IMPACT OF BUILDING ENVELOPE MODIFICATIONS ON THERMAL PERFORMANCE OF CLASSROOMS IN TYPICAL SCHOOLS IN HOT ARID CLIMATE OF OMAN

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by

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ABSTRAK

Kajian ini mengemukakan kealpaan genting dalam reka bentuk alam sekitar dan pemuliharaan tenaga untuk sekolah-sekolah kerajaan biasa di Muscat, Oman yang bergelut dengan penyesuaian yang tidak mencukupi terhadap iklim panas gersangnya. Ini menyebabkan ketergantungan berat pada sistem mekanikal untuk pengawalan suhu. Penyelidikan ini mengkaji prestasi terma elemen sampul bangunan dan kesannya terhadap suhu udara dalaman dengan mengubah suai dinding luar, bumbung, jenis kaca, kawasan tingkap, dan orientasi. Ia sekaligus menyediakan cadangan reka bentuk bernuansa untuk keselesaan terma yang optimum. Kajian ini dijalankan dalam dua fasa penting. Fasa pertama melibatkan pengukuran kerja lapangan di tiga sekolah menengah, memberikan gambaran sebenar keadaan terma sedia ada dalam bangunan tersebut. Fasa kedua menggunakan simulasi komputer menggunakan perisian Design-Builder untuk mereplikakan pengukuran lapangan, meneroka senario andaian dan mengubah suai elemen sampul bangunan. Suhu dalaman musim sejuk yang direkodkan dalam fasa kerja lapangan adalah antara 24.2^{o}C hingga 24.8^{o}C, memastikan pemahaman asas tentang keadaan sedia ada. Sebaliknya, suhu musim panas menjangkau dari 32.7^{o}C hingga 33.3^{o}C, menggambarkan turun naik suhu yang ketara di sekolah biasa. Pengukuran medan yang direkodkan dan hasil simulasi mendedahkan penjajaran rapat dengan perbezaan minimum kurang daripada 2^{o}C. Hal ini menyerlahkan kredibiliti kajian dan mengukuhkan kesahihan cadangan reka bentuk yang diusulkan. Kemudian, penyelidikan menilai prestasi empat kombinasi reka bentuk alternatif menggunakan Nisbah Tetingkap-ke-Dinding 20% sebagai kes asas. Penemuan, terutamanya pada musim panas, menunjukkan penurunan dalam suhu dalaman berbanding dengan kes asas tetapi masih gagal mencapai keadaan keselesaan terma. Reka bentuk yang dicadangkan mempamerkan perubahan purata kira-kira 1.9^{o}C hingga 2.3^{o}C, menekankan keperluan untuk sistem penyejukan tambahan semasa musim panas. Namun begitu, reka bentuk alternatif mempamerkan peningkatan ketara dalam bilangan jam tahunan di bawah keadaan keselesaan terma, terutamanya di bilik darjah yang menghadap ke selatan. Selain itu, penyingkiran bumbung plaza meningkatkan suhu bilik darjah dalaman, antara -2.1^{o}C hingga 1.1^{o}C untuk semua orientasi. Pada masa yang sama, suhu menurun lebih cepat pada waktu malam tanpa bumbung. Dualiti ini mempamerkan pelbagai peranan struktur bumbung dalam mengawal suhu dalaman, menjadikannya penemuan utama penyelidikan. Tambahan pula, mengalihkan bumbung plaza telah mengurangkan jam tahunan di bawah suhu keselesaan terma maksimum dengan ketara dalam bilik darjah. Tuntasnya, kajian ini menyumbang secara signifikan kepada reka bentuk bangunan sekolah yang mampan dan cekap tenaga, terutamanya dalam iklim yang gersang panas. Ia menekankan keperluan untuk pemahaman holistik tentang keadaan iklim dan mencadangkan cadangan reka bentuk khusus yang disahkan melalui kerja lapangan dan simulasi.

IMPACT OF BUILDING ENVELOPE MODIFICATIONS ON THERMAL PERFORMANCE OF CLASSROOMS IN TYPICAL SCHOOLS IN HOT ARID CLIMATE OF OMAN

ABSTRACT

This study addresses a critical oversight in environmental design and energy conservation for typical government schools in Muscat, Oman, which grapples with inadequate adaptation to its hot-arid climate, leading to a heavy reliance on mechanical systems for temperature control. This research examined the thermal performance of building envelope elements and their impact on indoor air temperature by modifying the exterior wall, roof, glazing type, window area, and orientation. Simultaneously, it provided nuanced design recommendations for optimal thermal comfort. The study was conducted in two pivotal phases. The first phase involved fieldwork measurements in three secondary schools, providing a real-world snapshot of existing thermal conditions within such buildings. The second phase employed computer simulations using Design-Builder software to replicate field measurements, explore hypothetical scenarios and modify building envelope elements. Winter indoor temperatures recorded in the fieldwork phase ranged from 24.2oC to 24.8oC, ensuring a baseline understanding of the existing conditions. In contrast, summer temperatures spanned from 32.7oC to 33.3oC, illustrating the considerable temperature fluctuations of typical schools. The recorded field measurements and the simulation results revealed a close alignment of minimal differences of less than 2^{o}C, highlighting the study's credibility and strengthening the validity of the proposed design recommendations. Then, the investigation evaluated the performance of four alternative design combinations using a 20% Window-to-Wall Ratio as the base case. The findings,

