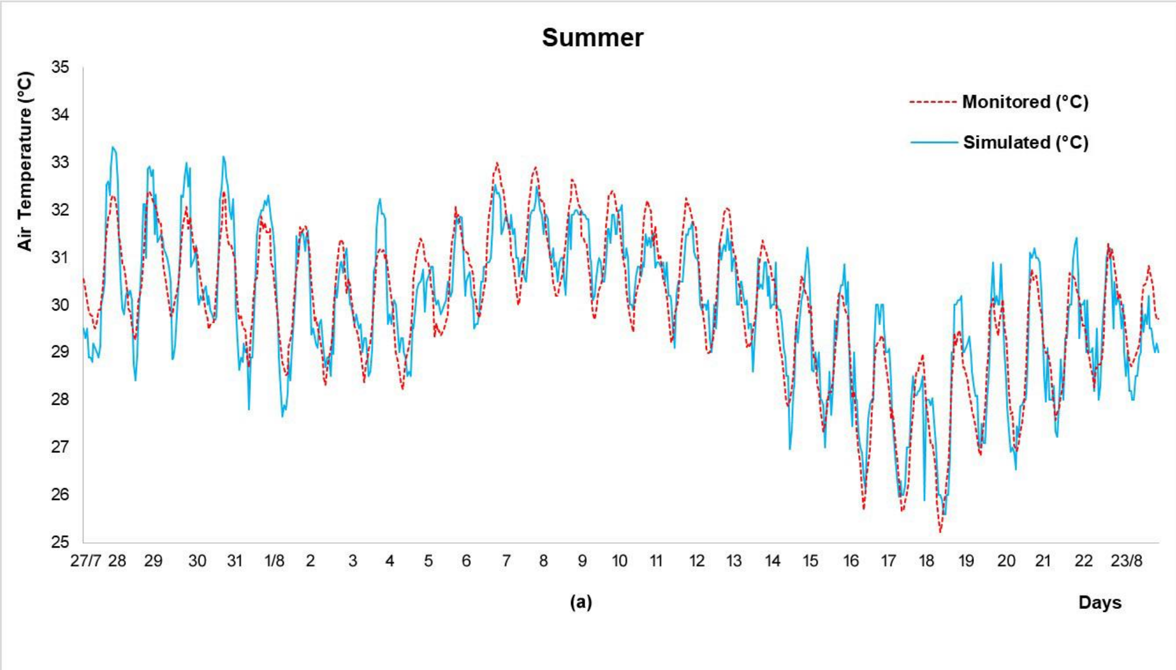
5.2.6. Bioclimatic Design Strategies Analysis

Psychometric charts can be difficult to understand for many architects. Therefore, a simplified chart for climate analysis was used (Attia et al., 2019; Horan & Luther, 2010; Roshan et al., 2017a; Roshan et al., 2017b). The chart of DeKay and Brown was used to visualize the potential of bioclimatic design strategies based on the simulation results. The results are integrated with DeKay and Brown's chart (DeKay & Brown, 2014) to quantify the potential of bioclimatic design strategies to improve thermal comfort.

6.3. Results

6.3.1. Validation of Calibration of the Simulation Model

The simulation model was calibrated for two important seasons, i.e., summer and winter. Manual calibration was selected as a method of calibration, and several iterations were run for this purpose. The simulated results were matched with the monitored indoor air temperatures. Furthermore, the NMBE and CV(RMSE) equations were applied for the calibration, considering the allowable limits to satisfy both equations.



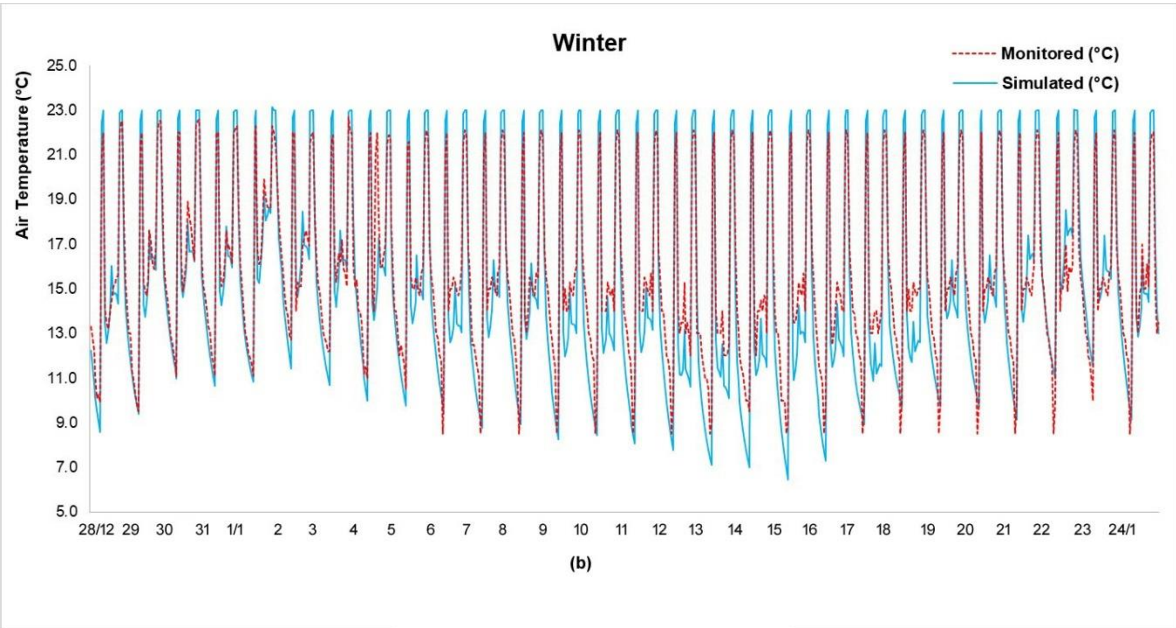
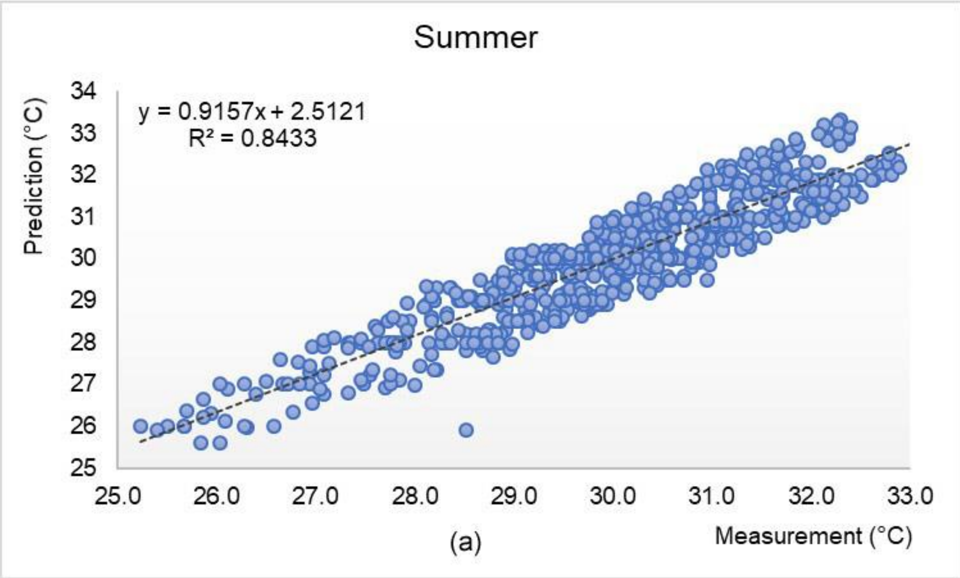


Figure 6.3 Comparison between measured and simulated air temperatures during the monitoring period. (a) July 27th–August 23rd, 2017; (b) December 28th, 2017–January 24th, 2018.



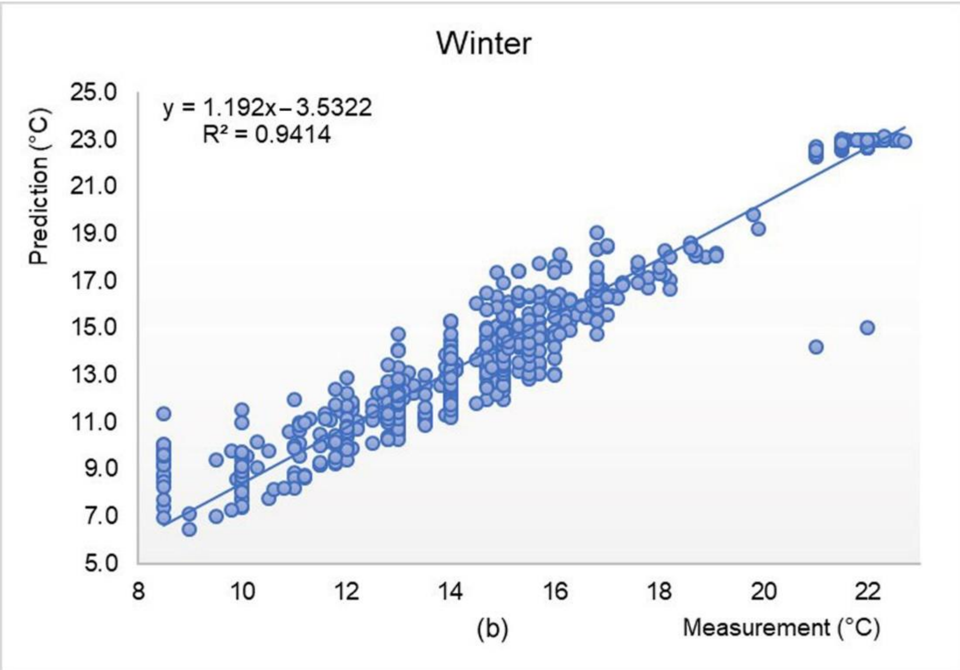


Figure 6.4 (a) and (b). Linear regression analysis of calibration of the simulation model for both summer and winter.

In order to assess the accuracy and correlation of the calibration, linear regression analysis was performed. The correlation coefficient (R^2) of the final prediction versus measurements of 0.843 in summer and 0.941 in winter was considered satisfactory to verify the simulation model's calibration. Table 6.3 and Figures 6.3a,b and 6.4a,b summarize and present the simulation model's calibration for both summer and winter seasons.

Table 6.3. Validation summary of the calibration criteria of the simulation model

Validation Criteria	Summer Indoor Air Temperature	Winter Indoor Air Temperature
NMBE (%)	0.4	2
CV(RMSE) (%)	3	6

Legend: NMBE, normalized mean bias error; CV(RMSE), coefficient of variation of root square mean error.

6.3.2. Comfort Model and Parametric Analysis

The results of comparing four different comfort models can be found in Figure 6.5. The whole year's outdoor air temperature is presented together with the comfort ranges of each comfort model. Fanger found that the optimal operative temperature satisfies most people at given clothing and activity, ranging between 18 °C and 22 °C (Fanger, 1970). The temperature range in the adaptive comfort model-EN 16798-1 ranges between 29 °C in summer and 20 °C in winter; these temperatures are not suitable comfort temperatures for the climate of Quetta. Givoni’s bioclimatic model ranges 30–32°C with a relative humidity of 90–93%. Since the climate of Quetta is dry and semi-arid, these ranges will not provide comfortable indoor conditions. However, the ASHRAE 55 adaptive comfort model presents comfort temperatures ranging between 22 °C in winter to 26 °C in summer with respect to the outdoor temperature. Hence, this model was found to be most suitable for the climate of Quetta.

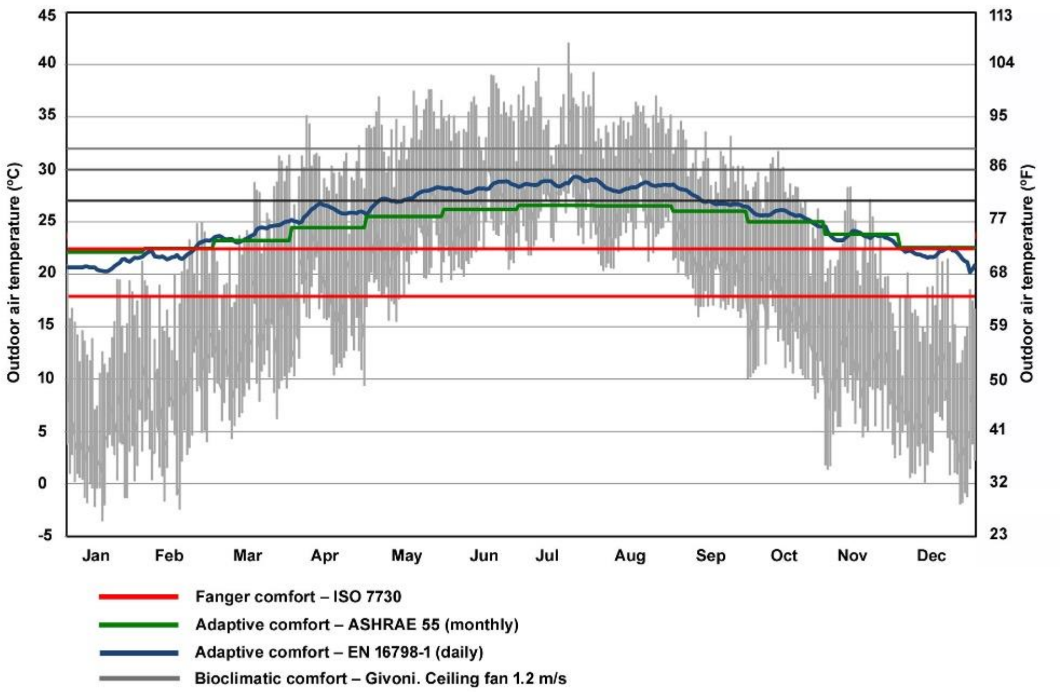
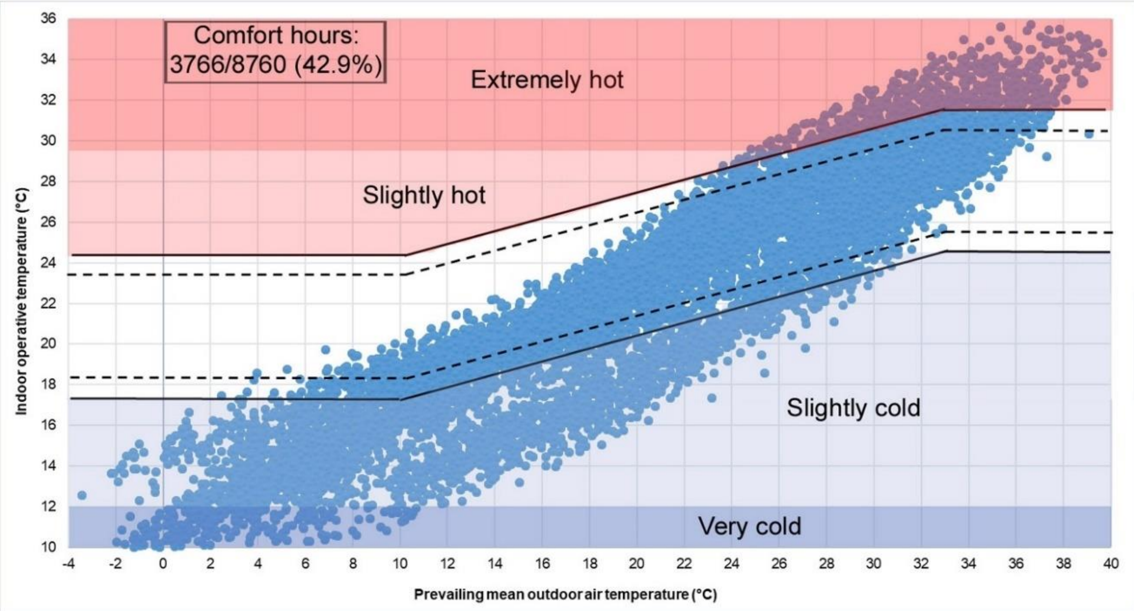
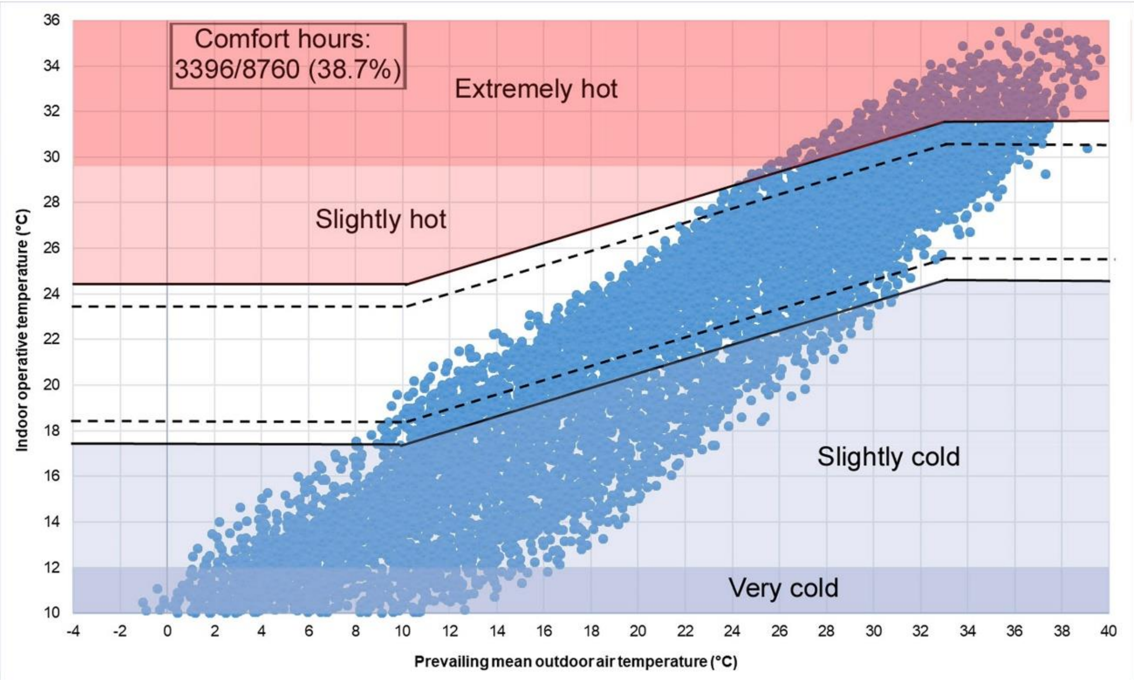


Figure 6.5 Comparison of four comfort models for the climate of Quetta.



(a)



(b)

Figure 6.6 (a) Comfort result and analysis of reference case (with heating). (b) Comfort result and analysis of reference case (without heating).

A whole year simulation was performed to identify comfort hours using the ASHRAE-55 adaptive comfort model. This model was found to be suitable for the climate of Quetta as it focuses on temperature and considers allowable humidity of up to 100%. Figure 6.6a,b present the comfort hours in the reference case with heating (42.9%) and without heating

(38.7%). This shows that the existing heating equipment is unable to provide optimal thermal comfort, which leads to the adaptive measures of comfort, which have been previously discussed by Mahar & Attia (Mahar & Attia, 2018c). The calculated comfort percentage was taken from the number of hours that fall under the 90% limit of the ASHRAE-55 adaptive comfort model (*ASHRAE 55*, 2017).

Effect of the Orientation

The thermal comfort of a building also depends on its orientation. In order to find out the best possible orientation of the reference case, eight possible orientations were assumed. Figure 6.7 and Table 6.4 present the possible orientations for the selected reference case and the percentage of comfort hours for each orientation. It was found that the existing orientation of the reference case, i.e., south, is the best possible orientation for more comfort hours throughout the year.

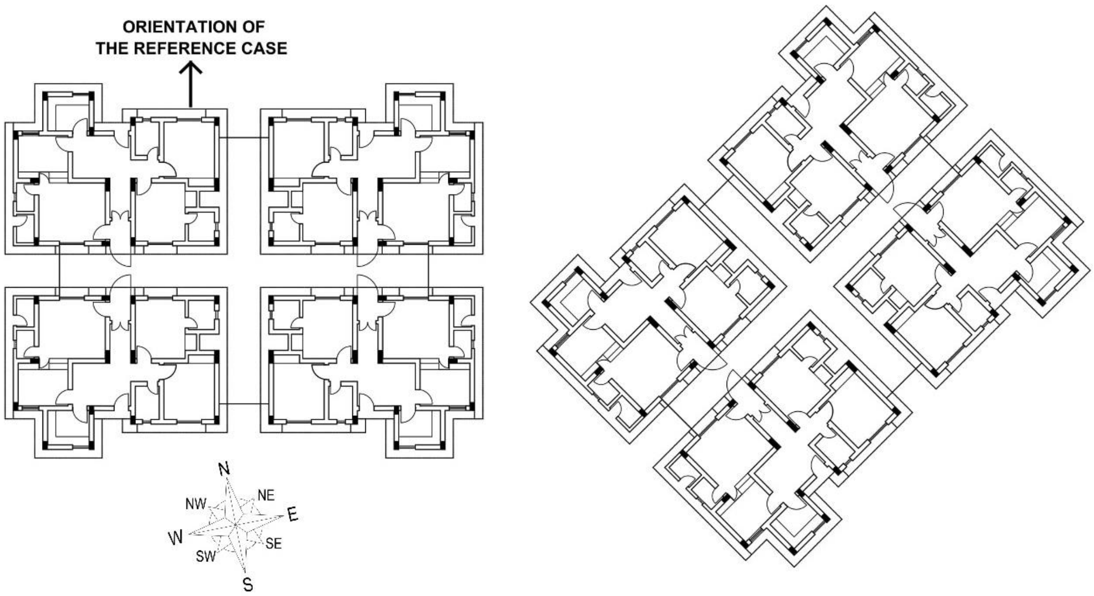


Figure 6.7 Eight possible orientations of the same house.

Table 6.4 Comfort percentages of the same house with different possible orientations.

Orientation	Result Comfort (%)	Comfort Improvement?
South	42.9	Reference case
North	41.2	No
West	42.3	No
East	42.5	No
NW	42.1	No
NE	42.5	No
SW	42.6	No
SE	42.8	No

Effect of Other Strategies Compared with the Reference Case

Some architectural strategies were used, and their effectiveness was examined in terms of thermal comfort. These strategies include thermal mass, insulation materials, ventilation, and changing thermal properties of the materials etc. The description of each strategy together with the corresponding comfort improvement is given in Table 6.5.

Table 6.5 Details of strategies used and their simulated performance.

Strategies	**Name**	**Description**	**Comfort Hours (%)**	**Comfort Improvement (%)**
Thermal mass	Case A	The thickness of the external walls was doubled from 0.34 m to 0.6 m. This raised the thermal resistance from 0.69 to 1.17 m^2 K/W.	43.9	Yes (1)
Low U-value windows	Case B	U-value of the external windows was reduced from 5.7 to 1.4 W/m^2 K i.e. to double glazing.	43.1	Yes (0.2)
Low U-value windows	Case C	U-value of external windows was reduced from 5.7 to 0.7 W/m^2 K i.e. to triple glazing.	44.3	Yes (1.4)
Low U-value roof	Case D	An insulated roof composed of asphalt and plasterboard. This raised the thermal resistance from 0.3 to 3.8 m^2 K/W.	53.6	Yes (10.7)
Low U-value walls	Case E	Three layered external walls: concrete walls (0.1 m), R-13 mineral fiber insulation (0.1 m), and concrete walls (0.15 m). This raised the thermal resistance from 0.6 to 3.2 m^2 K/W.	45.1	Yes (2.2)
Combination of strategies	Case F	Combination of Cases D and E.	56.1	Yes (13.2)
Combination of strategies	Case G	Combination of Cases C, D, and E.	57.5	Yes (14.6)
Combination of strategies and ventilation	Case H	Combination of Cases C, D, and E, and full day ventilation in summer.	58.5	Yes (15.6)

By applying the above strategies, comfort improvement was noticed in Cases C (1.4%), D (10.7%), and E (2.2%). Therefore, these strategies were combined for comfort improvement, as shown in Cases F (13.2%) and G (14.6%). In Case H, a combination of Cases C, D, and E strategies were applied together with full-day ventilation in summer. The results showed improved indoor thermal comfort from 42.9% to 58.5%, i.e., an increase of 15.6%, which is also presented in Figure 6.8.

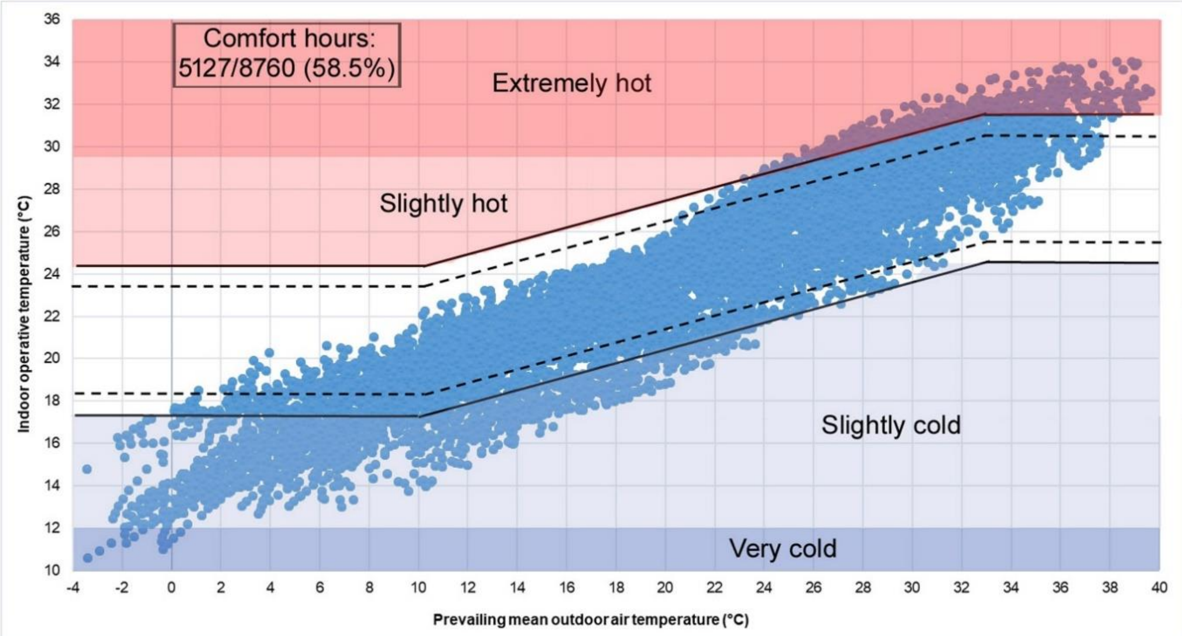


Figure 6.8 Comfort result and analysis of case H (a combination of all positive strategies).

6.3.3. Bioclimatic Design Strategies Analysis

DeKay and Brown's chart (DeKay & Brown, 2014) was used further to explore the potential for various bioclimatic design strategies. The aim was to avoid the use of psychometric charts, which are difficult to understand for many architects (Attia et al., 2019; Roshan et al., 2019). The potential of bioclimatic design strategies based on the climate of Quetta is illustrated in Figure 6.9. It can be seen that high thermal mass and passive solar heating can significantly improve comfort in winter. Shading, natural ventilation, and humidification are more important in summer.

Results from the optimized model (i.e. Figure 6.8) were plotted on DeKay and Brown's chart. Table 5.6 presents each bioclimatic design strategy's quantified values, the number of effective hours, and the comfort percentage in a year. It was concluded that bioclimatic strategies such as passive solar heating (38.6%), shading (17.5%), high thermal mass (10.6%), natural ventilation (7.8%), and humidification (23%) could be used in the climate of Quetta. However, the effects of the combination of two or more strategies are not explored in this study.

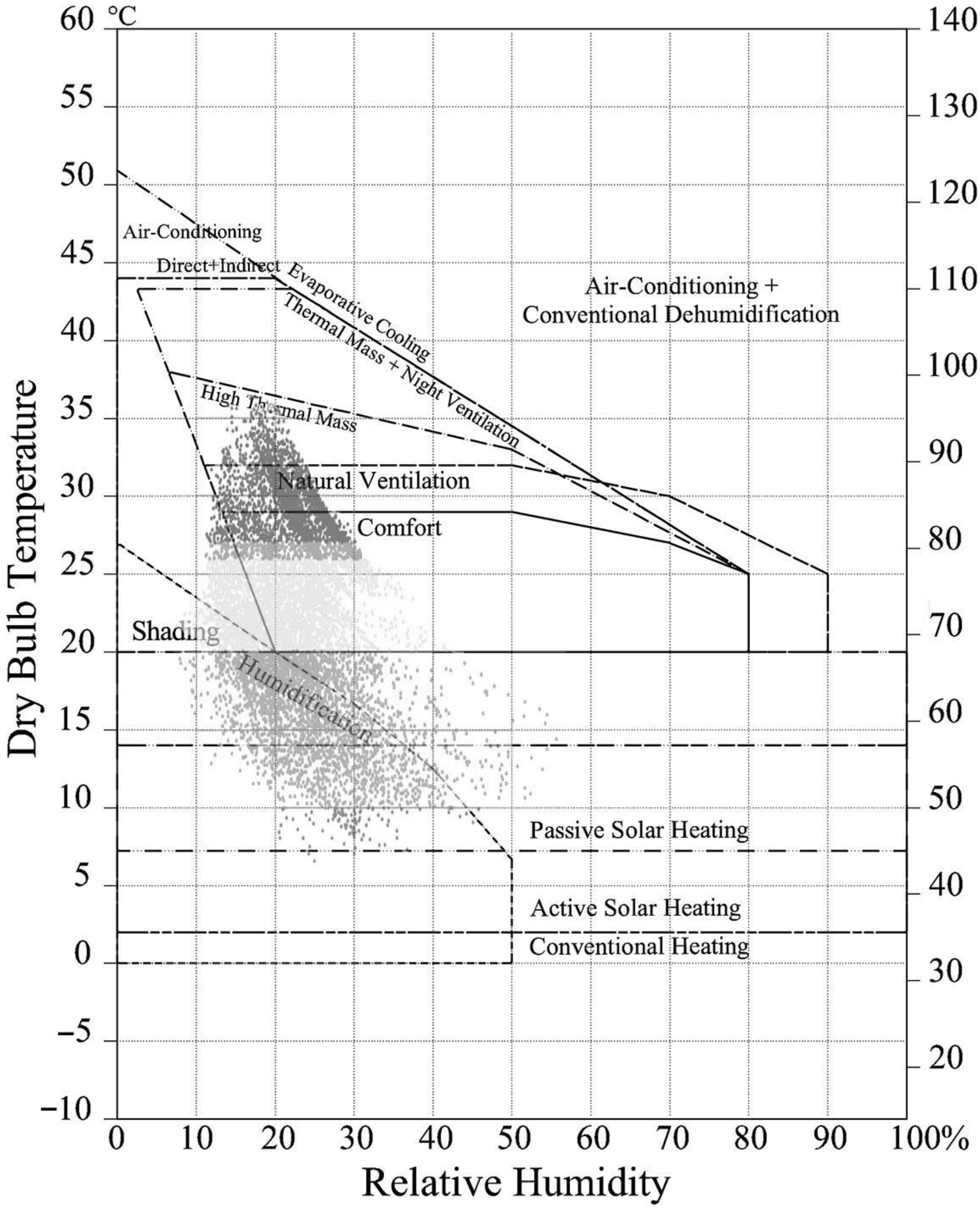


Figure 6.9 Bioclimatic design strategies using DeKay and Brown's chart (DeKay & Brown, 2014)

Table 6.6 Potential of bioclimatic design strategies based on Figure 9.

