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Evaluation and improvement of thermal performance of residential buildings in hot and dry climate with reference to Saudi Arabia

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Abstract

The historical low energy costs funded by high subsidies have influenced Saudi attitudes to thermal comfort. Citizens who for years were exposed to the rigours of a harsh climate understandably were willing to pay a high energy cost to achieve comfort. However, changes in the Saudi economy and reduced buying power linked to higher energy prices have made the cost of comfort an issue for societies and governments. Buildings with optimal indoor air conditioning and low fuel consumption produce less carbon dioxide emissions and thus cause less environmental pollution. There are significant demands on the building industry in Saudi Arabia, primarily relating to the extensive energy demands during the hotter parts of the year for air conditioning purposes and the use of poor-quality building materials. Throughout the country, electricity consumption increases by more than double in the summer months. Over 50% of the country's electricity is consumed by residential buildings. Moreover, 70% of existing buildings are not fitted with resistive insulation.

Given this situation, this study explores the indoor environment of residential buildings in Saudi Arabia with a particular focus on the thermal environment. The study selected four houses located in four different climatic regions as case studies. The features of the existing houses were assessed, including their design criteria, forms, materials and surrounding conditions. The investigation of these four case studies will largely aid in determining the current status of residential buildings and highlighting the indoor features that require further improvements. Thermal retrofitting of existing buildings may be an effective solution to enhancing the environmental performance of the building industry.

The two primary methods used to assess the thermal indoor conditions in the study are physical measurements and computer modelling. Instruments were used to monitor the houses during both the summer and winter months. After collection, the data were presented and visualised in Excel and subsequently analysed. Thermal Analysis Software (TAS V9.4.2) was used to thermally model the houses for two purposes. Firstly, to determine the current thermal performance of buildings and secondly, to identify areas in which improvements could be made using proposed alternate materials.

Through field monitoring and thermal simulation, it was clear that the most significant factor increasing A/C use was the loss/gain of heat through the building materials. Different parts of the building (including the roof, walls, ground floors and windows) were simulated using different fabric combinations to achieve the optimum cooling reduction. The findings suggest that cooling reduction of up to 79.5 % is possible. Consequently, the intensity of the proposed annual cooling for the four chosen houses ranges between 12.4 kwh/m2/y and 83 kwh/m2/y. Moreover, buildings located in the same climatic regions should also adopt similar approaches and the methods used can be transferred to other buildings in different areas. Recommendations can then be made regarding how to improve the situation. Lastly, conclusions were made in the research and areas that require further research were identified.

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In the name of Allah, the Most Gracious and the Most Merciful

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List of Publications

Alaboud, M, & Gadi, M. (2019). Indoor environmental monitoring of residential buildings in Saudi Arabia, Makkah: a case study. *IOP Conference Series: Materials Science and Engineering*, *609*(4), 042044. https://doi.org/10.1088/1757-899X/609/4/042044

Alaboud, Mosaab, & Gadi, M. (2020a). The effect of thermal insulation on cooling load in residential buildings in Makkah, Saudi Arabia. *Future Cities and Environment*, *6*(1), 4. https://doi.org/10.5334/fce.87

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Chapter 1

Introduction

1. Introduction

1.1. Background (overview)

This chapter introduces the research including the objectives, aims, research problems and questions. Additionally, the research scope, structure and limitations will also be discussed in this chapter.

At present, the status of residential buildings in Saudi Arabia is unsustainable despite the efforts being made to lower the extensive energy use in houses. More work is required to effectively address the issue. By modifying buildings in line with prevailing climatic conditions, energy consumption will be significantly reduced, thereby maintaining acceptable indoor conditions. As a result, household occupants will be more satisfied with their homes. For instance, temperature changes will be minimised, meaning that residents will be less dependent on air conditioning system to achieve thermal comfort.

Houses in four of the country's biggest cities each with different climatic conditions are examined. The purpose is to address problems with the designs of existing buildings and to identify methods for enhancing their thermal performance and reducing their energy consumption.

In the study, two key aspects are focused on, namely the assessment of the thermal performance in the chosen buildings during summer and winter, and the effects that improving building fabrics will have on cooling the property. During the latter stage, modification using external envelope materials will be considered.

1.2. Statements of the research problems

Despite the enthusiasm and well-designed strategies which character current Saudi approaches to sustainability, there remain insufficient sustainability practices in the Saudi market as a result of limited returns on investment, the comparatively elevated cost environment-friendly products, and the overall absence of public awareness of the need to be more energy efficient (Nachet & Aoun, 2015). Residential buildings are very important and thus are worthy of the best possible care and attention. Saudi Arabia consumes more energy than any other Arab country and is also one of the highest electricity consumers in the world. Every year, the national demand for electricity increases by 7%, in line with the increasing population, heightened spending power, increased general wealth, and very low energy prices. Over 50% of the country's electricity is consumed by residential buildings (SEEC, 2020). During the summer months, the demand for electricity increases significantly due to an increased domestic demand for air conditioning.

For all residential homes in all climates, wall and roof insulation is strongly recommended. The lack of uniform standards, erratically enforced regulations for saving energy in residential buildings and the absence of economic incentives has resulted in poorly insulated housing stock. Insulating the building envelope contributes to lowering peak loads and generally reducing energy consumption (Al-Homoud, 2004a).

Many factors impact cooling loads (the amount of heat energy that would need to be removed from a space to maintain an acceptable temperature range), the most significant of which are technological factors. Such factors are mainly associated with the thermal quality of buildings relevant to their specific cooling loads. The cost of electricity throughout KSA is low, meaning that residents are happy to extensively use air conditioning systems.

The prototype of residential building issue

The inadequate quality of the buildings create the most deep-rooted energy wastage problem (Nicol et al., 2012). As described in Chapter two, contemporary buildings lack essential architectural elements used in the vernacular desert architecture to control climate. Design features have ceased to be employed in the wake of the modern construction boom (Alrashed et al., 2017). According to Kharseh and Al-Khawaja (2016) have reported that most structures built in member states of the Cooperation Council for the Arab States of the Gulf were construction at thermal standards below the requirements stated in regulations, as exemplified by the persistent use of single-glazing windows. Moreover, the addition of insulation to external envelopes in building remains a seldom used practice.

Nicol et al., (2012) explain how poor quality of materials and building design is the fundamental factor causing energy waste. Contemporary buildings do not have the fundamental passive features, described in Section 2.3, which blended the vernacular desert architecture with climate conditions. During the construction boom over the past decades, such design features are no longer in use (Alrashed et al., 2017). However, the three tenets of Muslim culture reflected in the design of modest traditional homes - privacy, modesty, and hospitality – continue to be incorporated into Saudi design, albeit in a more lavish and modern style (Othman et al., 2015).

Kharseh and Al-Khawaja (2016) explain that a majority of buildings constructed in the Gulf Cooperation Council region fail to meet the official requirements in terms of thermal performance. For instance, single-glazed windows are still used today. What's more, insulation is rarely implemented in the external envelopes of buildings.

Moreover, household appliances have poor energy performance, and this is also impacting energy efficiency. The State Minister of Energy Affairs, Abdulaziz Bin Salman, stated in 2015 that 70% of buildings did not have thermal insulation (SASO, 2015). In 2010, the first attempt to resolve this issue took place. A royal decree was implemented which mandated the use of thermal insulation. However, not until 2014, this was applied to only new buildings.

Cheap Electricity Costs

Although the high subsidies which have kept energy prices low are now under review, their residual effect has been to discourage investment in energy efficiency measures (Nachet & Aoun, 2015). The government has reduced subsidies and has plans to connect energy and water prices to the international market by 2025. In 2012, energy subsidies totaled $80 billion, accounting for 11% of GDP in Saudi Arabia, indicating that oil, gasoline, and diesel remain the most highly subsidised areas. This is closely followed by electricity and natural gas (Sarrakh et al., 2020). Nonetheless, families from low and middle-class backgrounds will continue to receive support as part of citizen account from £120 to £240 per month as a result to deal with removing subsidies.

In 2010, the government set up the Saudi Energy Efficiency Centre in response to domestic oil consumption. Altogether, 28% of all energy used in the country is consumed by the building sector, making it the second-highest energy-consuming sector after industry. Collaboratively, the two sectors (buildings and industry) along with transportation use 96% of the total energy use. In terms of electrical energy demand, buildings are the biggest consumers, with approximately 75% of total power demand generated by this sector. Moreover, 70% of this demand is for air conditioning specifically (SEEC, 2020).

GCC countries are over-cooled by mechanical systems to reach as low as 18°C and this is another significant contributor to the problem (Kharseh and Al-Khawaja, 2016). What's more, research carried out in the UAE capital city of Abu Dhabi (where the weather is similar to Saudi Arabia) involving 20 air-conditioned buildings has revealed that air conditioning in buildings reaches unnecessary low levels. Many people involved in the study (80%) reported that they find the indoor temperature to be too cold (Todorova, 2012).

Harshness of Environment

The harsh climate is an unchanging but predictable factor influencing the high level of consumption. Around 80% of the energy consumed in buildings located in hot areas is used for air conditioning systems (Koch-Nielsen, 2002). The climate in such areas is very difficult to live with and thus achieving thermal comfort is vital. In such areas, more attention is required when designing buildings.

Lack of Published Research on Existing Residential Buildings in Saudi Arabia

Although many studies have researched the design of residential buildings and their architecture, few have focused on evaluating the indoor thermal performance of existing homes, even though most are modern recently built homes.

1.3. Research Aim and Objectives

The main aim of the research is to assess the indoor thermal performance of homes in Saudi Arabia and make recommendations for improvements. The primary focus is on lowering the dependence on mechanical cooling systems. The design strategies and building materials used in the construction of houses is reviewed to identify those most suitable for the different climate zones in the country. The research objectives presented below have been developed to achieve these research aims.

1. Analyse aspects causing the high cooling load in residential buildings and the chosen case studies including details about buildings age, location, architectural drawings, envelopes

materials used and their characteristics, as well as the forms they take and the surrounding conditions.

2. Investigate the climatic parameters of Saudi Arabia and how they impact the design of houses. This can be achieved with a thorough knowledge and understanding of the outdoor environmental conditions. Successful environmental design is inextricably linked to an understanding of the external climate and its influence on human requirements. This understanding plays a large part in determining which thermal properties are essential in the external building envelope.

3. Review a range of energy efficient design strategies and propose appropriate ones for reducing the high cooling use in residential buildings. Moreover, employ appropriate instruments and simulation software tool to evaluate, validate and improve the residential buildings thermal performance in a hot climate.

4. Evaluate the internal environmental conditions of the chosen case studies. This can be achieved by monitoring selected thermal environmental variables using instruments and computer model during winter and summer.

5. Valdiate the findings between the physical measurements and computer-modelling results.

6. Identify ways to modify building materials to retrofit energy efficient homes. By using the most suitable building materials, energy efficient houses can be created. This research uses Thermal Analysis Software (TAS) to identify the most suitable materials for building homes in hot regions. The findings may be used as a guide for building energy-efficient roofs, walls, floors and glazing in residential homes.

1.4. Research Scope and Limitations

This research assesses the indoor thermal performance of residential buildings in four climatic zones in Saudi Arabia. Based on this analysis, recommendations for improvements are made. Time and efficiency limitations made it impossible to evaluate and predict all internal thermal conditions of all the chosen buildings.

Moreover, the case studies of this research are limited to one residential building per climatic zone. The outcome of this study could be applied to similar houses or also other residential prototypes such as apartments buildings and traditional houses in the same climatic zones.

The fieldwork was conducted in winter and summer periods which cover the extreme times of the year. As each chosen house is in a different city and the distance between them is quite far. It was not possible to conduct a longer-term physical measurement. Thus, as the study involves the effect of the climate, and the fieldwork were conducted for only two seasons, it would be better to do a physical measurement covering the whole year in order to get a richer picture.

One of the most challenging aspects of the research was to identify houses that allow for two accesses during winter and summer. The main reason is privacy as owners of the houses call it. So, each house chosen was typical in design and materials to the targeted prototype. However, the roof of the Taif house were made of different building material compared to the other three chosen houses.

Also, arrangements for my visit prove difficult as a male guardian must be attended during the fieldtrips for each house. For this reason, it was not possible to choose specific rooms in each house. In addition, only two rooms are chosen for each house and this is because of the number of the instruments available to the researcher and also to focus more on the chosen rooms. Finally, the air conditioning in the house located in Riyadh was in constant use and thus the second guest room (GR3) was largely dependent upon the cooling system even in winter.

1.4. Methodology

After discussing the research scope and objectives, it is important to adopt a suitable research methodology to decide upon the methods used. Several different research methods were selected for use to achieve different aspects of the study. The two primary methods employed were physical measurements and computer modeling. The secondary methods include observations used to supplement the findings. These methods aided in determining the indoor thermal performance of the houses and the effects that different building materials can have. However, there are advantages and disadvantages to every method. Moreover, the use of a multi-method approach can safeguard against the possible limitations of any single chosen approach and allow for findings to be cross validated. Thus, using a variety of methods may generate a more accurate outcome (Gillham, 2008). The methods employed in the present research are discussed below.

1.4.1. Observations

Observation is a data collection method whereby a researcher watches and records the phenomena under investigation without contact with the participants. Observation is used in this research to obtain a firsthand insight into the key features of existing residential buildings in Saudi Arabia and the problems caused by aspects such as building materials, economic considerations and social issues. The data collected allowed the researcher to narrow down and define the research problem in detail. Moreover, the observed data creates a clear picture of the change induced by applying different permutations of the building envelope and was crucial in identifying effective and viable solutions to the problem.

1.4.2. Physical measurements (Instruments)

The physical measurements were taken in both the summer and winter months of 2018. To do so, instruments were used to monitor air temperature and air velocity, globe temperature, surface temperature and solar radiation. These were the primary physical variables for each case study. As all of the included houses had air-conditioning systems in all of the rooms, nearly all monitoring was carried out in rooms with the A/C switched off. This aided in calibrating the findings from the field tests and the computer models. Ultimately, it generated a clear picture of the thermal activity in the rooms. In each house, Elitech URC5 data-loggers, with errors of ±0.5°C were installed to measure air temperature. Data-loggers must not be positioned near a heat source of any kind. The tool should be set up to collect measurement data at 15-minute intervals. Also, other tools were used to collect spot measurements for the other environmental variables.

1.4.3. Computer Modelling

Computer simulation or computer modelling refers to the use of computer software to simulate a model of a specific system. To quantify the performance of the house, simulating the internal thermal performance is vital. This also helps with determining the energy used for cooling purposes and to identify viable alternatives to enhance indoor thermal performance. In the present research, TAS (Thermal Analysis Software) was used to simulate the chosen houses. The simulation was based on the features of the houses and the required outputs. Several variables are considered in the investigation, including heat conduction, energy consumption for cooling purposes and dry bulb temperature.

TAS was used at two stages in the research. Firstly, it was used to supplement the findings revealed by the physical measurements. This enabled accurate comparisons to be made between the two sets of results and arrive at conclusions. Secondly, TAS was used to determine the potential energy savings that could be made regarding cooling systems if alternative building materials are used to construct the exterior envelopes of the houses. This enabled the most suitable ones to be selected.

1.4.4. Weather Data

Two online sources can be used to find out historical weather data, namely Energy-Plus (which only displays historical weather data for Riyadh) and Meteonorm (which offers weather data for many areas of Saudi Arabia) (See table 1.1). To use Meteonorm, a license must be obtained. Nonetheless, this resource was used in the present research as it offers more comprehensive data for the chosen cities.

Table 1.1. historical weather data sources for the simulation.