particularly in summer, indicated a decrease in indoor temperatures compared to the base case but fell short of achieving thermal comfort conditions. The suggested designs exhibited an average change of about 1.9ºC to 2.3ºC, emphasizing the need for additional cooling systems during summer. However, the alternative designs showcased a notable increase in the annual number of hours below thermal comfort conditions, especially in the south-facing classrooms. Besides that, removing the plaza roof increased indoor classroom temperatures, ranging from -2.1oC to 1.1oC for all orientations. Concurrently, the temperature decreased quickly during nighttime without the roof. This duality showcased the multifaceted role of roof structures in regulating indoor temperature, making it a key research finding. Additionally, removing the plaza roof reduced the annual hours below the maximum thermal comfort temperature in classrooms. This study significantly contributes to sustainable and energy-efficient school building design, especially in hot-arid climates. It emphasizes the need for a holistic understanding of climatic conditions and proposes specific design recommendations validated through fieldwork and simulations.

CHAPTER 1

INTRODUCTION

1.1 Background

In the last fifty years, Oman has significantly developed in all aspects of life. This is due to the boom in oil production since the beginning of the seventies of the last century. Since that time, the economy in both the public and private sectors has experienced comprehensive development and significant growth. One of the most rapidly developing sectors in Oman is the education sector. The enrollment rate of students increased from 64975 in 1976 to 562,423 in 2016. Also, schools increased from 261 buildings in 1976 to 1,100 in 2016. In the 1970s, typical schools were built in different areas of Oman. This has resulted in a massive and rapid improvement in school buildings (Ministry of Education, 2017). The student enrollment rate in Oman continues to grow, resulting in an escalating demand for the construction of new schools (Schnitzler & Heise, 2021).

The main goal of the ministry of education was to reduce the cost and time of school construction throughout the country. Consequently, prototypical school design was introduced to be widely used countrywide without considering the region's variation in climatic characteristics. A typical building design is developed and approved according to the local authority's current standards and specifications for buildings in various locations (Perkins, 2002; vom Brocke et al., 2020). Therefore, a substantial amount of energy is consumed, increasing air pollution. The basic knowledge and awareness of environmental design principles in the early stages of the design processes could significantly reduce energy consumption (Z. Liu et al., 2019; Morganti et al., 2017; Salleh et al., 2016; Zografakis et al., 2008).

Energy consumption in the Sultanate of Oman has dramatically increased Over the past few decades. It was reported that energy consumption did not exceed 2 MW in Oman before 1970. The electricity production capacity currently exceeds 6800 MW, covering all governorates through power plants operating with natural gas fuel, steam, and diesel (The Public Authority for Electricity and Water PAEW, 2020). Since the 1970s, Oman has implemented many strategies and plans to achieve a sustainable and strong economy. Significant population growth and the arrival of foreign workers, particularly in the main urban centres, were among the main results of these dramatic changes in Oman's economy. Recently, energy consumption has dramatically increased due to the maintained high economic growth. According to the National Centre for Statistics and Information report (NCSI, 2014), an increase of about 149.5 % in electricity consumption in Oman was reported from 2005 to 2012. The recorded statistics demonstrate that electricity consumption has dramatically increased in this period. The total energy consumption jumped to 20,958.2 GW/H in 2012 and 8,402.0 GW/H in 2005. Based on the data provided by the NCSI, the government's overall energy consumption increased by 76% between 2005 and 2012, going from 1,594.0 GW/H to 2804.0 GW/H. This represents a significant jump in consumption (Figure 1.1).

Moreover, the demand for power in Oman is rising due to the increased population and industrial activities. The electricity consumption data in Oman was reported as 33,796.000 GWh in 2019, a considerable increase from 33,547.000 GWh in 2018, with an all-time high in 2019 and a low of 3604.000 GWh in 1991 (Al-Abri & Okedu, 2023).

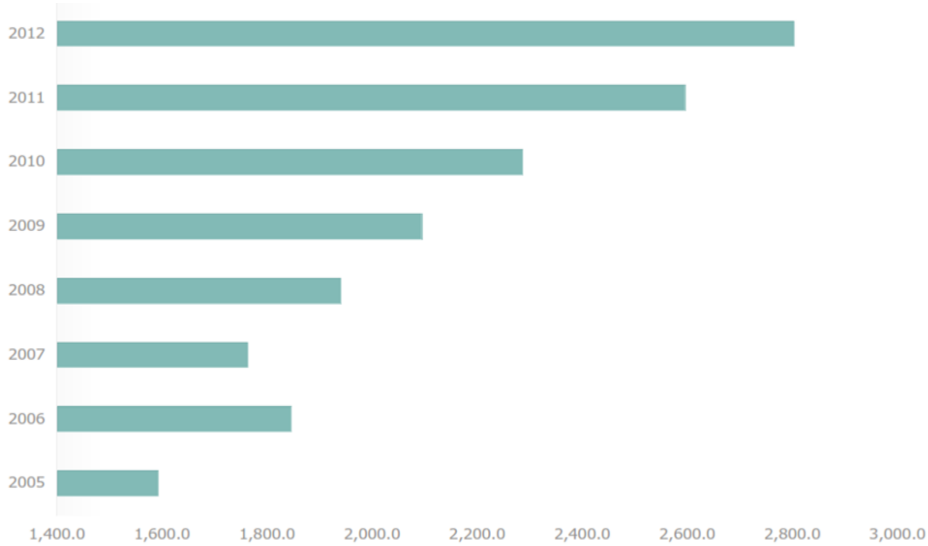

Figure 1.1 Electricity consumption in Oman from 2005 to 2012

Source: (NCSI, 2014)