Principle	**Strategy**	**Effective Hours (EH)***	**Comfort (%) (EH/8760*100)**
Comfort		2340	26.7
Passive heating	Passive solar heating	3390	38.6
Solar control	Shading (orientation)	1540	17.5
Thermal control	High thermal mass	930	10.6
Passive cooling	Natural ventilation	690	7.8
	Humidification	2020	23

* In DeKay and Brown's chart, the design strategies overlap, and therefore, the accumulated number of hours (percentage) exceed 8760 hours (100%).

6.4. Discussion

This study's findings are discussed further in three sub-sections, which include the main findings and recommendations, strengths and limitations of the study, and study implications and future research.

6.4.1. Main Findings and Recommendations

For this study, a reference case model was created using a representative typology. The indoor climate was monitored, and a virtual model was created, simulated, calibrated, and optimized using parametric analysis. Furthermore, the potential of bioclimatic design strategies was discovered using DeKay and Brown's chart (DeKay & Brown, 2014). The results show that up to 59% of annual comfort hours (with the existing heating system) can be achieved using passive design strategies without additional mechanical systems.

Since there are no thermal comfort models for Pakistan, four different comfort models were compared, and it was found that the ASHRAE-55 adaptive comfort model is the best fit-to-context thermal comfort model for Quetta. The potential of various bioclimatic design strategies was explored and quantified, as shown in Figure 6.9 and Table 6.6. The bioclimatic analysis indicates that passive design strategies, such as passive solar heating, shading, high thermal mass, natural ventilation, and humidification, can be useful in the climate of Quetta if buildings are designed and constructed properly.

6.4.2. Strengths and Limitations of the Study

The strengths of this study relate to combining real monitoring datasets with an advanced building performance simulation. The study used high-quality data gathered through monitoring, questionnaires, on-site visits, and semi-structured interviews with the residents. The calibration techniques applied in this study followed state-of-the-art methods which are similar to the previous studies of Nguyen and Fabrizio (Fabrizio & Monetti, 2015; Nguyen & Reiter, 2012).

This is the first study investigating the thermal comfort of buildings in the context of Quetta and Pakistan. This is in contrast to previous work of Nicol, Khan and Mahar (Khan, 2016; Mahar et al., 2018; Mahar & Attia, 2018c; Nicol et al., 1999), which has only focused on surveys and monitoring of indoor climate in residential and office buildings.

DeKay and Brown's chart was used to identify and quantify the potential of bioclimatic design strategies in Quetta, taking into account the buildings' performance. This method was also used by Attia and Roashan (Attia et al., 2019; Roshan et al., 2019). DeKay and Brown's chart simplifies the potential of various bioclimatic design strategies for the better understanding of architects compared to complex psychometric charts.

Additionally, four different comfort models were tested to identify the best-fit-context comfort model for the climate of Quetta. This was also important as there has been no comfort model previously used or adopted for Pakistan. The ASHRAE-55 adaptive comfort model was found to be the best comfort model for the climate of Quetta, which is a dry and heating-dominated climate.

On the other hand, this study has some limitations. It only focuses on one single building typology using a manual calibration method. The indoor air temperature, relative humidity and air velocity were monitored. The mean radiant temperature (MRT) and airtightness were not measured for this study. More importantly, the study did not investigate the combined effects of different passive design measures. Therefore, further research should explore wider solution spaces and reduce study uncertainty.

6.4.3. Study Implications and Future Research

This study raises awareness regarding thermal comfort and allows architects and building designers to inform their decision-making regarding design priorities and design strategy effectiveness. The study findings are helpful to create a new design guide for bioclimatic design in Quetta. In the long term, the presented results can further lead to the creation of an energy-efficiency code for Quetta city. Legislation must force permits and code-compliance certifications for renovation as well as new constructions to improve thermal comfort and energy efficiency in building stock.

Also, we should emphasize that the building construction quality of most residential houses in Quetta is poor from a thermal performance point of view. The construction market lacks the knowledge and materials to build good performing buildings. The Pakistani supply chain for green or energy-efficient construction materials and products is vacant. At the same time, our study proves that there is a very high potential to achieve good thermal comfort in dwellings by applying simple passive design measures combined with high-quality construction techniques. Our characterization of Quetta's climate and our case study's simulation confirm that basic thermal and solar control strategies, airtightness, and passive cooling strategies can significantly improve comfort. Therefore, future research should look at the materialization of strategies into solutions using affordable construction techniques and local materials. This can encourage developing design and construction methodologies and prototypes that can lead the transition of building stock towards being sustainable and energy-efficient.

We believe that the methodology used in this study can be transferred to other areas of Pakistan to investigate the most suitable design strategies to improve thermal comfort in different climatic zones of the country. Future research should focus on sensitivity analysis and multi-objective optimization combining comfort with cost, energy efficiency, carbon emissions, etc., to obtain optimal solutions for newly constructed residential buildings in Quetta.

6.5. Conclusion of the chapter

This study aimed to investigate the potential for improving indoor thermal comfort in the most common housing typology in Quetta, Pakistan. The findings are valuable for improving comfort in the existing building, but they can also be more effective in informing designers and homeowners of new constructions.

The results confirm that adopting passive design strategies may lead to up to 59% of comfort hours (with the existing heating system) without adding other mechanical solutions, which can be explored later to achieve maximum comfort throughout the year. The climate of Quetta is heating-dominant; therefore, passive solar heating and insulation are the most important design strategies. Hence, the focus should mainly remain on comfort in the cold season. The study concludes that the ASHRAE-55 adaptive comfort model is the best fit-to-context thermal comfort model for the climate of Quetta.

Given the geographic and climatic particularity of Quetta, since it is located at a high altitude and has its own micro-climate, this is the first study that investigates thermal comfort based on local and universal knowledge. In this study, a mixed study approach was used that allowed for the verification of the climatic, physical, and behavioural reality of housing in Quetta. An advanced simulation approach was used to test and validate design recommendations for future designers. The paper provides insights for local practitioners and sheds light on the best design practices for the climate of Quetta. This study allows future researchers to further investigate solutions and technologies to achieve maximum comfort throughout the year using passive design strategies.

The following recommendations are given based on the investigation of this study to improve thermal comfort in houses. The findings of this study prove that thermal comfort can be improved using passive and bioclimatic design strategies.

- High thermal mass, passive solar heating, and insulation are recommended in the climate of Quetta for the improvement of thermal comfort, particularly in the winter season.
- Shading, natural ventilation, and humidification will increase comfort in summer when the humidity level is very low.
- Behavioural adaptation such as opening windows and using fans can improve comfort.
- The ASHRAE-55 adaptive comfort model is the best fit-to-context comfort model for the climate of Quetta.
- Passive design measures can improve comfort; however, there will be a need for an efficient active system to achieve better comfort conditions.

CHAPTER 7: SENSITIVITY ANALYSIS[2]

Buildings are significant drivers of greenhouse gas emissions and energy consumption. Improving occupants' thermal comfort 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 passive design parameters' impact 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.

[2] This chapter is based on a the following journal publication.

Mahar, W.A., Verbeeck, G. Reiter, S., Attia, S. (2020). Sensitivity analysis of passive design strategies for residential buildings in cold semi-arid climates*. Sustainability*, 12(3), 1091.

7.1. 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 per cent of the expected urban population growth will occur in Asia (*EC*, 2020). Pakistan is among the Asian countries with high urbanization with 3 per cent growth annually—one of the fastest growth rates in Asia (Kugelman, 2013). According to the United Nations Population Division's estimates, by 2025, almost 50 per cent of the population will live in urban areas (more than one third do today) (UN, 2019). Pakistani cities' real challenge is to provide affordable and sustainable housing for their rapidly growing urban agglomerations (Mengal, 2018). As in most Global South countries, medium-sized cities in Pakistan play a determinant role as a transitional pivot between rural and urban networks (Bolay et al., 2019). The rapid urban transformation process impacts those medium-sized cities and affects their urban centres and extends 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 (*PBS*, 2017). 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) (Amber et al., 2018). The highest recorded summer temperature in Quetta was 42 °C, and the lowest temperature in Quetta can reach close to −18.3 °C (*PMD*, 2019). Compared to other easterly parts of Pakistan, Quetta does not receive heavy rainfall since it is located outside the monsoon region (*QDDP*, 2011). 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 the Central Asian States. Moreover, Balochistan Province is becoming the home to major infrastructure projects in China’s Belt and Road Initiative (BRI) (Cheng, 2016). Therefore, it is essential to develop the technical knowledge required to manage the city's growth, urbanization, and 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 the 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 (*PU*, 2014) because this deprives people of the land and space needed to build houses with solar access (Tabb, 1984). On the building design scale, architects, urbanists, builders, and homeowners need to build sustainable and low-impact housing that considers 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 (Molinar-Ruiz, 2017). As shown in Figure 7.1, the cold semi-arid climate (Köppen BSk) regions worldwide 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 Asia, covering part of China, Iran, Mongolia, Nepal, and Pakistan. The study of Huang et al. evaluated climate-responsive design measures in the cold semi-arid regions of Tibet, China (Huang et al., 2016). The study focused mainly on traditional passive designs addressing primarily thermal comfort. Similarly, Upadhyay et al. investigated climate-responsive building design in the Kathmandu Valley in Nepal (Upadhyay et al., 2006). Pourvahidi developed climate-responsive design recommendations using bioclimatic charts in Iran, including Shiraz, Yazd, and Isfahan (Pourvahidi & Ozdeniz, 2013). Then Roshan et al. investigated the impact of climate change on design recommendations for residential buildings falling in Iran's cold semi-arid regions (Roshan et al., 2019; Roshan et al., 2017). Bahria et al. investigated solar passive design principles in the cold semi-arid areas of Djelfa, Algeria (Bahria et al., 2016). Monge-Barrio investigated the passive solar potential of building-attached sunspaces in the residential architecture in Spain's cold semi-arid region (Monge-Barrio & Sánchez-Ostiz, 2015). 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. (Molinar-Ruiz, 2017). More recently, Ameur et al. used sensitivity analysis to evaluate the impact of passive design features, focusing on natural ventilation in a free-running residential building in Morocco (Ameur et al., 2020).

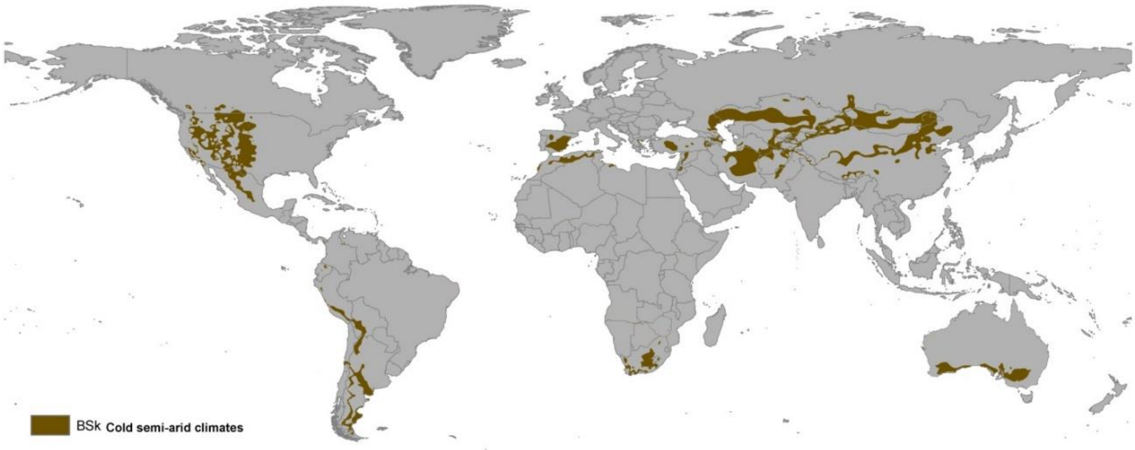


Figure 7.1 Cold semi-arid climate regions worldwide according to Köppen World Map (BSk) (Köppen, 2019)

The type of studies presented above contributes to 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 (Mahar et al., 2019). 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 the 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 help decision-makers identify the most relevant design variables (Lomas & Eppel, 1992). Sensitivity analysis determines how different values of an independent variable in a given set of boundary conditions affect a particular dependent variable (Saltelli, 2004). When we understand the relationships and the relative importance of design parameters, we can easily improve the building's performance (Nguyen & Reiter, 2015).

There have been many studies on residential buildings' energy performance and the evaluation of the influence of energy conservation measures on passive design measures using sensitivity analysis techniques. Gustafsso conducted a sensitivity analysis for energy retrofit measures for a residential building in Sweden (Gustafsson, 1998). Lam et al. conducted a sensitivity analysis for energy conservation measure implications for Hong Kong office buildings (Lam et al., 2008). Similarly, Heiselberg et al. conducted a sensitivity analysis for an office building in Denmark (Heiselberg et al., 2009). Breesch conducted a sensitivity analysis to evaluate passive cooling strategies in office buildings in Belgium (Breesch & Janssens, 2010). Tian conducted a sensitivity analysis of building performance using probabilistic climate projections for a case study in the United Kingdom (Tian & de Wilde, 2011). Yildiz et al. conducted a sensitivity analysis to reduce low-rise apartment buildings' energy requirements in Turkey (Yildiz et al., 2012). Attia et al. conducted a sensitivity analysis for a zero-energy building in Egypt (Attia et al., 2012). Huang & Hwang conducted a sensitivity analysis for passive adaptation measures to reduce cooling energy needs in a residential building in Taiwan (Huang & Hwang, 2016). Bre et al. investigated the potential of residential building design optimisation using sensitivity analysis in Paraná, Brazil (Bre et al., 2016). Ascione et al. investigated the potential of large-scale energy retrofit measures on the building stock using sensitivity analysis techniques (Ascione et al., 2017). Chen et al. performed a sensitivity analysis of passive design strategies for a high-rise residential building in China's hot and humid climate (Chen et al., 2017). While those papers offer design recommendations on how to design energy-efficient or sustainable buildings, none of those studies mentioned above caters to Pakistan's cold semi-arid climate. More importantly, the studies above mainly focus on fully space-conditioned or free-running buildings. None of those abovementioned studies focuses 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 buildings that are fully space-conditioned or fully in free-running mode. Simultaneously, several papers have found the most positive attributes of sensitivity analysis (Attia et al., 2013; Attia et al., 2012), which are short computation time and modelling simplicity (Østergård et al., 2017). The sensitivity analysis can be performed by consulting architects at the early stage of the building design and project delivery process (Hygh et al., 2012). Compared to automated optimisation, its main advantages are that its application decreases the calculation time and complexity (Samuelson et al., 2016).

While sensitivity analysis studies have been applied in residential and office buildings (Attia et al., 2012) 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 an effective tool that has previously successfully fulfilled research objectives (Østergård et al., 2016). 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, particularly 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. 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 improve. Therefore, acting on this paper's findings 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 Pakistan's cold semi-arid climate?
- 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 to build 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 7.2. Next, the results of the above questions are presented in Section 7.3. Section 7.4 discusses the limitations of the sensitivity analysis approach, and Section 7.5 concludes the paper.

7.2. Methodology

The conceptual study framework of this research illustrates the two major methodological steps (Figure 7.2) 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.

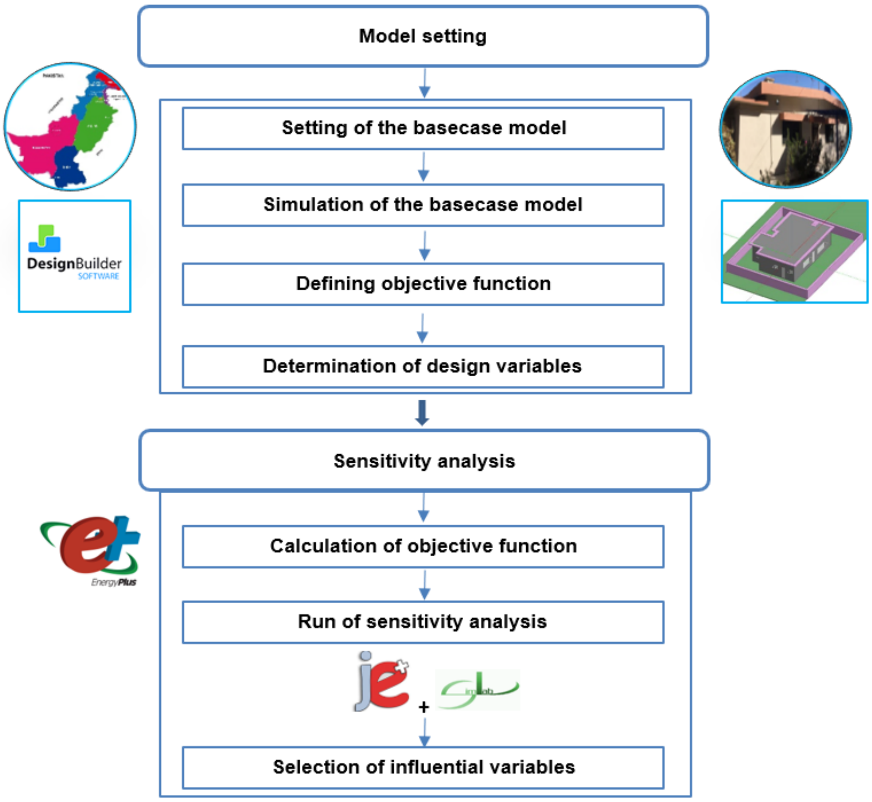


Figure 7.2 Conceptual study framework

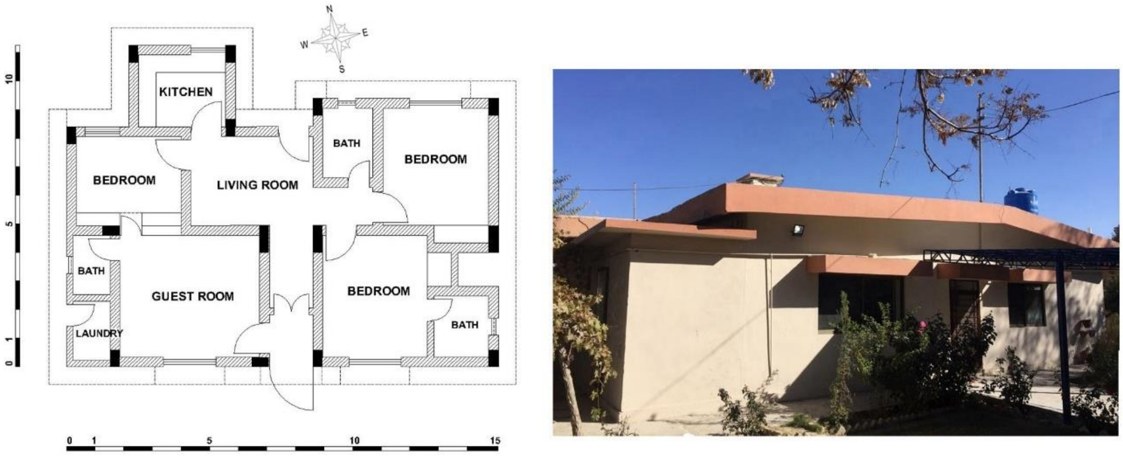
7.2.1. Model Setting

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 7.1) (DeKay & Brown, 2014). These design variables were supposed to be suitable solutions to improve the residential buildings' indoor thermal comfort in Quetta. The sensitivity analysis was performed aiming to identify the influential design variables that are significant to improve indoor thermal comfort.

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 (Mahar et al., 2017; Mahar & Attia, 2018a). A representative basecase model of a single-storey house was selected for this study. This building model was considered 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 7.3, 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 7.3. The thermophysical properties of the building materials and construction details are summarised in Table 7.1, and the input parameters used for the simulation are detailed in Table 7.2.



(a) (b)

Figure 7.3 (a) Plan and (b) view of the selected basecase.

Table 7.1 Thermophysical properties of building elements of the base

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 Layer 2 Layer 3	Plaster Brick Plaster	0.95 22.86 0.95	0.431 0.711 0.431	1250 2000 1250	1088 836 1088
2	Roof	Layer 1 Layer 2 Layer 3 Layer 4	Plaster Bitumen RCC slab Plaster	0.95 0.95 10.16 0.95	0.38 0.5 0.753 0.38	1150 1700 2300 1150	840 1000 665.9 840
3	Floor	Layer 1 Layer 2 Layer 3 Layer 4 Layer 5	Cement Mortar Concrete Aggregate Sand Earth/ Soil	0.95 5.08 7.62 10.16 22.86	0.72 0.753 1.8 1.74 0.837	1650 2000 2240 2240 1300	920 656 840 840 1046
4	Windows	Layer 1	Single-glazed with clear glass	0.63	1.046	2300	836.8

Legend: RCC, reinforced cement concrete.

Table 7.2 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 x 11.2 m	
Floor area	112.6 m^2	
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
	Airtightness	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.

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 (Fabrizio & Monetti, 2015; Nguyen & Reiter, 2012; Semahi et al., 2019). The calibration was further validated using linear regression analysis to graphically represent the accuracy and correlation between simulated and monitored data. The investigation of the basecase model's indoor thermal comfort was performed together with parametric analysis to identify the possible passive and bioclimatic design strategies to optimise indoor thermal comfort (Mahar et al., 2019).

Defining Objective Function

The objective function is also called fitness or optimization function, usually calculated using scientific simulation tools (Machairas et al., 2014). It is often used to improve indoor thermal comfort, assess environmental impacts, or calculate building energy demand (Guo et al., 2019). In a sensitivity analysis, the objective function(s) is used to identify the effect(s) of various input variables. In this study, 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 (Fanger, 1970)—the European adaptive comfort model EN 16798–1 (*EN*, 2019), Givoni's model (Givoni, 1969), and ANSI/ASHRAE Standard 55 adaptive comfort model (*ASHRAE 55*, 2017). 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 (Mahar et al., 2019). 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.

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 (Mahar et al., 2019). 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 7.3 provides details of the selected design variables, their units, variable types, basecase values, interval ranges, and variation steps used for sensitivity analysis.

Table 7.3 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.

The details and properties of the discrete design variables are presented in Tables 7.4–7.9. The upper limit of the heating setpoint temperature 22 °C, and the lower limit of cooling setpoint temperature 25 °C are based on the recommendations given in the Building Code of Pakistan (Energy Provisions-2011) (*BEC*, 2011). For the sensitivity analysis, cooling setpoint (X_{19}) and heating setpoint (X_{20}) were used as input variables. The type of variables is continuous uniform, as mentioned in Table 7.3. The variations of setpoint temperatures were also used in previous studies (Ascione et al., 2015; Delgarm et al., 2016; Feng et al., 2019). This study is only based on sensitivity analysis, and no optimization was done to identify the suitable setpoint temperatures for summer and winter.

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 (Mahar et al., 2018; Mahar et al., 2019; Mahar & Attia, 2018c). Table 7.4 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 7.5 and 7.6, 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 7.7. Description of window frames (X_{15}) are given in Table 7.8, while Table 7.9 sums up the details of the design variable window glazing type (X_{18}).

Table 7.4 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 7.5. 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 7.6 Floor construction

S. No.	Floor material	Conductivity (W/m K)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)
		ə	*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 7.7. Type of insulation for external walls, roof, and floor

S. No.	Building Element Composition	Conductivity (W/m K)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)
		ə	*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 7.8. Window frame type

S. No.	Window Frame Type	Frame Composition	Thickness (m)	Uf-Value (U frame) W/m^2 K
WF1	Aluminium window frame (no break)	Aluminium	0.005	5.8
WF2	Window frame (with thermal break)	Aluminium	0.002	5
		PVC	0.005	-
WF3	Wooden window frame	Oak (radial)	0.02	3.4
WF4	UPVC window frame	PVC	0.02	3.6

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

Table 7.9 Window glazing type

S. No.	Window Glazing Type	SHGC	LT	Ug-Value (U glass) (W/m^2 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.

7.2.2. 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 (*JRC*, 2004). 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.

Calculation of Objective Function (Comfort hours)

A simulation was performed to investigate the annual comfort and discomfort hours in the selected basecase model. The results were calculated using EnergyPlus, a scientific simulation tool. The calculation method was based on the ASHRAE Standard 55 adaptive comfort model Equations 1 to 5 defines the upper formula for the calculation of upper and lower limits of 80% and 90% acceptability limits and optimal comfort temperature. 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 (*ASHRAE 55*, 2017; S. Carlucci et al., 2018).

[illegible] *Equation 1*

[illegible] *Equation 2*

[illegible] *Equation 3*

[illegible] *Equation 4*

[illegible] *Equation 5*

Source: ANSI/ASHRAE Standard 55-2017

Run of Sensitivity Analysis

The sensitivity analysis performed for this study was global analysis, one of the major methods; the other is called local analysis (Mara & Tarantola, 2008; Nguyen & Reiter, 2015; Tian, 2013) . The global analysis method was selected to explore a vast space of the input factor around a basecase and the interaction between the factors, such as the shape of the probability density function and the effect of the 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 (Christian, 2004).

As described in section 7.2, 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) (Tian, 2013; Belleri et al., 2014; Calleja Rodríguez et al., 2013; Domínguez-Muñoz et al., 2010; Ioannou & Itard, 2015; Yıldız & Arsan, 2011). The SRC sampling indexes are widely used in building performance analysis, and the same method was used in this study.

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.

7.3. Results

7.3.1. Sensitivity Analysis

Calculation of comfort hours and the 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 7.2.2, 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% of the total 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 7.4 presents comfort hours in the basecase model calculated for a whole year using hourly data. This figure indicates the prevailing mean outdoor air temperature (x-axis) and indoor operative temperature (y-axis). Two solid lines specify the upper and lower 80% acceptability limits; whereas two dotted lines indicate the upper and lower 90% acceptability limits. A Microsoft Excel-based tool was created to plot the comfort hours and acceptability limits.

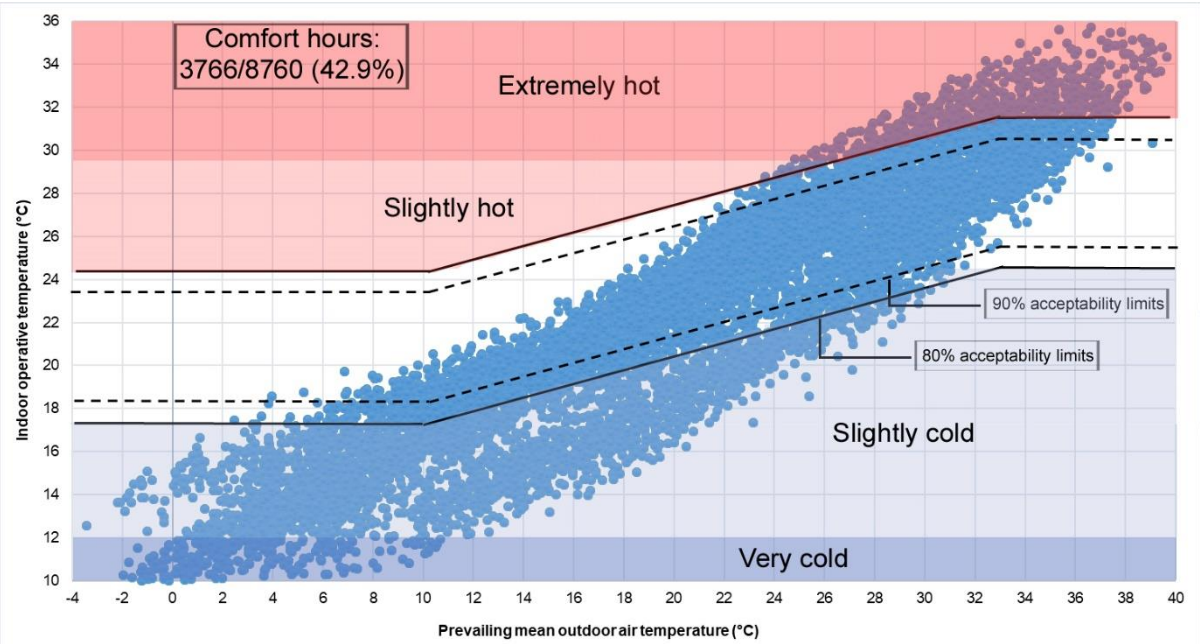


Figure 7.4 Annual comfort hours in the basecase model

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 7.5 and Table 7.10.

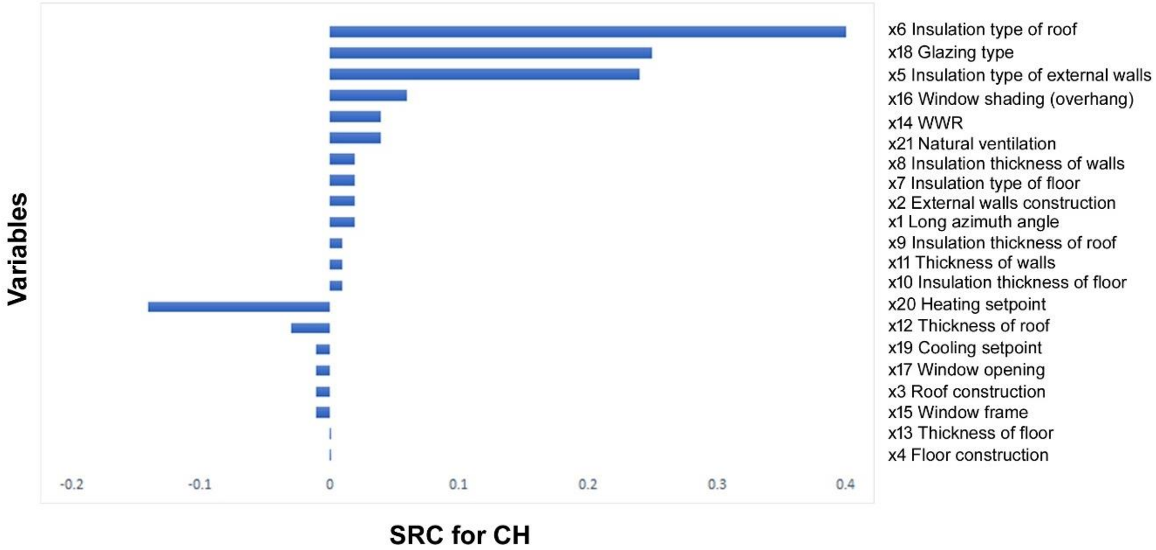


Figure 7.5 Sensitivity ranking of Standard Regression Coefficients (SRCs) for the comfort hours in the basecase model (relative threshold).

Table 7.10 Result of sensitivity analysis and SRC ranking for the discomfort hours in the basecase model.

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

Legend: SRC, Standard Regression Coefficient; CH, comfort hours.

The global sensitivity analysis results 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 the heating setpoint, while the two design variables showed no influence.

7.3.2 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 7.5 and Table 7.10, the building envelope's thermal insulation 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 (Mahar et al., 2018; Mahar & Attia, 2018c).

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 the actual north is at 0°. Since the actual north is tilted to approximately 15° to the north-northwest (NNW), the building's positioning at 180° to south-southeast (SSE) will match it with the actual south direction. It will expose the whole front façade to the southern direction and improve the 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.

7.4. 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.

7.4.1. 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 could 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 6.5 and Table 6.10, 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 the building. The size of windows plays an important role in the cold climate. The orientation of the azimuth angle of the long axis of a building at an angle where the 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 the building to 15° south-southeast (SSE) 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 that 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 (*BEC*, 2011; Mahar et al., 2019). There is a need to identify suitable indoor temperatures for the buildings in different climatic zones of Pakistan.

Based on this study's results, 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 the 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. A 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.
- The 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, the 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 in 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.