Historical Weather Data Source	Description
EnergyPlus	EnergyPlus includes weather data for more than 2100 areas. The data are in usable EPW format. Over 1100 of the locations included are in the USA and Canada, with the remaining 1000 locations being situated throughout the world (EnergyPlus, n.d.)
Meteonorm	The data provided by Meteonorm can be saved in over 35 formats. It has over 8300 weather stations across the world (Meteotest, 2020)

1.5. Structure of the Research

The thesis divides into two main sections. The first section is the Literature Review and the second is the Primary Research Section. There are three chapters in part one, in which the background of the topic is discussed to develop a theoretical framework. Moreover, the processes and principles relevant to the investigation are discussed in this section. It is crucial to explore the issues involved so that the collected data can be effectively analysed. Subsequently, in part two, there are four chapters representing the main body of the research. Here, aspects include methodology, physical measurements, the computer model calibration and recommendations for thermal improvements. Figure 1.1 maps the structure of the two sections. The chapters of the research are summarised below:

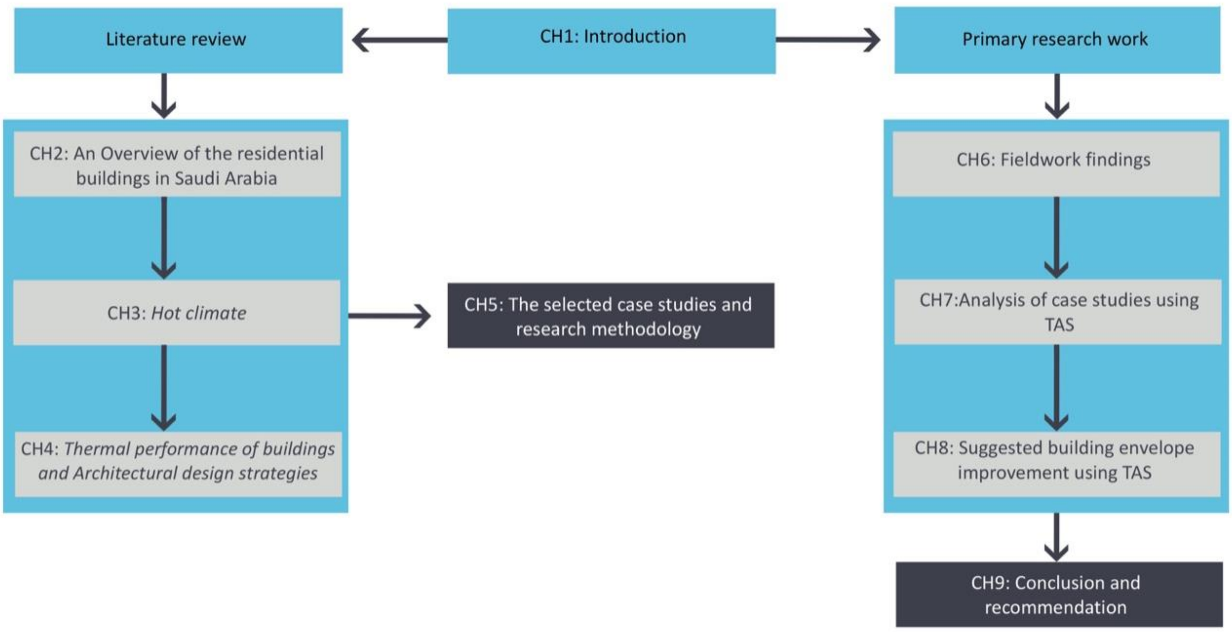

Figure 1.1. Outline of the Research Structure

Chapter 2: An Overview of residential buildings in Saudi Arabia: In this chapter, the current thermal status of houses in Saudi Arabia is assessed. Moreover, the houses' key physical features and the overall energy situation in Saudi Arabia are investigated in terms of available energy sources, consumption and prices. The designs and types of houses, as well as the building materials used to construct them, are considered.

Chapter 3: Hot climate: In this chapter, the different climatic conditions will be discussed. The country's hot zone will serve as the focal point. The key factors impacting thermal comfort in these hot climate areas is highlighted to identify the available options for improvement. The thermal comfort conditions that residents of hot climates prefer will also be outlined.

Chapter 4: Thermal performance of buildings and architectural design strategies for hot regions: In this chapter, the factors causing heat loss/gain in residential buildings will be investigated, after which the most important thermal models for residential homes is assessed. Subsequently, the different types of thermal insulation are discussed. The glazing properties that impact heat transfer are also discussed alongside the factors that impact the thermal efficiency of windows. Finally, the materials most appropriate for achieving thermal comfort in hot climates is discussed.

Chapter 5: The methodology used to study the residential buildings and fieldwork: In this chapter, the houses used in the research will be described in terms of their conditions and physical features. After this, the fieldwork processes carried out are described and the key challenges with the fieldwork are addressed. At this point, instruments and a thermal-modelling computer program are selected based on specific criteria. The features of the houses' are discussed in greater depth because they have a significant impact on the selection process.

Chapter 6: Monitored Internal Environmental Conditions (Fieldwork findings): In this chapter, the houses are evaluated for the first time through the use of specific tools. The data was collected during the winter and summer months of 2018. Subsequently, the thermal efficiency of each house was evaluated and comparisons made. The most significant factors impacting indoor thermal efficiency are also discussed here.

Chapter 7: Analysis of case studies using TAS: the second stage of evaluating the houses will take place in this chapter. At this stage, thermal-modelling software (TAS V9.4.2) has been used. The thermal efficiency of each house was evaluated, after which comparisons were made. Comparisons will also be made between the physical measurements and computer-modelling results.

Chapter 8: Recommendations for improvements to building envelopes using TAS: this chapter discusses the strategies for improving the thermal efficiency of houses. Here, the results of the thermal simulation of proposed houses' components (such as walls, roofs, floors and windows) is presented and recommendations are made for potential means of enhancing the thermal environment by applying each element separately and in combinations.

Chapter 9: Conclusion and Recommendations: this chapter sets out the conclusions and recommendations for future studies are made.

Chapter 2

Saudi Arabia: Overview and case studies

2. Saudi Arabia: overview and case studies

2.1. Historical background of Saudi Arabia

This chapter is divided into two sections. Section 1 is a synopsis of Saudi Arabia. This section initially sets out the context of the research by providing a brief historical synopsis of the country, and it examines the background, primary issues, and current factors that have impacted the state of the present housing conditions in the country. In section 2, the selected case studies are analysed.

Situated in the Arabian Peninsula, the Kingdom of Saudi Arabia lies at the intersection of Europe, Asia, and Africa and occupies approximately 80% of the land mass, making it the largest Arab country in Asia (figure 2.1). It is flanked by two seas; the Arabian Gulf to the east and the Red Sea to the west. It is bordered by eight nations, which are (to the north) Iraq, Jordan, (to the south) Yemen, (to the east, it shares the Arabian Gulf with smaller nations of Bahrain, Qatar, Kuwait, the United Arab Emirates, and to the southeast, Oman. The area of the KSA is circa 2.25 million km2 (GASME, 2016) and its approximate coordinates lie between north latitudes 17 and 31 and east longitudes 37 and 56 (Alkolibi, 2002).

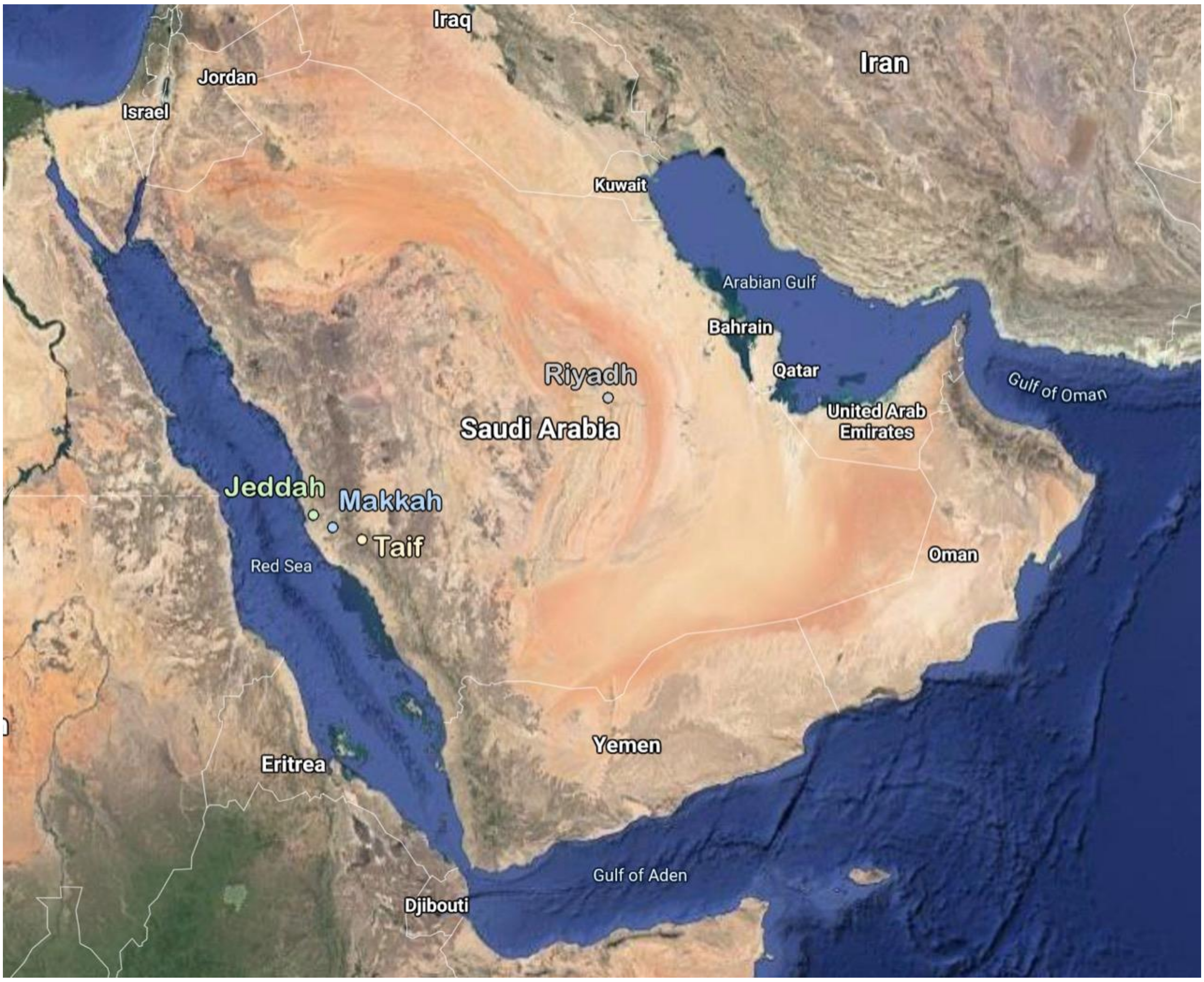

Figure 2.1. Map of the KSA (Google Maps, 2020)

The population was estimated at approximately 27 million in 2010 (last statistics) (General authority for statistics, 2010) and is estimated to be in excess of 34 million in 2019 (General Authority for Statistics, 2019). Makkah province and the Al-Riyadh province each account for 25% of all Saudi households; the two provinces encompass 50% of the entire population. There are 13 administrative provinces in the nation (figure 2.2).

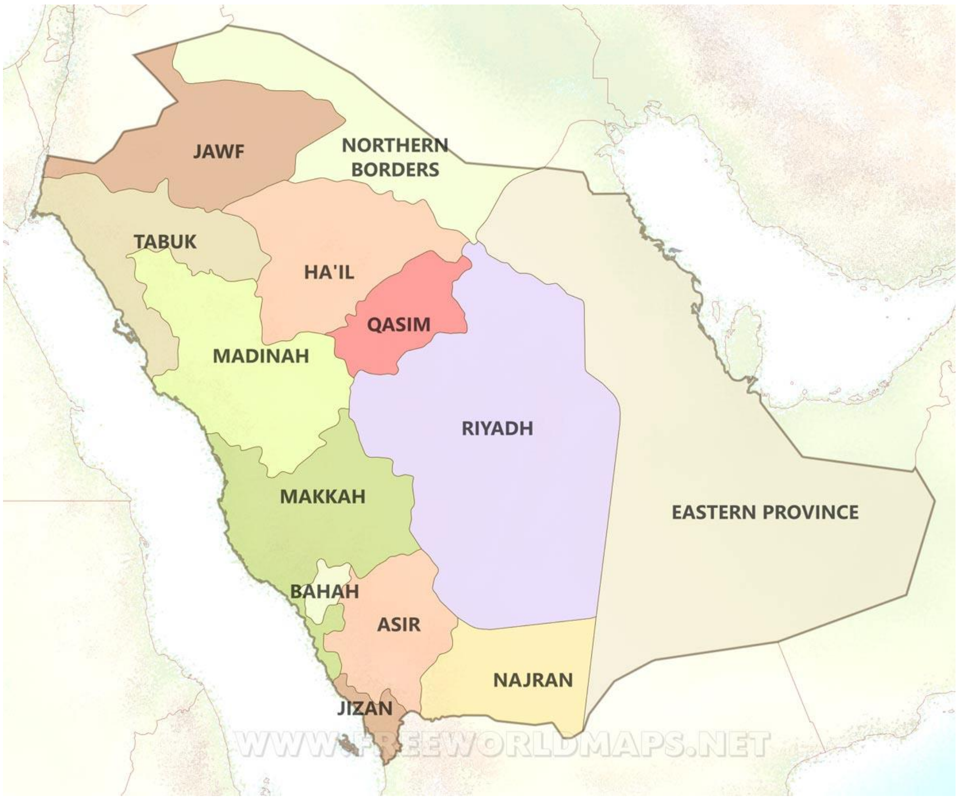

Figure 2.2. The thirteen administrative regions of Saudi Arabia (Derbyshire, 2019)

The coastlines of the Red Sea and the Arabian Gulf run for circa 1,760 kilometres (1,100 miles) and 560 kilometres (350 miles), respectively (figure 2.3). The Tihama narrow plains are situated on the Red Sea coast, with the Hijaz and Assir mountain ranges located to the east. At their peaks, they are over 2,000 metres high. Further east towards the centre are deserts and rocky plateaus that encompass 90% of the total area. The Al Nufud and Al Rub' Al Khali deserts are the largest in the north and south, respectively. Further east, wide coastal plains are situated along the Arabian Gulf coastline.

The country's wide expanse, has, and continues to experience massive geological developments and climate change impacts. Consequently, it has a varied and unique topography and terrain, filled with high mountains, uplands and plateaus, sand dunes, plains, and valleys. The aforementioned coastal plains of Tihama are approximately 1100 kilometres long and 60 kilometres wide. Their widest point is to the south, whereas they narrow as they approach the Gulf of Aqaba in the north.