Consequently, the government of the Sultanate of Oman is particularly conscious of the importance of saving energy through the built environment, including school buildings. The government has cut energy subsidization, which has led to a significant increase in energy costs, to reduce the waste of energy by consumers in all building types (A. Al-Badi et al., 2009; Amoatey et al., 2022). Furthermore, the government established an energy conservation campaign in 1999 to undertake all the necessary measures to decrease the energy consumption caused by mechanical equipment (NCSI, 2014). The Public Authority for Electricity and Water in the Sultanate of Oman is also running extensive research intending to reduce the peak time loads from April to September and total energy consumption to 20 and 30 per cent, respectively, soon (A. H. Al-Badi et al., 2011; Amoatey et al., 2022).

Since schools are one of the biggest consumers of energy, environmental design is crucial in educational facilities (Al Rashdi et al., 2022; A. Al-Badi et al., 2009). Environmental design can use available resources to provide a healthy, excellent, and pleasant learning and teaching environment for students and teachers while also cooling and heating the interior spaces of a school building (CIBSE, 1998; Manca et al., 2020). According to reports, a high-performance school building uses the most cutting-edge design principles and construction methods. It features peaceful, naturally light learning spaces with good air quality, creating a healthy and productive environment for students and teachers (Matboully, 2019; Olson & Kellum, 2003). In a long-term plan, the environmental design of school buildings also costs less to operate and would be easier to maintain, which saves funds for other essential learning supplies, such as books, computers, etc. (Green & Gilbert, 1995; Le et al., 2021).

According to PAEW, in 2012, Oman's demand for electricity increased quickly due to the country's recent solid economic and housing boom. The supply and demand balance has recently gotten worse despite Oman's efforts to secure energy resources in response to the rising demand for electricity. In addition, 90% of energy resources use gas turbines to generate electricity, reducing local natural gas supplies even when no demand-side measures are in place. The General Authority for Electricity and Water, or other small-scale initiatives led by the government, are the only current activity.

Under these circumstances, the government has developed a national plan to ensure energy efficiency and conservation in the energy sector and requested that Japan provide research support. To create laws and alternatives that encourage the reduction of energy use, enact laws to design environmentally friendly buildings that interact with the local environment in terms of climate and public location, and support and promote energy-efficient buildings and energy efficiency throughout the country. Moreover, private sectors have been encouraged to consider energy conservation principles before constructing new buildings (PAEW, 2012). As a result, it is essential to research and improve the internal climate of existing buildings and make recommendations for new construction using passive design principles. The design of the building envelope is the primary aspect that can be altered to enhance energy performance.

The construction components that isolate the interior environment of the structure from the exterior environment are referred to as the building envelope. It considers several variables: environment, technology, functionality, and aesthetics. Hence, the envelope design and indoor thermal comfort should be carefully inspected during the design phase; otherwise, it will negatively impact energy consumption and the occupants' performance (Ashrafian & Moazzen, 2019). The importance of saving energy is not only a local issue but also a common concern of humankind. The high energy consumption due to human activities affects the planet and the global climate. According to the UK Climate Impacts Program (2004), the primary cause of global climate change is a combination of both natural and human causes. However, human activity was the primary cause of climatic changes in the last century (Demeritt & Langdon, 2004). At present, about 6.5 billion tons of carbon dioxide (CO2) are emitted globally into the atmosphere each year, mainly through the combustion of coal, oil, and gas used to produce energy. The carbon emissions in the Sultanate of Oman have also climbed from 2.8 million metric tons in 1980 to 30.8 million metric tons in 2015 (NCSI, 2014).

Schools should be built concerning the local climate to utilize natural resources to cool, heat, and illuminate the interior spaces to reduce energy consumption (Alwetaishi & Taki, 2019). Achieving this goal will save the environment for future generations while studying in healthy and comfortable schools. This study aims to make typical schools' internal environments better to consume less energy. Opportunities for energy conservation through the building envelope can be taken advantage of from the pre-design stage of new school buildings. A smaller HVAC system may be used because of significant cooling and heating load reduction that could be achieved by the building envelope's ideal design. There are, however, fewer chances for existing schools to alter or modify the envelope's elements.

1.2 Statement of the Problem

The rapid economic growth in the Sultanate of Oman following the 1970s oil boom witnessed a surge in construction, particularly in the education sector. Unfortunately, environmental design concepts and energy conservation were not prioritized during this period. The Ministry of Education in Oman, facing a significant increase in population and student enrollment rates, responded by swiftly introducing typical school buildings to expedite construction processes while adhering to budget constraints (Ministry of Education, 2017). Regrettably, the nationwide implementation of these buildings lacked consideration for the diverse climatic conditions across Oman's regions.