7.4.2. 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 (*PES*, 2019). Passive design solutions can decrease the reliance on active systems, which will reduce 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 seconds 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 a 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 7.1).

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. 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 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 also be 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.

7.4.3. Study Implications and Future Research

The climate of Quetta and its geographical location makes 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 7.1 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 7.3 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 manufacture high-quality energy-efficient materials locally. There is a need to consider the cost of materials and taxes. Currently, most of the available materials in Pakistan are imported from abroad, which are not affordable for most 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 integrate the influential design variables in constructing new houses according to the local climate conditions (Tian et al., 2018). 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.

7.5. Conclusion of the chapter

The study aimed to identify the most influential design variables for indoor thermal comfort by sensitivity analysis of passive and bioclimatic design strategies. This study's findings 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:

- 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 the floor is essential to improve comfort. High thermal mass, passive solar heating, shading devices, natural ventilation, and low emissivity double-glazed windows are recommended for the construction of houses in Quetta.
- 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.
- It is recommended to explore the existing building materials and identify suitable materials to achieve indoor thermal comfort.
- There is a need for research at the national and local level to manufacture advanced, energy-efficient building construction materials at a low cost.

CHAPTER 8: MATERIALIZATION

8.1 Introduction

Materialization is the process of creating a solution based on unknown or new resources. It is also a process for creating a database that contains the results of a query. Materialization also provides a step-by-step guide for completing an idea, a thought or a policy.

This chapter presents the methods used for the materialization of passive design solutions based on influential design variables identified in Chapter 7. This chapter explores the energy-efficient and sustainable building materials that are locally available or manufactured in Pakistan to construct climate-responsive and thermally comfortable residential buildings. The primary challenges and questions while selecting such materials are the following:

- What are the materials which can assist in improving indoor thermal comfort?
- How to identify and select suitable materials?
- What is the common practice and experience of architects and residents?

The objectives of this study are defined considering the above questions (i) identification of locally available or manufactured energy-efficient building materials with better thermal performance, ii) identification of thermophysical characteristics of building materials, (iii) combining experiences of architects and residents regarding a variety of building materials. There is a lack of research and knowledge gap in Pakistan concerning sustainable and energy-efficient materials with improved thermal performance. The major issues and problems faced during the materialization are the following:

- Identification of materials and their thermal characteristics
- The standard for the identification and selection of materials
- Verification of thermal performance by lab testing, post-occupancy surveys, and monitoring
- Availability of material testing laboratory and monitoring equipment
- The standard of the manufacturing unit/ industry and the process

This chapter investigates the materialization taking into consideration the study objectives mentioned above. The first section of this chapter presents the introduction, aim, and objectives and underlines the problems faced in the materialization study. It further focuses on past research and knowledge gap in Pakistan and presents study design. Section 8.2 highlights passive design solutions based on Chapter 7. Section 8.3 presents an inventory of the essential building materials locally available and manufactured in Pakistan and their thermophysical properties. Section 8.4 summarizes the feedback of architects and residents. The discussion and recommendations are made in Section 8.5, and the last section concludes the findings of this study.

8.1.1 Past research

There is an extensive body of literature examining the process of materialization and barriers affecting the selection of building materials for construction projects. Several manuals provide the guidelines for selecting building materials (Akadiri & Olomolaiye, 2012; Baharetha et al., 2013; Florez & Castro, 2013). These studies focusing on sustainability, durability, energy efficiency, maintainability, and local materials to reduce environmental impact. In some studies, barriers affecting the selection of building materials were identified, including lack of knowledge, lack of relevant laws and legislation, lack of training and tools, maintenance concern, cost factor, limited availability etc. (Akadiri, 2015; Ikediashi et al., 2012). By reviewing past studies, it was found that the materialization process can improve decision-making by providing first-hand information in several ways:

- Increasing knowledge of materials and their performance
- Reducing decisional uncertainty
- Increasing the robustness of design

There is currently a knowledge gap regarding the energy-efficient and sustainable building materials that can be used to adopt passive design solutions in Pakistan. The potential for using such materials in the country is very high considering its large population, energy demand and growing housing sector. In recent years, the Government of Pakistan (GoP), the State Bank of Pakistan (SBP) and other stakeholders introduced several new measures to facilitate the housing and construction sector. Such efforts include a single platform for all planning, construction, utility and infrastructure permission, provision of loans on lower markup and easy instalments for the construction of houses (Iqbal, 2020; *SBP*, 2020). In this situation, the knowledge regarding building materials with better thermal performance and their selection will help the architects and residents in constructing thermally comfortable residential buildings, reducing the energy poverty and energy demand in the country.

8.1.2 Study design

The conceptual study framework for this research includes several steps, i) identifying influential passive design solutions to improve the indoor thermal comfort of houses in the climate of Quetta. (ii) identifying the locally manufactured and available building materials which can be used to adopt those passive design solutions. (iii) enlisting the thermophysical characteristics and thermal performance of the materials. (iv) and combining the experiences of architects and residents. In the last sections, a discussion and conclusion on the materialization are presented. Figure 8.1 illustrates the conceptual study framework for materialization study.

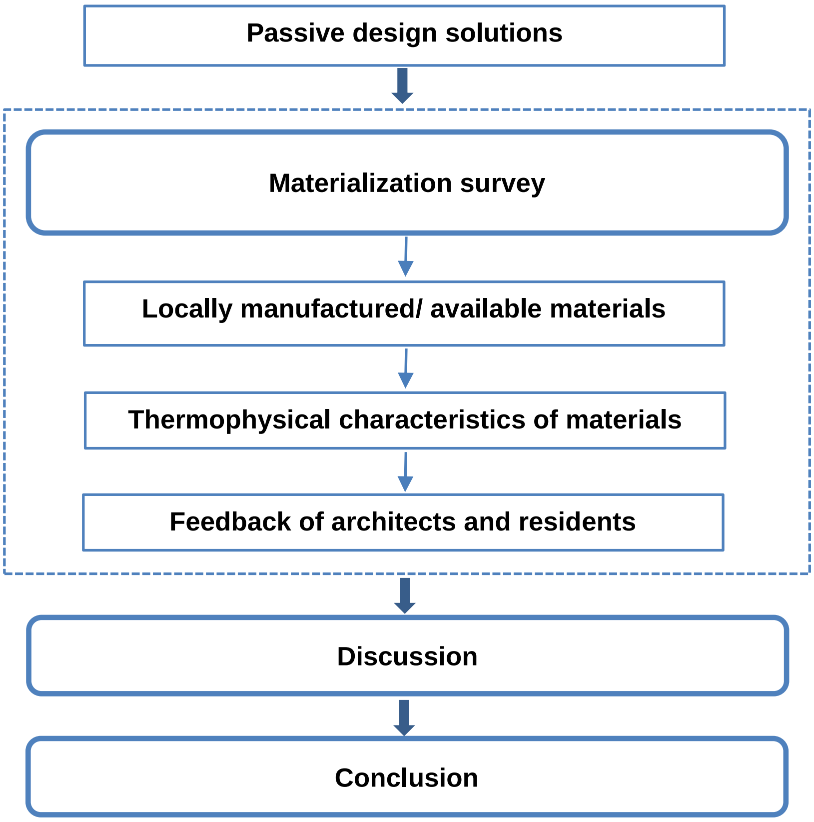


Figure 8.1. Conceptual study framework for the materialization

8.2 Passive design solutions

In Chapter 6, a sensitivity analysis of passive design strategies was performed to identify the influential design variables for improving indoor thermal comfort in the cold semi-arid climate of Quetta, Pakistan. Based on the results of this study, it was found that insulation, glazing type, windows shading, window-to-wall ratio, natural ventilation, the thickness of insulation materials, construction of external walls (thickness), building orientation (long azimuth angle) are the most influential design variables (Figure 7.5 and Table 7.10). The materialization of these design variables or solution is essential, which can be adopted in the construction of houses to improve indoor thermal comfort. Table 8.1 shows the most influential passive design solutions based on sensitivity analysis. It also highlights the building elements that need some materials or design interventions to improve indoor thermal comfort. In the materialization study, the focus will remain on insulation and glazing materials. The factors such as window-to-wall ratio (WWR), window shading, and building orientation depend on the design of houses. In comparison, natural ventilation depends on building design, climate, wind direction, design of opening, etc.

Table 8.1. Passive design solutions based on influential design variables

Passive design solution	Building element
Insulation	Roof
	External walls
	Thickness of Insulation in walls
	Floor
	Thickness of Insulation in roof
	Thickness of Insulation in floor
Glazing and	Glazing type
shading	Window shading (overhang)
	WWR
Ventilation	Natural ventilation
External wall	Changing construction materials
	Thickness of walls
Building orientation	South oriented

8.3 Materialization survey

A materialization survey was conducted in Quetta, Pakistan, to identify locally manufactured and available materials. The data collection was done through physical visits, questionnaire, semi-structured interviews, phone calls, emails, websites and product information brochures. In total, 17 material suppliers or distributors, ten architects and ten residents participated in this study. The data were collected using a snowball sampling technique, which is applied when samples with the target characteristics are not easily accessible (Naderifar et al., 2017). In several research studies, factors such as lack of human resources, inadequate equipment, high expenses, lack of precision, and population distribution prevent researchers from investigating the entire population (Ahmadzadehasl & Ariasepehr, 2010). The Snowball sampling method can be helpful in such studies. In this method, the current study's subject recruits future subjects chosen from their acquaintances, and the sampling is continued till data saturation. This method is also called the ‘chain method’. In this method, the first few samples are selected using convenience sampling. The researcher asks the subjects if they know anyone with a similar profile or situation to take part in the study. For example, the first few architects referred to more architects and residents who use or installed insulation and double glazing products. The first few material suppliers referred to other material suppliers who also sell similar products.

The materialization study was carried out in Quetta, Pakistan, during February and March 2020. Initially, the most common insulation and glazing products were identified using the websites, product brochures and material directory. Architects and Builders Source Book (ASB) is the most famous building materials and products directory in Pakistan. This directory also includes the listing of architectural, civil and construction firm. This directory is annually published since the year 2000 (*ASB*, 2019). The material suppliers in Quetta were then visited to gather the data regarding the available insulation and glazing products. The suppliers were asked to fill a short questionnaire. The semi-structured interviews were conducted with the architects and the residents to understand their knowledge and express with the selected materials. These interviews took place face-to-face, online, and via telephonic conversation. All participants were informed about the purpose of the research, and their consent was obtained. Table 8.2 presents the details of the participants. The data were analysed using both quantitative and qualitative approaches. The questionnaire used for the materialization study is reported in Annexure D.

Table 8.2. Details of the participants

Category	No of participants	Survey technique
Material supplier/ distributor	17	Questionnaire
Architects	10	Semi-structured interview
Residents	10	Semi-structured interview

8.3.1 Locally manufactured and available materials

It was found that some insulation and glazing products are manufactured in Pakistan. There is not enough competition among insulation products, and two of them are mainly used, Diamond Jumbolon and Master Thermoshield polyurethane roof insulation. In glazing products, most of the manufacturers mainly produce single glazed clear window glass. Table 8.3 presents the names and details of the identified insulation, glazing products. The manufacturers of double glazed window glass are only included in this list. In the following list, three glass distributor companies have no local manufacturing units in Pakistan, HiTec Engineering Services, Aluminium Product Corporation and Saint-Gobain Glass.

Table 8.3. Building materials and products manufactured/ available in Pakistan

Passive solution	Manufacturer/ Distributor	Product details
Insulation	Diamond Jumbolon	Board, spray, rolls, power mesh, sealer, nanocrete
	Conex Tile	Heat insulation tile
	Insugreen	XPS rigid insulation foam board
	Master	Thermoshield polyurethane roof insulation
	The Product Group	SPF spray polyurethane foam solution
	Arish Dry Wall Systems	Gypsum board
	Industrial Enterprises Pvt. Ltd.	Thermopore sheets
Glazing	HiTec Engineering Services	Glass facades, aluminium windows and doors
	Ghani Glass	Glass facades, double glazed glass
	Aluminium Product Corporation	Aluminium and glazing
	Greentech Glass Works Pvt. Ltd.	Glazing and glass
	Time Safety Tempered Glass	Glass and frames
	Gunj Glass	Tempered, double glazed glass
	Tariq Glass	Double glazed glass
	Akbari Glass	Double glazed glass
	Lakhani Glass	Double glazed glass
	Saint-Gobain Glass	Double glazed glass
Roof coatings	Diamond Jumbolon	Polyurethane spray
	Zahabiya Chemical Industries	SolaBlock RC-211 Roof Coating
	Nippon Pakistan	Nippon Weathershield coat

8.3.2 Thermophysical characteristics of materials

Thermophysical characteristics provide information on the thermal and energy performance of building materials. The most common factors to be considered are thermal conductivity, density and specific heat capacity. The solar heat gain coefficient (SHGC), light transmission (LT) and U-value are essential factors to be considered for glazing.

Table 8.4. Thermophysical characteristics of locally manufactured and available insulation products

Manufacturer / Distributor	Product name	Properties				
		Size (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Thickness (mm)
Diamond Jumbolon	Board	2500x900	0.026	32 ~ 38 (±10%)	---	20 ~ 75
	Rolls	---	0.029	25 ~ 70 (±10%)	---	---
	Concrete tile with thermopore	---	---	---	---	---
Conex Tile	XPS rigid foam	2500x900	0.028	32 ~ 40 (±10%)	---	20-75
Insugreen	Thermoshield polyurethane	---	0.018	35	---	---
Master	Spray insulation			32 ~ 35	---	
	XPS rigid board	---	0.028	---	---	---
	Polyurethane board	---	0.018	30	---	---
	Spray polyurethane foam	---	0.037	65 ~ 160	---	---
	Glass wool	---	0.041	32 ~ 38	---	---
The Product Group	PE foam sheet	---	0.034	---	---	---
Arish Dry Wall Systems	Gypsum board	1220x3050	0.19	---	---	9-15

Legend: XPS, extruded polystyrene; PE, polyethylene

In addition to that, the durability, porosity and fire-resistant properties of materials are also important. Table 8.4 presents the thermophysical characteristics of locally manufactured and available insulation materials, and Table 8.5 shows a list of locally manufactured glass products.

The Diamond Group of Industries is the largest manufacturer and distributor of insulation products in Pakistan marketed with the product name of Diamond Jumbolon in Pakistan. The company was established in 2005, and its manufacturing unit is located at Sundar Industrial Estate, Lahore, Pakistan. Diamond Jumbolon insulation products were used in various buildings across the country, including residential buildings, university campuses, hotels and commercial buildings. However, no data is available on post-occupancy survey and monitoring of indoor thermal comfort in these buildings. The second prominent manufacturer of insulation materials in Pakistan is the Master Group of Industries. Their products are marketed with the name of Master Thermoshield.

Table 8.5. Properties of locally manufactured glass products

Manufacturer/ Distributor	**Max. size (mm)**	**Min. size (mm)**	**Available thickness(mm)**	**Thermal characteristics**
Ghani Glass (Double glazed)	2500x3000	280x400	3-12	Unknown
Gunj Glass	2311x3480	---	---	Unknown
Greentech Glass Works Pvt. Ltd.	2500x3500	---	---	Unknown
Lakhani Glass	---	---	---	Unknown

Table 8.6. Glass performance specifications of Saint-Gobain Glass (SGG)

Coated glass DGU (6-12-6 mm)	**Low-E**	**LT (%)**	**SHGC**	**SC**	**U-value (W/m^2K)**
Clear glass	Unknown	80	0.76	0.87	2.8
KT 155	Unknown	47	0.38	0.43	1.88
KNT 140	Unknown	36	0.27	0.31	1.8
PLT T	Unknown	75	0.57	0.66	1.77
KS 138 II	Unknown	36	0.26	0.29	1.6
KS 146	Unknown	42	0.3	0.34	1.6
SKN 165	Unknown	60	0.33	0.38	1.54
SKN 154 II 140	Unknown	49	0.27	0.31	1.5

Legend: DGU, double glazed unit; LT, light transmission; SHGC, solar heat gain coefficient; SC, shading coefficient

The specific heat capacity of insulation materials and thermal properties of locally manufactured double-glazed glass products remain unidentified. During this study, the researcher contacted the manufacturers and suppliers; however, no data was provided regarding these two parameters. It was discovered that a few companies are mainly dealing as distributors of imported glass manufacturers. The most prominent of them is Saint-Gobain

Glass (SGG), a French multinational company. The SGG glass products were used in several construction projects in Pakistan, including hospitals, hotels, and commercial buildings. Table 8.6 provides the specifications of the available glass products of SGG in Pakistan.

8.3.3 Feedback of architects and residents

The feedback and opinion of architects and residents (who used insulation or double glazing in their houses) were gathered using semi-structured interviews. It was discovered that only Thermopore and Diamond Jumbolon board were locally available in Quetta city. The rest of the products are procured from other cities by creating an advance order of the required materials and their quantity. The aluminium and UPVC frames and double-glazed glass are locally unavailable, mainly procured from other cities, such as Karachi and Lahore. As mentioned in Chapter 4, only 25% of the houses in Quetta used double-glazed windows out of a sample of 215; while single-glazed windows were used in 71% of the houses, which shows that the use of double glazing is still limited.

Feedback of architects

The feedback of architects is incorporated in this study rather than of material suppliers and manufacturers. Table 8.7 provides insights into insulation and double glazing usage in Quetta. It is essential to mention that several homeowners also seek design and consultation services from architects based in other major cities of Pakistan, such as Karachi, Lahore and Islamabad.

Table 8.7 Use of insulation and double glazing in the houses of Quetta

Architect	**Years of practice**	**Use of insulation**		**Use of double glazing**
		(No. of houses)	**Insulation type**	**(No. of houses)**
1	27	1	Thermopore (own house) Walls: Thermopore (3.8 cm) Floor: MFD flooring	---
2	25	8 3 13	Diamond Jumbolon board Diamond Jumbolon spray Thermopore (3.8 cm)	30+
3	32	2	Thermopore (3.8 cm)	8
4	17	7	Thermopore (3.8 cm)	
5	19	0	----	----
6	16	0	----	----
7	16	3	----	----
8	14	0	----	----
9	7	0	----	3
10	6	0	----	9

Legend: MFD, metal floor deck

The use of insulation materials is uncommon in Quetta, and only 4% of the houses out of 215 were insulated (Chapter 4). In recent years, double-glazed windows are used in some houses, yet it is not very popular. The architects do not usually recommend using insulation materials and double-glazing unless the client asks for it. The thermopore sheets are considered the most popular solution. It is due to its easy availability and installation process. However, the thermal properties of the available thermopore sheets and their performance is unknown. Increasing the thickness of external walls is a common technique used in Quetta and many other parts of Pakistan. This technique is used for several decades and was even very popular during the British and post-independence period. In Quetta, the thickness of the outer walls is still preferred to be 27 cm. The architects also introduce a cavity wall in some of the houses. Most building professionals believe that the building bylaws in Quetta are exceptionally relaxed and don't provide necessary guidance regarding the construction of new houses. The existing bylaws also have no provisions or instructions related to climate-based design, selection of materials, indoor thermal comfort, and energy-efficiency improvement.

The use of insulation materials, their fixing and proper placement during construction is crucial for any project. The availability of skilled labour remains a challenge in many parts of Pakistan. The primary insulation manufacturers, i.e. Jumbolon and Master, always prefer that their trained staff install and apply insulation materials. In the case of Quetta, such a team come from Karachi for a specific project which increases the initial cost of the project.

Generally, cost and economic affordability are considered the primary factors while making construction decisions in Pakistan. In most cases, the lower initial cost is preferred than the long term cost saving. According to the building professionals in Quetta, when they inform their clients of increased cost using insulation or double glazing, the clients choose not to use any such interventions. Many of these clients could easily afford such cost and construction interventions, yet they don't think of long term cost saving. The designers and materials suppliers fail to provide satisfactory assistance and details to their clients to motivate them for energy-saving measures. Many manufacturing companies and suppliers focus on commercial, corporate, and public buildings rather than residential units. The nationals regulations also don't enforce measures such as using insulation and double glazing for residential buildings.

Some figures are included here based on the common practice for the application of insulation products. Figure 8.2 presents details of brick wall insulation, and concrete wall insulation details are shown in Fig. 8.3. The roof insulation with the mud layer is shown in Fig. 8.4, and

Fig. 8.5 represent the details of roof insulation with PCC slab. The recommended insulation board size should not exceed 1.5 m^2.

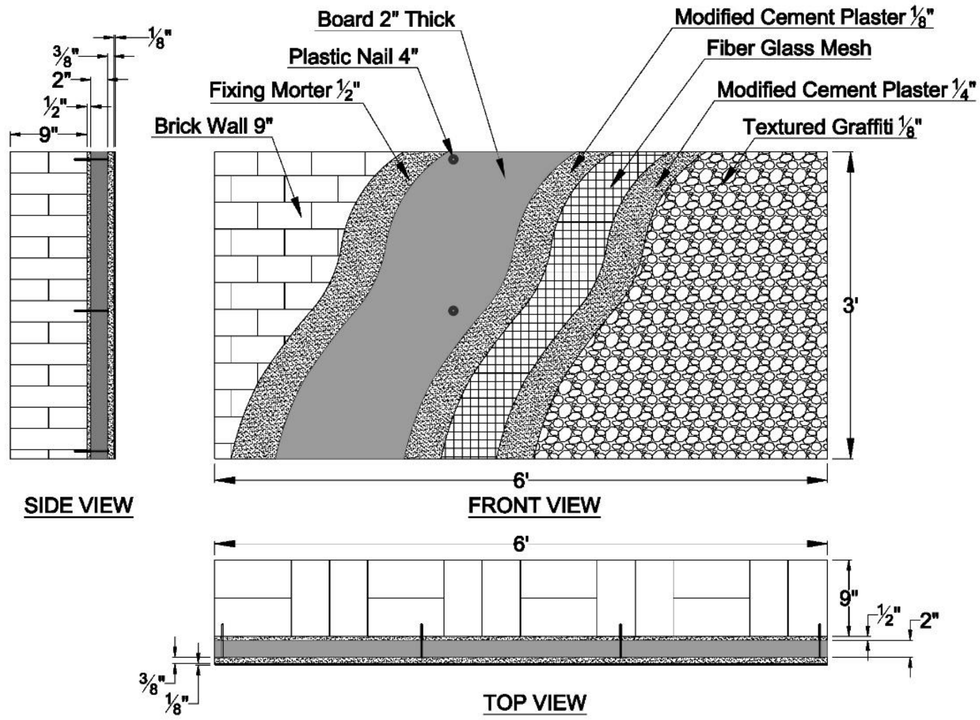


Figure 8.2 Brick wall insulation

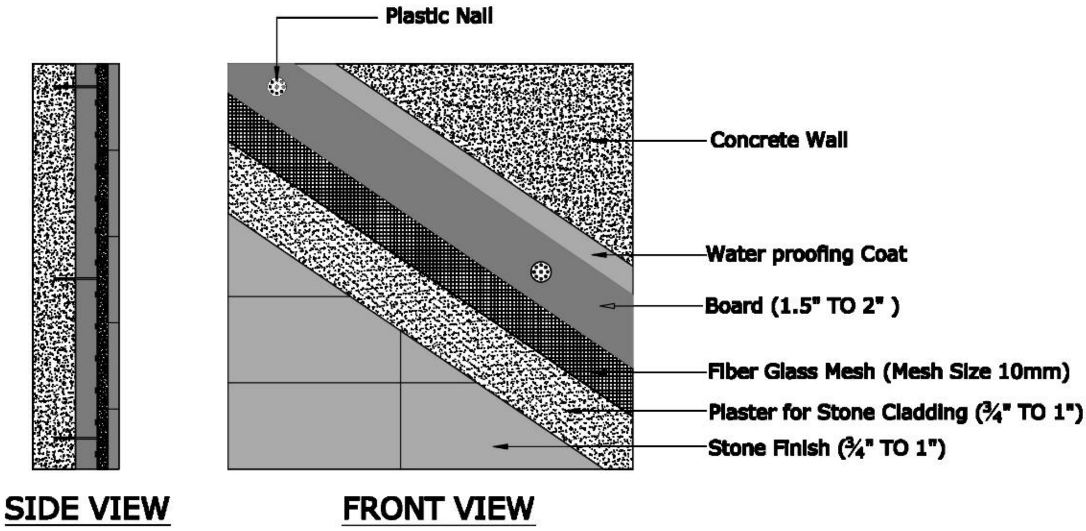


Figure 8.3 Concrete wall insulation

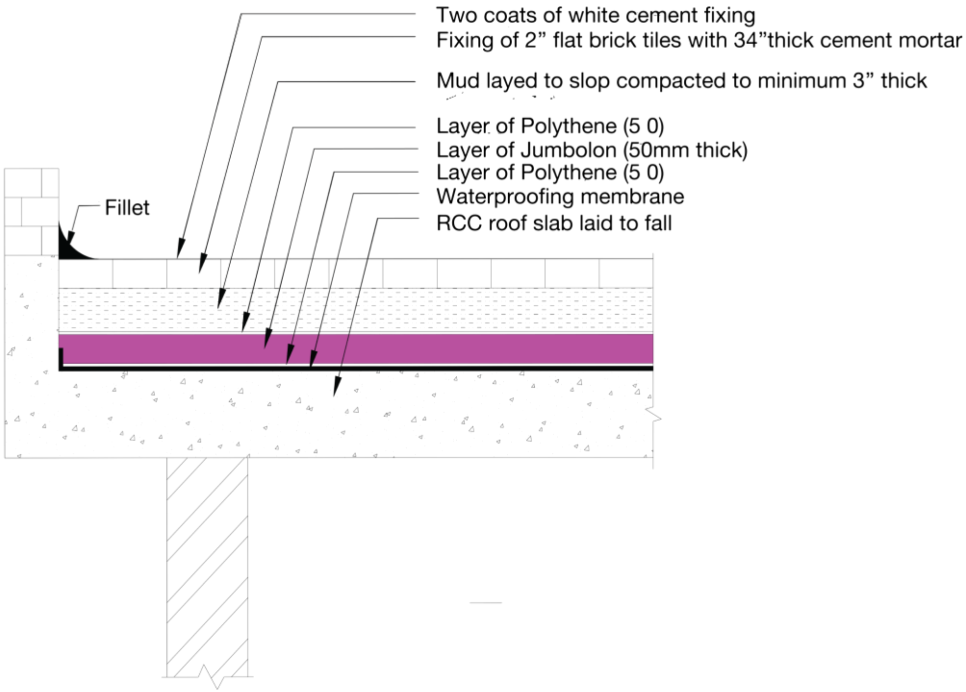


Figure 8.4 Roof insulation with mud layer

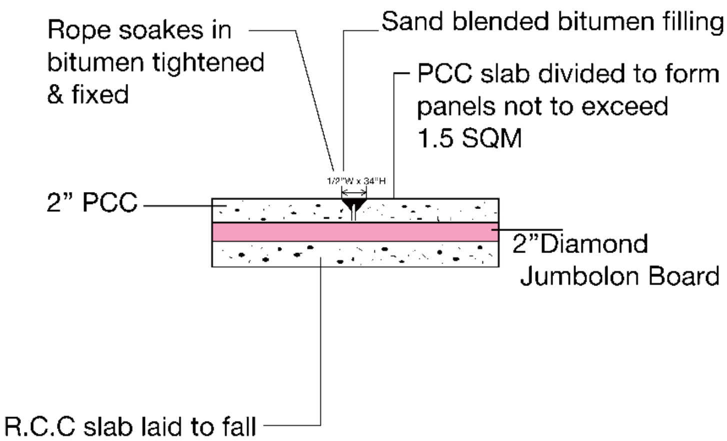


Figure 8.5 Roof insulation with PCC slab

Feedback of residents

The opinion of residents regarding insulation materials, glazing, and passive design techniques was also collected. The lack of awareness regarding the passive measures was noticed among the residents. The majority of households rely on active systems for cooling and heating.

It was noted that, although manufacturers claim to achieve comfort and temperature reduction by using their materials, they do not provide thermal properties or validation of their claims. The cost calculation factor is not emphasized to show the projected savings on energy expenses in future.

The residents who have insulated one or more building elements of their homes are unaware of the cost-saving or the actual indoor temperatures. Once a technique or insulation materials were used in a specific house, no indoor temperature or comfort analysis measurements were performed. It is also due to the lack of architects' knowledge and expertise and the unavailability of indoor climate measurement and simulation tools. Overall, the residents wish to improve their houses' indoor comfort using energy-saving measures and materials. Yet, they need to get credible information regarding material specifications and the potential of cost and energy savings.

8.4 Discussion

The findings of the materialization study are discussed further in the following sections.

8.4.1 Key findings and recommendations

For this study, a survey of locally available and manufactured materials was conducted in Pakistan to identify energy-efficient building materials. The survey also includes a questionnaire and semi-structured interviews with the architects and end-users to seek their feedback for specific materials. Thermophysical properties and the cost of materials were identified to assist decision support in selecting materials for architects and end-users. The results show a lack of energy-efficient and sustainable materials available and manufactured locally in Pakistan, especially in Balochistan province. It was found that none of those materials is manufactured in Balochistan and is mainly procured from other major cities of Pakistan such as Karachi, Lahore and Islamabad. There is also a lack of skilled labour for the application of such materials in building construction. The end-users need to procure materials from other provinces and need skilled labour, which increases the cost of construction.

Based on the comparison of various factors such as manufacturing, supplier's network and skilled labour for the application of building materials, it was found that Diamond Jumbolon insulation boards and insulation sheets are the best available options for the insulation of walls, roofs and floors. The imported double glazed glass by Saint-Gobain Glass is readily available and reliable due to its distribution network and glass quality. The thermal properties of locally manufactured glass were not available and provided by the manufacturers.

The study identified some crucial problems related to energy-efficient materials. Several material manufacturers failed to provided thermophysical characteristics of building materials. There was also no certification and laboratory testing report available for materials, including locally manufactured glass products, Conex Tiles, Insugreen board, Arish Dry Wall Systems, SolaBlock RC-211 Roof Coating. There is no standard and labelling or rating system at the national level to select energy-efficient materials in Pakistan. There is a lack of infrastructure and legislation to verify thermal characteristics and energy performance of building materials in Pakistan. Moreover, the regulatory body set no criteria or recommendation for the selection of materials.

Based on the study, some recommendations are made for the regulators, manufacturers, architects and end-users.

- The regulators need to create an ecosystem that would encourage the manufacturers to produce research-based, energy-efficient and affordable building materials. There is a need for a standard or guidelines for the selection of materials. A method of registration, certification, testing and validation should be followed before the availability of materials in the local market. Currently, there is no testing laboratory or certification and registration system at the national level. Furthermore, the regulators may develop a directory of such materials after following the strict registration and testing system to provide informed decision making support for architects and consumers. An inspection and quality check system should be adopted for the locally manufactured materials to ensure cost and energy-efficient materials at the local level.
- The material manufacturers need to introduce a research-based approach to ensure the quality and performance of manufactured materials. They also need to get certification and validation of the energy efficiency and thermal performance of materials. The manufacturers may also establish a state-of-the-art material testing laboratory for the testing of building materials. There is a need for creating awareness by providing scientific data based on cost-saving, energy-efficiency, long term saving and environmental benefits of the materials.
- The architects need to advance their knowledge in the field and introduce passive design measures and energy-efficient materials in their design. They also need to

provide valid information to their clients to select materials and cost-saving in the long term.

- The consumer needs to adapt to the passive design-based solutions to improve energy efficiency and indoor thermal comfort in dwellings rather than relying on active systems. It will provide a better indoor environment at a lower cost and less damage to the environment.