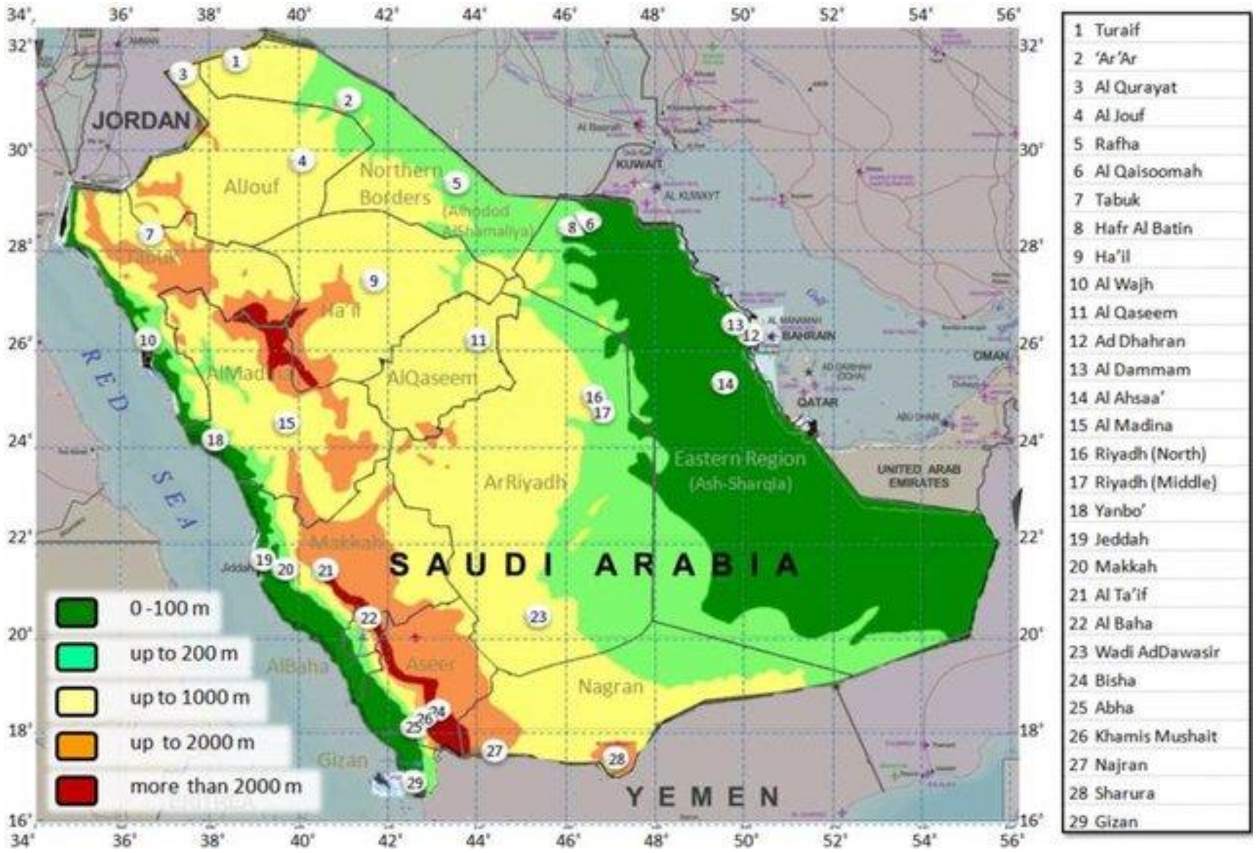

Figure 2.3. Geographic and Topographic map of Saudi Arabia, showing 13 districts and 29 meteorological stations (Albakry et al., 2010 cited in Elnesr, Abu-Zreig, & Alazba, 2010).

The high altitude Sarawat mountain chain (west of Saudi Arabia) lies to the east of the Tihama plains; in the South they reach approximately 9,000 feet and this height gradually decreases in the north to a height of 3,000 feet (Ministry of Education, 2019).

The KSA is frequently referred to as 'The Land of the Two Holy Mosques', which are those in Makkah and Medina. The Makkah Holy Mosque includes Qaaba, and Muslims throughout the world pray in its direction five times per day, whereas the Medina Holy Mosque is the prophet mosque (GASME, 2016). The economy is ranked 18th in the world, making it the largest economy in the Middle East. Since the 1970's the nation has been preeminent among the world's 'energy superpowers'. The KSA is second in the world for petroleum reserves and is the leading exporter. The economy is heavily reliant on the petroleum industry. Approximately 63% and 67% of budget revenues and export earnings, respectively, are derived from the oil industry. Diversifying the country's output is a primary economic concern. As oil prices have fallen in recent years, the KSA introduced VAT on consumer goods and has signed up to the OECD initiative which restricts Transfer Pricing. The KSA and the majority of European countries share similar costs of living; in the global cost of living index, Saudi Arabia is placed 62nd (of 136). Conversely, accommodation costs are typically higher than those in Europe. Mercer's City Living Index ranks how fluctuations in the prices of goods and services impact purchasing power. In this, Riyadh is 35th and Jeddah is 100th (of 209) (Kingpin, 2019).

2.2. Energy usage

As previously mentioned, the KSA holds the 2nd largest oil reserves globally, and the majority of the nations' revenue is generated from oil. Furthermore, the KSA is ranked 6th in the world for natural gas reserves (GASME, 2016).

The energy condition, and in particular the energy consumption ongoing in the KSA is untenable. Domestic consumption accounts for approximately 35% of the total oil and gas production (SEEC, 2020 and Fawkes, 2014). If the status quo continues, it is anticipated that by 2038, the KSA could become a net oil importer (Figure 2.4) (Lahn & Stevens, 2011).

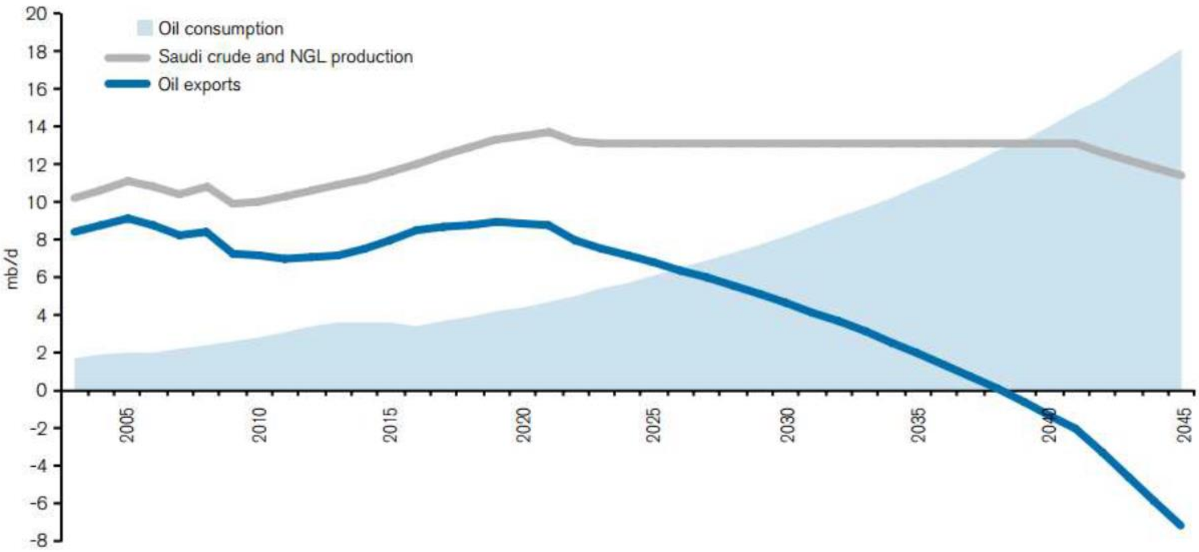

Figure 2.4. Oil balance in the KSA if trends remain on their current trajectory (Lahn & Stevens, 2011).

Globally, the KSA is one of the leading consumers of electricity. In fact, annually there is a 7% increase in electricity demand, which can be attributed to the growing population, greater spending power, higher overall wealth, and very low-cost energy (Fawkes, 2014). Around 80% of the electricity generated is consumed by buildings and more than 50% of this electricity use is consumed by the residential sector (SEEC, 2020; SEC, 2015; ECRA, 2020). Although its use has doubled since 2005, by 2015, 2016 and 2017, the residential use of electricity had flattened out at about 145 GWh, indicating higher price elasticity (Figure 2.5).

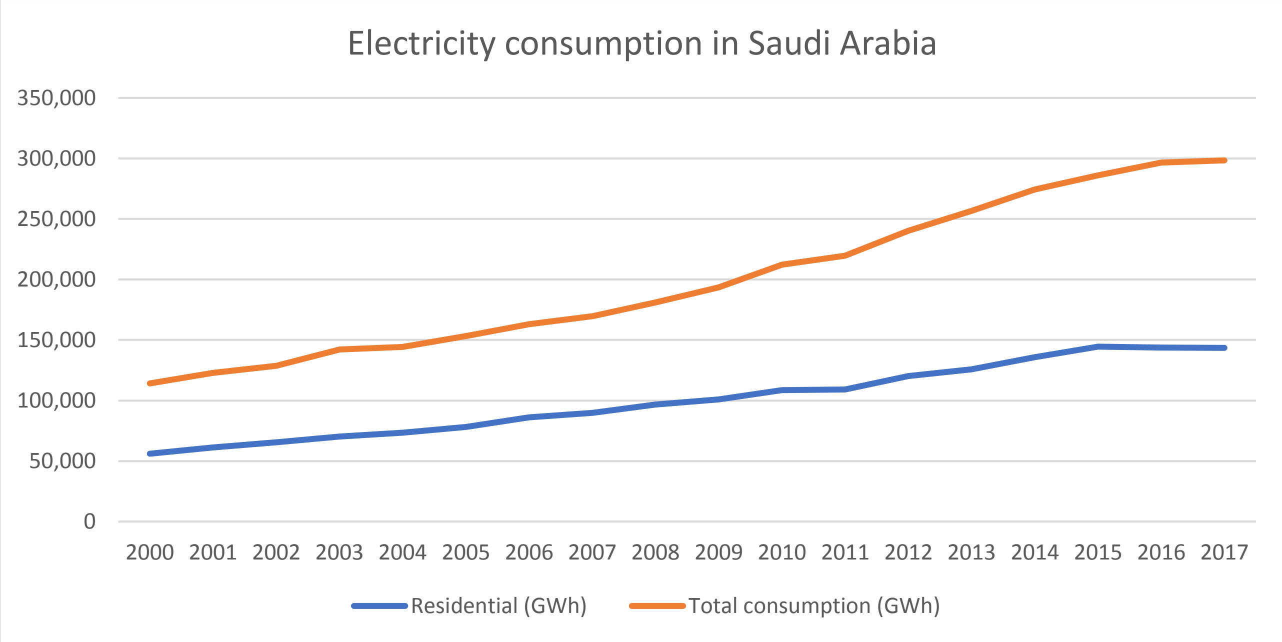

Figure 2.5. The KSA electricity consumption between 2000 & 2017 (Graph compiled with information obtained from SEC, 2015; ECRA, 2020).

Cheap electricity tariffs have contributed to high consumption in residential buildings. Tariffs have been historically low because Saudi Arabia subsidizes electricity to ensure that energy products reach consumers at low prices. (Alshehry & Belloumi, 2015). From 2000 to 2015, the electricity tariff for residential buildings remained unchanged. However, January 2016 saw the beginning of a policy change; a progressive modification was applied to the tariff for a two-year period. The first two monthly consumption categories (1-2000 and 2001-4000 kWh), which make up 87% of the monthly residential consumption bills valued less than SR300, remained untouched (ECRA, 2020). The change in tariff would affect only high consumers using more than 4000 kWh/month. In January 2018, a more radical reduction of subsidies set a new tariff which increased the cost by 72.3% and 44.5% for the first and second residential consumption categories (Table 2.1). The rise in electricity costs is part of an energy price reform policy to encourage rational consumption by the gradual removal of energy subsidies to arrive at market prices by 2025, while restructuring the social safety net to support eligible citizens and families (Fiscal Balance Program, 2019). In the fifteen years to January 2016, the electricity tariff for households started at 0.05 Saudi Arabian Riyals per kWh for the first 2 MWh per month, and progressively increased to 0.26 SAR per kWh for every unit used beyond 10 MWh per month. The negligible rates arguably encouraged profligate use of a finite resource (Matar 2017). The fact that rates do not vary throughout a twenty-four-hour period means there is no incentive for load shifting during peak hours. In parts of Europe and North America, time-of-use pricing incentivises households to postpone the use of appliances (washing machines etc) to off-peak hours when demand is low. That residential consumption of electricity ceased its annual increase of approx. 4% and flattened out after the 2016 and 2018 price rises supports this view and indicates an element of price elasticity and that progressive pricing policies can help reduce consumption. The consequence of government interference in the free market was that consumers were engaging in wasteful behaviour. Essentials like electricity and petrol are generally considered price inelastic commodities because usage is considered to be fixed and indispensable, and therefore unresponsive to price rises but the expectation that Saudis would continue as before and merely spend more as prices rose has proved unfounded. Households can respond to price changes by altering their thermostat set-point of air conditioning or increasing the discretionary use of appliances, restricting their use to only a few rooms (Matar, 2017).

Table 2.1. The electric energy tariff for the residential sector (table generated by the author based on historical information from (ECRA, 2020)

From 27 October 2000 – 31 December 2015		From 1 January 2016 – 31 December 2017		From 1 January 2018 - until now	
Monthly consumption categories (kWh)	Price per consumption (SR/kWh)	Monthly consumption categories (Kwh)	Price per consumption (SR/Kwh)	Monthly consumption categories (Kwh)	Price per consumption (SR/Kwh)
1 to 2000	0.05	1 to 2000	0.05	1 to 6000	0.18
2001-4000	0.1	2001-4000	0.1	More than 6000	0.3
4001-6000	0.12	4001-6000	0.2		
6001-7000	0.15	More than 6000	0.3		
7001-8000	0.2				
8001-9000	0.22				
9001-10000	0.24				
More than 10000	0.26				

The demand for electricity in residential buildings grew in 2013, 2014, and 2015 at 4.7%, 7.6%, and 5.7% respectively (ECRA, 2020). Among the reasons for this expansive growth are constant annual population growth, rising wealth, historically low energy prices, and urban and commercial development (Alshehry & Belloumi, 2015; Fawkes, 2014). However, in 2016 and 2017, the consumption of electricity in residential properties ceased its annual increase and held steady or even decreased by 0.6% and 0.2%, respectively (ECRA, 2020). The modification to energy prices on 1 January 2016 checked the growth of electricity use in the residential sector, but the effect of the January 2018 electricity tariff on residential consumption has yet to be seen. As significant as the actual initially modest tariff increases was the government's stated intent to gradually reduce energy subsidies. Saudi Arabia relies on crude oil and other fossil fuels, such as petroleum products and natural gas, for power generation. During the summer, the rate of electricity usage rises due to the additional demand for air conditioning in domestic residences.

In July 2014, 900,000 barrels of crude oil were burned daily (see figure 2.6). As per the Joint Organisations Data Initiative, this was the most ever recorded in July and the highest since the previous peak in August 2010. Moreover, in the period 2009-2013, Saudi Arabia used an average 0.7 million b/d of crude oil for power generation each summer (George, 2014). Saudi Arabia's oil-based power generation is higher than in any other country. Direct crude oil burn reached its zenith in the summer of 2015, averaging 0.9 million b/d from June to August that year. However, it had fallen considerably by the summer of 2018, being 41% lower at 0.5 million b/d. Moreover, the annual average of 2018 had fallen to 0.4 million b/d, the lowest amount since at least 2009, the earliest year that data are available (JODI) (George & Sandys, 2019). This reduction may be linked to raising the cost of domestic electricity closer to the tariff charged in the global market as of 1st January 2018.