The oversight of climatic characteristics during design is evident, especially in Muscat, where typical school buildings struggle to adapt to the external environment, relying heavily on mechanical equipment for temperature control. For instance, recent studies highlighted the challenges posed by inadequate thermal adaptation in typical school designs, resulting in heightened reliance on artificial climate control (Amoatey et al., 2023; Fadeyi et al., 2014; Ozarisoy & Altan, 2021).

While other research in Oman has explored environmental design and energy conservation in residential and commercial buildings (Al Rashdi et al., 2022; Alalouch et al., 2019; Al-Saadi & Al-Jabri, 2017), attention to typical or government schools remains limited. Data from (A. H. Al-Badi & Al-Saadi, 2020) underscores the need for a nuanced approach to school building design, especially in arid climates like Oman's, to ensure optimal thermal comfort without unnecessary energy consumption.

This study addresses this specific gap by investigating indoor thermal properties, particularly indoor temperature, and how the building envelope affects these properties. Drawing on the insights from previous studies, the research aims to uncover effective strategies for modifying the building envelope, especially during the summer, to enhance indoor thermal comfort. By incorporating data on indoor temperature patterns and referencing established works in the field, this study aims to contribute valuable insights for sustainable school development in Oman.

1.3 Research Objectives

The main goals of this study are to assess the thermal characteristics of the school envelope and determine the most effective ways and means of building envelope components to lower the indoor air temperature in Muscat, Oman's hot and dry climate. This will improve the thermal environment for students and reduce energy consumption. Hence, the following are the study's objectives:

1) To investigate the thermal performance of the existing building envelope elements that affect indoor air temperature in classrooms in typical schools in a hot-arid climate in Oman.
2) To investigate the effect of modifying different building envelope elements on indoor temperature in classrooms in typical schools in a hot-arid climate in Oman.
3) To develop design recommendations for building envelope that improves the indoor air temperature in classrooms in typical schools in the hot-arid climate in Oman.

1.4 Research Questions

The research questions of this study are as follows:

A) Objective 1:
   1) How is the thermal performance in terms of indoor temperature and relative humidity in classrooms in typical schools in a hot-arid climate in Oman?
   2) What are the climatic factors that will affect/influence indoor environmental conditions?

B) Objective 2:
   1) How do essential building envelope elements (exterior walls, roof, and windows) affect the indoor temperature in classrooms in typical schools in the hot-arid climate in Oman?
   2) How do exterior walls, roof, and windows affect space thermal performance? Particularly, how each element affects to reduce Indoor temperature and the number of hours below thermal comfort in classrooms in typical schools in the hot-arid climate in Oman?

3) What are the important elements of the building envelope that significantly contribute to indoor thermal conditions in classrooms in typical schools in the hot-arid climate in Oman?

4) How does plaza (courtyard) modification affect indoor thermal conditions in classrooms in typical schools in Oman's hot-arid climate?

C) Objective 3:

1) What recommendations can be made for building envelope design elements to improve the indoor thermal environment in classrooms in typical schools in the hot-arid climate in Oman?

1.5 Significance of the study

The primary significance of this research is that it will contribute knowledge to academic research. The findings of this study are expected to demonstrate that careful design of the building envelope will minimize energy consumption, enhance indoor thermal conditions, and contribute to lowering air temperature to be as close to the range of comfort conditions as possible. However, the primary benefit is economic, as it reduces the financial burden of establishing a substantial mechanical cooling system or lowers utility bills. The use of design to reduce heat gain in buildings and, as a result, their cooling loads is often less expensive than the use of cooling or heating equipment, even if they are passive. Environmental benefits include reduced air pollution, energy resource saving, and lower greenhouse gas emissions from heating, cooling, mechanical ventilation, and lighting (Omer, 2020). A set of recommendations for proper envelope design for architects, other engineers, and anybody concerned about internal thermal comfort is the intended outcome of studying the building envelope design of typical schools in a hot, dry climate. The study's practical advice will enhance indoor thermal conditions and reduce energy usage in schools in Oman's hot and dry climate. It is crucial to demonstrate how choosing the proper building envelope specifications and design may significantly improve indoor thermal comfort in a hot, dry region.

1.6 Scope and Limitation of the Study

The primary objective of this study is to examine the thermal performance of typical government schools in Oman, with a specific focus on optimizing the thermal conditions within classrooms. The investigation considers the diverse climatic characteristics in different zones across Oman, as Chapter Two details. For this research, the study is confined to the central climatic zone, where Muscat is situated, characterized by a hot-arid climate.

The selection of the Muscat region is deliberate, considering its significance as the country's capital city and hosting the largest number of typical schools. This geographic focus ensures a comprehensive understanding of the thermal dynamics within government schools that cater to a significant portion of the student population.

Furthermore, the scope of this research is limited to typical school buildings constructed and administrated by the Ministry of Education. While various educational authorities and institutes contribute to school infrastructure in Oman, the Ministry of Education oversees a substantial majority, accounting for 92.6% of school buildings nationwide. This focus ensures a concentrated examination of the thermal performance issues inherent in the predominant type of school infrastructure.

To provide a detailed analysis, the study was conducted during two distinct periods – winter and summer – specifically during class time in November and April.