8.4.2 Strengths and limitations of the study

This study's strength relates to its data collection and survey method, including material manufacturers, suppliers, architects, and consumers. The data was collected by physical visits, calls, emails, websites, product information brochures, questionnaires and semi-structured interviews. The study provided first-hand information and informed decision-support for selecting materials that can be used to improve indoor thermal comfort.

The study further includes architects' feedback and opinion regarding using specific building materials in the cold and semi-arid climate. It was found that the use of insulation and double glazing is not common in Quetta. This is due to the lack of information and confidence of architects and end-users in the available materials.

The study also has some limitations, including the materialization of products focused on improving building envelope to improve indoor thermal comfort. The focus remains on passive design solutions, which are influential in the climate of Quetta. The current materialization only consists of insulation materials and glazing products, including insulation boards, sprays, roof coatings, tiles, sprays, and glazing types available in Pakistan. The cost and economic affordability factors were not calculated in this study. The calculation of cost depends on several factors, i.e. type of material, the quantity of material, size of the project, application by skilled labour (locally available or outsourced), transportation etc. The affordability analysis needs to be done thoroughly by understanding the residents' financial profile, which is not within this study's scope.

8.4.3 Study implications and future research

Pakistan is a big country with a growing population and a variety of climatic conditions across the country. There is a lack of housing with a substantial annual backlog and increasing demand for new housing units. The government of Pakistan has an ambitious plan to build new houses by assisting developers and owners. However, the construction of sustainable, energy-efficient and thermally comfortable houses remain a big challenge. At the national level, there is no standard or policy to guide architects and consumers for energy-efficient materials which can be used to improve indoor thermal comfort. There is a need to develop a directory of the locally available and manufactured materials and their thermal properties and cost-saving benefits. A tool can be created for the comparison between various materials for their technical and economic benefits. Furthermore, the climate-based recommendation for the use of specific materials can be included in such a tool. The developed directory of materials and comparison tools will support architects and consumers to select materials to improve indoor thermal comfort.

A network of material testing laboratories can be established in major cities for the registration, validation and quality control of available building materials. The regulatory body can develop a labelling or star rating system for the materials based on their thermal performance, energy efficiency and cost-saving analysis. It will encourage manufacturers to produce high-quality materials based on advanced research and manufacturing standards. It will further motivate the architects and consumers to apply and adapt to the latest materials and construction techniques.

There is a need to explore sustainable and energy-efficient materials with better thermal performance in a specific climate. Using such materials will lead to cost-efficiency, energy efficiency and improved indoor thermal comfort. Therefore, further studies may focus on (i) laboratory testing, and validation of the thermal performance of specific materials, (ii) Cost efficiency and cost-savings achieved using particular materials, (iii) climate-based recommendations and guidelines based on scientific validation of the thermal performance of specific materials under certain climatic conditions.

8.5 Conclusion of the chapter

It is concluded from the findings of this study that there is a need of legislation and improvement of building code at the national or city level in Quetta. The building professionals need to learn new techniques and acquire knowledge for passive design and constructions. Awareness of residents is another important factor, where the public and private sector need to play their role to educate people for adopting passive design measures. However, the regulator needs to do a lot to ensure the available material's quality is of a high standard. There is a lack of policy, implementation and adaptation at the national level regarding sustainable, energy-efficient materials with better thermal performance. The existing infrastructure doesn’t provide testing and certification labs for several building materials which are locally manufactured or available.

CHAPTER 9: DEVELOPMENT OF DECISION-SUPPORT METHODOLOGY: A PRESCRIPTIVE GUIDE

9.1 Introduction

The lessons from practice show that improving indoor thermal comfort considering climate-responsive and passive design strategies is a complicated, arduous, and costly task. The uncertainty in decision-making for the design and construction of thermally comfortable houses (TCH) is high. The integration of passive and climate-responsive design strategies and selecting materials during the early design phases is a complex and time-consuming process. It requires an adequate level of expertise and the tools and software packages that are not readily available. At this stage, the architects are constantly searching for a design direction to provide informed decision support. The success or failure of a design can be determined by the decision taken at the early design stage. It is essential for thermal comfort in buildings to assure informed decision-making at the early design phases. It includes integrating climatic data and analysis with building performance simulation (BPS) tools at the early stages of the design process. However, it is not easy for architects to learn BPS tools and perform simulations for small residential projects. The primary question that arises at this stage is: How to design climate-responsive and comfortable buildings in a structured way in the cold and semi-arid climates?

This chapter's main objective is to develop a decision support methodology in the form of a prescriptive guide that can help architects design climate-responsive buildings with improved indoor thermal comfort. In architectural research, it is common to develop design support methodologies with a procedural approach, as discussed in Chapter 3. A methodology is ordered in a sequence to achieve a design solution for a design problem. This chapter combines the findings rendered in Chapters 4-8 to develop a decision-support prescriptive guide for architects to provide informed decision making at the early stage design. The focus remains on the effective passive design solutions in the cold and semi-arid climates of Quetta based on the sensitivity analysis performed in Chapter 7. This section covers the introduction, research aim and objectives—a description of the decision support prescriptive guide is presented in Section 9.2. The prescriptive guide's scoping analysis is reported in Section 9.3, while Section 9.4 introduces the developed prescriptive guide for architects. Section 9.5 and 9.6 consists of discussion and conclusion, respectively.

9.2 Description of the prescriptive guide

In response to the problems, barriers, requirements, and expectations related to thermal comfort in residential buildings of Quetta, a prescriptive guide was developed to provide informed design decision support for architects. This prescriptive guide provides a conceptual framework for a software-based tool that can be created in future but is not a part of this PhD research. The developed prescriptive guide aims to address the shortcoming by providing informed decision support to architects at early design stages for the design and construction of residential buildings with improved thermal comfort in the cold and semi-arid climate of Quetta. The guide is contextual and based on an embedded benchmark model and inventory of residential buildings in Quetta, including local materials and construction techniques. Figure 9.1 shows the process for the development of the prescriptive guide. These steps include the i) characterisation of housing stock in Quetta and benchmark study from the survey of 215 houses in 32 residential areas. ii) comfort and parametric analysis, iii) sensitivity analysis of 21 passive design variables for identifying influential variable in the climate of Quetta. iv) and materialization study. This prescriptive guide was then tested for its application and validation among the architects and architectural students through usability testing. The usability test also compared the building code of Pakistan with the developed prescriptive guide. Important feedback based on the usability test is reported in Chapter 9. This chapter highlights the prescriptive guide's development, while validation through the usability test is discussed in Chapter 10.

The prescriptive guide focuses on six important passive design solutions for the climate of Quetta, which includes insulation, openings, window shading, natural ventilation, external walls, and building orientation. This prescriptive guide's initial target audiences are architects and architectural students with little experience and knowledge of passive design and thermal comfort in buildings. This prescriptive guide will assist architects in lowering the barriers to designing buildings with improved thermal comfort. At the conceptual design phase, architects usually produce several design alternatives. At this moment, the prescriptive guide should be applied to increase the thermal comfort potential of the residential buildings.

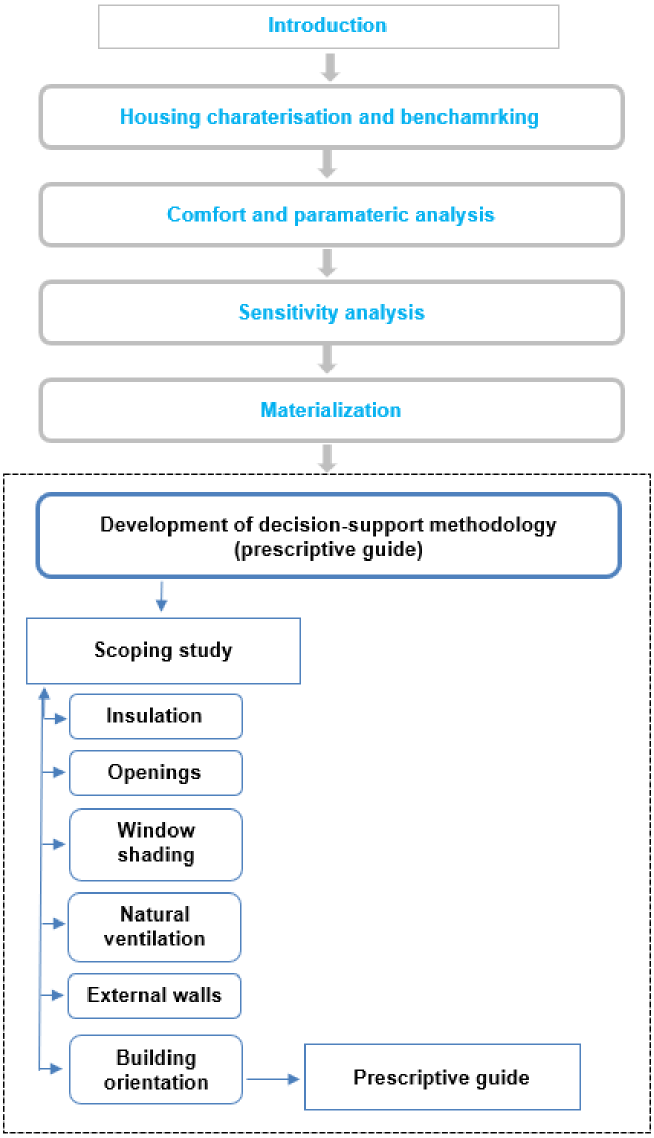


Figure 9.1 Process for the development of methodology (prescriptive guide)

9.3 Scoping study of the prescriptive guide

This section presents a scoping study of the effective passive design solutions for the climate of Quetta. In this scoping study, these passive design solutions are presented according to their importance associated with comfort improvement. The details of the scoping study are reported in the following sections.

9.3.1 Insulation

The climate of Quetta is heating dominated, where occupants face more discomfort during the cold season. The use of insulation is a common solution for the improvement of indoor thermal comfort. The buildings in Quetta are primarily constructed without using insulation. The sensitivity analysis results in Chapter 7 show that insulating the roof, external walls, and the floor significantly influences comfort. Table 9.1 presents the comfort improvement in the basecase model by using various types of insulations. The details of the basecase model are described in Chapter 6. It is found that polyurethane foam insulation is most effective in the selected climate.

Table 9.1 Comfort improvement using various types of insulation

Type of insulation	Thickness (mm)	U-value (W/m² K)		
		Roof	Wall	Floor
Polyurethane foam	30	0.7	0.66	0.56
	60	0.4	0.37	0.35
	90	0.28	0.26	0.25
Expanded polystyrene (EPS)	30	0.91	0.77	0.69
	60	0.54	0.49	0.45
	90	0.38	0.35	0.33
Stone wool	30	0.88	0.75	0.67
	60	0.52	0.47	0.43
	90	0.36	0.34	0.32
Glass–fibre batt insulation	30	0.96	0.8	0.71
	60	0.57	0.51	0.47
	90	0.41	0.38	0.35

9.3.2 Openings

The openings cover two important parameters, glazing type and window-to-wall ratio (WWR). Details regarding the scoping study of both parameters are given below:

Glazing type

By using sensitivity analysis, it was found that glazing is the second influential design variable in the climate of Quetta. The use of single glazed windows is a common practice in the dwelling of Quetta. However, the weather demands better quality, double glazed windows for the improvement of thermal comfort. Table 9.2 presents the decrease in U-value by using various types of windows glazing. Using LoE double glazed windows can reduce the U-value from 5.7 to 1.7 (W/m^2 K). In the materialization survey, it was found that LoE double glazed windows are not available in Pakistan. A double glazed window of 3mm (13mm air) is recommended in such a situation, which will reduce the U-value to 2.7 (W/m^2 K).

Table 9.2. Comfort improvement using various types of glazing

Type of glazing	**Thickness (mm)**	**SGHC**	**LT**	**U-Value (W/m^2 K)**
Single clear	3	0.86	0.89	5.7
Single LoE (e2 = 0.2) clear	3	0.76	0.82	3.8
Double clear (13 mm Air)	3	0.76	0.81	2.7
Double clear (13 mm Arg)	3	0.76	0.81	2.5
Double Reflective-D (13 mm Air)	6	0.42	0.3	2.6
Double Reflective-D (13 mm Arg)	6	0.42	0.3	2.4
Double LoE (e2 = 0.1) clear (13 mm Air)	3	0.59	0.76	1.7
Double LoE (e2 = 0.1) clear (13 mm Arg)	3	0.59	0.76	1.5

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

Window-to-wall (WWR) ratio

The Window-to-wall ratio is another essential variable to be considered in the cold climate. The existing practice in Quetta is of using windows with small glazing and opening. It is also due to privacy and cultural consideration in some tribal and religious environments. The WWR ratio must be carefully determined for any residential project considering its site, geographical and climatic features.

The window-to-wall ratio is calculated using the following equation. Solar exposure can be reduced in summer by using internal curtains, blinds, or heat resistance films.

$$[illegible] = \frac{B_{[illegible]}}{B_{[illegible]}} \quad (1)$$

9.3.3 Window shading

Window shading is an essential factor that needs to be carefully considered in the building envelope design. The provision of shading devices in a hot climate can improve thermal comfort. While in a cold climate, shading is not an effective method. In the climate of Quetta, shading can provide comfort during hot summer, especially in June, July and August, when the outdoor temperature is above 25 °C. There is a need to design shading devices that can be used in summer and removed or adjusted in winter to get advantages of daylighting and solar heat gain.

9.3.4 Natural ventilation

Natural ventilation can assist in the improvement of indoor thermal comfort, especially in summer. An increase of 3% was noticed by introducing summer ventilation at night in the selected basecase model. It is recommended to carefully design windows and opening to benefit cross-ventilation (Table 9.4). However, privacy-related concerns limit the size of windows and openable area in the houses in Quetta.

Table 9.4 Comfort improvement using various ventilation scenarios

Scenario	Hours	Air changes per hours (ac/h)	Comfort improvement (%)
Night purge in summer	22h-06h	5	3

9.3.5 External walls

Burnt brick is the most common building material used for the construction of walls. The U-value of brick is much higher than the aerated concrete blocks and concrete hollow blocks of the same thickness, i.e. 22.86 cm. The following Table 9.5 reports the results of U-value reduction by changing materials and thicknesses. By increasing the thickness of bricks, a lower U-value can be achieved, which will lead to the improvement of comfort. However, increasing the thickness of walls will result in reduced indoor space and increased construction cost. Alternative materials such as aerated concrete block and concrete hollow blocks are better alternatives in this situation.

Table 9.5 Comfort improvement using various material in the external wall

External Wall Material	Conductivity (W/m K)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Thickness (cm)	U-value ($W/m^2 K$)
	λ	*D*	C_p		
Aerated concrete blocks	0.24	750	1000	22.86	0.85
				30.48	0.67
				45.72	0.47
Concrete hollow block	0.48	880	840	22.86	1.44
				30.48	1.17
				45.72	0.85
Sand-lime brick	0.75	1730	880	22.86	1.92
				30.48	1.61
				45.72	1.21
Burnt brick	0.85	1500	840	22.86	2.07
				30.48	1.7
				45.72	1.07
RCC walls	2.5	2400	1000	22.86	3.2
				30.48	2.97
				45.72	2.51

Legend: RCC, reinforced cement concrete

9.3.6 Building orientation

A comparison of eight possible orientations was performed for the basecase model. The results indicate that the best orientation for the climate of Quetta is the South. These results are reported in Chapter 6 (Section 6.3.2). The second best orientation was Southeast. The findings of sensitivity analysis reported in Chapter 6, show that the south is the best orientation for the long side of a building to benefit from solar heat gain during cold winter. The city of Quetta and its neighbouring areas receive average global solar insolation of 6.5-7.5 kWh/m^2/day, as shown in Figure 3.11 (NREL, 2007). The average sunlight hours in Quetta are 8-12.5h per day. It shows the potential of using sunlight during winter.

9.4 Decision support prescriptive guide

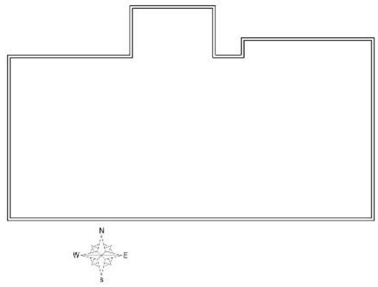
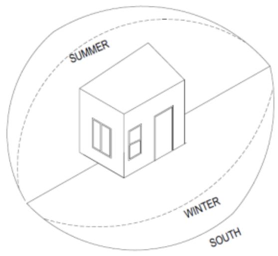
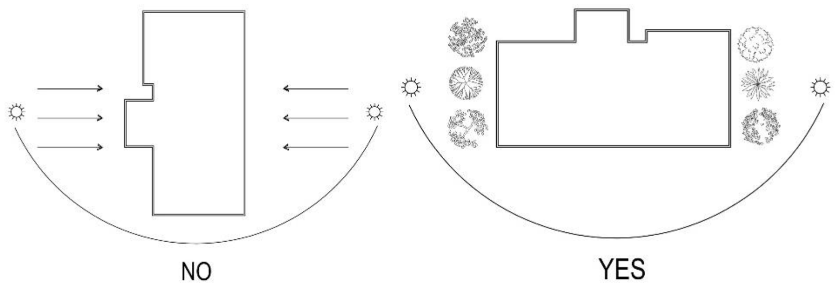
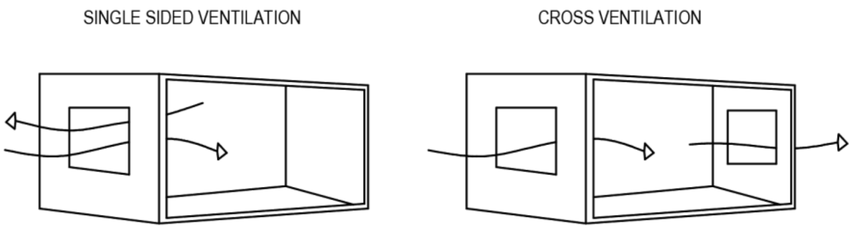
The prescriptive guide is the result of the findings made during various stages of this PhD research. This guide provides informed decision support to architects to improve indoor thermal comfort by applying six effective passive design solutions. In the prescriptive guide, these solutions are ordered considering the design process for a better understanding of architects. These solutions include building orientation, external walls, insulation, openings, window shading and natural ventilation.

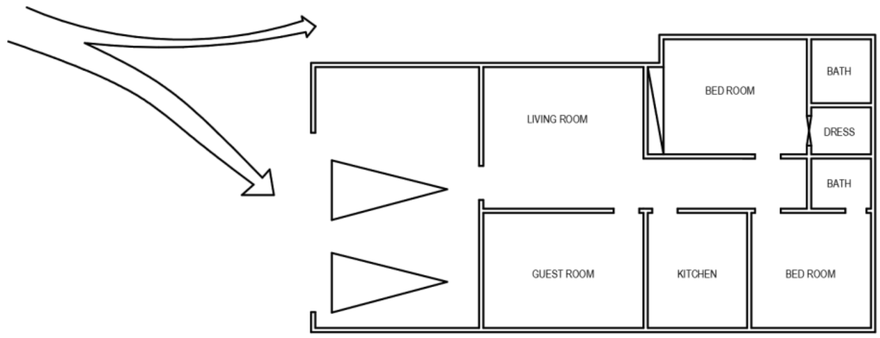
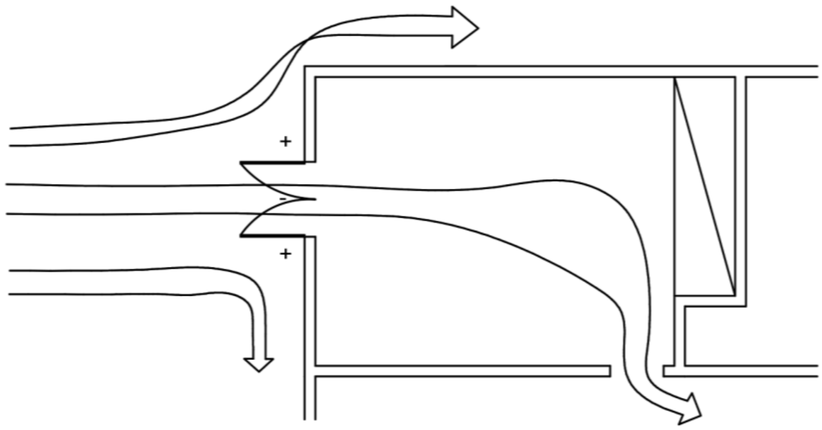
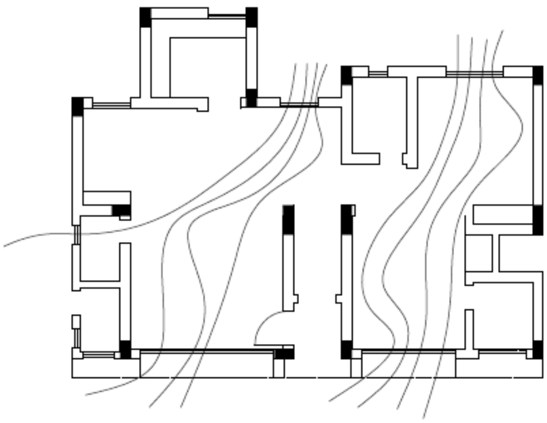
Purpose

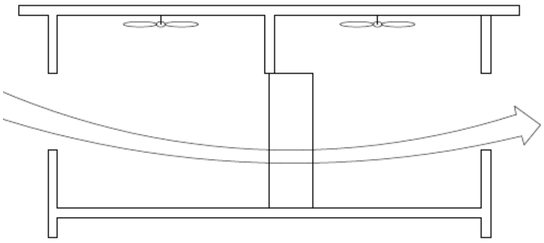
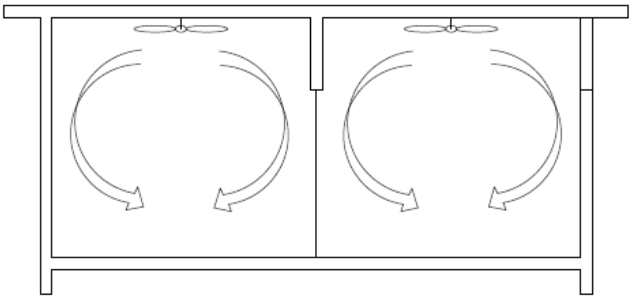
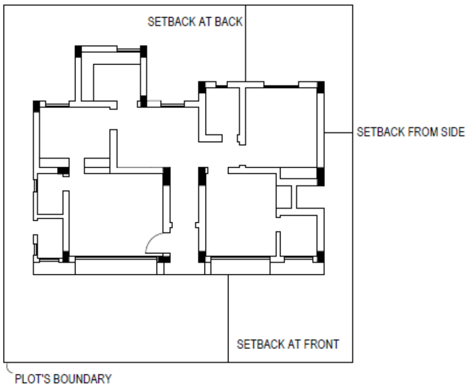
This prescriptive design guide aims to provide informed design decision-making support to architects for the design and construction of residential buildings with improved thermal comfort in Quetta, Pakistan. The guide also aims to create awareness among architects regarding thermal comfort, indoor environmental quality, and climate sensitivity in future constructions.

Building type

This prescriptive guide is limited to residential buildings and is context-based; however, a few recommendations can also be applied to other types of buildings in similar climatic conditions. The guide only focuses on reinforced concrete frame (RCF) houses and the thermal performance of new constructions. Some recommendations can also be useful for existing houses.

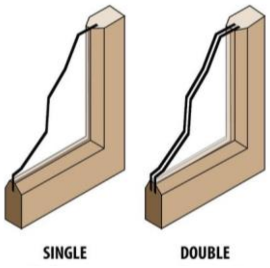
Building orientation	Position the long side of the building in the direction of the South. This will increase the potential of solar heat gain in winter. 
	Orient long building surface away from the hot western sun. Only the north and the south side can be easily shaded to avoid the sun in summer. 
	Arrange the floor plan to allow the penetration of winter sun during the day—position spaces used during the daytime toward solar orientation. Provide trees or plants on the west to avoid the sun in summer.
Natural ventilation	In summer, use natural ventilation at night. It will improve the comfort of up to 3%. Design houses with cross ventilation to provide better comfort in the hot summer.  Consider the security and privacy factors while designing a ventilation scheme.

	Locate parking and storage areas on the side of the building facing the coldest wind to keep building insulated. 
	Adequate natural ventilation can reduce or eliminate airconditioning in the warm summer. Orient windows to prevailing wind direction and provided shade during summer. 
	For better cross-ventilation, locate door and window openings on opposite sides of the building. Place larger opening facing the wind direction. 
	Use whole house fan or natural ventilation to store night cooling in summer in high thermal mass interior surface (nigh flushing) to reduce or eliminate air conditioning.

	
	In hot summer days use ceiling fans or indoor air motion. It cools the indoors up to 2.8 C and reduces air conditioning. 
Openings	There are two important factors while designing openings of a building, i) Window-to-wall ratio (WWR), and ii) glazing type. ***Window-to-wall ratio (WWR)*** Use larger windows on the South to get the benefit of solar heat gain in winter. Use smaller windows on the west to avoid the sun in summer. WWR shouldn't exceed more than 40%. In practice, small windows are used considering privacy and cultural factors. By providing setback within the plot's boundary, the issue of privacy can be addressed. This will allow architects to provide windows of appropriate size. 

Type of glazing

Use double glazed windows.



A comparison of reduction in U-value is shown below using different glazing types.

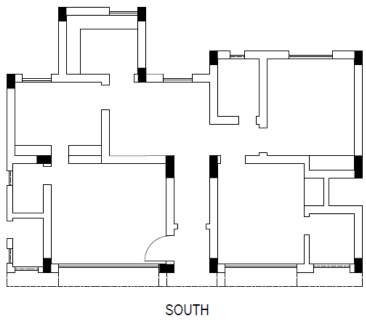
Glazing type	SHGC	LT	U-value (W/m^2 K)
Single glazing	0.81	0.88	5.7
Double glazed (3mm/13mm air)	0.76	0.81	2.7
Double glazing (LoE) (3mm/13mm air)	0.59	0.76	1.7

Windows frames: Use aluminium frames to benefit heat loss/ gain and maintain the indoor temperature.

Use double glazed high performance (Low-E) windows on the west, north and east side.

Use clear double glazed windows on the south side to maximize passive solar heat gain.

Face most of the glazed area to the south to maximize winter sun exposure.
Design overhangs to fully shade and avoid solar exposure in summer.



Window shading

Use adjustable shading to gain more benefit of solar light in winter and avoid the sun in summer, especially on the south side.
No shading is recommended in winter.

The curtains and window blinds are recommended in summer to avoid solar heat gain.

Use window overhangs (designed for the latitude) or operable shades (awning that extend in summer) to reduce or eliminate air conditioning.

Insulation

Use insulation to improve thermal comfort.

Insulating roof, walls and floors can increase thermal comfort by reducing the U-value.

By using 60 mm polyurethane foam insulation, a significant reduction was noted in the U-value of the common housing type.

<table>
<tr><td></td><td>
<table>
<tr><th>Building element</th><th>U-value (W/m^2 K) without insulation</th><th>U-value (W/m^2 K) with 60mm insulation</th></tr>
<tr><td>Roof</td><td>2.9</td><td>0.4</td></tr>
<tr><td>Walls</td><td>1.4</td><td>0.37</td></tr>
<tr><td>Floor</td><td>1.8</td><td>0.35</td></tr>
</table>
</td></tr>
<tr><td></td><td>Heat gain from lights, appliances and people reduce heating needs to keep the home tight and well insulated.</td></tr>
<tr><td></td><td>Use high thermal mass such as slab floors and thick walls to store passive heat in winter and night cooling in summer.</td></tr>
<tr><td></td><td>Use high thermal mass walls with exterior insulation (such as EIFS foam) and expose the mass on the interior side or cover with a plaster</td></tr>
<tr><td></td><td>Use light coloured building materials and roof coatings or cool roofs (with high emissivity) to minimize heat gain.</td></tr>
<tr><td>External walls</td><td>
Standard material: Burnt bricks with a thickness of 9” (22.86 cm)

U-value can be decreased by changing the materials. For example, an external wall constructed of aerated concrete block or concrete hollow blocks of the same size (22.86 cm) has a lower U-value.

A comparison of the U-value of 4 different materials is presented below:
<table>
<tr><th>Material</th><th>Thickness (cm)</th><th>U-value (W/m^2 K)</th></tr>
<tr><td>Aerated concrete block</td><td>22.86</td><td>0.85</td></tr>
<tr><td>Concrete hollow block</td><td>22.86</td><td>1.44</td></tr>
<tr><td>Burnt brick</td><td>22.86</td><td>2.07</td></tr>
<tr><td></td><td>30.48</td><td>1.7</td></tr>
</table>
The following materials are recommended considering their thermal performance in the selected climate.
1. Aerated concrete blocks,
2. Concrete hollow block,
3. Burnt brick
</td></tr>
<tr><td>Air leakages</td><td>
Air leakage means excessive energy loss and increasing cost. The problem of air leakages is common in Quetta, especially in winter when there is a need to maintain indoor temperature.

Most of the air leakages occur through window and doors.

Gaps around the door, window and ventilator frames (openings) should be sealed properly to avoid possible air leakages.
</td></tr>
</table>

9.5 Discussion

9.5.1 Summary of main findings

The decision support prescriptive guide was made to encourage informed decision-making to design thermally comfortable buildings at early design stages. It also increases the knowledge about indoor thermal comfort, building materials' thermal performance, climate sensitivity and passive design strategies. The developed prescriptive guide reduced the uncertainty in design decision making. The participants who used the prescriptive guide reported a high level of knowledge and achieved their design from an informative decision support approach rather than an evaluative trial and error approach. However, based on usability testing, the current prescriptive guide has not reached the architects' complete satisfaction level due to its limitation on six effective passive design solutions. As such, this prescriptive guide is a starting point for developing a widely applicable tool to assist decision making for the design of comfortable dwellings in Quetta.

9.5.2 Strength and limitations

This is the first decision-support prescriptive guide for the early-stage design of thermally comfortable buildings in Pakistan. This prescriptive guide's strength lies among its capacity to inform design before decision-making while reducing the time to perform extensive simulation analysis and evaluating complex data. The prescriptive guide is based on a representative benchmark for the residential buildings in Quetta using local building construction techniques and materials. Its link to advanced building performance and data analysis tools such as DesignBuilder, EnergyPlus, jEPlus and SimLab 2.2 reinforces its validity and certainty in decision-making. On the other hand, the tools based on weather data and the psychometric chart also include some strategies which are not suitable for the climate of Quetta, such as the provision of the courtyard, and verandah etc. The prescriptive guide is easy to use, with a structure based on passive design strategies for the improvement of thermal comfort. The prescriptive guide can help to improve the indoor thermal comfort of residential buildings in the cold and semi-arid climate of Quetta. At the early and conceptional design stage, better-informed decisions will help achieve occupant’s thermal comfort. The usability testing results revealed that the prescriptive guide provides better-informed decision support than the existing Building Code of Pakistan. It is hoped that several design trials will significantly impact the decision-making of architects and design outcomes and proceed further to creating a decision support tool in the future, which is not under the scope of this PhD research.

The current guide is mainly focused on passive design measures based on the influential variables identified using a sensitivity analysis. It does not cover several aspects such as building geometry, selecting materials, and active systems. The guide is the starting point to provide validated and context-based recommendation for improving indoor thermal comfort. The current prescriptive guide can be extended in the future to provide a holistic approach for designing residential buildings with optimal comfort combining active and passive systems and considering different design parameters and options.