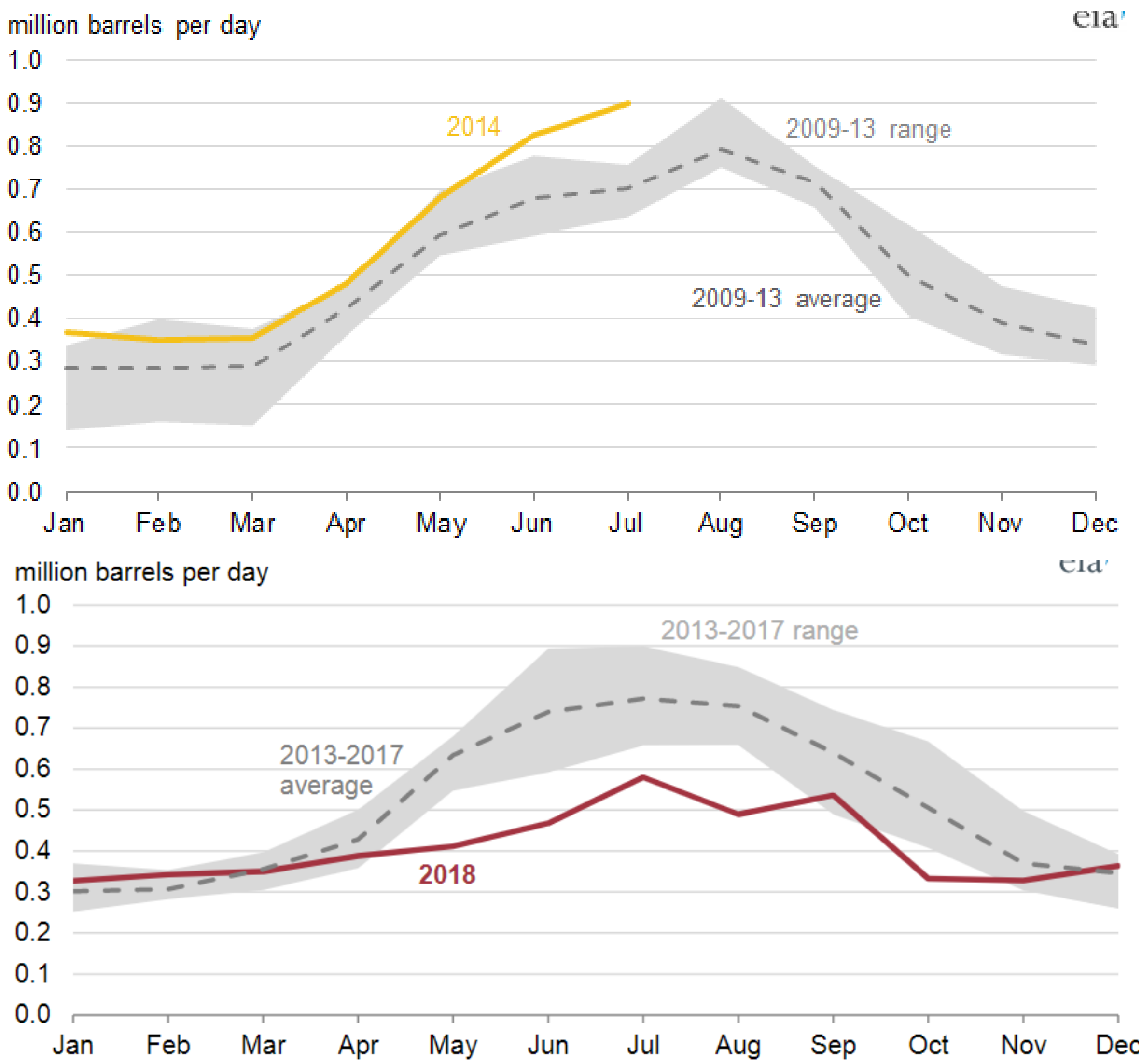

Figure 2.6. The direct consumption of oil for the generation of electricity in KSA from 2009 to 2014 (Above). The direct consumption of oil for the generation of electricity in KSA from 2013-2018 (Below).

The cooling load represents 70% of the electrical energy consumption in residential buildings (SEEC, 2020; ECRA, 2020). 'Cooling load' refers to the energy required to cool a building to a temperature that is comfortable for the occupants (Nicol et al., 2012).

As previously mentioned, cooling is a primary contributor to the overall level of electrical consumption, particularly in residential structures. To decrease consumption, energy efficiency in buildings must be improved. Doing so may entail retrofits such as the installation of thermal insulation, and the use of shading devices to lessen cooling loads. A primary cause of the increasing electricity consumption is the prevalence of air conditioners, used to alleviate discomfort from the nation's high ambient temperatures , particularly during the summer months (Taleb & Sharples, 2011).

Research conducted by Krarti et al., (2017) analysed both economic and the environmental implication of energy efficiency strategies in relation to new and existing housing stock in Saudi Arabia. Their finding revealed that extensive retrofitting programmes aimed at existing residential stock not only have the power to diminish energy expenditure and carbon emissions, but also have the potential to generate employment. It is estimated that 100,000 GWh of electrical energy consumption by KSA residential housing can be eliminated per annum, equating to a carbon emission reduction of 76 million tons. Moreover, the retrofitting programme could create up to 247,000 new jobs per year over a decade-long implementation period, representing 2,470,000 job-years. In addition, the retrofitting programme would be extremely cost-effective since it is estimated that a basic household retrofit would pay for itself in under one year, even when reduced electricity costs are taken into consideration.

A range of climatic, demographic, economic, policy, and technological aspects affect cooling loads. For instance, technological factors refer to how the thermal quality of buildings affects their particular cooling load. Ineffectively designed buildings typically have substantially higher cooling requirements than buildings demonstrating a high thermal performance.

Other aspects that impact the demand for cooling and air conditioning are financial and economic parameters such as the level of family income, the cost of air conditioning equipment and the price of electricity (Santamouris, 2016).

Krarti et al., (2017) concluded that existing KSA energy efficiency regulations be rigorously applied to any new builds, supplemented by the gradual application of the energy efficiency code to all extant building stock. This strategy should be accompanied by a progressive increase in electricity prices, designed to promote energy efficiency. From an economic perspective, given the low electricity prices, it makes little sense for homeowners to invest in energy efficiency. However, a consideration of the wider assessment of benefits accruing from reduced fuel consumption and the concomitant reduction in national electricity generation capacity makes energy efficiency investments cost effective, especially for residential buildings (Felimban et al., 2019).

In 2012, new minimum energy performance standards (MEPS) were introduced for refrigerators, freezers and washing machines (Krarti et al., 2017). Since 2014, the Saudi government has required the mandatory installation of thermal insulation in walls and roofs for all new buildings as a condition for connection to the electricity grid. However, low energy prices have prevented consumers and the private sector from prioritising investment in energy efficiency leading to lax enforcement of these regulations (Asif, 2016). A price of electricity at $0.0479/kWh conceals the cost of subsidies and constructing and running power plants. The 'opportunity cost' of subsidising the price is the huge economic and environmental cost of investing in new power plants.

Krarti et al., (2017) calculate the market cost of electricity at $0.1678/kWh based on international prices. However, this concept of the 'true' cost of electricity can be misleading because, for example, only 32% of the UK bill reflects the wholesale market cost. Twenty-one percent of the bill goes on environmental and social obligations, 17% goes on operating costs, twenty-three percent on network costs, and five percent goes on VAT. Saudi consumers are accommodating to change. Instead of subsidising profligate use, government policy will force consumers to meet their environmental and social obligations to conserve finite natural resources by 'hitting them in the pocket' Charging $0.17 per kWh would save the cost of state subsidies and raise the profile of sustainable energy. Consumers would be motivated to pay closer attention to their thermostat settings at a tariff of $0.17 per kWh. Felimban et al (2019) refer to how consumer behaviour influences consumption; the cultural aspects of extended families offering generous hospitality and user preferences for a room temperature of below 24 ◦C, requires "massive amounts of cooling". However, sacrificing comfort is not necessary to save energy, but saving energy can help save money - it has been estimated that turning off AC systems when rooms are unoccupied can save up to 40% of end-use cooling energy in a typical dwelling (Alshahrani & Boait, 2018). When consumers respond to increased tariffs, everybody wins – not just the government – because reduced consumption at home means more oil and gas to sell abroad and an excess to hold in reserve at OPEC as a means of regulating the oil supply and setting favourable world prices which benefit the country (Safi, 2019). Cuts in energy usage will benefit the Kingdom's environment and, more specifically, its air quality (Sarrakh et al., 2020). Public information campaigns and the certainty of tariff increases has raised user awareness and made a "slight improvement to residential buildings' energy efficiency" (Felimban et al., 2019). The need for increased public awareness is clear when the size of state subsidies is taken into account. For instance, in 2015, the International Monetary Fund (IMF) estimated that the total energy subsidies amounted to $128.9 billion, or an imposing 13.6 percent of Saudi GDP in 2013, including electricity subsidies of $19.1 billion (IMF, 2015). If the price and therefore the revenue from oil declines, the price of electricity will go up as subsides become unaffordable.

Air conditioning demand is determined by climatic factors including the solar radiation and ambient air temperature. Warm climatic areas demonstrate a significantly higher demand for cooling and have greater air conditioning sales than cooler climatic zones.

A study examining the potential development of energy consumption for future heating and cooling in the residential sector found that the global cooling demand will rise by approximately 72% by the turn of the century, which is due to climate change (Isaac & van Vuuren, 2009). It is anticipated that the future energy consumption levels for cooling residential buildings will rise by up to 75% from 2010 levels. In the face of unsustainable levels of demand and the concomitant burning of fossil fuels, the building sector, with government support, is tasked with using building design and materials to reduce domestic energy consumption. One measure that is advisable to prioritise is the energy retrofitting of existing structures (Santamouris ,2016). Krarti et al (2020) suggest that a rigorous retrofitting programme could half annual energy consumption in the residential sector, thereby reducing simultaneously carbon emissions and electricity generation capacities. This claim is outlined in Section 2.3. and retrofitting is discussed briefly in Section 4.3.

- **Vision 2030**

"'All success stories start with a vision, and successful visions are based on strong pillars"'.

Mohammad Bin Salman Bin Abdulaziz Al-Saud

In April 2016, the government introduced Vision 2030 a program of change management for sustainable growth and diversified socio-economic development on a national level. It is a broad plan for decreasing the country's reliance on oil. Vision 2030 has three pillars, one of which is the commitment to becoming a leading power in global investment. The country has significant investment capabilities, which the government intends to use to promote the economy and open other streams of revenue. The solution to economic sustainability is diversification; whilst oil and gas remain vital to the economy, efforts have commenced to expand investments into new sectors. The government is focused on diversifying revenue streams to adapt to 21st century economic circumstances.

The changing global energy market – increased demand for sustainable 'green' sources - has driven a policy of diversification away from an economy based on natural resources towards a digitally enabled economy based on trade, tourism and investment, thereby unlocking the human potential of a predominantly young population.

Vision 2030 includes 96 strategic objectives. To accomplish them, the Council of Economic and Development Affairs announced 13 Vision Realisation Programmes. One of these, the Fiscal Balance Program, assesses the existing capital expenditures, their approval process, and their return on investment. It also evaluates pertinent regulations and oversees expenditures. As a result, there was a 30% rise in non-oil revenues in 2019. The intention is to continue on this path and implement new measures to increase the proportion of non-oil exports in GDP from 16% to 50%. As trade and logistical flows improve, the economy will benefit from a rise in non-oil revenues, thereby ensuring greater diversity and balance. The target is to grow non-oil government revenue from SAR 163 billion to SAR 1 trillion (Vision 2030, 2016).

Over the last four years, several reform measures have included the limited introduction of VAT and energy price reform. Their contribution to increasing and diversifying revenue will be evident in a change in attitude and expectations over the coming years. Furthermore, the government plans to establish structural ongoing revenue improvements to finance expenditures (primarily those with high social effect), and to reduce the budget deficit. It was estimated that in 2019, the oil revenues, which encompass the fiscal impact of the energy price reforms, were SAR 662 billion, which is an increase of 9% from the 2018 level of SAR 607 million. By 2021, it is projected that the revenues (including oil revenues) will reach SAR 840 billion. The energy price reform initiative is an important aspect of economic policy. Its aim is to promote consumption in moderation by progressively decreasing energy subsidies, so that by 2025, the reference price or market price of electricity will be levied. The Fiscal Balance Program, in the medium-term, will support vulnerable citizens whilst the social safety net is restructured (Fiscal Balance Program, 2019). A primary aim of 'Vision 2030' is to decrease oil usage locally in the three key sectors of building, transport, and industry, to a degree that equates to approximately 1.5 million barrels per day (SEEC, 2020).

2.3. Residential buildings development design and prototype

For hundreds of years, and through trial and error, traditional architecture has developed aesthetically pleasing characteristics and demonstrated climate appropriateness and economic viability while satisfying social and cultural needs. In hot dry climates, several vernacular architectural approaches have employed to improve the thermal capacity of structures and the comfort levels for residents. The architectural features which blended with climatic conditions include courtyards, thick walls, wind and cooling towers, domes, wall ponds, roof ponds, Mushrabiyahs or Rowshans - projecting bay windows enclosed with elegant carved wood latticework - and solar chimneys (Alp, 1990). Generally, contemporary structures do not include the aesthetic features described below that contributed to enhanced thermal performance. The characteristics of the traditional home in terms of the organization of space and indoor domestic behaviours reflected cultural and religious values. Design accommodated the need for privacy, modesty, and hospitality and each of these principles can be linked to aspects of the homes. For example, windows were small and placed at high-levels, entrance doors were carefully situated, building heights and balconies were set not to invade privacy of neighbours and micro-climate courtyards and gendered spaces also satisfied social and family needs (Othman et al., 2015). In contrast, contemporary houses typically have thinner roofs and walls, and are chiefly constructed from reinforced concrete and hollow blocks. These mass-produced concrete blocks made connection to power and water utilities much easier but they lacked the thermal mass of heavier denser traditional materials. However, builders were not overly concerned that their materials were not made to moderate the extremes of desert temperatures because they relied upon HVAC systems that cost very little even if they did consume massive quantities of energy (Alrashed et al., 2017).

The covered bazaars and narrow, bustling streets familiar to visitors to the older parts of many Middle Eastern cities conceal how their builders adapted expertly to the harsh demands of a hot, dry climate. Few of the construction principles they applied have been revived in a modern context. These old cities are worthy of our attention because they successfully melded the environmental demands of the desert with cultural and religious values that balanced the requirement for family privacy with the characteristic urge to offer hospitality. This architecture met both physical and social human needs; thick walls and roofs gave protection from daytime heat and the cool night. The narrow streets and tall buildings gave shelter from the sun's heat. The builders of these cities used a familiar aspect of the desert climate - temperature differences between night and day known as diurnal swings – to their advantage. The phenomenon of night cooling occurs in countries such as Saudi Arabia due to the low humidity of desert air (Moisture in the air retains heat). Consequently, building in this region favour thick walls and small windows in order to reduce solar heat gain. Builders harness the advantages of thermal mass, wherein the ability of heavy, dense materials to absorb and store heat is exploited. Stone and earth absorb solar energy during the day. Their extensive thermal mass means that when stone and earth are used to build walls and roofs, they enable to accumulation of heat during the day to be employed to keep interiors warm when exterior temperatures begin to fall in the evening. By morning, the thermal mass has cooled, which allows interior to remain cool during the day when external temperatures rise (Turkustani, 2008).

The merchants of Jeddah modified their dwellings to make them as comfortable as possible under humid conditions. The following description of the passive construction strategies used in Jeddah long before electricity is revealing. The basic principles of thermal comfort have remained unchanged. Despite its low-rainfall, Jeddah's proximity to the Red Sea gives it relatively high humidity. 18 and 19th century merchants adjusted their buildings to deal with humid conditions. With limited night-time cooling, continuous ventilation became the answer to achieving comfort. Well ventilated houses, some up to seven stories tall, were built to protect residents from solar heat. At the same time, enough space was maintained between buildings so as not to interfere with the flow of air. More widely, walls with high thermal mass serve a dual purpose of storing heat for cold days and, 'storing coolness' for when it was hot. Natural heating and ventilation through well-placed windows also keep a dwelling comfortable. Streets and alleys are kept narrow, which leaves them mostly shaded—an important criterion in Middle Eastern urban design (Johnson, 1995). The densely built environment helped protect homes; by sharing as many as three walls ,they shaded each other throughout the day from the sun's heat (Almehrej, 2015). Saudi Arabia's rapid economic growth was first manifest in the mid-1950s and coincided with the discovery of oil. The consequent dramatic rise in wealth had enormous implication for the lives of the Saudi people (Bahammam, 1998).