The exclusion of May to September, characterized by extremely hot weather, is due to the school summer holiday period.

The research involved field measurements taken in three representative schools at the secondary level, each featuring classrooms with a typical rectangular layout conforming to the standardized dimensions prevalent in Oman's typical school design. Three classrooms from different levels were selected for thorough investigation within each school. This structured approach enhances the study's applicability and relevance to the broader context of typical government schools in Oman.

1.7 Research Framework

Before beginning any research, it is essential to create a detailed plan outlining the stages and methods that will be used to complete the study correctly. Figure 1.2 shows this study's research framework, which consists of three major phases: literature review, research methods and techniques, and results analysis and discussion. The first phase consists of two components: defining the research topic and reviewing relevant resources, including books, journals, and theses, to determine its context, challenges, objectives, and research questions and develop a clear framework for carrying out the research. The second stage is identifying the climate in the study location, followed by a review of the definitions of essential terms and prior research and studies conducted in similar contexts, focusing on the impact of building envelope elements on indoor thermal conditions. In conclusion, the indoor thermal performance of schools and prior research in this area will be evaluated.

The second part is the research methodology, which includes survey, simulation, and case study methods. The first step (the survey's methodology) will review the equipment to be utilized, the elements on the checklist, and the procedure for gathering data from the field. The simulation, on the other hand, is the second step and entails evaluating building simulation software and software selection. The actual findings from the field investigation will be used to calibrate the model. There will also be a description of the changes that will be made to the building envelope components. The final step is describing the chosen case study, which includes the key plan, location plan, and layouts.

The third stage is the analysis, which consists of two distinct components: an analysis of the fieldwork data and an analysis of the building simulation model. After that, an examination by case study and a comparison of the indoor air temperatures in every location will be conducted. The second half of this discussion will focus on modifying and analysing the primary building envelope parts and combining all optimum modifications. In conclusion, recommendations for the envelope's design will be placed to improve the thermal environment inside the classroom.

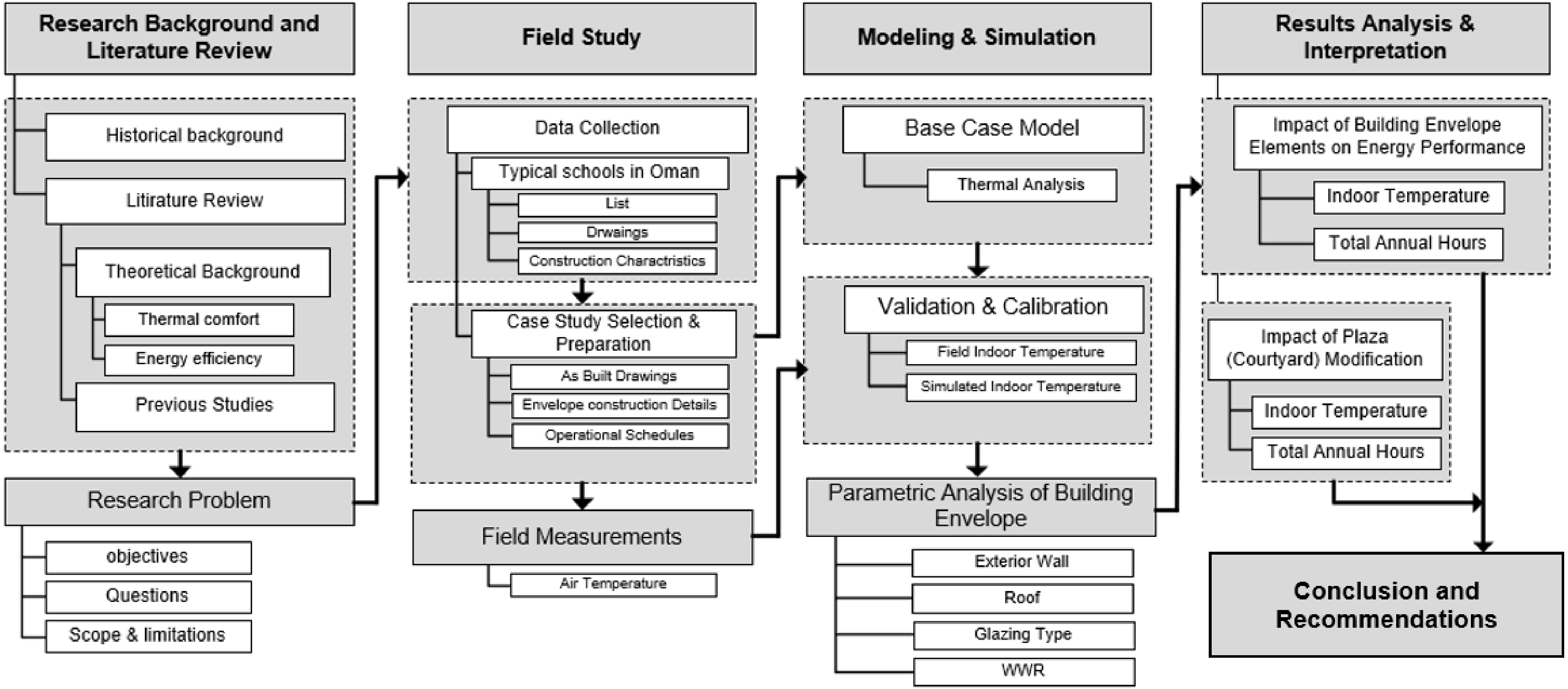

Figure 1.2 Research Framework

1.8 Organization of the Thesis

This thesis is structured into five distinct chapters, each contributing uniquely to the comprehensive exploration of the study. The overview in Chapter One serves as an introduction, presenting key elements such as the research title's keywords, a thorough review of relevant literature, the statement of the problem, research questions, the purpose of the study, research framework, significance, and the scope and limitations of the research.