9.5.3 Implications and future research

The prescriptive guide developed in this PhD research creates a basis for developing building code, standards, and guidelines for constructing residential buildings with improved thermal comfort in Quetta. The prescriptive guide is based on passive design strategies; combining active systems can lead to better and more comfortable indoor thermal conditions.

A design tool can be developed based on this prescriptive guide's findings to provide quick analysis and support in architects' decision-making. Future studies may focus on geometrical form and other design features of buildings. Issues such as active systems and renewable energy resources need to be studied to guide toward energy-efficient, sustainable, and nearly zero-energy buildings (nZEB) in Pakistan.

9.6 Conclusion of the chapter

The study aimed to develop a prescriptive guide to provide informed decision-making support to architects to design houses with improved thermal comfort in cold and semi-arid climates. The findings are useful for improving thermal comfort in existing houses and can be more effective in informing the designers and future dwellings residents. The results identify the six most effective passive design solutions for the climate of Quetta. The scoping study of various parameters and ranges assists in selecting the most suitable solution to be adapted for the improvement of indoor thermal comfort.

Considering the climate and geographical position of Quetta, this is the first study that provides informed decision making support for improving indoor thermal comfort in residential buildings based on local and universal knowledge. The prescriptive guide is developed using a mixed-mode approach that verified the climate, cultural, physical and behavioural reality of housing and construction in Quetta. The study allows future researchers to investigate solutions and technologies further to achieve maximum comfort by combining passive design and active systems.

CHAPTER 10: APPLICATION AND VALIDATION OF THE PRESCRIPTIVE GUIDE

10.1 Introduction

Informed design decision-support is the basis for the design of thermally comfortable houses (TCH). This chapter investigates the use of the prescriptive guide and Building Code of Pakistan: (Energy Provisions-2011) to inform the decision making for architects. This study evaluates the effects of prescriptive guide and BPC (EP-2011), on informed decision-making by performing a usability test. The objective is to assess the impact of prescriptive guide and building code on three specific outcomes: (i) knowledge and satisfaction when using the prescriptive guide or building code; (ii) users' decision-making attitudes and patterns, and (iii) performance robustness based on design analysis. The chapter utilizes the four design case studies to test informed decision-making by prescriptive guide and building code in designing climate-responsive and comfortable residential buildings. An assessment of the prescriptive guide's role in informing the decision-making was ascertained through several self-reported metrics. The chapter provides results that shed light on the prescriptive guide and BCP's effectiveness to inform the design decision support.

The background, objectives and research questions are discussed in this section. Section 9.2 covers the steps regarding the usability test and methods. The result of the usability test is presented in section 10.3. The prescriptive guide developed in Chapter 9 is further modified based on the usability test findings in section 10.4. Sections 10.5 and 10.6 covers the discussion and conclusion, respectively.

Aim and objectives

This usability test aims to test the prescriptive guide based on the findings of this PhD research and building code for informed design decision-making. It further aims to test and validate the prescriptive guide's application in the context of Quetta and propose possible improvements by adopting necessary changes based on the results of the usability test.

The following objectives are set for this study:

- To identify the standard design techniques and methodologies (in practice) used by architects and architecture students.
- To provide informed design decision support to architects and students for the improvement of indoor thermal comfort
- To test the improvement in design based on the existing Building Code of Pakistan (Energy Provision-2011) (*BEC*, 2011)
- To test and the improvement in design based on the developed prescriptive guide

10.2 Usability test

The usability test's main objective was to access and validate the improvements in the design of a typical house in Quetta by providing informed design decision support. The usability test comprises *effectiveness, efficiency and satisfaction* for a group of core tasks supported by the design guide to designing houses with better thermal performance using the techniques and solutions based on passive design principles and strategies. The ISO definition of usability comprising the three attributes-*effectiveness*, *efficiency*, and *satisfaction* was used as the basis for the metrics collected (*ISO 9241-11*, 2018).

A conceptual study framework was developed for this usability test, see Figure 10.1. The process is divided into two significant steps: preparation for the usability test and conducting the usability test. These processes are further defined in the following sections.

10.2.1 Preparation of usability test

The preparation of the usability test involved the following four steps:

- Identification of potential participants
    - Architecture students: 3rd year and above
    - Architects: with professional design experience
- Test procedures
    - ISO 9241-11:2018 Standard
    - Usability test brief
    - Workshop I: Building Code of Pakistan (Energy Provisions-2011)
    - Workshop II: Prescriptive guide
    - Surveys: After scenario questionnaire (ASQ)

- Location/ venue:
    - Á BUITEMS University Quetta (Takatu campus)
- Selection of the participants
    - Á Sending invitations and getting confirmation
    - Á Case study groups formation

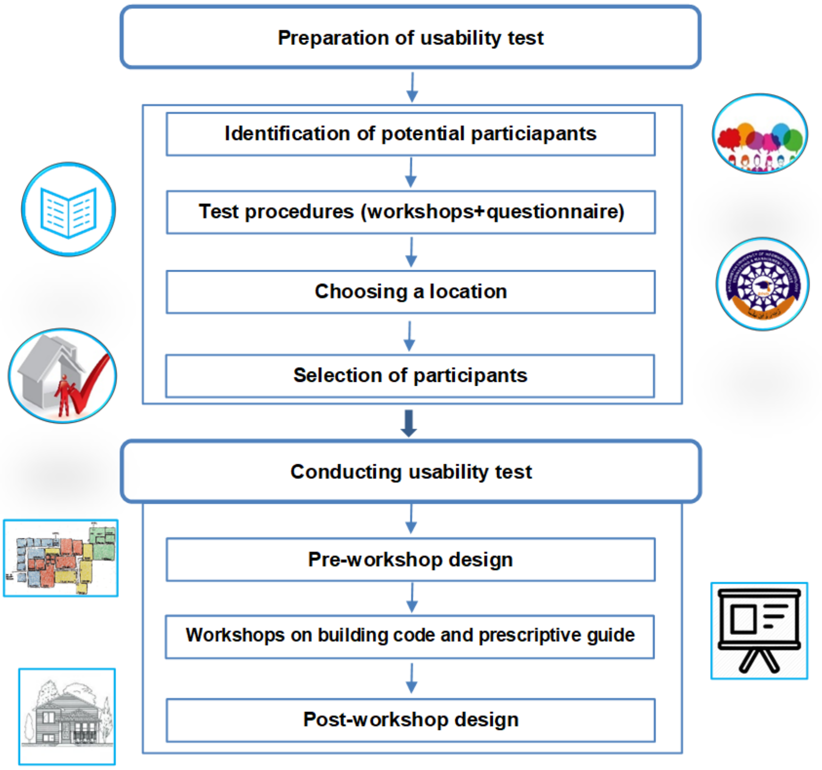


Figure 10.1 Conceptual study framework for the usability test

10.2.2 Conducting the usability test

The usability test was conducted for two days (4-5 March 2020) in the Department of Architecture at Takatu Campus of BUITEMS Quetta. On day one (4.03.2020), students of architecture 3rd year and above participated in the usability test. The architects with professional working experience participated in the usability test on day two (5.03.2020). A whole day was planned for this test from 10 am to 6 pm, including coffee/ tea and lunch breaks. An introductory session was held first to familiarize participants regarding the usability test, its purpose and steps. They were then divided into two different groups to design a house as per their standard design practice. In total, four case studies/ designs were created as the students and architects were divided into two groups (see Annexdix H for the participants' details). The following requirements were given to the participants for designing a single storey house. The design requirements were set the minimum (Table 10.1) to provide enough freedom for participants in terms of creativity and design interventions.

Table 10.1 Design requirements for case studies

Design requirements	
Family size	5-6 persons
Bedrooms	Min. 3 (min. area 16 m^2)
Bathrooms attached	Min. area 4.5 m^2
Living room/ lounge	1
Drawing room (male guest)	1
Kitchen	1
Laundry	1

The following three steps involved to complete the usability test:

- Pre-workshop design
    - The participants were divided into two groups. Each of the groups had to design a single-family house as per their standard practice using the design requirements given in Table 10.1
- Workshops on prescriptive guide and building code
    - Workshop-I on Building Code of Pakistan (Energy Provisions-2011): BCP(EP-2011)
    - Workshop -II on the prescriptive guide
- Post-workshop design
    - Group I and III (Workshop on BCP)
    - Group II and IV (Workshop on the prescriptive guide)

After the first session, each group of students and architects attended a workshop on building code and prescriptive guide, respectively, to educate the participants about i) energy provision in existing standard and passive design techniques and ii) the prescriptive guide. The BCP workshop was mainly based on chapter 4 of BCP (EP-2011), focused on Building Envelope (Annex I). In contrast, the second workshop presented the results of this PhD and focused on the prescriptive guide. The participants were then asked to redesign the same house based on the workshops' information joining their respective groups. In total, 24 participants took part in the usability test. Out of which 13 were students, and 11 were architects.

10.3. Results of the usability test

The results section is divided into four subsections. Subsection 9.3.1 identifies the influence of thermal comfort knowledge on the decision-making before and after the workshops. The results of the after scenario questionnaire are presented in subsection 10.3.2. The summary of decision-making attitudes and patterns is given in subsection 10.3.4. The last subsection 10.3.5, covers participants' suggestion to bridge the gap between BCP and the prescriptive guide to build comfortable and climate-responsive residential buildings in Quetta.

10.3.1 Knowledge and satisfaction

By using self-reported metrics, the background knowledge and understanding of indoor thermal comfort and the satisfaction with the use of building code and the prescriptive guide were determined.

Knowledge

Evaluating the effectiveness of BCP and prescriptive guide in informing design decision support requires an understanding of the participant's pre-and post-knowledge of thermal comfort. The respondents completed pre-and post-workshops surveys to assess the prescriptive guide or BCP's value to enhance their understanding of thermal comfort and both methods regarding design influence to construct buildings with improved thermal comfort.

Table 10.2 Pre-workshop and post-workshop t-test analysis

Item	Pre-workshop mean	Post-workshop mean	Mean difference	*t*	p	n
How would you assess your ability to design TCHs? (G-I)	3	4	-1	8.4	0.0014	6
How would you assess your ability to design TCHs? (G-II)	3.33	3.83	-0.5	13.18	0.0971	7
How would you assess your ability to design TCHs? (G-III)	3	3.83	-0.78	8.0	0.0041	6
How would you assess your ability to design TCHs? (G-IV)	3.16	4.33	-1.17	3.4	0.0038	5

On a scale of 1 (no skills) to 5 (very advanced), a five-point Likert scale was used in the survey questions, with the responses "very advanced", "advanced", "fair", "poor", and " no skills".
In order to access participants' knowledge about thermal comfort-related design issues, participants were asked: "How would you assess your ability to design thermally comfortable

houses?" Table 10.2 shows the paired t-test analysis of pre-and post-workshop responses of four groups, showing a statistically significant increase especially in the participant of workshop-II.

Satisfaction (After-Scenario Questionnaire)

The After-Scenario Questionnaire (ASQ) developed by Lewis (1995) was used to measure three fundamental areas of usability as mentioned in the standard (*ISO 9241-11*, 2018): effectiveness (question 1), efficiency (question 2), and satisfaction (all three questions). Participants were asked to fill a questionnaire by responding to their statements accompanied by a five-point Likert rating scale "strongly agree" to "strongly disagree", as shown in Figure 10.2.

The results indicate a high level of satisfaction regarding the ease of completing the design using the prescriptive guide for each group. Similarly, results indicate a high level of satisfaction with the amount of time taken to complete the design using the prescriptive guide. The satisfaction regarding the prescriptive guide's information was also ranked higher than those who used the building code. The results show a comparatively lower level of satisfaction using BCP regarding ease of design completion, time is taken to complete the design, and satisfaction regarding the information provided in BCP was rated.

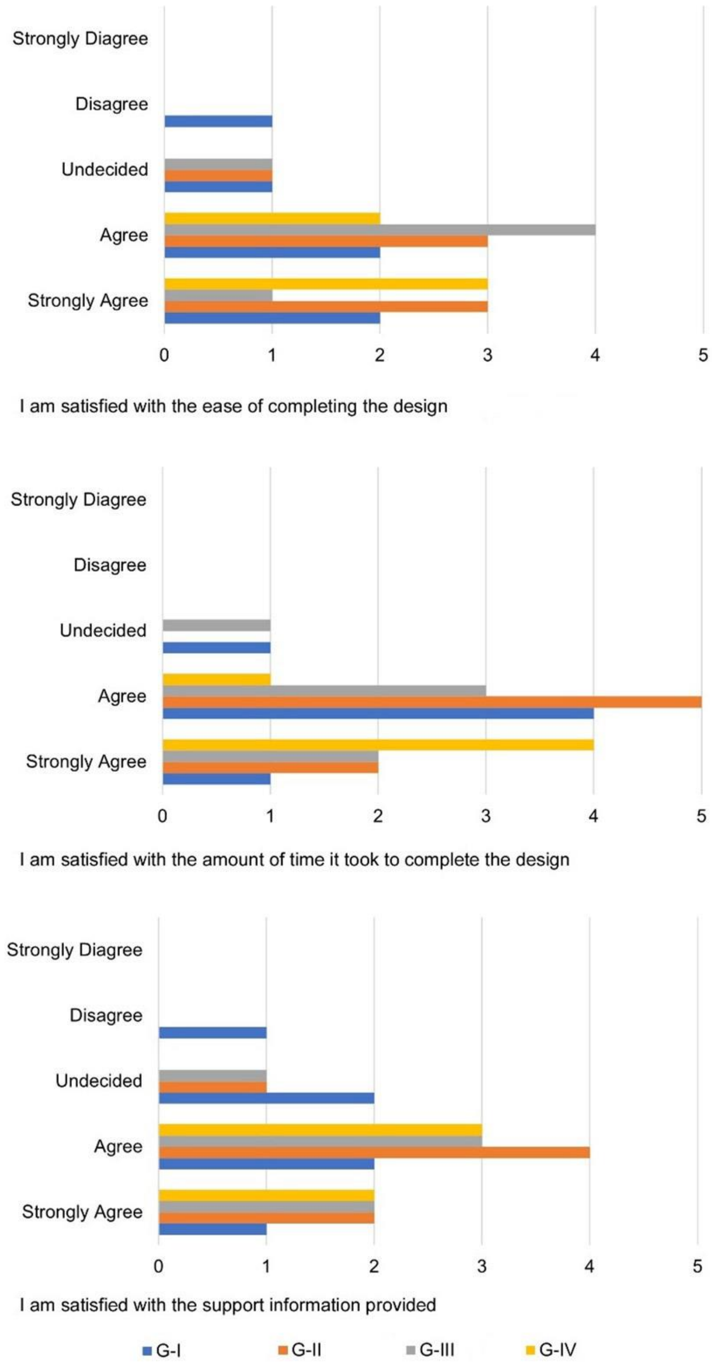


Figure 10.2 The results of after scenario questionnaire of all four groups

10.3.2 Decision-making attitudes and patterns

Another self-reported usability metric was a post-workshop questionnaire administered to participants regarding how far using the prescriptive guide and BCP informed their decision-making and led to higher reliability and robustness for the design of comfortable dwellings. Participants were asked to fill in a questionnaire with six questions.

Informed Decision-Making

Figure 10.3 show that participants' questionnaire responses vividly indicate agreement with the statement "informs your decision-making," comparing both the prescriptive guide and building code.

Concerning the "informing" question, 100% of participants recognized the prescriptive guide's importance in informing the decision-making of TCH design, and none of the questionnaire respondents disagreed with the statement. In Group I, 66.6% of respondents strongly agreed or agreed, while 33.4% were undecided. In Group II, all of the respondents (100%) strongly agreed or agreed. In Group III, 83.3% of respondents strongly agreed or agreed, while 16.7% were undecided. Lastly, in Group IV, 100% of respondents strongly agreed or agreed. In total, 25% of participants were undecided that the use of BCP made them confident about their decision-making in TCHs design.

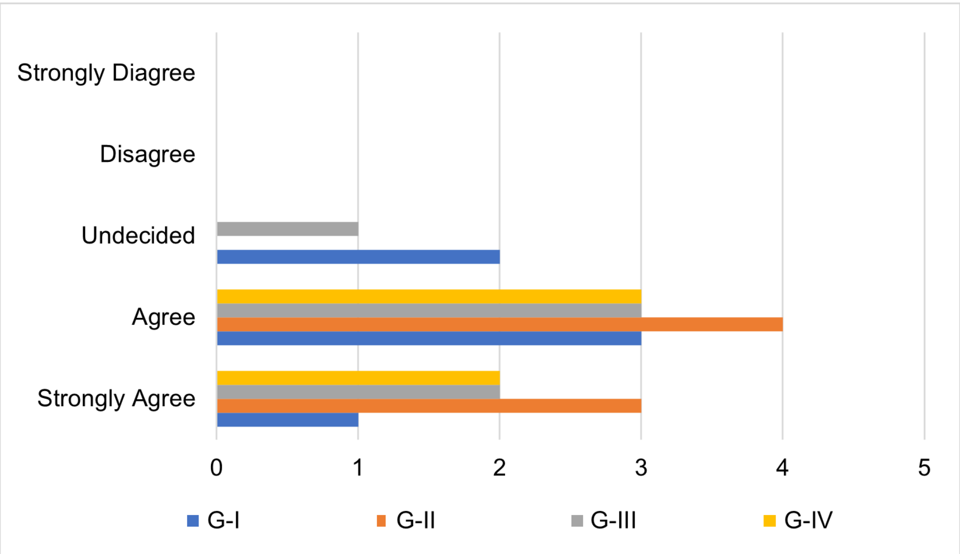


Figure 10.3. Participants' response to the question "Working with BCP or prescriptive guide informed your decision-making."

Concerning the "informing" question, 100% of participants recognized the prescriptive guide's importance in informing the decision-making of TCH design, and none of the questionnaire respondents disagreed with the statement. In Group I, 66.6% of respondents strongly agreed

or agreed, while 33.4% were undecided. In Group II, all of the respondents (100%) strongly agreed or agreed. In Group III, 83.3% of respondents strongly agreed or agreed, while 16.7% were undecided. Lastly, in Group IV, 100% of respondents strongly agreed or agreed. In total, 25% of participants were undecided that the use of BCP made them confident about their decision-making in TCHs design.

However, regarding the statement “working with BCP or prescriptive guide made you confident to make design decisions”, none of the participants showed disagreement. In Group I, 66.6% of the respondents were strongly agreed or agreed, while 33.4% were undecided. In Group II, 85.7% of the respondents strongly agreed or agreed, and 14.3% were undecided. 83.3% of the respondents in Group III strongly agreed or agreed, while 16.7% were undecided. In Group IV, 80% of the respondents strongly agreed or agreed with the above statement, while 20% were undecided. The results show that more participants strongly agreed or agreed that the prescriptive guide made them confident to make design decisions.

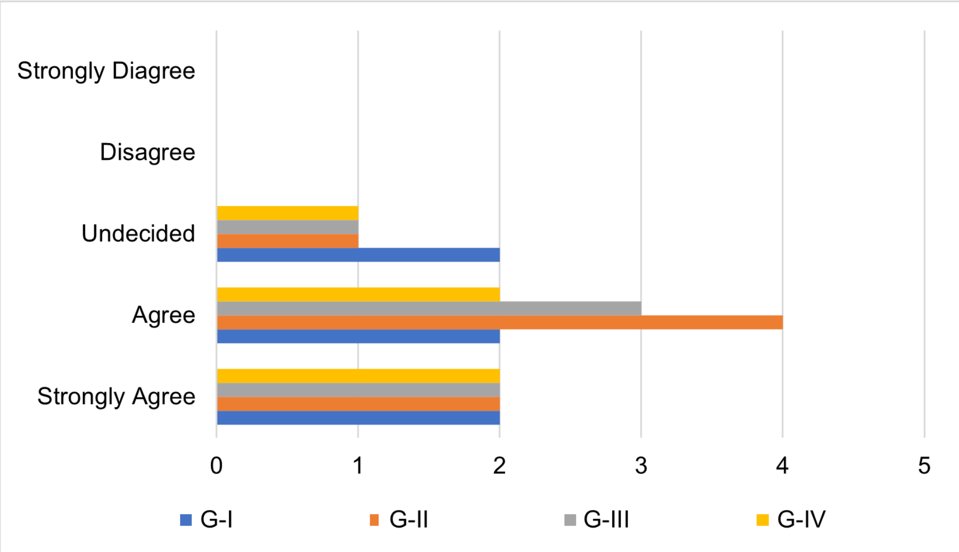


Figure 10.4. Participants’ response to the question “Working with BCP or prescriptive guide made you confident to make design decisions.”

Reliability and robustness of design

Figures 10.5, 10.6 and 10.7 show that participants’ questionnaire responses regarding the prescriptive guide and BCP's reliability and robustness to design TCHs. Regarding the statement “working with the prescriptive guide or BCP allowed you to achieve the goal of designing comfortable houses”; In Group I, 16.6% of the respondents agreed, 50% were undecided, while 33.4% of them disagreed. In Group II, 85.7% of the respondents strongly agreed or agreed, and 14.3% were undecided. In total, 33.4% of Group III respondents agreed with the statement, 50% were undecided, while 16.6% showed their disagreement. Lastly, in Group IV, 80% of the respondents were strongly agreed or agreed, while 20% were undecided.

Regarding the statement “working with the prescriptive guide or BCP is essential for designing comfortable houses”. In Group I, 50% of the respondents strongly agreed or agreed, while 50% were undecided. In Group II, 85.7% of the respondents strongly agreed or agreed, and 14.3% were undecided. In total, 50% of Group III respondents agreed with the statement, 33.4% were undecided, while 16.6% showed their disagreement. Lastly, in Group IV, 80% of the respondents were strongly agreed or agreed, while 20% were undecided. The results indicate that participants who used the prescriptive guide showed more confidence to design TCHs.

In the last question related to reliability and robustness of design, In Group I, 33.4% of the respondents agreed, 50% were undecided, and 16.6% disagreed. In Group II, 85.7% of the respondents strongly agreed or agreed, and 14.3% were undecided. In total, 33.4% of respondents in Group III agreed with the statement, 33.3% were undecided, while 33.3% showed their disagreement. Lastly, in Group IV, 80% of the respondents were strongly agreed or agreed, while 20% were undecided.

We analysed this qualitative data looking for high-frequency patterns of attitude that might suggest inherent problems using the prescriptive guide or building code. Once this analysis was complete, we prioritized the issues based on the frequency and our subjective ratings of severity to help prioritize the order of presentation in our study. The results demonstrated less confidence in using BCP to design TCHs compared to the prescriptive guide. To analyse this issue, the participants were asked to provide an explanation during the group discussion, which is presented in section 10.3.5.

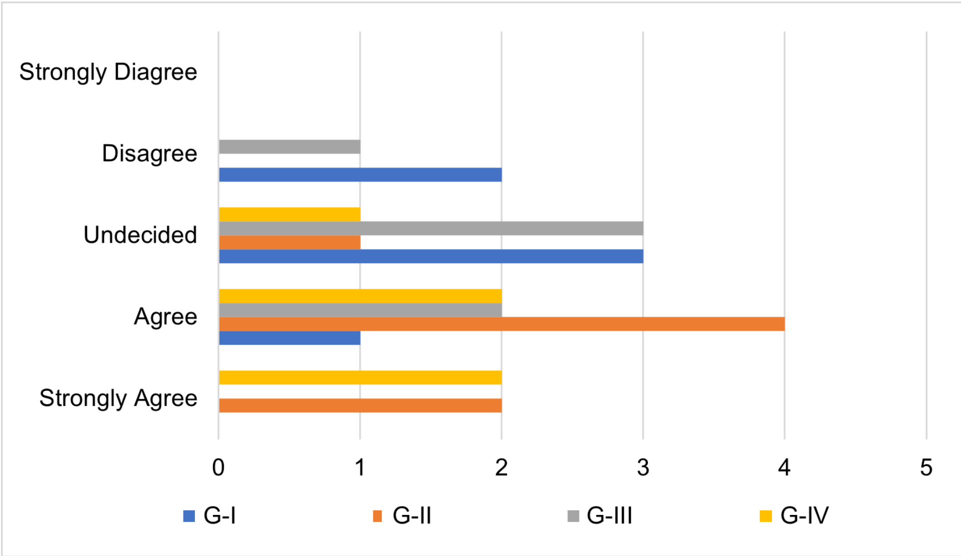


Figure 10.5 Participants' response to the question "Working with BCP or the prescriptive guide allowed you to achieve the goal of designing comfortable houses."

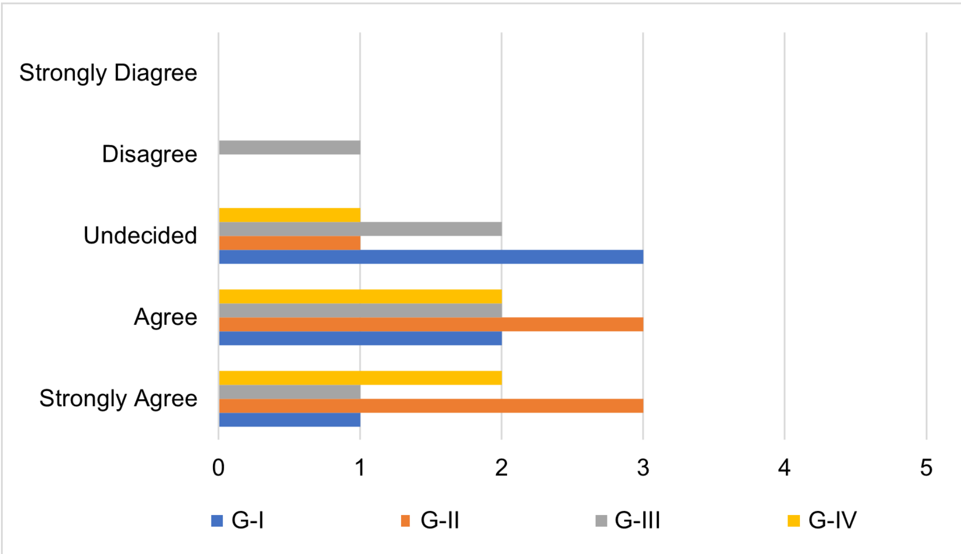


Figure 10.6 Participants' response to the question "Working with BCP or the prescriptive guide made you confident to make design decisions."

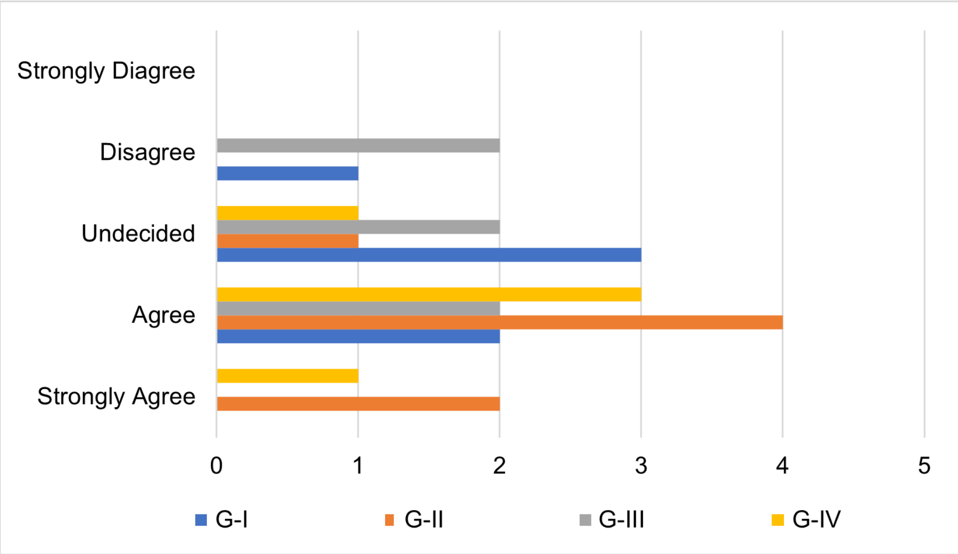


Figure 10.7 Participants' response to the question "Working with BCP or the prescriptive guide helps to produce reliable and robust designs of comfortable houses."

10.3.3 Analysis of design case study houses

This section presents four different design case study houses drawn by each group during the usability test. The case study houses consist of two phases, pre-and post-workshop design, as mentioned in section 10.2.2. The usability test results of the design case study houses (design improvement) are discussed below. For comparison purposes, the presented results include the simulated thermal comfort of the original with the improved versions of the four design case studies.

Case study I (Group I)

The first case study group consists of six participants, including two participants from each year of the architecture program 3rd, 4th, and 5th year. After the introductory session, the group members gathered in a design studio to design their pre-workshop house as per their everyday practice, considering the requirements given in Table 10.1. The initial design is based on a sketch made by the participants after discussing and drawing bubble diagrams and initial sketches. Figure 10.8 presents the initial plan of the case study house (pre-workshop design). The house is facing south orientation, and the given space requirements were adjusted. The participants of group-I then attended a workshop on the Building Code of Pakistan (Energy Provision-2011). After the workshop, they were asked to modify their existing design.

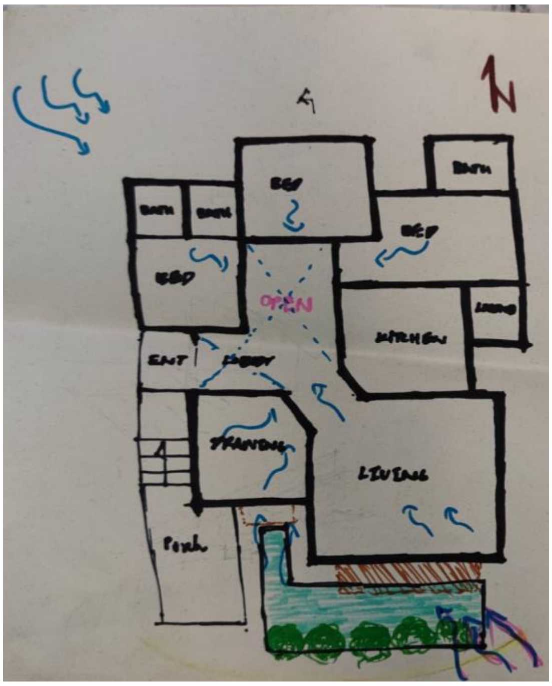


Figure 10.8 Pre-workshop design (Group-I)

Figure 10.9 and 10.10 presents the view and plan of post-workshop design of the same house drawn by the participants using SketchUp and AutoCAD software. The participants didn't make any significant changes or interventions in design except providing ventilators and increasing the height of passage between the bedrooms and living room. In addition to that, they offered the following recommendations, Table 10.3.