As explained above, the traditional form of the Arab town was dictated by the natural environment and the socio-cultural needs of its people. As modernisation became the order of the day, ARAMCO's architects and engineers stepped in to produce modern designs for villa-style houses. This new pattern of urban development was used in Riyadh's Al-Malaz district where it became a standard pattern for the urban development of the state (Saleh, 2001). Planning regulations required ventilation and natural lighting to the spaces in the building and wide access for emergency services.

Government assistance - free plots of land and interest free loans - made it possible to build more and bigger houses (Bahammam, 2011). Planning became regulated, building heights were restricted to eight metres; a building footprint of not more than 60% of the site; and a minimum of two metres setback on all sides of the building. The state subsequently adopted this modern grid pattern and villa style for development in all Saudi cities (Al-Said, 2003). The traditional enclosed private courtyard was supplanted by a building surrounded by space, exposed to the climate and visible to passers-by. Although robust and adaptable modern materials were an advance on clay bricks, some aspects of common sense in traditional house design were lost; the building envelope became magnified and the aspect of shade and protection from the elements was arguably sacrificed to the prestige of owning a large home set in a private plot.

In terms of the already built residential houses, no well-funded government backed measures have been taken to examine the possibility of reducing their energy consumption. While the construction industry awaits the mandating and enforcement of common standards for insulation in new buildings, the achievement of low carbon emissions in the building sector remains reliant on retrofitting existing buildings. Such buildings have an anticipated life span of several generations. (Lucon et al., 2014). It is essential that long-lived structures undergo major renovations cyclically, set at a minimum of once every thirty years. Doing so has the potential to decrease energy consumption levels by 50% or more (Harvey, 2009). Krarti et al., (2020) argue that energy efficiency measures should take account of housing type (large villa, small apartment etc) and when and where they were built. They use a variety of methods to rate the cost-effectiveness of various measures and reported a wide variation in retrofit costs depending on housing type, vintage, and location; they estimated a cost of $200 for a new apartment unit in in the generally mild climate of Abha to over $23,000 for an old villa in Jeddah.

This prohibitive cost of retrofitting makes other more easily implemented energy saving policies more attractive; one that is easily implemented is tariff adjustment; using time-of-use pricing to incentivise households to plan or defer the use of appliances to off-peak hours when demand is low. Another effective policy is to weatherise existing structures against heat. For instance, as a consequence of the 1970's boom in oil prices, in 1976 a weatherization assistance programme was introduced by the Department of Energy in America. This programme helped low-income families to make energy efficiency investments that would otherwise have been unaffordable. According to the US Department of Energy, this has significantly decreased the energy demand nationally, and expressed as barrels of oil per annum, the savings equate to 24.1 million barrels each year. In the wake of successful investment policies in energy efficient buildings, several recommendations have been put to the government (Lahn & Stevens, 2011). Firstly, the government could decrease its costs by weatherising existing structures against heat, which would allow it to raise social welfare benefits. Secondly, introducing regulations for building standards could decelerate the rise in energy demand.

So to curtail future energy usage in existing houses , it is critical that the Ministry of Municipality should monitor, conserve, and manage the energy consumption of the KSA's housing sector ; thus, the establishment of an energy usage code for residential building is advised (Aldossary et al., 2014). the enforcement of regulations and energy efficient technologies is advised (Asif 2016). It is important that the decreased energy usage could be aided by several factors recommended by (Aldossary, 2015), such as the following:

- Building materials efficiently designed.
- Architectural design
- Onsite renewable energy implementation
- Public awareness

Potentially, substantial energy savings can be made by upgrading the components of residential structures' building envelopes (Alaidroos & Krarti, 2015). Energy efficiency enhancements to residential buildings are advantageous to both the government and the homeowners themselves. The government can reap significant savings in annual energy costs (reduced subsidies) by determinedly encouraging energy efficiency programmes for new and existing structures via incentives and investments.

Towards late 2010, the government began to focus on this issue with the establishment of the Saudi Energy Efficiency Centre (SEEC). Their 2012 programme specified that their objective is to "reduce energy consumption and improve energy efficiency to achieve the lowest possible energy intensity". The purpose of the programme is to manage the demand side, and it concentrates on three particular sectors, one of which is buildings. The aim is to ensure that national codes and standards are comparable to those in other energy-conscious nations (Fawkes, 2014).

The Saudi Energy Efficiency Centre attributes the high rates of electricity consumption to low-efficiency appliances, and, more convincingly to the low proportion of residential buildings with thermal insulation- only 30% (SEEC, 2020). The high electricity use in the residential sector makes is critical that sustainable energy policies in residential homes are developed (Alrashed et al., 2017). Also, optimum reductions in energy consumption can be achieved by targeting existing buildings (Thomas, 2010).

Setting building standards in Saudi Arabia can considerably contribute to consumption reduction in the household sector (Nachet & Aoun, 2015). Recently, a consequence of the huge building sector growth is an energy consumption crisis due to the massive usage levels. In 2018, executive regulations for the building codes and the classification of violations were issued by the National Committee for the Saudi Building Code (SBC). In the energy conservation category (SBC 602), the purpose of the building regulations is to specify the minimum requirements for designing and constructing energy efficient low-rise residential buildings. Of particular focus are the maximum thermal transmittance U-values for residential building envelopes, including roofs, external walls, ground floors and type of glazing depending on climatic conditions (SBC, 2018) (table 2.2). Buildings are categorised under three climatic zones depending on their geographical location as shown in Figure 2.7.

Table 2.2. The thermal transmittance (U-Values) requirements for low-rise / residential buildings for Saudi building envelopes depending on climatic zones.

Climatic zones	U-value (W/m^2.K)					SHGC
	Walls	Roof	Floor	Windows	Door	Glazing
Zone 1	0.342	0.202	0.496	2.668	2.839	0.25
Zone 2	0.397	0.238	0.496	2.668	2.839	0.25
Zone 3	0.453	0.273	0.496	2.668	2.839	0.25

Zone 1 includes: **Riyadh**, **Makkah** (excluding Al Taif), Al Sharkiyya, Al Madina, Najran, Gizan, Bisha **regions**. **Zone 2** includes: Gassim, Hail, Tabuk, Al Jouf, the Northern border **regions** (excluding Tarif and Guriat), Assir **region** (excluding Abha, Khamis, Moshet, and Bisha), **Al Taif** and Al Baha **region.** **Zone 3** that includes: Abha, Khamis Moshet, Guriat, and Tarif.

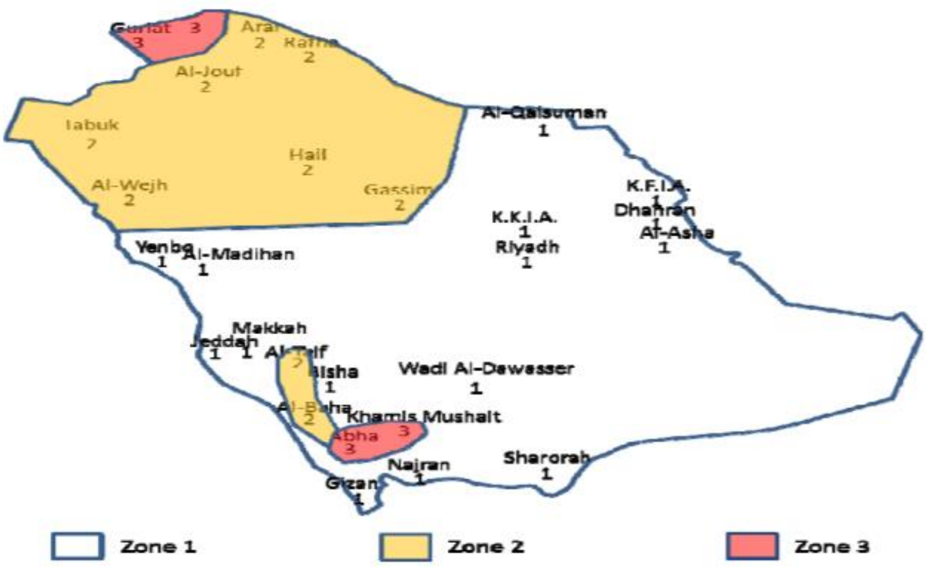

Figure 2.7. Saudi Arabia Climate Zones

From July 2018, the building code was applied to spatial elevation aspects of building design by the municipalities. From the 1st of January 2021, it will be mandatory for builders of small residential buildings to submit applications in advance to ensure compliance with basic insulation standards. According to Dr Saad Al-Qasabi, the Head of the National Committee for the Saudi Building Code, the suggested approach for the codes' application will enable inspection services to be provided by the private sector. In addition, he discussed the creation of a group to monitor innovations in contemporary construction methods, led by the Ministry of Housing. The group would first evaluate the methods and the feasibility of their implementation, and subsequently adjust them to fit the codes' requirements (Saudi Gazette, 2018).

There are many kinds of residences in the KSA, including traditional houses, penthouses, villas, apartments, and duplex villas. Table 2.3 below presents the diverse range of dwellings in the country, and their prevalence.

Table 2.3. General Authority for Statistics, the KSA (General authority for statistics, 2010)

Breakdown of housing types	
Villa	36.3%
Apartments	34.2%
Traditional House	28.0%
Other	1.2%

As depicted above, villas are the most popular type of home, housing 36.3% of the population and because of this, this research is chosen villa typology as a case study. The aim is to ascertain the impact of building fabrics on indoor thermal performance and also on the use of cooling in four climatic zones in Saudi Arabia.

2.4. Analysing the case studies

This section focuses on the four dwellings types selected as case studies for this research. It encompasses the architectural drawings, glazing type, orientation, location, cooling system, and construction materials utilised in each house.

Four currently occupied houses were chosen from four different cities: Makkah, Jeddah, Riyadh, and Taif. These cities are located in two regions of the country that accommodate 50% of the population. Table 2.4 presents the details for each house.

The details are as follows:

- Makkah: House constructed in 2008, located in the Alsharaya district in the east of Makkah
- Jeddah: House constructed in early 2000s, located in the east Sulaymaniyah district in the east of Jeddah
- Riyadh: House constructed in 2010, located in the Almunsiyah district in the northeast of Riyadh
- Taif: House constructed in 2015, located in the Alsayl Alsaghir district in the north of Taif

Table 2.4. Details of the Case Studies

Property location	Total site area m^2	Total built area m^2	Number of occupants	Number of Stories
Makkah	436	563	7	3
Jeddah	580	882	13	3
Riyadh	208	213	5	2
Taif	518	231	4	1

2.4.1. Architectural drawings of the case study building in Makkah

The architectural drawings for the house in Makkah show two entrances on the ground floor; a rarely used guest entrance to the front, and a frequently used occupant entrance to the side. The ground floor plans also include a male guest bathroom, a female guest bathroom, two dining rooms, one occupant bathrooms, one bedroom, one kitchen, and one storage room. This is a typical house layout in the KSA. The first-floor plans encompass a master bedroom with en-suite, four further bedrooms, a storage room, two more bathrooms, and a family seating area in the centre. The second floor has a housekeepers' bedroom, bathroom, and laundry room, which covers less than 30% of the floor area. The other 70%+ of the second floor does not have defined rooms, as KSA regulations state that houses may only have two built-up floors (i.e. ground and first floors) with only a few third floor (i.e. second floor) rooms (Figure 2.8).

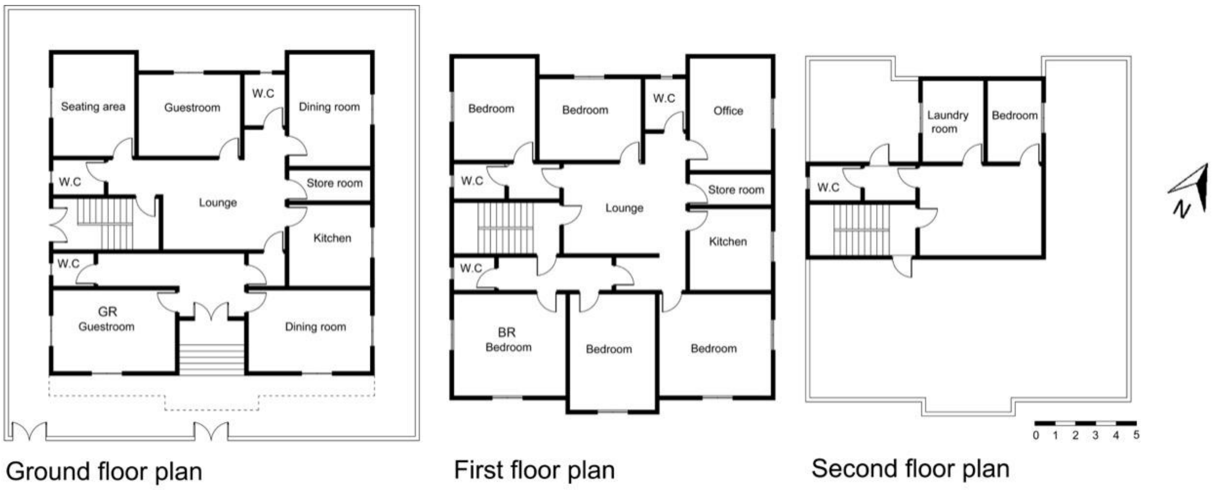

Figure 2.8. Architectural drawings of the case study building in Makkah

2.4.2. Architectural drawings of the case study building in Jeddah

Similar to the house in Makkah, the plans for the ground floor of the house in Jeddah show two entrances, one to the side used frequently by the occupants, and the other front entrance used sporadically by guests. The ground floor plans also show three guest bedrooms (two are for male visitors and one for females), two dining rooms, one other bedroom, four bathrooms, a kitchen, and a storage room. On the first floor, there are five bedrooms, four bathrooms, two guest rooms, a storage room, and a family seating area in the centre. Again, the second floor has a housekeeper's bedroom, bathroom, laundry room, and storage room, which covers less than 30% of the floor area. The other 70%+ is not set as rooms due to the above-mentioned regulations (Figure 2.9).

Figure 2.9. Architectural drawings of the case study building in Jeddah.

2.4.3. Architectural drawings of the case study building in Riyadh

As with the architectural design of the houses in Makkah and Jeddah, the ground floor plan for the Riyadh house shows two entrances used in the same fashion as those in Makkah and Jeddah. The ground floor also includes two guest rooms (one for male visitors and one for females), two bathrooms, a dining room, and a lounge room. On the first floor, there are two bedrooms, two bathrooms, a seating area room, a kitchen, and a centrally located lounge (Figure 2.10).

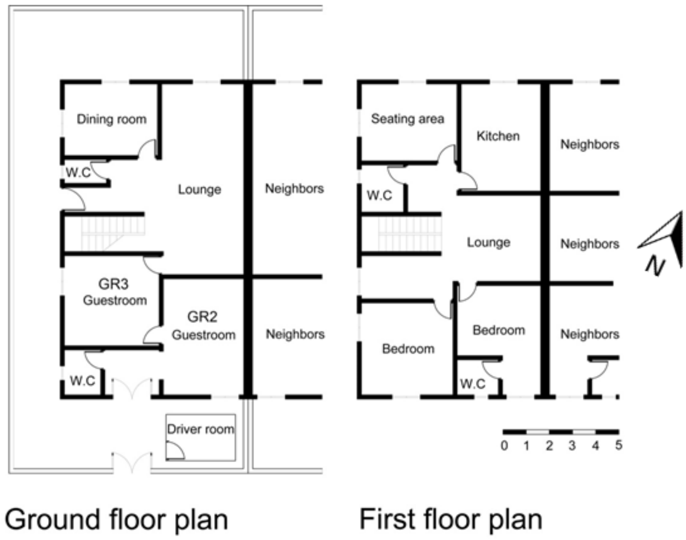

Figure 2.10. Architectural drawings of the case study building in Riyadh.