Chapter Two delves into the existing literature, specifically focusing on the building envelope and its impact on thermal performance. A detailed examination of crucial building envelope parameters, including walls, roofs, windows, and orientation, is provided. This chapter also integrates insights from prior research in the field, establishing a foundation for the subsequent analyses.

In Chapter Three, the research methodology is meticulously outlined. This includes a comprehensive description of the chosen methods and the experimental setup. Details regarding data collection methods, case study selection, construction materials, tools, devices, the timing of the research, the selection of simulation tools, and the chosen analysis method are all illustrated. This chapter sets the stage for a robust and systematic investigation.

Chapter Four presents the findings derived from the analysis conducted. Tabular and graphical results are included, encompassing insights from the calibration and modelling processes of the simulation software. Additionally, this chapter articulates the outcomes anticipated by the simulation software in response to changes made to the building envelope. The rigorous examination of these findings is critical to addressing the research questions.

The conclusive Chapter Five answers the research questions and offers a comprehensive conclusion based on the research findings. Additionally, this chapter provides broad recommendations tailored for the design of school envelopes in Oman's hot and arid climate. It serves as a valuable resource for practitioners and policymakers seeking insights into enhancing the thermal performance of school buildings. Furthermore, Chapter Five extends its impact by outlining recommendations for future research endeavours, ensuring a continuous and evolving understanding of the subject matter.

In summary, this organizational structure ensures a logical progression of ideas and findings, guiding the reader through the study's exploration, analysis, and implications.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter thoroughly reviews previously conducted studies on the building envelope design's impact on indoor air temperature to comprehensively understand the study's theoretical background. This chapter describes influential factors affecting indoor thermal conditions, the desired thermal comfort, and related aspects. After introducing the topic, the climatic conditions which prevail in the Arab region (the Arabian Peninsula) are provided as human thermal comfort can be influenced mainly by such climatic factors. It is, therefore, essential to understanding the study's selected geographical location and the dominant climatic nature. In this chapter, the development of education and schools in Oman has also been elaborated on in detail. The chapter presents various definitions of the building envelope and key envelope elements' effect on indoor thermal conditions. The chapter includes relevant studies on reducing indoor air temperature in school buildings, improving thermal comfort conditions, and reducing energy consumption in Oman's hot and dry climate. The chapter also focuses on energy efficiency in buildings and different methods for reducing energy consumption. The chapter also provides previous research on the impact of building envelope design on energy consumption environment, thermal comfort zone, and its calculation in dry, hot climatic conditions.

2.2 The Geographical Area and Climate of the Study

Typical school buildings can be found in all cities and villages of Oman. However, the scope of this research is limited to typical school buildings located in

Muscat, the capital city of Oman. A school building design should be built following the local climate of the Muscat region to achieve users' satisfaction and save energy. Thus, it is necessary to give a background of the city of Muscat and describe the prevailing local climate. It is quite essential to grasp climate because it controls the exposure of the building's solar radiation amount and, at the same time, governs the mean outdoor temperature, wind, and humidity. Local climate also controls the energy utilized for heating, cooling, and lighting (Haase & Amato, 2009).

2.2.1 Hot and Arid Climate

The hot, dry climate is the most prevalent global climate. A new global climate map utilizing the KŐppen- Geiger system was created by Peel et al. (2007), who described that the arid climate is the most prevailing climate on earth by land area at (30.2%). Arid climate can be divided into four different types; the most prevalent is the hot/arid desert land, which makes up around 14.2 per cent of the world's geographical area. Many scholars have defined hot and arid climates. Meir and Roaf (2002) and Gut and Ackerknecht (1993) stated that it is characterized by high temperatures with distinct diurnal, daily, and seasonal fluctuations. Summer days are arid and hot, evenings are cold, and daily temperatures range between 15 °C and 20 °C or higher. Other scholars observed that hot, dry climates have high temperatures, with the mean temperature of several warm months above 25 °C. There is a significant difference in temperature between day and night due to clear skies at night, which receive a considerable amount of direct sunlight and intense sunshine. Due to low relative humidity and the lack of trees to provide windshields, strong winds can carry away sand and dust (Holdsworth & Sealey, 1992; Rosenlund, 2000; Schiller & Evans, 2000).

Moreover, when there is an acute lack of available water and infrequent rainfall, the climate is considered arid (Konya, 1980; Gut & Ackerknecht, 1993). The average annual rainfall is between 50-150 mm, but less than 250 mm, while a climate with an annual rainfall range of 250-500 mm is called a semi-arid-steppe climate. (Huddart & Stott, 2010).