Table 10.3. Interventions proposed by the participants in Group-I

Item	Thickness (cm)	U-value ($W/m^2 K$)
Double glazed low-E glass (Argan filled)	0.3 cm	1.9
Foam insulation	9	0.2
Brick walls	22.8	2.0
Internal and external plaster	2	---
Aluminium frames (windows and doors	---	---

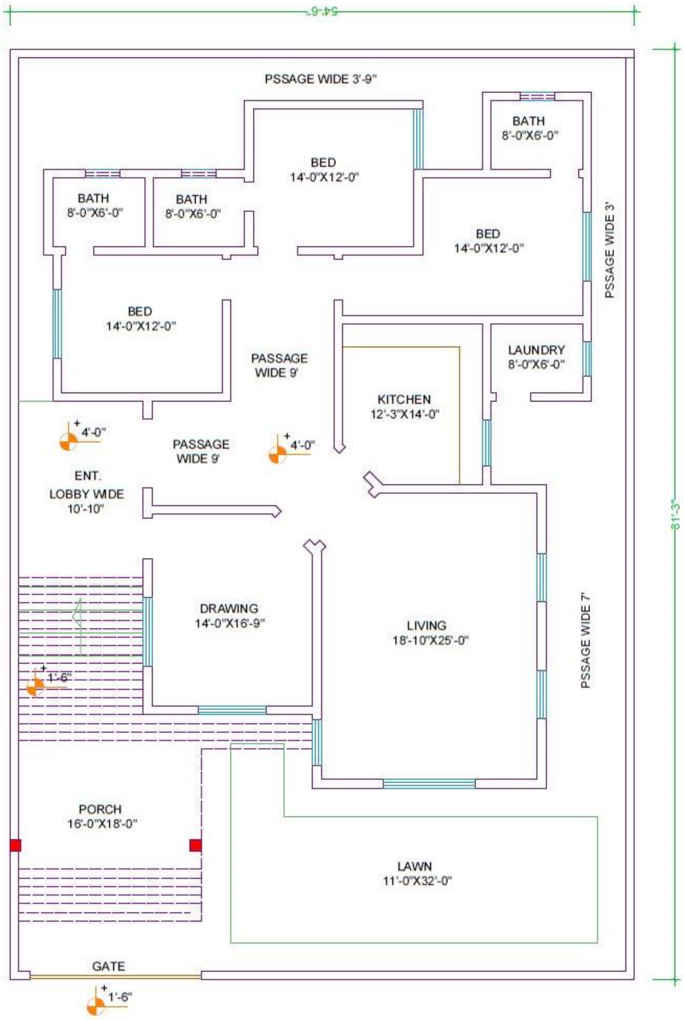


Figure 10.9 Post-workshop design (Group-I)

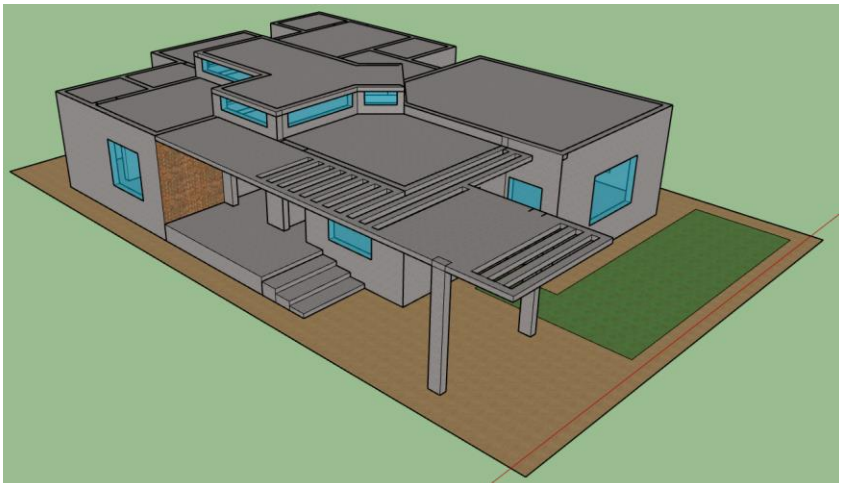


Figure 10.10 View of case study house: Post-workshop design (Group-I)

Case study II (Group II)

In the second group, seven students participated in the usability test. The group consists of three students from the 5th year and two students from each 3rd and 4th years of the architecture program. Figure 10.11 presents the initial sketch of the house, which faces its longitudinal side towards the South. The members of group II attended a workshop on the prescriptive guide after their initial design. Then they modified their initial proposal based on the instructions given during the workshop.

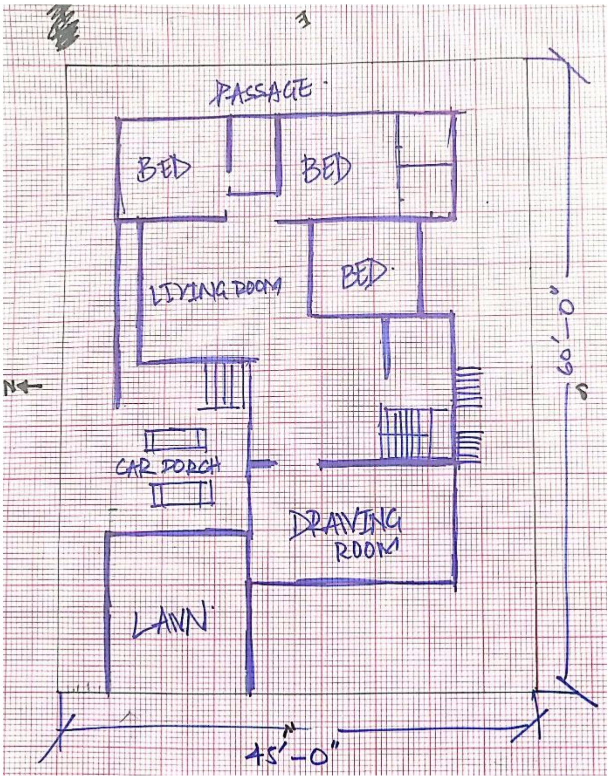


Figure 10.11 Pre-workshop design (Group-II)

Figures 10.12, 10.13 and 10.14 present the post-workshop design of the house and its view. The updated plan shows the house's change of orientation to gain more passive solar heat during the winter. Large windows and sloping roof are provided for solar heat gain and reduce heat transmittance through a flat roof in summer. In addition to that, the participants also provided some recommendations, which are summarized in Table 10.4. The results show that group II participants considered extra measures to control indoor climate, such as the provision of 0.6 cm thick double glazed low-E glass, cavity wall, and EPS insulation in wall construction, false (dropped) ceiling with an air trap of 30.4 cm.

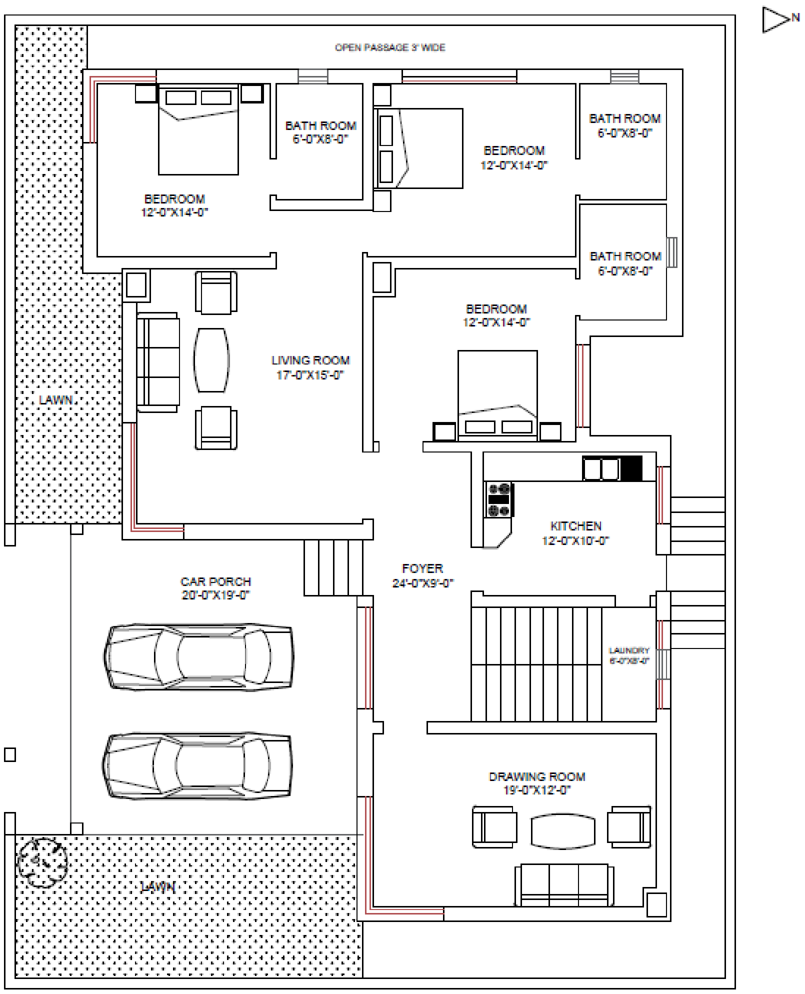


Figure 10.12 Post-workshop design (Group-II)

Figure 10.13 View of case study house: Post-workshop design (Group-II)

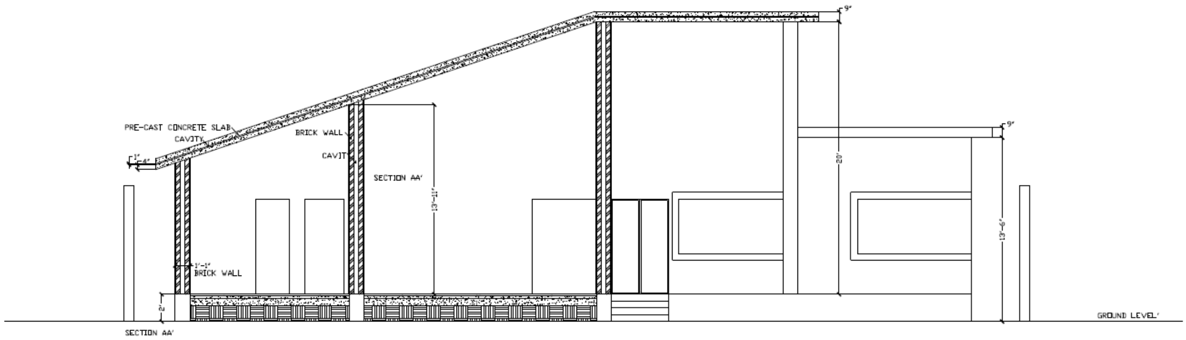


Figure 10.14 A section of the case study house: Post-workshop design (Group-II)

Table 10.4. Interventions proposed by the participants in Group-II

Item	Thickness (cm)	U-value (W/m^2 K)
Double glazed low-E glass (Argan filled)	0.6 cm	1.6
Cavity wall (wall construction)	10	---
EPS insulation board (in walls)	---	----
Ceiling (air gap/ trap)	30.4	---
False (dropped) ceiling	---	---
Aluminium frames (windows and doors	---	---

Case study III (Group III)

The third case study group consists of six practising architects having working experience between 2-9 years. The group III participants attended a workshop on building code (same as the group I) after their pre-workshop design, shown in Figure 10.15. The participants of this group didn't indicate the orientation of the case study house. Post-workshop design is, and elevation is presented in Figure 10.16 and 10.17, respectively. The sloped roof is proposed at the centre of the house, while a flat roof is suggested for most spaces. The participants of group III also provided some recommendations, which are included in table 10.5.

Table 10.5. The recommendation proposed by the participants in Group-III

Item	Thickness (cm)	U-value (W/m^2 K)
Double glazed glass (Air filled)	0.3 cm	---
External walls	34.2	---
Internal/ partition walls	22.8	---
Roof (pitched at the centre)	---	---
Fibreglass insulation (in the roof)	5	
Vinyl frames (windows and doors	---	---

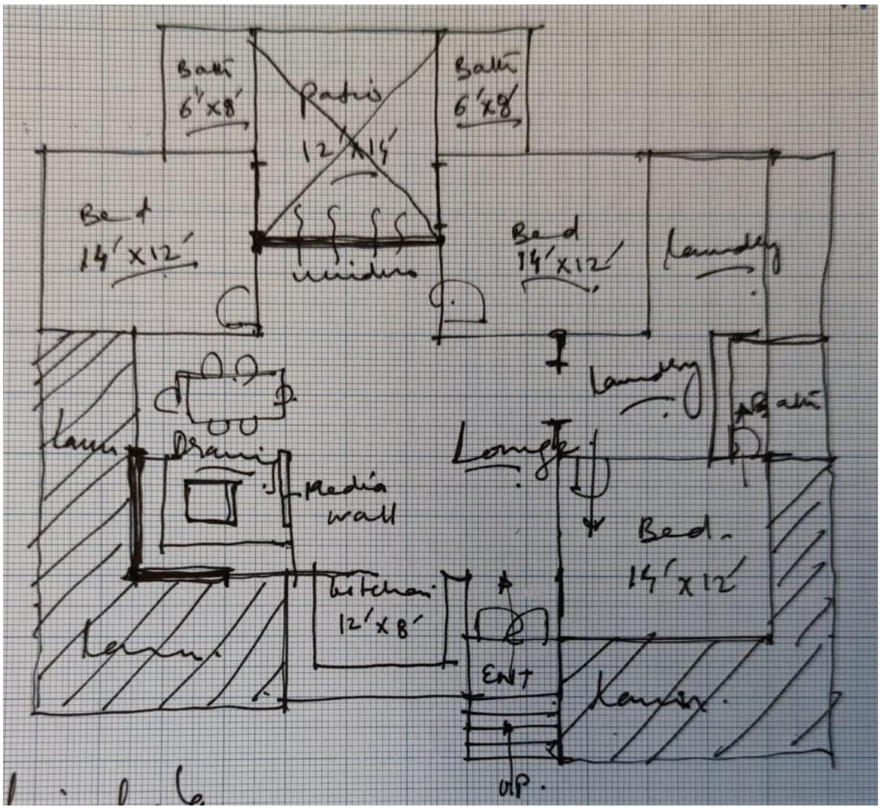


Figure 10.15 Pre-workshop design (Group-III)

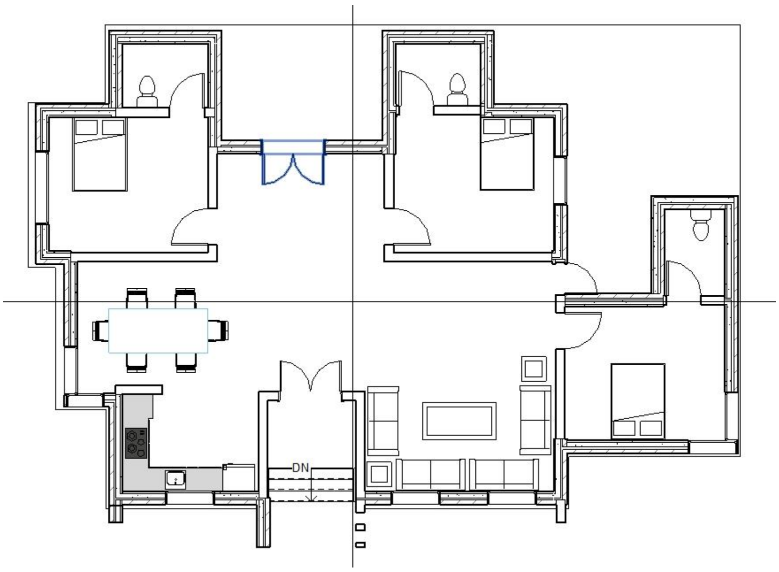


Figure 10.16 Post-workshop design (Group-III)

Figure 10.17 Front elevation: Post-workshop design (Group-III)

Case study IV (Group IV)

The fourth and last case study group consists of five practising architects having working experience between 2.5-11 years. The group IV participants attended a prescriptive guide workshop (same as group II) after their initial design. The pre-and post-workshop designs of case study IV is shown in Figures 10.18 and 10.19. A double wall is proposed for the exterior wall and a cavity, while interior (partition) walls remain single. A view of the post-workshop design of the case study house is presented in Figure 10.20.

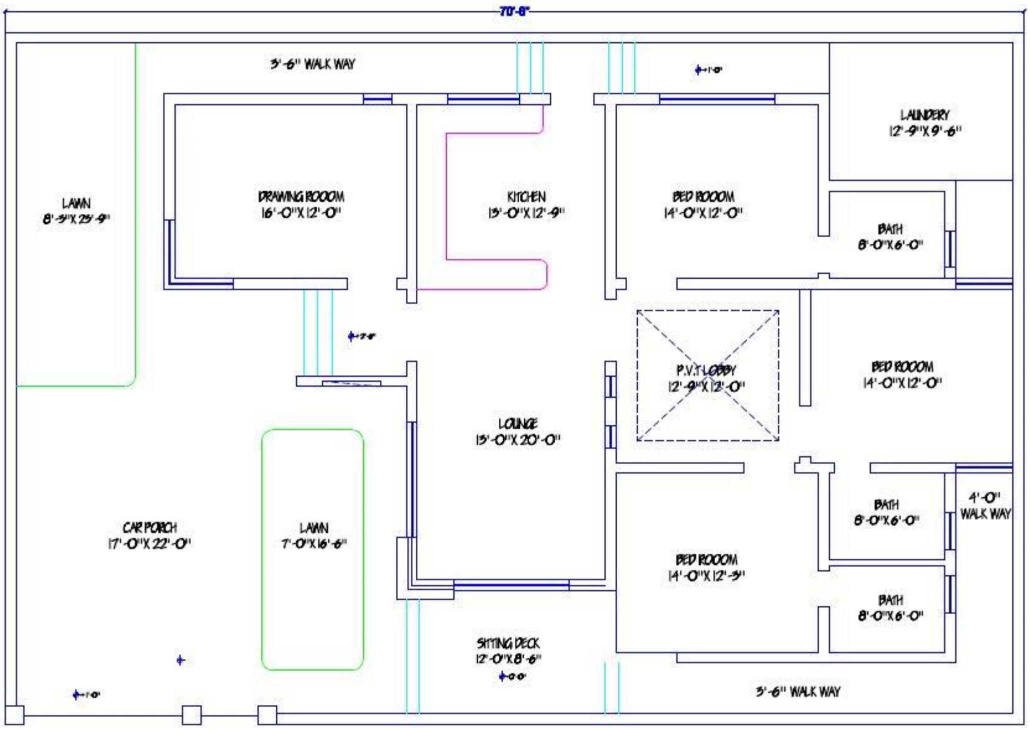


Figure 10.18 Pre-workshop design (Group-IV)

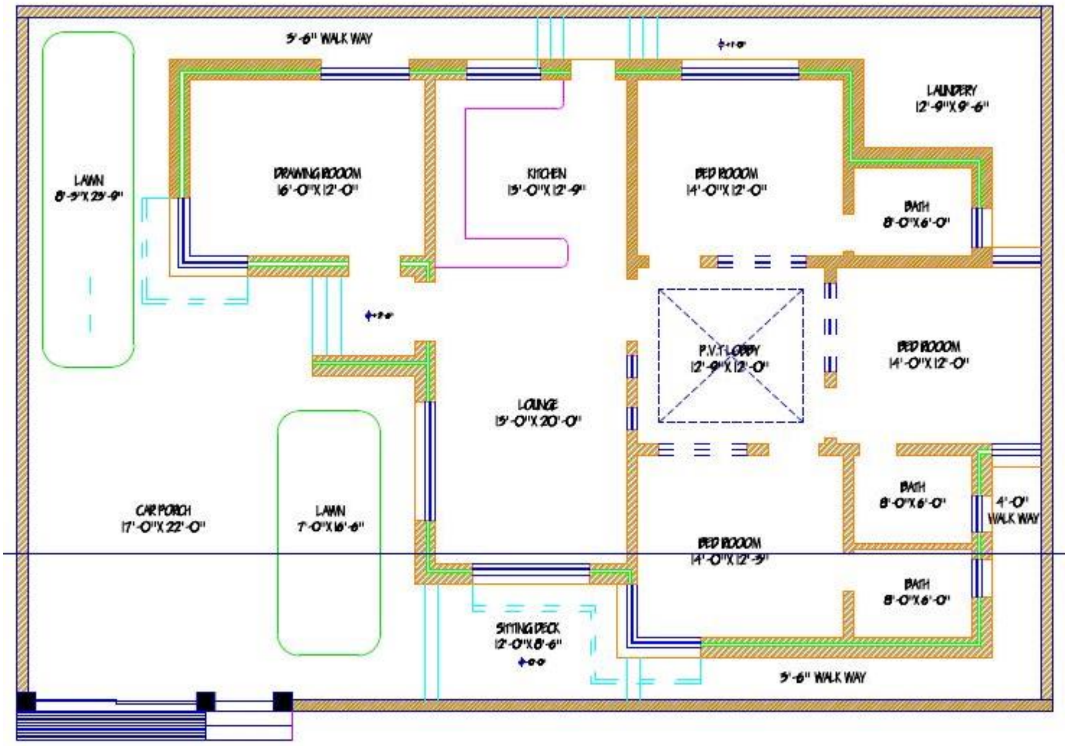


Figure 10.19 Post-workshop design (Group-IV)

Figure 10.20 View of case study house: Post-workshop design (Group-IV)

The participants of group IV also suggested the following interventions:

- Double glazed windows with a shading device at 15 curve
- Roof tiles of 45.7cm x 45.7 cm over the bricks to create a second roof

- Cavity wall with the introduction of PVC pipes to provide air circulation and to create stack-effect.

The strategies proposed above are also used locally in some of the houses. However, their impact of indoor thermal comfort is not yet monitored. Creating a second roof to introduce air can help reduce solar gain on a flat roof and provide more comfort during summer.

Conclusion of case studies

Four case studies are presented in the section. The workshops based on building code and the prescriptive guide were conducted with the students and practising architects. Each group was asked to prepare two designs, pre-and post-workshops. The design improvement is noticed in post workshops designs. The significant improvements were observed in group II, and IV post-workshop design houses attended the prescriptive guide workshop. Each group's final designs are portrayed above, including their recommendations and interventions to improve thermal comfort.

9.3.4 Open-ended question

An open question followed the workshop to allow respondents to share their thoughts and comments. The question was concerned about what should be done to bridge the barrier between using design tool/ code and achieving informed decision-making. A selection of the suggestions for future improvements and their frequencies are classified as follows:

- Combining the prescriptive guide with simulation tools (2)
- New houses must be designed based on the building code and bylaws (3)
- There is a need for educating designers and creating awareness regarding building codes and bylaws (5)
- There is a need to reformulate and strictly implement the building bylaws (6)
- Designers must include passive design strategies in their everyday practice (3)
- Introducing passive design in architecture education and practice (5)
- Designers need to ensure the compliance of building codes and bylaws (4)
- Awareness campaigns for masses regarding the energy consumption of the housing sector (1)
- A guide for using available building materials to improve thermal comfort (3)

- More workshops regarding comfort and energy to be conducted for students and designers (6)
- Exhibitions of building material along with the necessary information regarding their thermal performance (2)
- The locally adopted techniques and practices must be analysed to assess their comfort improvement (2)
- A design guide that covers passive design techniques, materials, their thermal properties, and so on for designing comfortable houses in Quetta (5)
- Provide informed design-decision support to designers to construct more comfortable houses (3)
- A guide, code or bylaws must be easy to understand and adopt so that designers do not lose or invest more time to come up with better solutions (3)

According to the results, the freedom of geometrical modelling and the coupling of design tools with simulation tools were the most frequently named topics.

10.3.5 Group discussion

At the end of the four case studies, design group discussions were organized to discuss the participants' reflections on the workshops' findings and questionnaire results. Overall, participants perceived the prescriptive guide as useful and informative to achieve improved thermal comfort in houses. Most participants considered that the prescriptive guide gave added value in informing and validating the design decision to achieve the design objective. Many respondents highlighted the importance of parametric and sensitivity analysis, combing passive design techniques and materialization to guide the design. The participants endorsed the role tools such as design guide or building code to design TCH houses aiming to improve comfort using passive design and low-tech solutions.

On the other hand, not all participants feel the need to learn a simulation tool and invest so much time designing a house based on simulation techniques. This is due to a lack of resources, knowledge and complication of tools and limited time. They also mentioned that clients do not appreciate it if the design takes more time. Some of them described simulation tools as complicated, tedious, and restrictive to creativity. However, they acknowledged the added value of BPS tools to improve the design and providing details regarding comfort hours, cost and design aspects. All participants agreed on the importance of the prescriptive guide or building code to design TCH houses using simple steps and process. They also acknowledged that the prescriptive guide is based on the BPS, actual weather data, activity schedule, and virtual model tested based on the real situation. The participants highlighted the importance of design decision support provided by the prescriptive guide to make a better and quick decision while designing houses. A few of them suggested including a list of materials that can be used in the climate of Quetta to achieve more comfort in houses without using active systems. The participants also suggested including building geometry in the prescriptive guide.

10.4 Discussion

10.4.1 Summary of findings

The use of the prescriptive guide and building code in the design of comfortable and climate-responsive houses demonstrated a strong correlation between design efficiency and achieving informed decision-making. In order to evaluate the prescriptive guide and building code as tools for informing design decision support, the participants completed several questionnaires assessing their informative effectiveness. The questionnaires reveal participants' perception of the design tool's informative importance in their design decision-making. Especially, the open-ended questions and group discussion addressed the value of barriers to the use of the design tool as a decision-support method. To validate the study findings, a formal analysis was performed of all four case studies. The group discussions were also used as an informal triangulation to facilitate the validation of the survey results reported below:

- The use of prescriptive guide increased knowledge uptake of between 45% and 87% compared to pre-workshop knowledge
- The levels of satisfaction with the ease of use and the time taken to complete the design using BCP and prescriptive guide were relatively high at 35-72% and 53-89%.
- The level of satisfaction with the information support given to complete the design using BCP and prescriptive guide was relatively high at 75-88%
- The prescriptive guide's importance in informing the decision-making was recognized by 81% of the respondents. The importance of BCP in guiding the decision-making of TCHs was recognized by 72% of the respondents.

- It was found that 16.6% of respondents were undecided, and 4.1% of participants disagreed that prescriptive guide and BCP's use made them confident about their decision-making in TCHs design.
- It was found that 12.5% of respondents disagreed that prescriptive guide and BCP's use allowed them to achieve the TCHs design.
- It was found that 66.6% of respondents agreed that prescriptive guide and BCP are essential, and 83.4% agreed that prescriptive guide produced reliable and robust TCHs design.

10.4.2 Strength and limitations of the study

The participants of the usability test include architecture students and practising architects. The choice to perform validation among students and architects was made on purpose to test the informed decision-making and prescriptive guide's role at the early stage of design. The pre-and-post design of houses shows that the design of students and architects who used the prescriptive guide was considerably improved. More participants agreed that pre-post knowledge (up to 87%), informing decision making (81%), reliability and robustness of design (83.4%) increased using the prescriptive guide. It was also noted that climate and passive design measures are usually not considered a priority by architects and architecture students. The results produced in this PhD study made them aware of climate responsive and passive design measures by identifies the essential factors that can lead to improved indoor thermal comfort. This prescriptive guide can help the students and architects making better decisions at the early stage of their architectural design.

The validity of the study's findings is potentially open to criticism as only four design groups were used for this study. It would have been desirable to recruit architects from a more significant number of design practices to ensure a broader socioeconomic and geographic population distribution. However, we would argue that this study differed significantly in that it focused on the informative aspects of the prescriptive guide, which was not featured in the trial. A quantitative methodology (survey and performance analysis) and a qualitative method (discussion) were employed in this study.

10.5 Conclusion of the chapter

The following conclusions are made based on the results of this usability test.

- The developed prescriptive guide and building code provided informed decision-support to architects for designing thermally comfortable houses.
- The architects found that the prescriptive guide is more useful compared to the existing building code.
- The architects prefer to use a guide or tool which guide them to make informed decisions regarding TCH rather than using simulation tools.
- The architects highlighted the importance of available materials and techniques which can be used for the design of TCH in Quetta, Pakistan.
- The existing bylaws and building codes need to be reformulated and adequately implemented.
- There is a need to create more awareness among designers and residents regarding comfort and passive design.
- Improvement in design was noticed using the prescriptive guide and BCP regarding informed design-decision support.
- Timesaving, reliability, and robustness were noticed using a prescriptive guide for the design of TCH.

CHAPTER 11: CONCLUSION AND RECOMMENDATIONS

11.1 Introduction

The last chapter concludes this PhD thesis by summarizing the original contributions developed in this PhD thesis and providing future research recommendations. Climate change has increased the significance of thermal comfort, energy consumption, and buildings' energy efficiency in achieving sustainable development. The recent pandemic of Coronavirus SARS-CoV-2, also known as COVID-19, has changed how we live and work. The pandemic forced governments to close business and limit people to work from home. It also changed the lifestyle of millions of people who needed to do several interventions at home to create a better working environment. Until now, 50% of the workforce in Pakistan is obliged to work from home. The situation increases the need for indoor thermal comfort to meet the living and working styles. The existing standard and policies in Pakistan do not cater to the thermal comfort needs of residential buildings. Thus, there is a strong need to provide solutions to improve indoor thermal comfort in houses.

This PhD thesis sought to understand the importance of occupant's thermal comfort and evaluate the potential of comfort improvement using passive design strategies based on climate and context-based studies. The findings provide informed decision support for designing thermally comfortable residential buildings in cold and semi-arid climates. The city of Quetta was selected as a case study. This city represents two significant challenges related to its climate and geographical location; cold semi-arid climate (BSk) and its high altitude. In addition to that, lack of regulatory framework, increasing urban population, urban sprawl and slow development further complicate the situation. Despite being the capital of the largest province of Pakistan (in terms of area), the city remains the least developed among other major cities. Many cities in developing countries face similar challenges. Nevertheless, architects, building professionals, and researchers play a role in producing local knowledge and designing climate-responsive buildings.

11.2 Original contributions of the thesis

This section summarises the original contributions made in the field of research during various stages of this PhD dissertation.

11.2.1 Characterisation of housing stock and households in Quetta

The characterisation was done to identify the characteristics of existing housing and households living in such houses. The study also included a summary of climate condition, energy situation, water and waste systems in Quetta, Pakistan. This lead to produce an inventory of housing and related facilities. The inventory created a starting point for this PhD research. The data collection in Quetta was a challenging task due to its multiethnic, tribal, and religious environment and unsatisfactory law and order situation. The data collection techniques can also be helpful for future researchers to collect data in conflict-prone regions. The results provide valuable insights to understand the housing details, construction techniques, materials, and practices used in Quetta. The inventory results are based on a survey of 215 houses in 32 residential areas and a review of several documents, literature, and data collected from different institutions and agencies.

From the survey results, three housing construction typologies were found in Quetta, which are sundried brick/ mud houses, brick masonry houses, and reinforced concrete frame (RCF) houses. The RCF houses is the most common and acceptable construction type (65% out of 215), which is also widespread in Quetta and other parts of Pakistan. The majority (75%) of residential buildings in Quetta are self-built without professional supervision. The use of thermal insulation is uncommon in Quetta, where only 11% out of 215 surveyed houses had some form of insulation. On the other hand, marble and ceramic tile floor finishes provide a comfortable temperature in summer. In winter, carpets and mats are used to reduce the cold. Single glazed windows are commonly used in Quetta. The central heating system is installed in a few houses (8%), while most of the houses use radiant gas heaters. Due to the high gas prices, the central heating system is not a suitable and affordable choice. It should also be noted that gas is also used for cooking meals and hot water.

The inventory also focuses on climate and related facilities of housing. The climate of Quetta is cold and semi-arid (BSk), with cold winter and mild to hot summer. The city lies at a high altitude of 1680m and receives less snowfall in December, January and February. An electricity outage (load shedding) of 4-8h per day varies in the summer and winter season. There is a shortage of water and the disruption of water supply in several areas of Quetta. Waste collection and disposal system is inefficient in several residential areas. The results also revealed that the housing sector in Quetta consumes 74% of the electricity used in the city. Electricity usage increases in summer due to fans and air conditioners, while gas usage increases in winter due to the heating. By using passive design solutions, the dependence on active systems to improve thermal comfort can be reduced. Hence, more comfort can be achieved using less energy throughout the year.