2.4.4. Architectural drawings of the case study building in Taif

The house in Taif differs from the three previously discussed as it is a one-storey house. It has the same two entrances (rarely used front and frequently used side for guests and occupants, respectively). Additionally, there are two guest rooms (one for male visitors and the other for females), three bathrooms, a living room, and a kitchen. Although this is a smaller house, the style is also prevalent in the KSA (Figure 2.11).

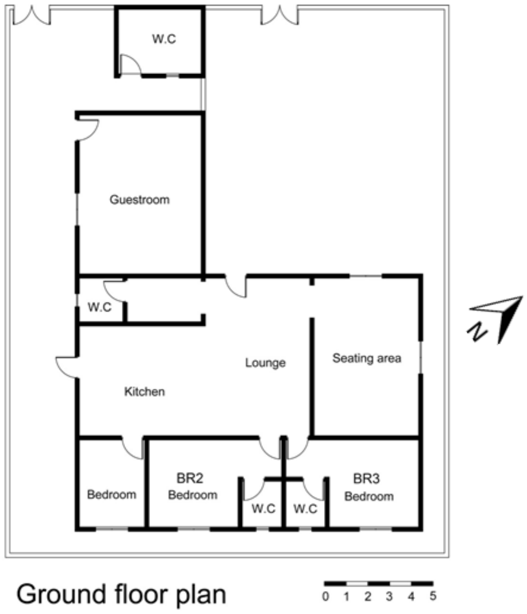

Figure 2.11. Architectural drawings of the case study building in Taif.

2.4.5. Construction element tables

All four houses examined in this research utilised the same construction materials. The tables 2.5, 2.6, 2.7 and 2.8 below depict these materials as per the official construction plans.

Table 2.5. Building fabrics for the houses in Makkah

Element	Description	U-value (w/m².˚C)	Conductance (w/m².˚C)
External wall (main elevation)	40 mm limestone (outside) 20 mm external rendering 200 mm red hollow conc. block 20 mm internal plaster white paint (inside)	1.49	1.995
Other walls	Paige paint (outside) 20 mm external rendering 200 mm red hollow conc. block 20 mm internal plaster white paint (inside)	1.549	2.102
Roof	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.901	1.111
Ground floor	20 mm terrazzo tiles (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 150 mm soil	0.933	1.153
Windows	Single glazing	5.5	

Table 2.6. Building fabrics for the houses in Jeddah

Element	Description	U-value (w/m².˚C)	Conductance (w/m².˚C)
External wall (main elevation)	30 mm marble stone (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	2.955	5.936
Other walls	Paige paint (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	3	6.412
Roof	20 mm terrazzo tiles (outside) 100 mm sand cement mortar 300 mm reinforced concrete slap 20 mm gypsum board and internal plaster white paint (inside)	1.395	1.972
Ground floor	20 mm terrazzo tile (inside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 100 mm soil	1.683	2.201
Windows	Single glazing	5.5	

Table 2.7. Building fabrics for the houses in Riyadh

Element	Description	U-value (w/m².˚C)	Conductance (w/m².˚C)
External wall (main elevation)	30 mm limestone (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	2.897	5.708
Other walls	Paige paint (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	3	6.412
Roof	20 mm terrazzo tiles (outside) 100 mm sand cement mortar 300 mm reinforced concrete slap 20 mm gypsum board and internal plaster white paint (inside)	1.395	1.972
Ground floor	20 mm terrazzo tile (inside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 100 mm soil	1.683	2.201
Windows	Single glazing	5.5	

Table 2.8. Building fabrics for the houses in Taif

Element	Description	U-value (w/m².˚C)	Conductance (w/m².˚C)
All walls	Paige paint (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	3	6.412
Roof	red paint (outside) 3.17 mm metal deck 1000 mm loft space 9.5 mm plasterboard (inside)	1	3.795
Ground floor	20 mm terrazzo tile (inside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 100 mm soil	1.683	2.201
Windows	Single glazing	5.5	

Chapter 3

Climatic characteristics of Saudi Arabia

3. Climatic characteristics of Saudi Arabia

3.1. Hot climate (climatic zones)

Under the bioclimatic design approach, the given climate should be assessed and understood in relation to human needs (Szokolay, 2014, p.57). The 'climatically adaptive' methodology is linked with intelligent building, where passive conditions are incorporated into the architectural design to offer thermal comfort without requiring high energy usage. Thus, a building's architectural design should take account of topography, orientation, wind-direction and other local conditions in general. Using compact natural materials with low surface to volume ratios for those materials are basic aspects of passive cooling (Etzion et al., 1997).

As described in Chapter two, for hundreds of years, the physical and cultural principles of thermal comfort were based on passive thermal control within compact buildings, and these strategies had worked well for many years. In the 1950's, the sudden expansion of family homes into the suburbs was funded by oil revenues and designed by US architects working for Aramaco (Saleh, 2001). The importation of an American 'villa' style abandoned the robust simplicity of basic Saudi houses. Homes had been extensions of one another; however, closely packed dwellings with compact micro-climate courtyards and overhanging balconies were replaced by detached houses set in large plots of land sometimes located far from the 'old town'. These changes were largely signs of progress but, in the dash to be modern, some common sense 'science' on passive cooling was unnecessarily discarded. However, lately, the wheel had come full circle as the utility of passive features is being reassessed and green energy sources are complementing natural resources. As it becomes increasingly financially viable, Saudi Arabia – potentially - has the inexhaustible resource of solar power. The country has tripled its renewable energy target and has successfully tendered for large-scale projects in wind and solar energy (Safi, 2019). Meantime, consumers will adapt their consumption patterns in the face of more expensive electricity and look for passive strategies to save money., and perhaps, in addition make a small contribution to slowing global warming on the planet (Haase & Amato, 2009).

Initially, the country is split into architecturally meaningful climatic zones, to make appropriate decisions about the passive solar (climate) design strategy. A number of subtypes can be established, which in certain locations will overlap or display unique localisation characteristics. A specific area's climate will be examined from its unique perspective, providing information on passive solar climate design response types and then the control zone will be chosen. In turn, suitable passive solar (climate) control strategies can be selected regardless of label or classification of the climate in question (Rabah, 2005). In the context of building design, four unique climates exist. Firstly, there are cold climates, where the issue is limited heat. Secondly, temperate climates change from one season to the next in under heating and overheating. Thirdly, in hot-dry climates, the key issue is overheating, with dry air and significant diurnal temperature change. Lastly, warm-humid climates have less overheating that hot-dry regions, but the high humidity and less diurnal temperature difference is an additional problem.

Specifically, climatological properties must be taken into account when planning groups of buildings, and also when designing single structures. Buildings must be shielded as much as possible from powerful winds, and strong solar radiation (particularly in hot countries), and they must use the sun's radiation in winter for passive heating, manipulate landscape architecture to boost microclimate, employ sufficient building and insulation materials, as well as other elements that can make a substantial difference to indoor climate. In turn, energy sources will be used to a much lesser extent for heating and cooling. It should be noted that when air conditioning is used less, energy is saved, and air pollution is reduced, but also human comfort and even health can benefit (Bitan, 1992).

Solar radiation, air temperature, wind, humidity and precipitation are the prominent climate elements which effect building design (Konya, 1980; Gut & Ackerknecht, 1993). A climate consists of the energy used for heating or cooling, as well as how much energy is employed for lighting (Haase & Amato, 2009). Shown in Figure 3.1, the hot dry climate is positioned around 15° and 30° North and South of the equator. Key characteristics include extremely hot summers, and cooler winters, with a significant daily variation in temperature. In the hot season, dry bulb temperature averages a maximum of more than 40°C, and a mean minimum of roughly 20°C. On the other hand, the average maximum in winter is roughly 30°C, but at night it averages between 10 and 20 °C, depicted in Figure 3.2. When it comes to radiation, the daytime temperature shows high solar radiation, with a predominantly clear sky. With regards to humidity, relative humidity is fairly limited, ranging from 10% to 55%. Precipitation only occurs sporadically, but daytime winds are powerful with the potential to cause sand storms (Gut & Ackerknecht, 1993).

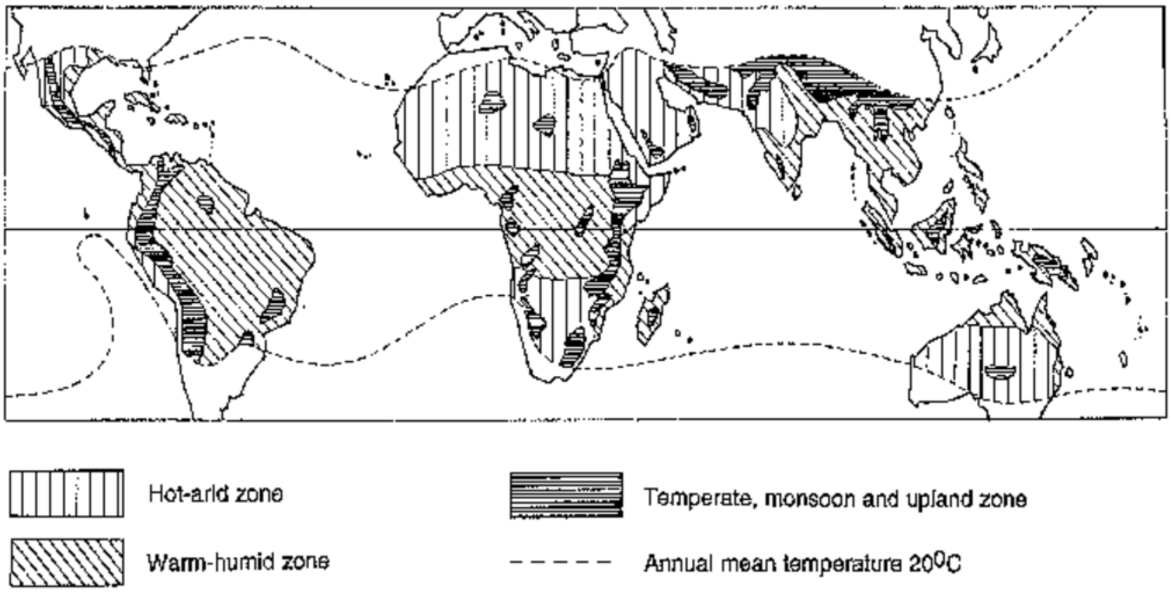

Figure 3.1. The hot climate zones in the world, including the dry and humid hot climate.

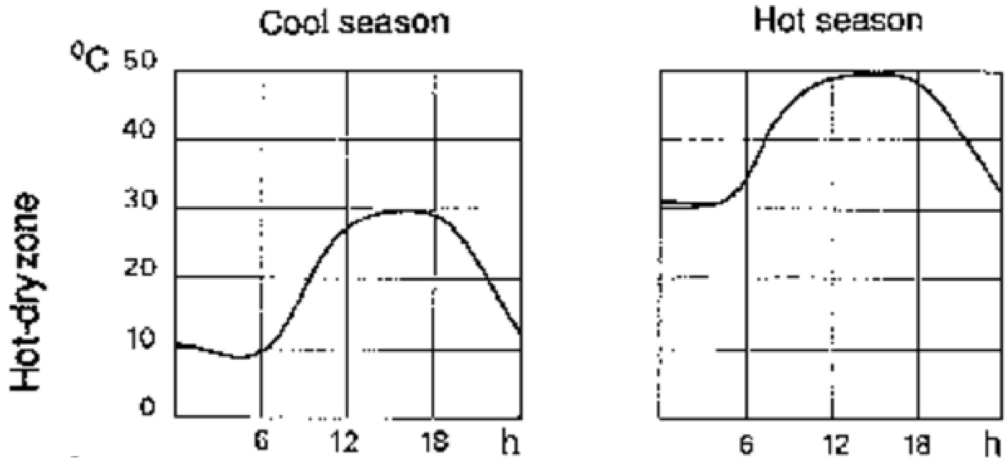

Figure 3.2. Illustrating the average air temperature of a typical day for the hot dry climate zone during summer and winter.

Saudi Arabia has a dry zone climate, despite the rainfall in the north and throughout the western mountain ranges. This is particularly the case in the southwest, which is exposed to monsoon rains in the summer. In addition, rain can appear in other regions as well, with the potential to bring substantial flooding. These conditions are seen in Riyadh, where the air and prevailing winds are extremely dry. The mixed terrain and the unique characteristics of the region produce a varied climate throughout the nation's different areas. While the Kingdom's terrain can be impacted by tropical high pressure events, there is a continental climate in general, with hot summers and cold winters with moderate rainfall. A more moderate climate is seen in the western and south-western heights, with hot dry summers and cold dry winters in the central areas. During the rainfalls of the winter and spring, the temperature and humidity rises in the coastal regions. Rain is seasonal is summer but heavier the rest of the year in the south-western region, but overall rainfall is still limited across the majority of the kingdom's areas. The majority of the time sees a relative rise in humidity across the western coasts and heights, with the opposite towards the centre of the kingdom (Ministry of Education, 2019).

On the other hand, Alrasheda & Asif (2015) state that this simplification of the regionalized Saudi climate as dry is not a fair description, since it masks the substantial climatic deviation throughout the different regions. Saudi Arabia is a vast nation, between 32°N and 17°N latitude and 56°E and 28°E longitude, with variance in its elevation between 0 and 3,000 meters above the sea level. There are numerous characteristic climatic properties across its various areas, which are evident in day to day life. Saeed et al (2003) have divided the country into five inhabited climatic zones and one uninhabited zone, seen in Figure 3.3 and described below:

Zone 1 is a hot and dry maritime subzone.

Zone 2 is cold and dry, with a desert subzone.

Zone 3 is hot and dry, with a desert subzone.

Zone 4 is hot and dry, with a maritime desert subzone.

Zone 5 is subtropical, with a Mediterranean subzone and a mountainous subtype.

Zone 6 is very hot and very dry (Al-Ruba Al-Khali desert), which is not inhabited (Almisnid, 2017).

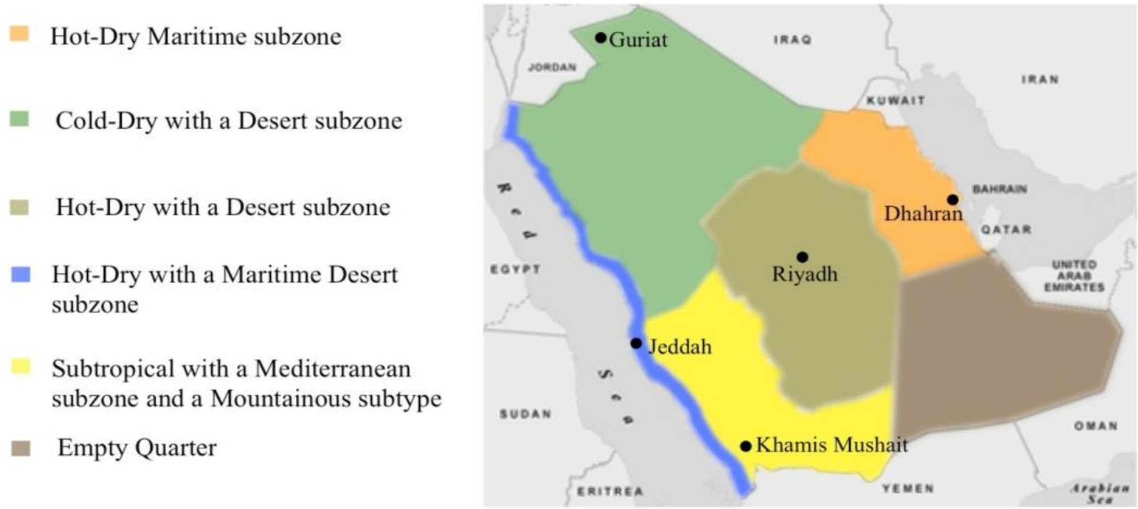

Figure 3.3. The climatic zones in Saudi Arabia represented by 5 cities (Saeed et al., 2003 cited in Alrasheda & Asif, 2015).