2.2.2 Geographical Location

As the map illustrates in Figure 2.1, Oman is geographically located in the extreme east and southeast of the Arabian Peninsula. Its northern border is with the United Arab Emirates, its western border is with Saudi Arabia, and its southern border is with Yemen. In the north of the Sultanate, Oman and Iran are separated by the Gulf of Oman. An 80 km-wide stretch of the UAE territory divides the rest of Oman from a region in the north (called the Musandam Peninsula). The Sultanate's coastline stretches approximately 1,600 kilometres along the Indian Ocean, and its area is 309,500 square kilometres (Dean, 2004).

Geographically, Oman has four main areas, including the coastal plain (i.e., largely populated); the plateau area (i.e., primarily a cultivation area around several oases); a range of mountains, all of which are barren except for the famous Jabel Akhadar in the Governorate of Nazwa; as well as a mountainous region in the Governorate of Dhofar to the north. The well-known Rub al Khali desert (Empty Quarter Desert land) is a vast, barren desert of 650,000 square kilometres in southeastern Oman. Smaller portions of this desert can be found in Yemen and Oman, but the vastest desert is in southeast Saudi Arabia.

Figure 2.1 Oman map

(Source: http://www.mapsofworld.com/oman/map.html)

The Sultanate is divided into Eleven Governorates, which are, in turn, divided into 61 Wilayats as follows: Muscat Governorate, Dhofar Governorate, Musandam Governorate, Al Buraimi Governorate, Ad Dakhliyah Governorate, Al Batinah North Governorate, Al Batinah South Governorate, Ash - Sharqiyah South Governorate, Ash - Sharqiyah North Governorate, Adh Dhahirah Governorate, Al Wusta Governorate (Figure 2.2).

Figure 2.2 The distribution of the Sultanate's governorate/ region

2.2.3 Ambient Climatic Conditions in Muscat, Oman

Oman's capital and largest city is Muscat. The Governorate of Muscat's biggest city and administrative centre is located there. As of September 2015, the Muscat Governorate had 1.56 million residents. The urbanized area covers over 3,500 km^2 (NCSI, 2014). Muscat lies to the northeast of Oman, at 24°00′N 57°00′E. Al Batinah Region plains are located to the west, and the Ash-Sharqiyah area is east of Oman. The inner plains of the Ad-Dakhiliyah Region form Muscat's southern border, and Oman Gulf forms its northern and western boundaries. Along the coast of the capital, Muscat frequently runs deep to create a couple of natural harbours in Muscat and Muttrah. Al Hajar Mountains to the west often run through Muscat’s northern coastline.

Muscat has witnessed remarkable infrastructure development since Qaboos bin Said became Sultan of Oman in 1970, which has driven a thriving economy and a multiethnic culture. The capital, Muscat, is the centre for political and economic authorities and houses large-scale administrative, commercial, financial, cultural, and educational facilities. The central region, where Muscat is located, also plays a crucial role in the country's agricultural, industrial, and development. These facilities have made Muscat an attractive city for people to move into. Many people have moved from small villages and counties to Muscat city for better jobs, business, or higher education. Oman’s noticeable population growth during the past forty years, which occurred at a national average of 2% per year between 1993-2010, has been spatially lopsided in favour of the coast. The central coastal regions of Al Wusta, Al-Batinah, and Muscat usually reported higher yearly growth rates than 2% nationally, making this phenomenon particularly obvious in the previous ten years. The three regions have witnessed annual rates of 5.0%, 2.19%, and 2.14%, respectively, between 2003-2010. In the early 1990s, the population was 622,000, which had increased to 1.5 million in 2015 (NCSI, 2015).

Due to the massive growth of the city and the enrolment rate of students, there was an essential need to implement new school buildings among various development projects in the Muscat area. The Muscat region was chosen as the reference for this research because it houses the largest number of typical schools. However, the findings of this research could be applied to other places with a climate similar to that of the Muscat region, inside or outside the country.

Oman’s climate can be categorized as subtropical dry or an abnormally hot desert climate because the Sultanate resides on the southeastern tip of the Arabian Peninsula. Low yearly rainfall mixed with high humidity characterizes Oman’s climate. In the summer, it also experiences different temperatures between maximum and minimum temperatures, especially in the centre (Federal Research Division, 2010). The summer season starts in the middle of April and continues until the end of October in Muscat and the rest of the Sultanate. No rain falls at this time, but temperatures can rise to over 50 °C in the shade, with humidity levels reaching 90%. However, due to the cold winds coming from the Indian Ocean, Dhofar experiences a light monsoon climate, with an average summertime temperature of 26 °C and substantial average rainfall (Federal Research Division, 2010). The weather in Muscat is specifically hot and arid, with long, very hot summers but mild winters. About 100 mm of rain falls annually, primarily from December to April. Muscat generally experiences little precipitation, with several months typically receiving only a trace of precipitation. The summertime temperature can rise to 49°C, which is extremely hot, and rain rarely falls in Muscat except in winter. Muscat also experiences north winds (called Shamal winds) during summer.