11.2.2 Assessment of indoor thermal comfort

At this stage, the assessment of indoor thermal comfort of the most common housing typology, i.e. reinforced concrete frame (RCF) houses, was performed along with a survey on housing and household characteristics, HVAC, energy, lighting, comfort perception, clothing, and consumption behaviour of the residents. In total, ten houses were selected for this purpose.
The results show that the existing houses do not provide adequate thermal comfort to residents. Active heating and cooling systems are mainly used to improve comfort. Fans are primarily used to ventilate the rooms in summer, while personalized radiant heaters are commonly used in winter. The energy situation is unsatisfactory due to power outage mainly in summer and low gas pressure in winter. The compact fluorescent tube lights, fluorescent lamps and light-emitting diodes are mainly used; however, incandescent bulbs are still used. Comfort adaptation practices such as opening windows in summer and putting on an extra layer of clothes while remaining indoors is common. In general, the occupants remained less satisfied with their existing houses' overall indoor thermal comfort and more discomfort was noticed during winter. It was observed that while residents expressed their dissatisfaction with the energy system and prices. Yet, most of them were unaware of the energy pricing method and were found ignorant to turn off unnecessary appliances.

11.2.3 Development of benchmark and the selection of comfort model

A representative house was selected for the benchmark study. The monitoring of indoor air temperature and relative humidity was done in both summer and winter seasons. In addition to that, a questionnaire and a semi-structured interview were used to gather the data on household characteristics. A visit of the selected house was done to enlist the material specification, construction details and draw plans. A virtual model of the representative house was created in DesignBuilder, and the monitored data was used for calibration. A parametric analysis was performed using various passive design solutions for the improvement of indoor thermal comfort.

A comparative analysis of four comfort models was performed in this study to evaluate the best fit-to-context comfort model. It was concluded that the ASHRAE 55 adaptive comfort model was the best fit for predicting comfort in the climate of Quetta. The results show that up to 59% of annual comfort hours (with the existing heating system) can be achieved using passive design strategies without using other mechanical systems. The potential of bioclimatic design strategies was explored using DeKay and Brown's chart. It was identified that passive design strategies such as passive solar heating, shading, high thermal mass, natural ventilation, and humidification could be useful in the climate of Quetta if the buildings are designed and built correctly.

The study proves that passive design strategies can increase annual comfort; however, efficient active systems may be needed for optimal comfort. The behavioural adaptation, such as opening windows and using fans, can improve comfort in summer; simultaneously, the high thermal mass, passive solar heating, and insulation are recommended to improve thermal comfort in winter.

11.2.4 Identification of effective passive design strategies and their materialization

The sensitivity analysis can assist decision-makers in identifying the most relevant design variables. It also determines how different values of an independent variable in a given set of boundary conditions affect a particular dependent variable. When we understand the relationships and the relative importance of design parameters, we can easily improve the performance of the building. In this study, a sensitivity analysis of 21 design variables based on passive design strategies (which might be influential in the climate of Quetta) was performed using building performance simulation. The study was based on a single objective function of comfort hours (CH), evaluated based on the ASHRAE 55 adaptive comfort model's 90% acceptability limits. It was found that thermal insulation, glazing type, shading, window-to-wall ratio, natural ventilation, the building orientation, and external wall construction are the most influential design variables in the climate of Quetta. The results show that the use of thermal insulation is essential for the improvement of indoor thermal comfort.

After identifying effective passive design strategies, a materialization survey was conducted to select available materials that can be used to improve thermal comfort. The availability of suitable and affordable building materials is essential for the construction of residential buildings. Besides the availability, proper know-how of materials, performance (thermal), and skilled labour for their application are also necessary. It has been found that the knowledge regarding the thermal performance of building materials in Pakistan, especially in Quetta, is limited. A survey of available building materials was done for the materialization of the most effective passive design solution in the climate of Quetta. An inventory of locally available insulation and glazing materials was made, including their cost and thermophysical properties. The results indicated that insulation materials and double-glazed windows are not locally available in Quetta. These materials are procured and transported from other major cities of Pakistan, such as Karachi, Lahore and Islamabad.

The available knowledge regarding energy-efficient materials is limited, and the architects are not confident in the actual thermal performance of building materials available in the country. It is also because most of these material manufacturers don't provide the basic thermophysical properties of these materials, which includes thermal conductivity, specific heat capacity, thickness, and density. The thermophysical properties of double-glazed glass manufactured in Pakistan are unknown in most cases since there is no certification or testing facility available in the country. This situation creates uncertainty and doubts among architects.

11.2.5 Development and testing of decision support prescriptive guide for architects

Based on the surveys, data collection, analysis and simulations performed in this study, a prescriptive guide was developed to provide informed decision support for architects to design climate-responsive, thermally comfortable and sustainable residential buildings. The methodology focuses on passive design solutions based on influential design variables for the climate of Quetta. The developed prescriptive guide is easy to understand and use. It provides the most suitable solutions without going through a complicated and extensive process of building performance simulation.

This prescriptive guide was tested and compared with the Building Code of Pakistan (Energy Provision-2011) through the usability test conducted among four groups of architects and architecture students. The usability test results proved that the developed prescriptive guide provides informed decision support to the architects and students for designing comfortable and climate-responsive houses at an early stage. It further helps the architects by offering first-hand knowledge of passive design solutions and techniques which are more effective in the climate of Quetta.

11.3 Study implications and recommendations for future research

The field of thermal comfort and its related tools and databases are continuously evolving. With the development of technology and computation power, is it becoming more convenient to perform simulation studies that reflect reality. New methods, tools and databases are under development and are expected to be available in the near future. Global warming, climate change, and increasing energy usage and demand raise awareness of the need to adopt passive and sustainable ways to improve thermal comfort and reduce energy consumption in buildings. The cost of fossil fuels is no more affordable option for many nations and is creating fuel poverty. The power generation mix in Pakistan and several other countries is not sustainable and has an adverse environmental impact. In this situation, by using passive design techniques and adoptive measures, indoor thermal comfort can be improved without creating adverse effects on the environment. The knowledge regarding thermal comfort and passive design measures in Pakistan is limited. This PhD study covers a significant research problem of discomfort in cold and semi-arid climates by providing informed decision support for architects to improve indoor thermal comfort using passive design solutions. There is a need for further development of the prescriptive guide developed in this PhD research. For example, the prescriptive guide should be extended to include the financial cost, energy performance and life cycle analysis. In that way, an integrated assessment of environmental impact, financial cost, energy performance, and life cycle will be possible, which is required to make well-informed and balanced decisions during the design process.

The regulations and education based on science are essential for the development of a country. This study's recommendations are divided into these two parts, recommendations for regulators and further research.

11.3.1 Recommendations for regulators

Development of a design guide, bylaws and building code

This study's findings can be used to create a design guide for the city of Quetta and help reform the future bylaws and building codes in Pakistan. Although this PhD research is focused on the city of Quetta, the results (prescriptive guide) can also help to design residential buildings in cold semi-arid climates and with some interventions in the other parts of Pakistan. For example, natural ventilation and shading strategies can be useful in several areas of the country during extreme summer conditions. In comparison, passive solar heating and thermal insulation can be applied in a cold climate.

Defining thermal comfort

There is a need to define occupant thermal comfort and comfort temperatures for the different climatic zones of Pakistan. These comfort temperature and ranges should correspond to climatic conditions and buildings. The existing building code does not provide climate and context-based comfort temperatures and is focused on active methods.

Training and skills-based learning for architects

As of August 2020, the total number of registered architects with the Pakistan Council of Architects and Town Planners (PCATP) is 6028, while the ratio of architects per 1000 population is 0.028. This shows an indicative shortfall of 90530 architects compared with the OECD average. There are 33 architecture schools in the country, which represent a ratio of 0.16 schools per million population (PCATP, 2020). These figures show an urgent need to emphasise this profession for the sustainable development of the country.

The existing education programs of architecture in Pakistan lack basic training such as design internships and fieldwork. The majority of the graduates learn necessary practicals skills and knowledge after their graduation. It is essential to focus on the training and learning of architects and buildings professionals. The educationals programs should be restructured to provide the latest knowledge and practical skills by including field studies and internships. The concerned bodies and regulators should organized skill-based learning and training for practising architects.

Support for local manufacturers and industry

Most of the materials used in Pakistan to adopt passive measures are imported from other countries. This creates a burden on the economy and affects the affordability of materials by increasing their prices. Manufacturing such materials in Pakistan can provide economic benefits by reducing the import bills and will facilitate the local industries by providing an opportunity to enter into such a market. The regulators need to encourage local initiatives and assist them in manufacturing high-quality, energy-efficient building materials.

Material testing, certification and directory of materials

Building materials testing labs and research institutes should be established in all major cities of the country. A system for the registration, validation and certification of materials need to be introduced at the national level. A ranking and labelling systems for the materials should be adapted based on their characteristics, thermal performance and energy efficiency. This will lead to the development of sustainable materials and an ecosystem to support and promote sustainability in building construction and the built environment. In future, a directory of available building materials can be introduced at the national level to assist architects and building owners in making a better selection of building materials for construction.

Research grants and funding

Scientific research related to the built environment and construction industry needs special attention. Research grants and funding in these fields would help researchers come up with new and context-based research related to thermal comfort, energy efficiency, and sustainable development. At present, there is a lack of qualified researchers in the field of architecture. Most of the architectural schools have no faculty members with higher qualification. A research-oriented system should be established to reinvent the construction sector of the country.

Urbanization

Pakistan is one of the countries facing rapid growth in the urban population. According to the estimates, the country’s urban population will grow 207% between 2020-2050. This situation will create a new challenge for architects and building professionals. The economic activities are many moving to urban areas. There is an urgent need to focus on the upcoming urban challenges to cater to the future population's demands, including housing and related facilities. The growth in the urban population will lead to new construction of houses and buildings. Such new developments should be carefully planned, designed and built to achieve indoor thermal comfort, energy efficiency and sustainable development.

11.3.2 Recommendations for further research

Development of comfort model(s) for Pakistan

At present, there is no comfort model for Pakistan. The country has various climatic zones and climate variations in its different parts, and there may be a need for more than one comfort model: climate and context-based. Longitudinal comfort surveys and monitoring are proposed for the development of comfort model(s) for Pakistan. Currently, ASHRAE standards are mainly used in the country, and the Building Code of Pakistan (Energy Provision-2011) is primarily based on ASHRAE Standard 90.1-2004. The behavioural adaptations and cultural aspects can play an essential role in the occupant's thermal comfort. These two factors must be studied along with the climate, materials and construction practices.

Local materials and indigenous construction

The research on local materials, their use, and performance are limited. Indigenous materials and construction practices are mainly limited to farther and rural areas of the country. Local materials and indigenous methods can be used in such places to construct houses that will take less effort and benefit the environment. It will reduce the cost of the materials and help in the long term to cater to the housing sector's growing demands. Such efforts were made in Pakistan before constructing houses for the population affected by natural disasters in Mansehra, Tando Allahyar and Awaran.

Thermal performance of vernacular houses

Vernacular houses in Pakistan are slowly diminishing, yet in many rural and farther areas, such houses are mainly constructed and used for living. Future research may focus on the investigation of the thermal performance of local and vernacular houses. It is observed that vernacular architecture is mainly climate-responsive and context-based. The comfort demand and satisfaction level of the residents of such houses may be lower than those living in urban areas. There is a high chance that with minimum interventions, the occupant thermal comfort in such houses can be improved.

Passive design strategies and climate-responsive solutions for non-residential buildings

The buildings other than dwellings or buildings with less than half of their gross floor area used for dwelling purpose are considered non-residential buildings. In reality, non-residential buildings are a substantial part of building stock. These buildings often have different occupancy patterns and various functions; however, these buildings may require a particular design and strategies which are much different from the residential buildings. A significant number of non-residential buildings are public, educational, office or industrial buildings, where the occupant's work performance, comfort and energy consumption are the primary concerns of architects. The climate-responsive and passive design solutions can also be applied to non-residential buildings to improve occupants' thermal comfort (improve their work performance) and reduce energy demand for cooling, heating, and lighting.

Thermal comfort and indoor environmental quality optimization

The indoor thermal comfort can be improved considering climatic factors, building design, alternative materials and construction techniques, passive design measures etc. However, to achieve optimal thermal comfort, there is a need to combine passive and active systems. The priority should remain to keep the minimum usage of active systems as Pakistan's energy mix is mainly dependant on fossil fuels. The energy produced using fossil fuels is overpriced, which creates fuel poverty and adverse effects on the environment. The active systems ought to be energy-intensive to reduce the cost of heating and cooling. Future studies may consider devising a design criterion to achieve optimal thermal comfort using passive and active systems.

The indoor environmental quality (IEQ) affects the occupants' comfort, health, well-being, and overall quality of life. The IEQ is determined by several factors, including air quality, lighting, and damp conditions. In Pakistan, 47% of households use gas for cooking (urban areas 86%, rural areas 24%). The percentage of using clean fuel (not hazardous for health) for cooking, lighting and heating is high in urban areas. In Balochistan, 24% of households use clean fuel for cooking, lighting and heating, 47% in urban areas and only 15% in rural areas (*PSLM*, 2020). If a kitchen is not in a separate room or outside the house, it seriously affects the IEQ. During this PhD research, a monitoring survey of CO_2 concentration was performed in five houses. However, this PhD thesis only focuses on thermal comfort. The existing studies on IEQ in Pakistan are limited (Bughio et al., 2020; Mir et al., 2016). Future studies need to focus on improving IEQ in the building sector of Pakistan.

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Appendices

Appendix A: Safety Questionnaire

Dear respondent,

Thanks for your participation in this survey. I am a faculty member at the Department of Architecture BUITEMS Quetta, and currently, I am doing my PhD research in Belgium. My research focuses on the characteristics of the existing housing and developing a methodology for sustainable houses in Quetta. In the context of my research, I would request you to fill in the following questionnaire. The results of this questionnaire will create a start point for this research. This questionnaire aims to identify the safe areas of Quetta city, where it is possible to visit the existing houses for a housing stock survey.

Please, carefully reply to the following questions based on your knowledge and information. It will take approx 10 minutes to complete this questionnaire. The collected data will be dealt with anonymously and will only be used exclusively for the research purpose. If you have any question, please feel free to contact me at my email address: architectwaqas@hotmail.com

For this survey, Quetta city is divided into the following eleven areas based on their location, access and their link with major roads and highways:

a) Airport road and Baleli road

b) Brewery road

c) City Centre and surrounding areas

d) Double road and Sirki road

e) Eastern Bypass

f) New Hanna road

g) Raisani road and Qambrani road

h) Samungli road

i) Sariab road

j) Spinny road and Joint road

k) Western Bypass

Quetta Cantonment is not included in this survey due to difficulties that might be faced in obtaining permission and conducting a housing survey.

Part 1: Demographic information

Q1. Kindly fill in the following information: What is your age?

- o under 20 years (1)
- o 21-30 years (2)
- o 31-40 years (3)
- o 41-50 years (4)
- o 51-60 years (5)
- o above 60 years (6)

Q2. What is your gender?

- o Male (1)
- o Female (2)

Q3. What is your mother tongue?

- o Balochi (1)
- o Pashtu (2)
- o Hazaragi (3)
- o Punjabi (4)
- o Urdu (5)
- o Sindhi (6)
- o Siraiki (7)
- o Farsi (Persian) (8)
- o Uzbek (9)
- o Tajik/ Tajiki (10)
- o Kashmiri (11)
- o Brahui (12)
- o Other (please specify) (13) ____________________

Q4. What is your highest level of education?

- o Primary (1)
- o Middle (2)
- o Matriculation (3)
- o Intermediate (4)
- o Vocational/ Technical education (5)
- o Bachelors/ University (6)
- o Masters/ M.S/ M.Phil. (7)
- o Doctorate/ Ph.D. (8)

- o Other (please specify) (9) ____________________

Q5. What is your current employment status?

- o Employed (1)
- o Unemployed (2)
- o Student (3)
- o Retired (4)
- o Other (please specify) (5) ____________________

Part 2: Familiarity of the residential areas

Q6. Which of the following areas are you familiar with?

- o Airport road and Baleli Road (1)
- o Brewery road (2)
- o City Centre and surrounding areas (3)
- o Double road and Sirki road (4)
- o Eastern Bypass (5)
- o New Hanna road (6)
- o Raisani road and Qambrani road (7)
- o Samungli road (8)
- o Sariab Road (9)
- o Spinny road and Joint road (10)
- o Western Bypass (11)

Q7. Which of the following areas are you familiar with (if *'Airport road and Baleli road'* is selected)?

- o Bazai (1)
- o Chaman Housing Society (2)
- o Chashma Achozai (3)
- o Chiltan Housing Scheme (4)
- o Garden Town (5)
- o GOR Colony (6)
- o Kala Kakozai (7)
- o Khujalzai (8)
- o Killi Almas (9)
- o Killi Barech Abad (10)
- o Killi Chohi (11)
- o Killi Dumaran (12)

- Killi Gohar Abad (13)
- Killi Gul Muhammed (14)
- Killi Kotwal (15)
- Killi Malak Aman Kasi (16)
- Killi New Chohi (17)
- Killi Shaboo (18)
- Killi Umer Khan (19)
- QESCO Colony (20)
- Sheikh Manda (21)

Q8. Which of the following areas are you familiar with (if *'Brewery road'* is selected)?

- College Road (1)
- Durrani Town (2)
- Essa Nagri (3)
- Faisal Town (4)
- Gulshan Town (5)
- Lehri Abad (6)
- Muslim Town (7)
- Railway Housing Society (8)
- Wahdat Colony (9)

Q9. Which of the following areas are you familiar with (if *'City Centre and surrounding areas'* is selected)?

- Circular road (1)
- Fatima Jinnah road (2)
- Gurdat Singh road (3)
- Hali road (4)
- Jan Muhammad road (5)
- Kasi road (6)
- Liaquat Bazar (7)
- M.A. Jinnah road (8)
- Mariabad (including Gulistan colony, Hazara housing society and Alamdar road) (9)
- Masjid raod (10)
- McConaghey raod (11)
- Mission road (12)
- New Garden Town (13)
- Patel road (14)

- Prince road (15)
- Quarry road (16)
- Toghi road (17)
- Zarghun road (18)

Q10. Which of the following areas are you familiar with (if *'Double road & Sirki road'* is selected)?

- Ahmedzai Colony (1)
- CGS Colony (2)
- Double road area (3)
- Sirki road area (4)
- Satellite Town (5)

Q11. Which of the following areas are you familiar with (if *'Eastern Bypass'* is selected)?

- Badizai Colony (1)
- Bhatti Colony (2)
- Mehmood Khan Kakar Town (3)
- Mulla Khel Abad (4)
- Muslim Ittehad Colony (5)
- New Baloch Colony (6)
- New Pashtun Abad (7)
- Norzai (8)
- Rind Gar (9)
- Rodhi Alizai Town (10)
- Zaman Khan road (11)

Q12. Which of the following areas are you familiar with (if *'New Hanna road'* is selected)?

- Kashmir Colony (1)
- Khilji Abad (2)
- Killi Khanan (3)
- Labour Colony (4)
- Miankheil Abad (5)
- Milozo (6)
- Nawai Killi (7)
- Saraghurgai (8)
- Tareen Shar Kakar Abad (9)
- Teachers Colony (10)
- Wapda Colony (11)

Q13. Which of the following areas are you familiar with (if *'Raisani road and Qambrani road'* is selected)?

- Arbab Karam Khan Road (1)
- Berro (2)
- Kamallo (3)
- Qumbrani (4)
- Sheikhan (5)
- Sumalani (6)

Q14. Which of the following areas are you familiar with (if *'Samungli road'* is selected)?

- Arbab Town (1)
- Jail road (2)
- Jinnah Town (3)
- Killi Ismail (4)
- Pashtun Bagh (5)
- Shahbaz Town (6)

Q15. Which of the following areas are you familiar with (if *'Sariab Road'* is selected)?

- Bibi Ziarat Town (1)
- Grid Station Colony (2)
- Kechi Baig (3)
- Kili Chiltan Lehri Abad (4)
- Malghani Mohallah (5)
- Mengal Abad (6)
- Pak PWD Colony (7)
- Pirkani Abad (8)
- Sariab Mills Colony (9)
- Shahnawaz (10)
- Shahwani (11)

Q16. Which of the following areas are you familiar with (if *'Spinny road and Joint road'* is selected)?

- Ahmedzai Colony (1)
- Faqirabad (2)
- Joint road area (3)
- Killi Deba (4)
- Killi Hudda (5)
- Railway Housing Society (6)
- Tarkha Kasi (7)

Q17. Which of the following areas are you familiar with (if *'Western Bypass'* is selected)?

- Badizai Town (1)
- Emaan Housing Society (2)

- Gohar Abad (3)
- Hazarganji (4)
- Hazara Town (including New Hazara Town and Hazara Colony) (5)
- Kharot Abad (6)
- Khilji Killi (7)
- Killi Khaizi (8)

Q18. Which of the following areas are safe to visit and conduct a housing survey (please select all relevant option). Only areas selected as familiar in the above questions will appear.

Q19. Choose the suitable option(s) for the areas marked safe by you?

- I live/ lived here (1)
- I visited here (2)
- Both of the above (3)

Appendix B: Housing survey questionnaire

Introduction and Consent

Asalam-o-Alaikum

My name is ____.

I am architecture student/ faculty member at the Balochistan University of Information Technology, Engineering & Management Sciences (BUITEMS) Quetta. We are surveying existing housing in Quetta. The survey is part of research being conducted in Belgium by a faculty member of BUITEMS. The study focuses on the characteristics of the existing housing and developing a methodology for sustainable houses in Quetta.

The information collected will be helpful for the completion of this research. I will ask you some questions about your house and visit your house (if possible). It will take 20 to 30 minutes to finish this questionnaire. All answers will be considered confidential and will not be shared with anyone other than our survey team members.

If I ask you any question you don't want to answer, just let me know, and I will go on to the next question, or you can stop the interview at any time. In case you need more information about the survey, you may contact the person listed on this card (provide the name card of Waqas).

Do you have any questions?

May I begin the interview now?

Signature of respondent: _________________________ Date: ______________________

Respondent agreed to be interviewed 1

Respondent refused to be interviewed 0

Signature of the interviewer: _____________________ Date: _______________________

Identification and Basic Info			
1. Area/ Neighborhood:			
2. House/ Plot No.		4. Name of owner/ head:	
3. Address:		5. Name of architect:	
		6. Date/ year of construction:	

7. Interviewer Visits			
	1	2	3
Date:	____________________	____________________	____________________
Interviewer name:	____________________ ____________________	____________________ ____________________	____________________ ____________________

8. Result 1 Completed ☐ 2 Refused ☐ 3 Other (specify): ____	9. Mother tongue:
10. household size: Total no. of family members: ____________________ No. of male members in household: _______________ No. of female members in household: ______________ No. of adults in household: _______________________ No. of children (under 18) in household: _____________	11. Education of head of household: a) Uneducated ☐ b) Primary ☐ c) Middle ☐ d) Matriculation ☐ e) Intermediate ☐ f) Bachelor ☐ g) Masters ☐ h) PhD or above ☐ i) Other: _______________
13. Nature/ type of employment: a) Salaried ☐ b) Daily wages ☐ c) Self-employed ☐ d) Business ☐ e) Other (specify): _______________________________________	12. Employment status of head of household a) Employed ☐ b) Unemployed ☐

No.	Question	Skip
14	Total area/ size of the house:	

15	Covered area:	
16	No. of floors in the house:	
17	No. of bed rooms in the house:	
18	Structural system (super structure): a) R.C.C frame structure b) Brick/ Stone masonry c) Sun dried bricks d) Rammed earth e) Other (specify): ______________________	
19	Thickness of the Exterior walls:	
20	Finish of the Exterior walls (record observation): a) Plaster (mud/ cement/ lime) b) Cladding (stone/ brick/ marble/ tile) c) White washed/ painted d) Other (specify): ______________________	
21	Main material of the Exterior walls (record observation): a) Mud wall (sun dried bricks/ rammed earth) b) Baked bricks (mud mortar/ cement mortar/ lime mortar) c) R.C.C walls d) Concrete Blocks with cement mortar e) Stone (mud mortar/ cement mortar/ lime mortar) g) Other (Specify): _____________________	
22	Thickness of the Interior/ partition walls:	
23	Finish of the Interior walls (record observation): a) Plaster (mud/ cement/ lime) b) Cladding (stone/ brick/ marble/ tile) c) White washed/ painted d) Wallpaper e) Wood paneling f) Cloth/ fabric g) Other (specify): ______________________	
24	Finishing of the Floor (record observation): a) P.C.C floor (plain/ coloured) b) Tile (ceramic/ marble/ vinyl/ terrazzo/ stone/ mosaic) c) Brick d) Chips/ terrazzo e) Carpet/ mat	

	f) Earth/ sand/ mud g) Wood planks h) Other (specify): ____________________	
25	Main material of the Floor (record observation): a) P.C.C floor b) Brick/ burnt brick tile c) Earth/ sand/ mud d) Wood e) Other (specify): ____________________	
26	Main material of the Roof covering (record observation): a) R.C.C b) Reinforced Brick/ R.B.C c) Tile (concrete roof tile, burnt brick) d) Asbestos sheets e) Corrugated Galvanized Iron (GI) Sheets f) Thatch/ Palm/ Bamboo g) Plastic/ Polycarbonate sheets h) Fiber glass sheet i) Other (specify): ____________________	
27	Main material of the Roof framing (record observation): a) R.C.C beams b) Truss (Iron/ Wooden) c) Wooden beams with bamboos d) T-iron with girders e) Wooden beams with girders f) Other (specify): ____________________	
28	Main material of False ceiling: if any (record observation): a) Card board sheets b) Plaster of Paris (Gypsum sheets) c) Polystyrene sheets (Thermopore) d) Mud false ceiling e) Wooden/ Lasani sheets f) PVC false ceiling g) Other (specify): ____________________	
29	Have you applied/ used insulation in any of the following? a) Walls b) Roof c) Floor d) Not at all	

30	Is there any Cavity wall (s) in your house? a) Yes b) No	
31	If Yes, the thickness of Cavity wall (s):	
32	Glazing in windows: a) Single glazed b) Double glazed c) Triple glazed	
33	How many rooms do you heat during winter:	
34	Source of heating rooms: a) Gas b) Electricity c) Wood/ Coal/ Dung d) Other (specify): ______________________	
35	Heating system: a) Central heating b) Direct heating c) Other (specify): ______________________	
36	In Summer, what is your average electricity bill per month? a) less than Rs. 2, 000 b) Rs. 2, 000- Rs. 3, 000 c) Rs. 3, 000- Rs. 5, 000 d) Rs. 5, 000-Rs. 10, 000 e) Rs. 10, 000 and above	
37	In Winter, what is your average electricity bill per month? a) less than Rs. 1, 000 b) Rs. 1, 000- Rs. 2, 000 c) Rs. 2, 000- Rs. 3, 000 d) Rs. 3, 000- Rs. 5, 000 e) Rs. 5, 000 and above	
38	In Summer, what is your average Gas bill per month? a) less than Rs. 5, 00 b) Rs. 5, 00- Rs. 1, 000 c) Rs. 1, 000- Rs. 2, 000 d) Rs. 2, 000- Rs. 3, 000 e) Rs. 3, 000 and above	

39	In Winter, what is your average Gas bill per month? a) less than Rs. 2, 000 b) Rs. 2, 000- Rs. 3, 000 c) Rs. 3, 000- Rs. 5, 000 d) Rs. 5, 000-Rs. 10, 000 e) Rs. 10, 000 and above	
40	What is the main source of water for your household? a) Tube well or borehole b) Water Supply c) Water Tanker d) Cart with small tank e) Other: ________________	
41	Do you need to pay for your water usage/ consumption? a) Yes b) No	
42	If yes, what is your average/ fixed water bill per month? a) up to Rs. 3, 00 b) Rs. 3, 00- 5, 00 c) Rs 5, 00-1, 000 d) Rs. 1, 000 and above	
43	How do you store water? a) Overhead Tank b) Underground Tank c) Drums d) Water Cane/ Plastic bottles e) Pots f) Other: _____________________	
44	Where do you drain off the wastewater? a) Public sewer/ drainage line b) Septic Tank c) Soak Pit d) Open ground e) Water channel f) Other: _____________________	
45	How do you dispose of solid waste? a) House to house collection b) Community bins c) Leave at street/ road d) Leave at disposal site e) Leave at empty plot/ open land f) Other: _____________________	

46	What is the monthly income of your household (PKR)? a) Up to 15, 000 b) 16, 000 to 45, 000 c) 46, 000 - 80, 000 d) 81, 000 - 105, 000 e) 106, 000 - 150, 000 f) 150, 000 and above			
47	Does your household have:	YES	NO	
	a) Electricity	□	□	
	b) Natural gas	□	□	
	c) Fan/ Air cooler	□	□	
	d) Press Iron	□	□	
	e) Room heater	□	□	
	f) Mobile phone	□	□	
	g) Television	□	□	
	h) Washing machine	□	□	
	i) Water geyser/ boiler	□	□	
	j) Refrigerator	□	□	
	k) Motorcycle or scooter	□	□	
	l) Charpai	□	□	
	m) Bed	□	□	
	n) Dining table	□	□	
	o) Sofa	□	□	
	p) Microwave oven	□	□	
	q) Vacuum cleaner	□	□	
	r) Air-conditioner	□	□	
	s) Computer	□	□	
	t) Internet connection	□	□	
	u) Car	□	□	
	v) Domestic servant in the household	□	□	
48	Can I draw a sketch/ plan of your house? a) Yes b) No			
49	Can I take some pictures of your house? a) Yes b) No			

Appendix C: Comfort survey questionnaire

Identification and Basic Info				
1. Area/ Neighbourhood:				
2. House/ Plot No.		5. Name of owner/ head:		
3. Type of house: attached/ detached etc.		6. Name of architect:		
4. Address:		7. Date/ year of construction:		
8. Visits				
	1		2	3
Date:	____________________		____________________	____________________
9. Monitoring period				
In Summer			In Winter	
From ___________	To ______________		From ______________	To ______________
10. No. of weeks/ days				
In summer			In winter	
11. Mother tongue:				

12. household size: Total no. of family members: ____________________ No. of male members in household: _______________ No. of female members in household: ______________ No. of adults (18 and above) in household: _______________________ No. of children (under 18) in household: _________________________	13. <u>Education of head of household:</u> a) Uneducated □ b) Primary □ c) Middle □ d) Matriculation □ e) Intermediate □ f) Bachelor □ g) Masters □ h) PhD or above □ i) Other: ______________
15. Nature/ type of employment: a) Salaried □ b) Daily wages □ c) Self-employed □ d) Business □ e) Other (specify): _______________________________________	14. Employment status of head of household: a) Employed □ b) Unemployed □

Architectural aspects

No.	Question	Comments

16	Total area/ size of the house:	
17	Total Covered area:	
18	Building volume:	
19	Orientation:	
20	No. of floors in the house:	
21	No. of bed rooms in the house:	
22	Thickness of the Exterior walls:	
23	Thickness of the Interior/ partition walls:	
24	Finish of the Exterior walls: a) Plaster b) Cladding (stone/ brick/ marble/ tile) c) White washed/ painted d) Other (specify): ______________________	
25	Main material of the Exterior walls: a) Baked bricks b) Concrete Blocks with cement mortar c) R.C.C walls d) Other (Specify): _____________________	
26	Finish of the Interior walls: a) Plaster b) Cladding (stone/ brick/ marble/ tile) c) White washed/ painted d) Wallpaper e) Wood panelling f) Cloth/ fabric g) Other (specify): ______________________	
27	Finishing of the Floor: a) P.C.C floor (plain/ coloured) b) Tile (ceramic/ marble/ vinyl/ terrazzo/ stone/ mosaic) c) Chips/ terrazzo d) Carpet/ mat e) Wood planks f) Other (specify): _____________________	
28	Main material of the Floor (record observation): a) P.C.C floor b) Brick/ burnt brick tile c) Wood d) Other (specify): _____________________	
29	Main material of the Roof covering: a) R.C.C b) Reinforced Brick/ R.B.C c) Other (specify): _____________________	

30	Main material of the Roof framing: a) R.C.C beams b) T-iron with girders c) Other (specify): ______________________	
31	Main material of False ceiling (if any): a) Card board sheets b) Plaster of Paris (Gypsum sheets) c) Polystyrene sheets (Thermopore) d) Wooden/ Lasani sheets f) PVC false ceiling g) Other (specify): _____________________	
32	Have you applied/ used insulation in any of the following? (details) a) Walls b) Roof c) Floor d) Not at all	
33	Cavity wall(s) and its thickness	
34	Window glazing: a) Single glazed b) Double glazed c) Triple glazed	
35	Windows covering a) Curtains b) Window blinds c) Other (specify): _____________________	
36	Overhang/ shading devices (projections):	
37	Can I take some pictures of your house? a) Yes b) No	
38	Measurements: a) Yes b) No	
	Household wealth & Income	
	What is the monthly income of your household (PKR)? a) Up to 15, 000 b) 15, 001 to 45, 000 c) 45, 001 - 80, 000 d) 80, 001 - 105, 000 e) 105, 001 - 150, 000 f) above 150, 000	

	Does your household have:	YES	NO	
	a) Electricity	□	□	
	b) Natural gas	□	□	
	c) Fan/ Air cooler	□	□	
	d) Press Iron	□	□	
	e) Room heater	□	□	
	f) Mobile phone	□	□	
	g) Television	□	□	
	h) Washing machine	□	□	
	i) Water geyser/ boiler	□	□	
	j) Refrigerator	□	□	
	k) Motorcycle or scooter	□	□	
	l) Charpai	□	□	
	m) Bed	□	□	
	n) Dinning table	□	□	
	o) Sofa	□	□	
	p) Microwave oven	□	□	
	q) Vacuum cleaner	□	□	
	r) Air-conditioner	□	□	
	s) Computer	□	□	
	t) Internet connection	□	□	
	u) Car	□	□	
	v) Domestic servant in the household	□	□	

Semi-structured interview questions

HVAC systems, energy consumption & lighting

1. How many rooms do you heat during winter? Which ones? Type and number of heating devices? Hours and months (peak and off-peak).
2. Source of heating rooms (Gas/ electricity)?
3. Heating system (Direct heating/ central heating)? Location of heating system/ devices and details. Heating elements (radiators/ convectors/ underfloor heating)?
4. Control of heating system (Thermostat/ sensors)?
5. How many rooms do you ventilate/ cool during summer? Which ones? Type and number of cooling devices? Hours (peak and off-peak).
6. In which rooms you need more cooling/ heating? And why?