It should be noted that, in the aforementioned study, a total of 20 cities/towns were used for analysis. In Zone 1, the climate was established through a single city, while Zone 5 did not include Makkah, despite its climate disparity from the cities of this zone. In addition, the Zone 5 cities were more than 1100m above sea level, whereas Makkah is only 300m above sea level. However, Makkah is positioned within a valley with mountains all around it. In 2015, a different classification of Saudi climate zones was completed, where Makkah and Taif were split into separate climatic zones (SASO, 2015).

This study uses four different climatic zones: Makkah, Jeddah, Taif and Riyadh. Makkah is characterised by extremely hot summers and warm winters, Jeddah by hot summer and warm winter, Riyadh by extremely hot summers and cold winters, and Taif by hot summers and cold winters. This decision is based on their climatic differences and the fact that these are the four largest cities in Saudi Arabia, positioned in the Makkah and Riyadh regions, accounting for half of the population (General authority for statistics, 2010). Researching the climate is vital in order for structural energy performance to be improved. The following section presents related climate data in graph form.

3.1.1. Makkah

Located in Saudi Arabia's Western Province, Makkah comes under the region of Al-Hijaz, shown in Figure 3.4. It is considered that Makkah is the holiest of all Islamic cities, for Makkah is the birthplace of Muhammad the Prophet (c. 570–632). Kaaba, the most sacred Islamic shrine is located there and extends an annual welcome to visiting Muslim pilgrims. Across the world, devout Muslims pray five times each day, bowing down towards Makkah. Each Muslim must complete a hajj (pilgrimage) to Makkah, once in their life. Makkah is 300 meters above sea-level, positioned roughly 45 miles east of the Red Sea port of Jeddah. With a latitude of 21.48° N and longitude of 39.83° E, the city is located within a valley, surrounded by the Sarwat Mountains (Encyclopedia, 2020). Figures 3.5 to 3.8 present related climate data in graph form.

Figure 3.4. Makkah location (google map, 2020).

Air temperature

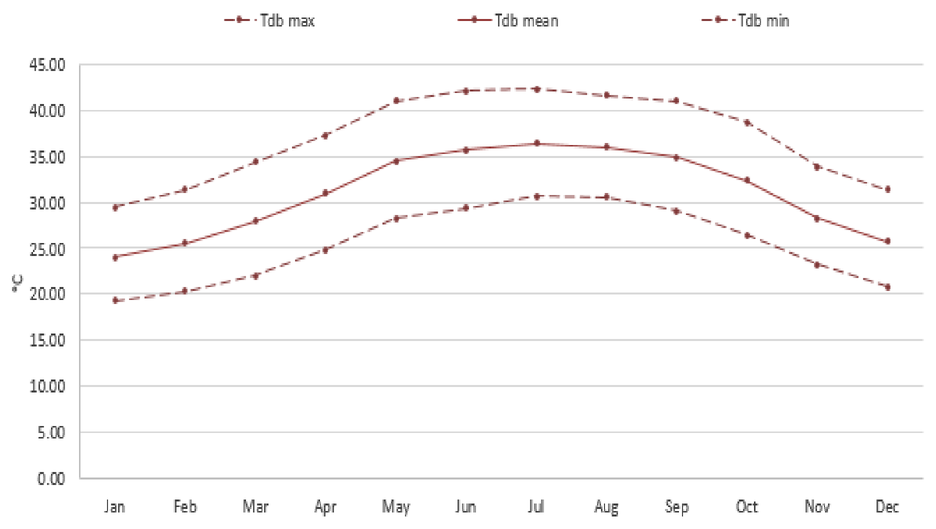

Figure 3.5. Average monthly temperature for Makkah (author generated from Meteonorm 7.0)

Across the year, temperature ranges between 20°C and 42°C. The hot season lasts May to September, and the winter season from December to February, with average monthly temperatures of 36 °C and 25°C respectively for the two seasons.

Solar radiation

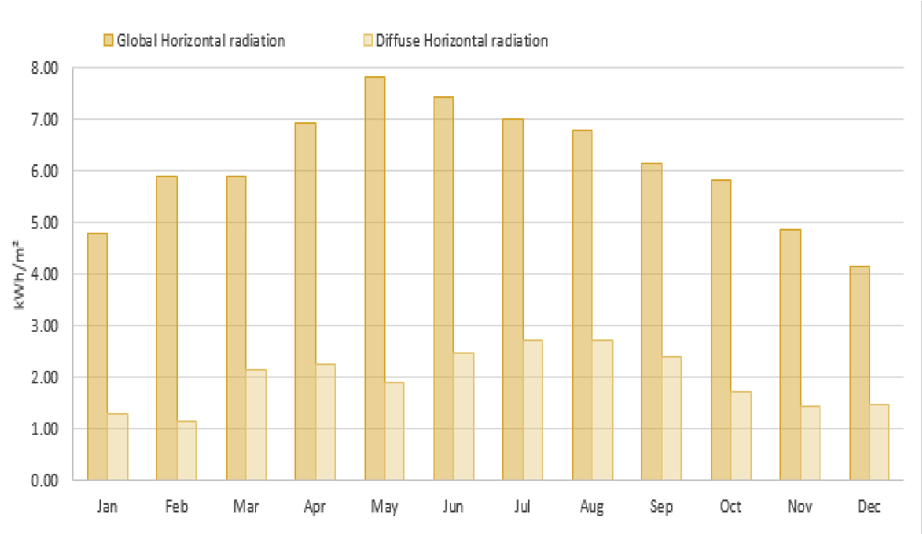

Figure 3.6. Average monthly solar radiation for Makkah (author generated from Meteonorm 7.0)

The year's seasons have substantial variation in average daily incidence of solar radiation, with an average daily solar radiation per square meter between 7.3 – 8 kWh/m2 during the summer and between 4.7 - 5.4 kWh/m2 in winter. A day lasts 11 to 13 hours in Mecca, varying throughout the year (Weather Spark, n.d.).

Humidity

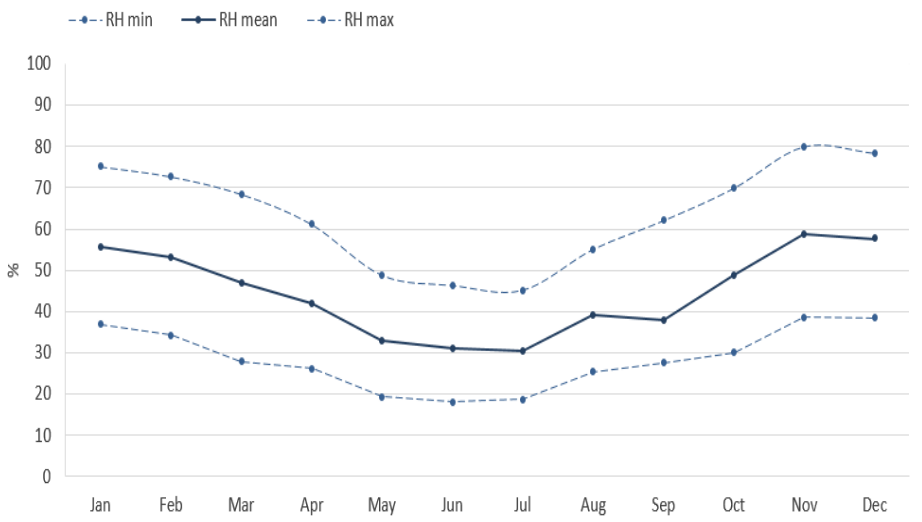

Figure 3.7. Average monthly relative humidity for Makkah (author generated from Meteonorm 7.0)

The average monthly relative humidity in winter is roughly 60%, and 40% in summer.

Precipitation

Precipitation does not occur frequently, but when it does occur in winter, it has a maximum of 22 mm. The annual average is 101mm (National centre of Meteorology, 2021).

Wind

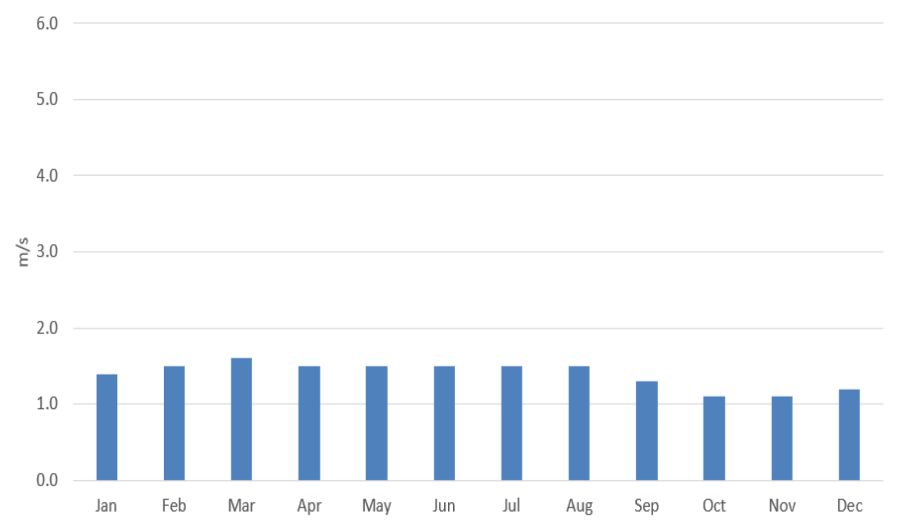

Figure 3.8. Average monthly wind velocity for Makkah (author generated from Meteonorm 7.0)

Makkah's location in a mountain valley gives it a yearly average wind speed of 1.4 m/s, ranging from 1.1 to 1.6 m/s.

3.1.2. Jeddah

Located in the western part of Saudi Arabia, on the Red Sea, Jeddah is the kingdom's second largest city after Riyadh, as illustrated in Figure 3.9. It is found at a latitude of 21.68°N and longitude of 39.15°E and stands as the country's largest port on the Red Sea. It is the main entrance point at which the majority of pilgrims arrive in Saudi Arabia, by air or by sea, to undertake Umrah, Haj or to visit the two holy mosques. It has all the features of a modern city, as well as the characteristic features, such as squares and courtyards, of a late medieval trading centre. It acts as an industrial and active commercial center, and also attracts a large number of tourists, with an eighty-kilometer-long corniche on the Red Sea coast. Within Jeddah, the King Abdul Aziz University, King Abdul Aziz International Airport and Jeddah Islamic Port can be found (The Saudi Network, n.d). Figures 3.10 to 3.13 present related climate data in graph form.

Figure 3.9. Jeddah location (google map, 2020).

Air temperature

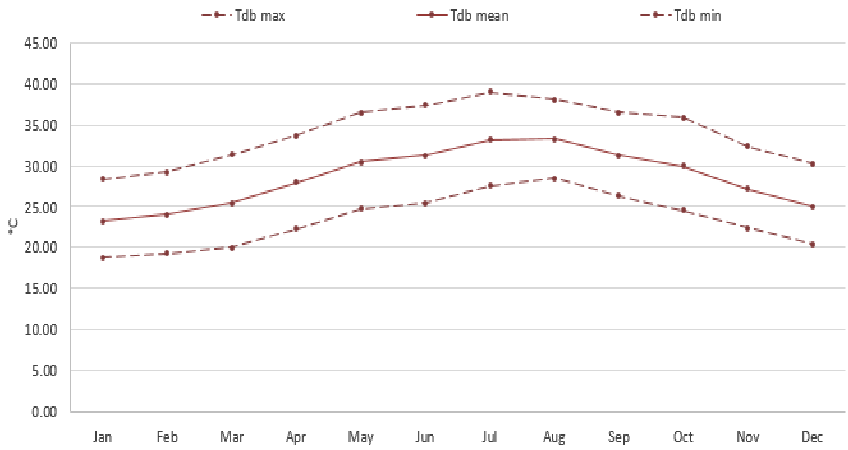

Figure 3.10. Average monthly temperature for Jeddah (author generated from Meteonorm 7.0)

Across the year, temperature is between 20°C and 38°C, with the hot season lasting from May to September, and the winter season lasting from December to March. The average monthly temperature is 34 °C in July and August, over 30 °C in June and September, falling to around 25°C in winter.

Solar radiation

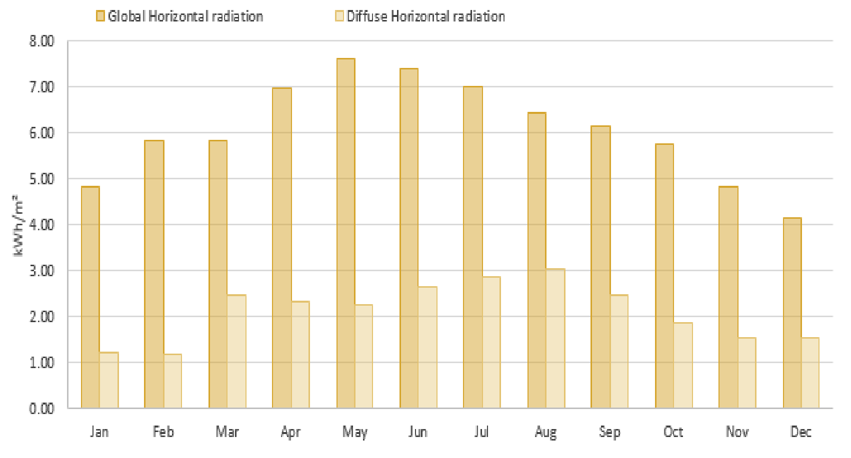

Figure 3.11. Average monthly solar radiation for Jeddah (author generated from Meteonorm 7.0)

There are substantial differences in average daily incidence of solar radiation across the seasons. The average daily solar radiation per square meter is 7 – 8 kWh/m2 in the summer, and this can fall to less than 5 kWh/m2 in winter. Across the year, days last 11 to 13 hours in Jeddah.

Humidity

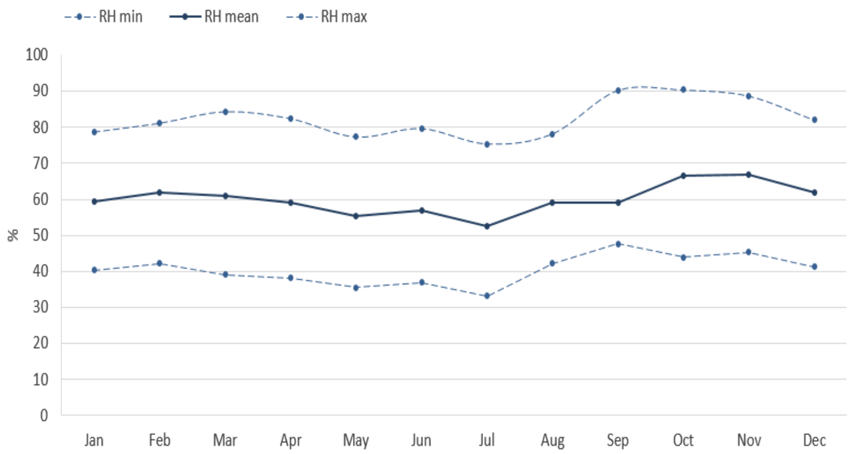

Figure 3.12. Average monthly relative humidity for Jeddah (author generated from Meteonorm 7.0)

Across the year, relative humidity is around 60%, remaining consistently above 50% in the summer and no higher than 70% in autumn.

Precipitation

A maximum of 25 mm precipitation falls in winter, on rare occasions. The annual average is 55.3 mm (National centre of Meteorology, 2021).