2.2.3.1 Temperature

The rate at which the earth’s surface cools and warms determines the temperature of the air. A warm surface heats direct contact air via conduction, and the upper layers are heated via convection (Givoni, 1981). Several factors, such as colour, capacity, heat conductivity, and the amount of radiation received, influence a surface's heating and cooling rate. The average annual temperature ranges from 17 to 40 degrees Celsius, rarely falling below 15 or above 44 degrees Celsius. The warm season stretches from April 28 to July 24, with daily high temperatures typically exceeding 37°C. The year's hottest day is May 26, with an average higher temperature of 40 degrees Celsius and a lower temperature of 30 degrees Celsius. The average daily maximum temperature is below 27 degrees Celsius during the cold season, which stretches from December 3 until March 3. However, January 18 is the chilliest day of the year, with an average lower temperature of 17 degrees Celsius and a higher temperature of 24 degrees Celsius, as demonstrated in Figure 2.3. The high air temperatures in Muscat have heavily affected the interior environment of typical school buildings. Air temperature in Muscat or other hot, dry climates significantly influences buildings' indoor conditions and thermal comfort. It should be considered while designing school buildings to minimize its effect on the interior environment, especially during overheated times of the year, to reduce mechanical equipment's cooling load.

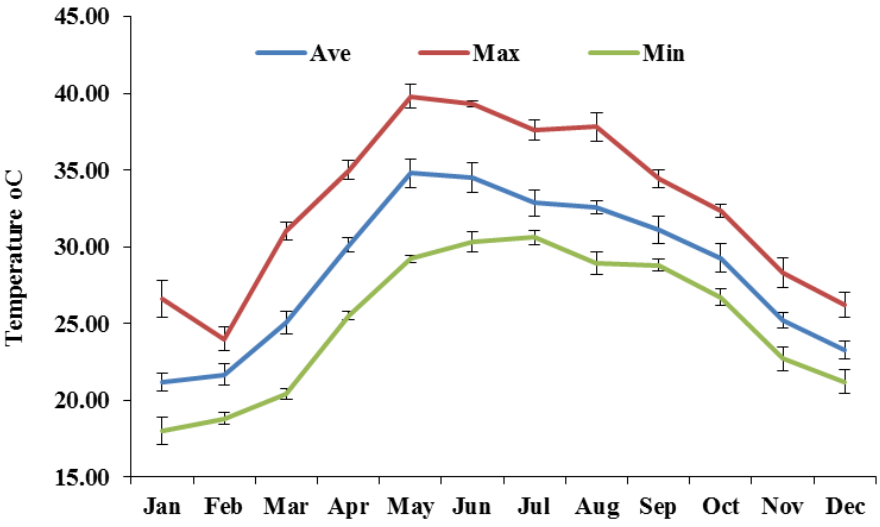

Figure 2.3 Annual maximum, minimum, and average temperature of Muscat, Oman

Source: (Al-Bahry et al., 2014)

2.2.3.2 Relative Humidity

The proportion of the actual absolute humidity to the air's highest moisture capacity is the relative humidity at any temperature (Kramer et al., 2017). Humidity in a region is a major factor influencing comfort in hot, dry climates. The air capacity for water vapour is increased and decreased by its temperature. The relative humidity normally fluctuates between 19%-90% throughout one year, infrequently falling below 9% or rising over 96%. Around May 12, the relative humidity reaches its lowest point, falling to under 23% every four days. Around August 25, the relative humidity reaches its highest point, reaching 88% three out of every four days, as shown in Figure 2.5. In these circumstances, designers should introduce practical design strategies, such as evaporative cooling and vegetation, to increase moisture in the air to subtract the air temperatures of school buildings' microclimate and enclosure spaces.

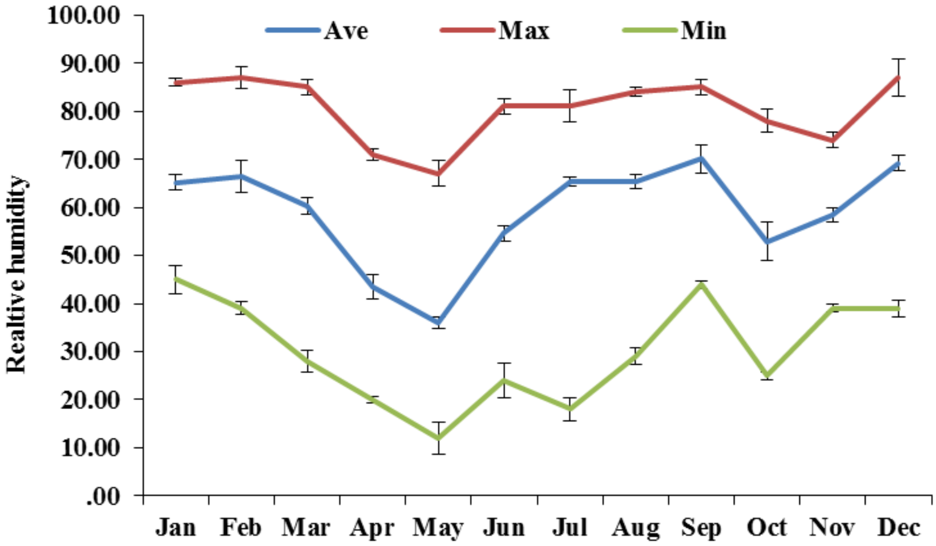

Figure 2.4 Maximum, minimum and average relative humidity for Muscat, Oman

Source: (Al-Bahry et al., 2014)