7. How do you heat water [Gas geyser/ electric geyser/ Stove (pots or container)]? Does the water geyser have a thermostat? If not, how many hours do you heat water?

8. Electricity bill during (4 summer months and 4 winter months)? Or whole year (July ‘17-June ‘18).

a) May 2017:
b) June 2017:
c) July 2017:
d) August 2017:
e) November 2017:
f) December 2017:
g) January 2018:
h) February 2018:

9. Gas bill during (4 summer months and 4 winter months)? Or whole year (July ‘17-June ‘18).

a) May 2017:
b) June 2017:
c) July 2017:
d) August 2017:
e) November 2017
f) December 2017
g) January 2018
h) February 2018

10. How satisfied are you with the electricity bill (price)/ consumption:

a) Slightly satisfied
b) Very satisfied
c) Neither satisfied nor dissatisfied
d) Very dissatisfied
e) Slightly dissatisfied

11. How satisfied are you with the gas (price)/ consumption:

a) Slightly satisfied
b) Very satisfied
c) Neither satisfied nor dissatisfied
d) Very dissatisfied
e) Slightly dissatisfied

12. Source of fuel/ energy used for cooking?

13. Do you experience electricity load shedding? How do you light/ ventilate rooms during load shedding hours? Details of systems used? And hours of load shedding (in summer and winter)
14. Do you experience low gas pressure/ load shedding in cold winter? How do you heat the room and cook meal during that time? Details of systems used? Hours and months of load shedding?
15. Do you use hot water for taking a shower in summer? If yes, why? How do you heat water in summer and for specific hours/ months?
16. Does someone stay at home during the day? If yes, which parts of the house they mostly use? And which appliances?
17. Do you know the price per unit (kWh) of electricity? Or per m3 of the natural gas?
18. Types of lighting used in the house [light bulb (Incandescent/ Halogen Fluorescent)/ Energy saver (Compact fluorescent lamp)/ Tube light (Fluorescent lamp)/ Gas light/ LED light]

Behavioural insights

1. What do you do? When you not using any room/ part of the house?
2. What do you do while leaving the house for few hours? Few days?
3. Do you turn on lights during the day? If yes, Reason? In which parts of the house you use artificial lights during the day?
4. Do you turn off extra lights when they are no more needed? Do you turn off lights when you are leaving home?
5. Do you turn off gas appliances when they are no more needed, or you are leaving your home/ room? Do you turn off gas appliances before going to bed? If no, why? (To keep the room warm, the size of heater and performance is not satisfactory, gas bills are not that high)
6. Which of the following ventilation/ cooling system do you prefer? (Natural ventilation, Fan, Air-cooler, Air-conditioner). Why? And which one you mostly use? And why?
7. Do you open windows for ventilation/ fresh air? When? Which season? How long? If No, then reason?

Comfort, energy efficiency and clothing

1. During the cold winter, how do you feel in your living room? (during the day)
    a) Slightly hot
    b) Very hot
    c) Neither hot nor cold
    d) Very cold
    e) Slightly cold

Reason for feeling cold and hot?

2. During the hot summer, how do you feel in your living room? (during the day)
    a) Slightly hot
    b) Very hot
    c) Neither hot nor cold
    d) Very cold
    e) Slightly cold

Reason for feeling cold and hot?

3. During the cold winter, how do you feel in your bedroom? (during the night)
    a) Slightly hot
    b) Very hot
    c) Neither hot nor cold
    d) Very cold
    e) Slightly cold

Reason for feeling cold and hot?

4. During the hot summer, how do you feel in your bedroom? (during the night)
    a) Slightly hot
    b) Very hot
    c) Neither hot nor cold
    d) Very cold
    e) Slightly cold

Reason for feeling cold and hot?

5. What is your satisfaction level with the existing cooling/ ventilating system?
    a) Very satisfied
    b) Fairly satisfied
    c) Neither satisfied nor dissatisfied
    d) Fairly dissatisfied
    e) Very dissatisfied
    f) Don't know

Reason for satisfaction or dissatisfaction?

6. What is your satisfaction level with the existing heating system/ devices?
    a) Very satisfied
    b) Fairly satisfied
    c) Neither satisfied nor dissatisfied
    d) Fairly dissatisfied

e) Very dissatisfied

f) Don't know

Reason for satisfaction or dissatisfaction?

7. What kind of fabric clothing you wear during winter/ summer? Type of fabric? Type of clothing; i.e. trousers, shorts, shirt, waist-coat etc.

8. Ask the above questions (of this section) from the other family members if possible? Including clothing of female/ male/ child/ old? Age and gender of the respondents?

9. Have you made any energy-saving improvements in your house? If Yes, which change(s) have you made?

10. Would you like to do the renovation for the better energy performance of your house?

11. Would you prefer to use insulations knowing that the initial cost will be higher?

12. Would you prefer to use alternative materials than RCC cement if it makes your house more energy-efficient and comfortable?

Renewable energy

1. Do you know about renewable energy? If no, then explain. If yes, then: What do you know about renewable energy?

2. Would you prefer to use renewable/ alternative energy sources?

3. Would you like to invest in renewable energy knowing that the initial cost will be higher? If yes, why? Or would you like to get some subsidies for it?

4. Do you think solar energy can be a good solution to Pakistan's load shedding/ energy crisis?

5. Would you prefer to install solar PVs, solar water heater/ geyser at your house?

Appendix D: Materialization survey

This survey is part of a PhD research being conducted at the University of Liège, Belgium. This study explores the existing energy-efficient materials available and manufactured in Pakistan. The questionnaire targets manufacturers, suppliers, distributors of building materials, the practising architects, and Quetta residents who used insulation and double glazing in their houses. The collected information will be treated with complete confidentiality, and your identity and anonymity are guaranteed. The results will only be used for research purpose.

Thanks for your valuable contribution.

<u>Questions asked from the materials suppliers and distributors</u>

1. Name of the business/ company ____
2. Name of the respondent (optional)____
3. Experience in budiling materials (MM/YY)____________________________________
4. Do you sell/ supply any insulation and double glazing products?
   - o Yes
   - o No
5. If yes (4), which insulation do you deal with? List the names
6. If yes (4), which double glazing do you deal with? List the names
7. Any of these products or locally produced in Quetta or Balochistan?
   - o Yes
   - o No
8. From which cities you procure the products? List the names.
9. Do you know if these products improve indoor thermal comfort?
   - o Yes
   - o No
10. Do you know the thermal properties of these products?
    - o Yes
    - o No
11. Have you ever used any of these products in your own building/ construction project(s)?
    - o Yes
    - o No

Questions asked from the architects

1. Name of the business/ company ____

2. Name of the architect (optional)____

3. Experience (MM/YY)____

4. Are you familiar with any insulation and double glazing products?

   - o Yes
   - o No

5. If yes (Q1), which of the insulation products you are familiar with? List the names

6. If yes (Q1), which of the glazing products you are familiar with? List the names

7. Any of these products are locally produced in Quetta or Balochistan?

   - o Yes
   - o No

8. From which cities and suppliers you procure the products?

9. Do you know if these products improve indoor thermal comfort?

   - o Yes
   - o No

10. Do you know the thermal properties of these products?

   - o Yes
   - o No

11. Have you ever used any of these products in your designed building project(s)?

   - o Yes
   - o No

12. If yes (Q8), how many projects have you used insulation or double glazing?

13. Have you tested the comfort improvement after using insulation and double glazing products?

   - o Yes
   - o No

14. Do you recommend your clients for using insulation and double glazing in residential buildings?

   - o Yes
   - o No

15. Do you need to convince clients for using insulation and double glazing products?

   - o Yes
   - o No

16. Would you like to tell us more about your experience and challenges related to the use of insulation and double glazing products?

Questions asked from the residents

1. Name of the respondent____

2. Address____

2. Name of the architect (optional)____

4. Year of construction____

4. Have you used insulation and double glazing products in your house?

- o Yes
- o No

5. If yes (Q4), which insulation product(s) have you used? List the names

6. If yes (Q4), which glazing product(s) have you used? List the names

7. Any of these products are locally produced in Quetta or Balochistan?

- o Yes
- o No

8. From which cities and suppliers you procure the products?

9. Do you know if these products improve indoor thermal comfort?

- o Yes
- o No

10. Do you know the thermal properties of these products?

- o Yes
- o No

11. Have you tested the comfort improvement after using insulation and double glazing products?

- o Yes
- o No

16. Would you like to tell us more about your experience and challenges related to the use of insulation and double glazing products?

Appendix E: Thermal Zones and Thermal Properties of Building Materials (Reference Case)

Table E1. Description of zones.

Zone	**Surface (m^2)**	**Volume (m^3)**	**Zone**	**Surface (m^2)**	**Volume (m^3)**
Master bed	15.6	47.24	Bedroom 1	11.42	34.71
Kid's room	15.36	46.69	Guest room	20.81	63.26
Living room	13.33	40.52	Kitchen	7.66	23.28
Toilet 1	4.06	12.34	Toilet 2	4.27	12.98
Toilet 3	2.66	8.08	Laundry	2.66	8.08

Table E2. Thermal properties of building materials. Legend: RCC, reinforced cement concrete.

Building Element Composition	**Thickness (cm)**	**Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific Heat Capacity (Wh/kg K)**
	E_p	ɚ	D	C_p
Walls (3 layers)				
Plaster	0.95	0.431	1250	1088
Brick	22.86	0.711	2000	836
Plaster	0.95	0.431	1250	1088
Ceiling (4 layers)				
Plaster	0.95	0.38	1150	840
Bitumen	0.95	0.5	1700	1000
RCC slab	10.16	0.753	2300	665.9
Plaster	0.95	0.38	1150	840
Floor				
Cement mortar	0.95	0.72	1650	920
Concrete	5.08	0.753	2000	656
Aggregate	7.62	1.8	2240	840
Sand	10.16	1.74	2240	840
Earth/ soil	22.86	0.837	1300	1046
Windows (single glazed) with clear glass	0.63	1.046	2300	836.8

Appendix F: Lighting, Domestic Hot Water, and Occupancy Schedules (Reference Case)

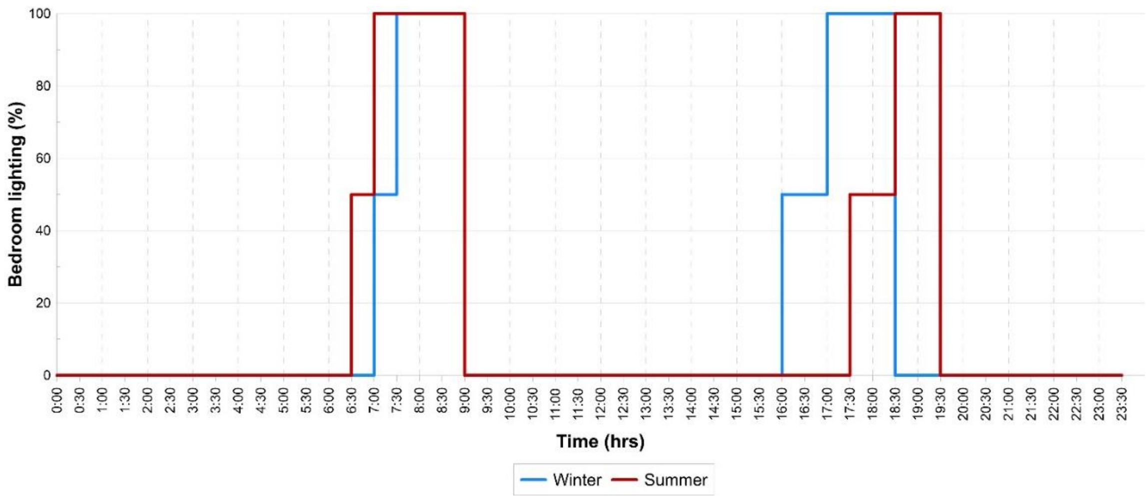

Figure F1. Lighting schedule of bedrooms.

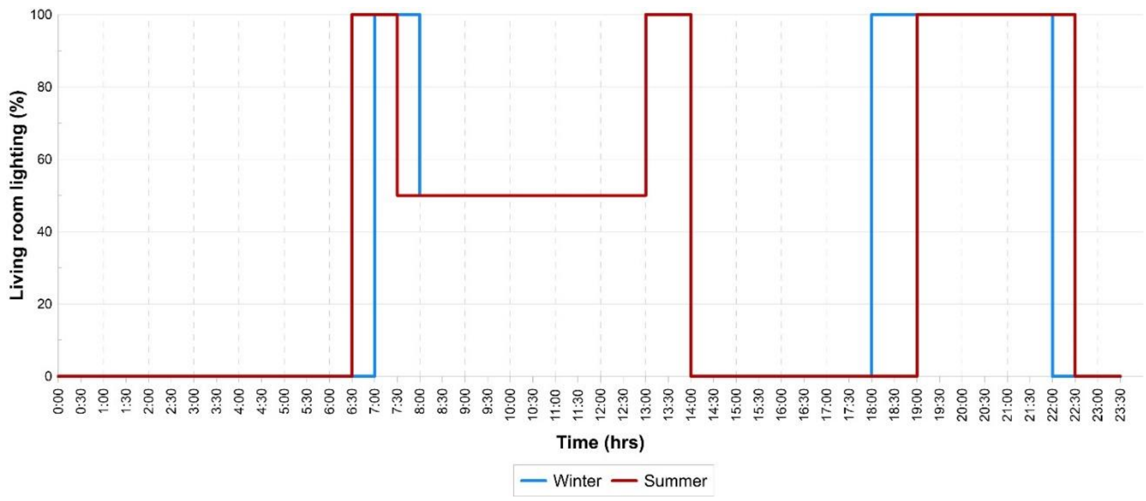

Figure F2. Lighting schedule of living room.

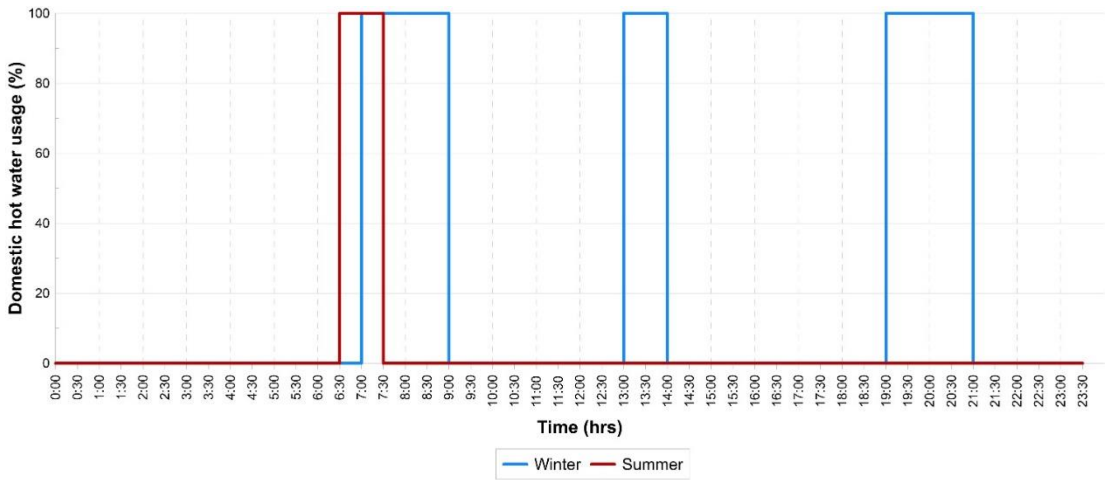

Figure F3. Domestic hot water schedule.

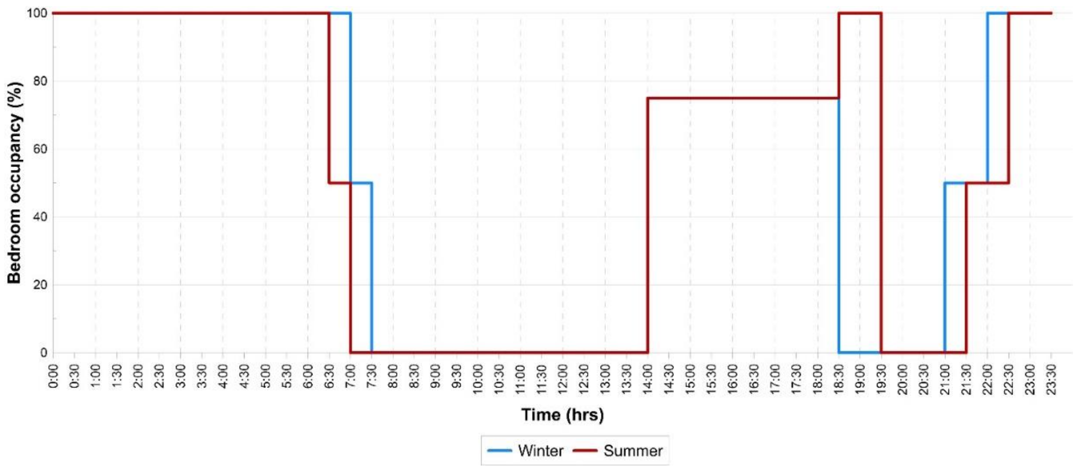

Figure F4. Bedroom occupancy schedule.

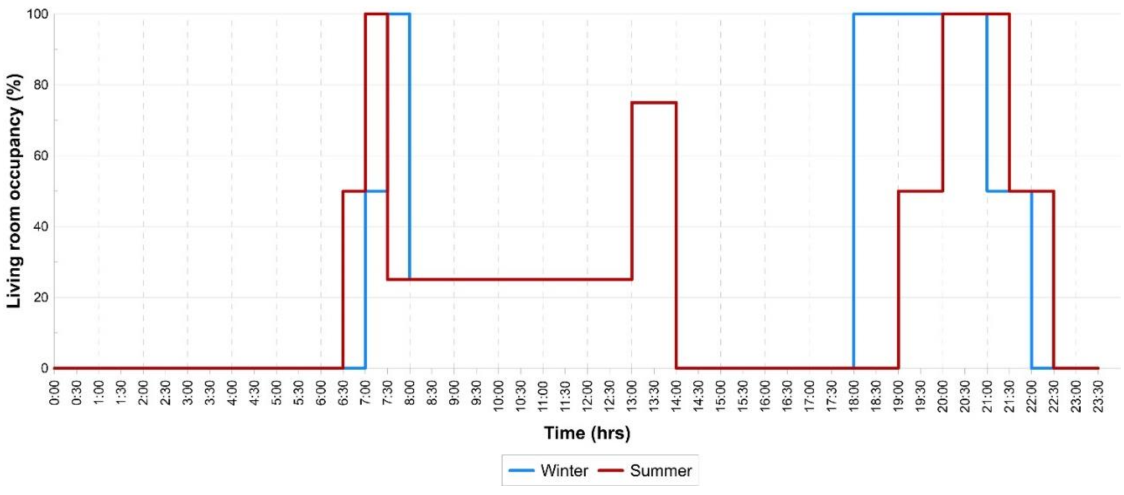

Figure F5. Living room occupancy schedule.

Appendix G: Usability test questionnaire

1. Personal information

1.1 Name: ____________________________________ 1.2 Gender: ☐ Male ☐ Female

1.3 ☐ Architect Experience (Yrs n months):___________________

1.4 ☐ Student Year/Semester:_____________________________

---

2. Pre-and Post-Knowledge

2.1. How would you assess your ability to design “Comfortable houses” (before the workshop)

☐ Very advanced ☐ advanced ☐ Fair ☐ Poor ☐ no skills

2.2. How would you assess your ability to design “Comfortable houses” (after the workshop)

☐ Very advanced ☐ advanced ☐ Fair ☐ Poor ☐ no skills

---

3. Satisfaction (After scenario questionnaire)

3.1. I am satisfied with the ease of completing the design using the “Building code/ prescriptive guide”.

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

3.2. I am satisfied with the amount of time it took to complete the design using the “Building code/ prescr. guide”?

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

3.3. I am satisfied with the information provided by the “Building code/ prescriptive guide”?

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

---

4. Decision making attitude and patterns

4.1. Working with the “Building code/ prescriptive guide” informs your decision making?

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

4.2. Working with the “Building code/ prescriptive guide” makes you confident about your decision making?

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

4.3. Working with the “Building code/ prescriptive guide” allows you to achieve the goal of “comfortable houses”.

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

4.4. Working with the “Building code/ prescriptive guide” is essential for designing “comfortable houses”?

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

4.5. Working with the “Building code/ prescriptive guide” helps to produce reliable and robust designs of “comfortable houses”?

☐ Strongly agree ☐ agree ☐ undecided ☐ disagree ☐ strongly disagree

---

5. What should be done to bridge the barrier of using a building code/ prescriptive guide and achieving informed decision making?

____

____

____

____

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Appendix H: Participants of the usability test

Figure H1. Architects participated in the usability test along with the organizers

Front row (left to right): Mehwish Sarwar, Maryam Ali, Samreen, Samana Batool, Batool Fatima and Aqsa Nasir

Back row (left to right): Syed Faiq Bukhari, Naveed Ahmed, Waqas Ahmed Mahar, Sanuallah Aziz, Shahroze Shah, Abdul Wahab Awan and Adeel Zahoor

Figure H2. Architecture students participated in the usability test along with the organizers

Front/ 1st row (left to right): Kalsoom Raza, Minah Khalid, Rubab Fatima, Umaima Gohar and Saba Naz

2nd row (left to right): Maheen Waseem, Malak Kamal, Abdal Kakar, Mubeen Akbar and Aqdas Ali

3rd row (left to right):, Muhammad Noman, Hameedullah, Muhammad Musab, Waqas Ahmed Mahar, Shahroze Shah and Adeel Zahoor

Appendix I: Building Code of Pakistan (Energy Provision-2011)

Chapter 4, Building Envelope

How to design a house with improved indoor thermal comfort based on the information given in the Building Code of Pakistan (Energy Provisions-2011): BCP (EP-2011)

- External Walls and Roof
  - Overall U-values of external walls and roofs shall not exceed limits

Walls	U: 0.57 W/m^2 K (0.10 Btu/h.ft^2 °F)
Roof	U: 0.44 W/m^2 K (0.078 Btu/h.ft^2 °F)

- Glass and framing system
  - For buildings with external glass area, not exceeding 40% of the external wall area of the building

Heat Transmission Coefficient (U)	3.5 W/m^2 K (0.44 Btu/h.ft^2 °F)
Shading Coefficient (SC)	0.76

- Air Leakage and infiltration
  - Air leakages for revolving/ sliding/ swinging entrace/ exit doors shall not exceed 5.0 L/s/m^2
  - And for doors, air leakages shall not exceed 2.0 L/s/m^2

List of Abbreviations

AEDB	Alternative Energy Development Board
AJK	Azad Jammu and Kashmir
ANN	Artificial Neural Network
ANSI	American National Standard Institute
Arg	Argon
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASQ	After Scenario Questionnaire
BCP	Building Code of Pakistan
BESTEST	Building Energy Simulation Test
BPS	Building Performance Simulation
BRI	Belt and Road Initiative
BUITEMS	Balochistan University of Information Technology, Engineering and Management Sciences
CDD	Cooling Degree Days
CH	Comfort Hours
CPU	Central Processing Unit
CV(RMSE)	Coefficient of Variation of Root Square Mean Error
DGU	Double Glazed Unit
DHW	Domestic Hot Water
DHS	Demographic and Health Surveys
EEA	European Economic Area
EHS	English Housing Survey
EP	Energy Provisions
EPS	Expanded Polystyrene
EU	European Union
EW	East-West
F	Floor
FY	Fiscal Year
GB	Gilgit-Baltistan
GPDR	General Data Protection Regulation
GHz	Gigahertz
GI	Galvanized Iron

GoB	Government of Balochistan
GoP	Government of Pakistan
HCPC	Habibullah Coastal Power Company
HDD	Heating Degree Days
HEC	Higher Education Commission
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICT	Islamabad Capital Territory
IDSP	Institute for Development Studies and Practices
ISO	International Organization for Standardisation
IWEC	International Weather for Energy Calculation
IUCN	International Union for Conservation of Nature
K-Electric	Karachi Electric
KP	Khyber Pakhtunkhwa
LHS	Latin Hypercube Sampling
LoE	Low Emissivity
LT	Light Transmission
M.A. Jinnah	Muhammad Ali Jinnah
MCA	Monte Carlo Analysis
MFD	Metal Floor Deck
MIS	Management Information System
MMCFD	Million Cubic Feet Per Day
MW	Megawatt
NCDC	National Climatic Data Centre
NCEI	National Centres for Environmental Information
NGO	Non-Governmental Organization
NMBE	Normalised Mean Bias Error
NNW	North North-West
NREL	National Renewable Energy Laboratory
NSGA-II	Non-dominated Sorting Genetic Algorithm
nZEB	Nearly Zero-Energy Buildings
PBS	Pakistan Bureau of Statistics
PCC	Plain Cement Concrete
PCC	Partial Correlation Coefficient
PDPB	Personal Data Protection Bill

PE	Polyethylene
PES	Pakistan Economic Survey
PEPCO	Pakistan Electric Power Company
PKR	Pakistani Rupee
PLB	Pishin Lora Basin
PMD	Pakistan Meteorological Department
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PVC	Polyvinyl Chloride
PV	Photovoltaic
QDA	Quetta Development Authority
QDDP	Quetta District Development Profile
QESCO	Quetta Electric Supply Company
R	Roof
RCC	Reinforced Concrete Cement
RCF	Reinforced Concrete Frame
Rs.	Rupees
SA	Sensitivity Analysis
SC	Shading Coefficient
SBP	State Bank of Pakistan
SDGs	Sustainable Development Goals
SHGC	Solar Heat Gain Coefficient
SOGA	Single-Objective Genetic Algorithm
SRC	Standard Regression Coefficient
SSE	South South-East
SSGC	Sui Southern Gas Company
TCH	Thermally Comfortable House
TMY	Typical Meteorological Year
TRY	Test Reference Year
UIA	Union of International Architects
UN	United Nations
UoB	University of Balochistan
UPS	Uninterrupted Power Supply
UPVC	Unplasticized Polyvinyl Chloride
USAID	United States Agency for International Development

W	Window
WASA	Water & Sanitation Authority
WF	Window Frame
WFP	World Food Programme
WP	Workpackages
WS	Window Shading
WWR	Window-to-wall Ratio
XPS	Extruded Polystyrene

Profile of the PhD candidate

Waqas Ahmed MAHAR

Waqas Ahmed Mahar is an architect and planner. He studied architecture at Mehran University of Engineering & Technology (MUET) Jamshoro, Pakistan, and graduated in 2008/9.

After graduation, he started to work as an architect at 'The Global Architects' Hyderabad, Pakistan. Later in 2010, he worked as an internee/ teaching assistant at the Department of Architecture, MUET Jamshoro.

In June 2010, he started M.Sc. (Planning-Housing) at Universiti Teknologi Malaysia (UTM) and graduated in 2012 with the distinction 'Best Student Award'. During his master, he did an internship at Universiti Tunku Abdul Rahman (UTAR) Malaysia, where he assisted senior faculty in the design studio of first-year architecture. Waqas also worked as a 'Manager of Housing and Residential Care Facilities' at Handicapped and Mentally Disabled Children Association Johor, Johor Bahru, Malaysia, for six months.

In 2013, he joined the Department of Architecture at Balochistan University of Information Technology, Engineering & Management Sciences (BUITEMS) Quetta, Pakistan, where he is currently working as an Assistant Professor of Architecture & Planning. He started his PhD at Hasselt University, Belgium, in 2015. In 2017, he moved to the University of Liège and continued his PhD at the Sustainable Building Design (SBD) Lab.

Architectural design is complex, ill-defined, uncertain, and exploratory. The outcome is based on the inclusion of better research, experience, and advanced knowledge in building science. A multidisciplinary approach is mandatory for decision making at the early stage of design by architects. Support at the early design phase is more important since small scale projects lack the budget and resources.

The study aims to develop a decision-making prescriptive guide for climate-responsive residential buildings in cold semi-arid climates. It involves building performance simulation to perform comfort analysis, parametric analysis and sensitivity analysis. Building simulation is a complex process, not readily available and requires specific skills, knowledge level and equipment, such as high-performance computers. The situation makes it difficult for the architects to practice in developing countries and design residential buildings using simulation tools due to limited resources, time, and projects. In such a situation, a prescriptive guide can provide firsthand information to architects for designing houses with improved thermal comfort without spending a lot of time and effort.

BPS tools were used to develop this decision-making prescriptive guide based on the effective passive design solution identified using a sensitivity analysis. The decision-making was evaluated by performing a usability test. The results highlight the effectiveness of the prescriptive guide for providing informed decision-making to architects for designing climate-responsive residential buildings in an efficient way.

ISBN: 978-2-930909-21-9

SBD LAB Sustainable Building Design Lab

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