Wind

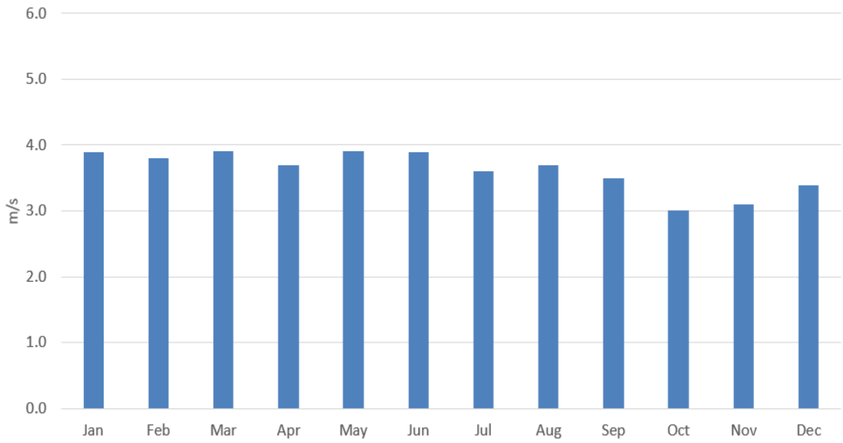

Figure 3.13. Average monthly wind velocity for Jeddah (author generated from Meteonorm 7.0)

Wind speed is an average of 3.5-4m/s for ten months of the year, but in October and November it is roughly 3 m/s.

3.1.3. Riyadh

Based on geographical location, Riyadh, the capital of the Kingdom of Saudi Arabia, is positioned in the middle of the world's continents, as shown in Figure 3.14. It is found in the centre of the Kingdom, in the eastern section of the Arabian Peninsula, at latitude 24.71° N and longitude 46.73° E, and sits 600m above sea level (The Saudi Network, n.d). Figures 3.15 to 3.18 present related climate data in graph form.

Figure 3.14. Riyadh location (google map, 2020).

Air temperature

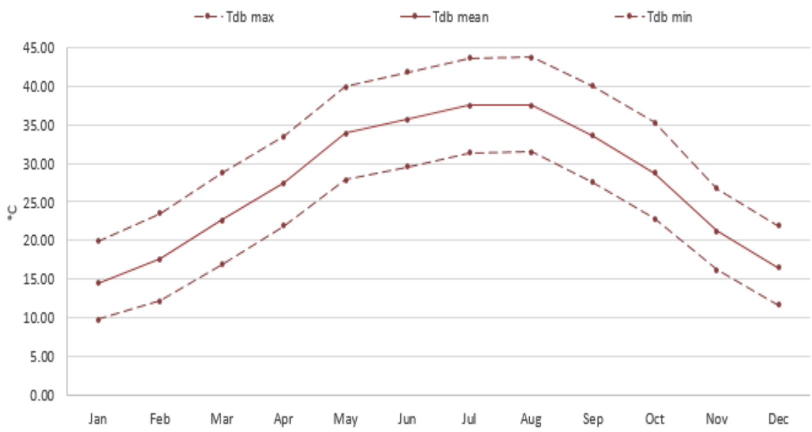

Figure 3.15. Average monthly temperature for Riyadh (author generated from Meteonorm 7.0)

Across the year, temperature ranges from 10 °C to 44 °C. From May to September, there is a five-month hot season, when the temperature is an average of 35°C or above. In winter (December to February), the average monthly temperature is under 20 °C.

Solar radiation

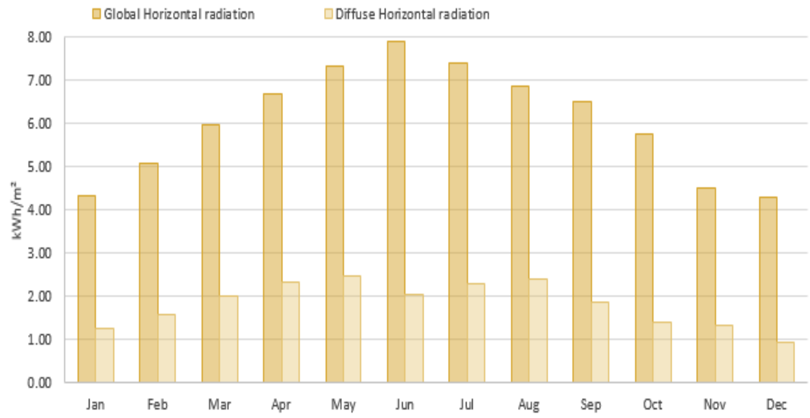

Figure 3.16. Average monthly solar radiation for Riyadh (author generated from Meteonorm 7.0)

There is a substantial level of seasonal variation across the year when it comes to average daily solar radiation. The average daily incidence of solar radiation per square meter is 7 to 8 kWh/m2 in the summer, but 4 -5 kWh/m2 in winter. In addition, days last 11 to 13 hours in Riyadh.

Humidity

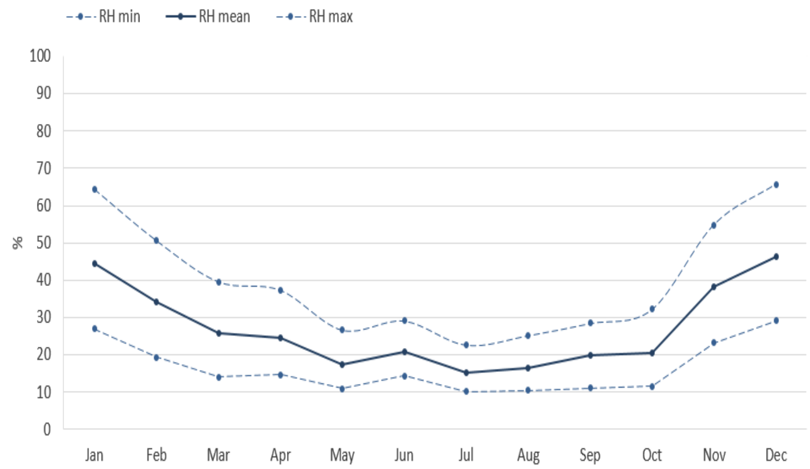

Figure 3.17. Average monthly reltive humidity for Riyadh (author generated from Meteonorm 7.0)

Humidity is extremely limited on an annual relative basis, with less than 20% humidity in summer and 40-50% in winter.

Precipitation

It can rain in most of the year's months, with the most falling in February and June at 20 mm maximum precipitation. The annual average is 105.5 mm (National centre of Meteorology, 2021).

Wind

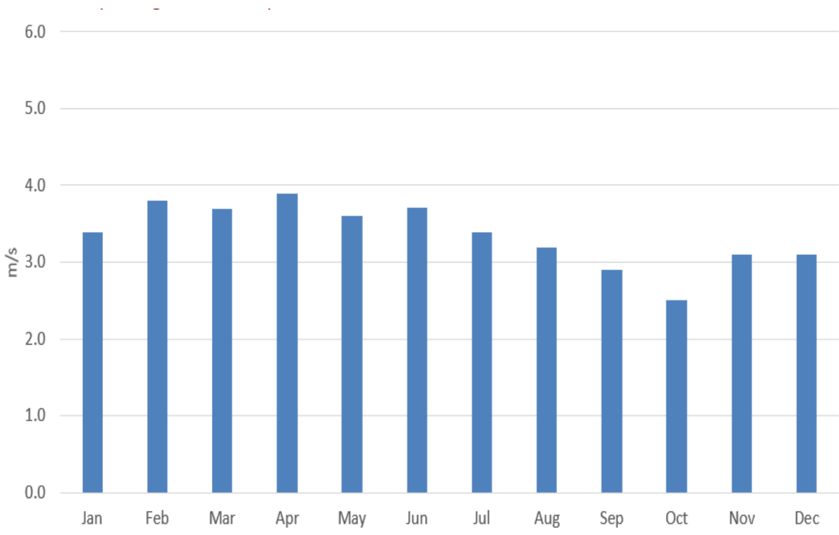

Figure 3.18. Average monthly wind velocity for Riyadh (author generated from Meteonorm 7.0)

Wind speed remains 3 – 4 m/s during most of the year.

3.1.4. Taif

Taif lies East of Jeddah and Makkah, roughly 1400 meters above sea level within the Al-Sarawat Mountains, as seen in Figure 3.19. At latitude 21.4373° N and longitude 40.5127° E, it is south of the Medina region and north of the Leith and Maysan provinces. Moyeh, Trubah and Maysan provinces lie to the east, while Alkamel province lies to the west. After Jeddah and Makkah, it is the third most populated governorate (Taif municipality, n.d). Figures 3.20 to 3.23 present related climate data in graph form.

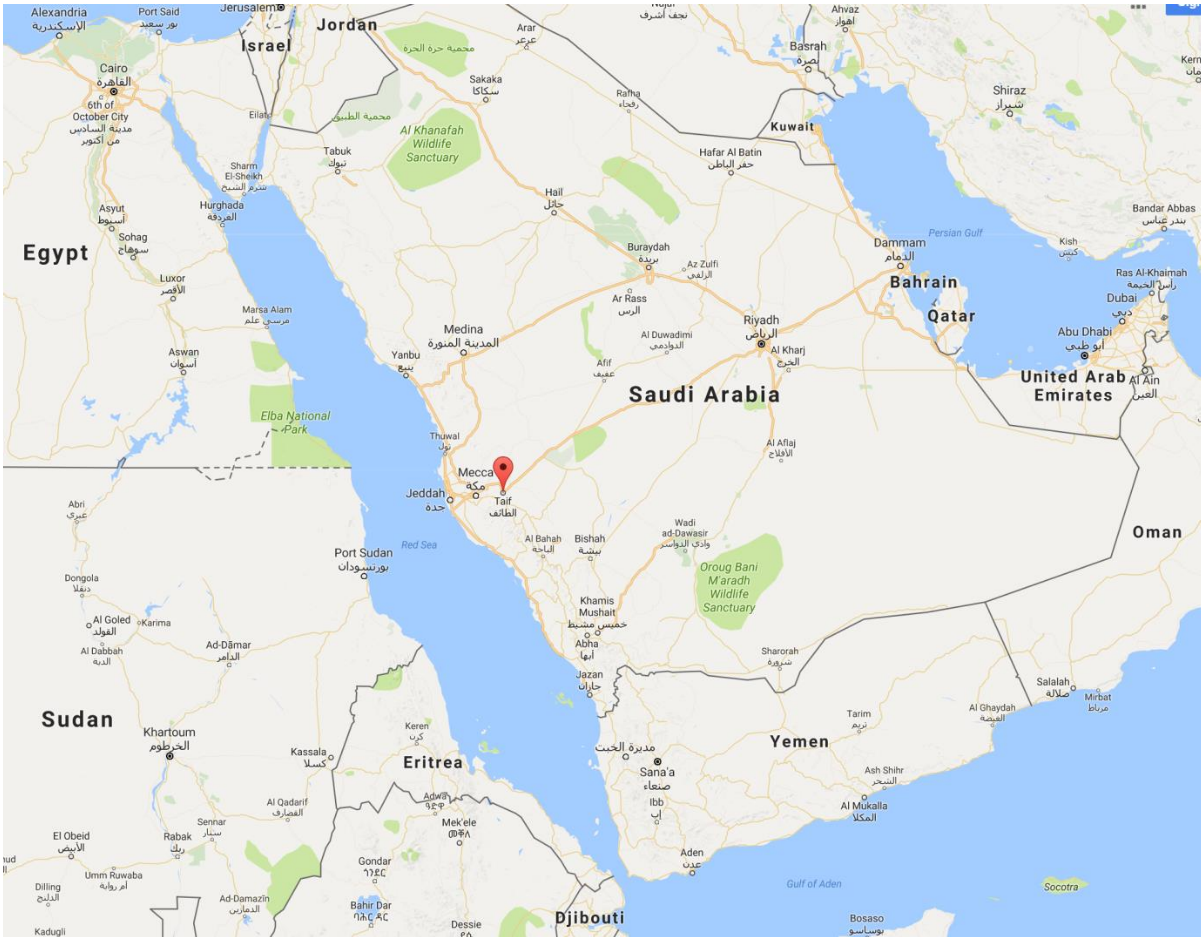

Figure 3.19. Taif location (google map, 2020).

Air temperature

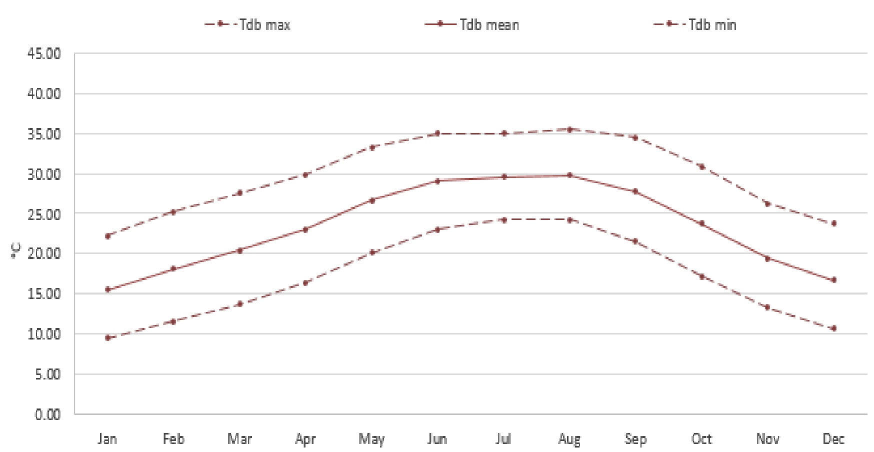

Figure 3.20. Average monthly temperature for Taif (author generated from Meteonorm 7.0)

Ranging between 10 °C to 35 °C, air temperature varies throughout the year. In the hot season - June, July and August - the average monthly temperature is roughly 30 °C. In winter, from November to March, the average temperature is 18°C.

Solar radiation

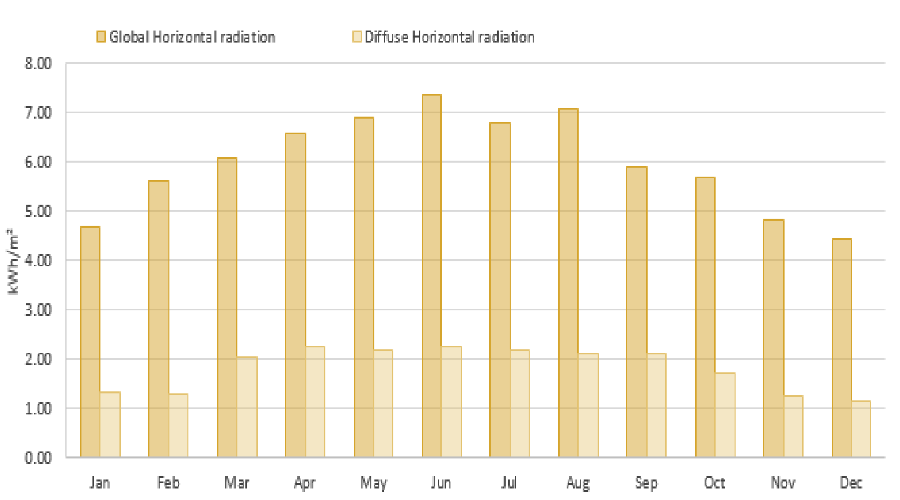

Figure 3.21. Average monthly solar radiation for Taif (author generated from Meteonorm 7.0)

Throughout the year, the average daily incidence of solar radiation can vary substantially, between 7 and more than 8 kWh/m2 in the summer (with the exception of cloudy days, where it is lower), and staying at roughly 4 kWh/m2 in winter. The length of the day in Taif varies from around 11 to 13 hours over the course of the year.

Humidity

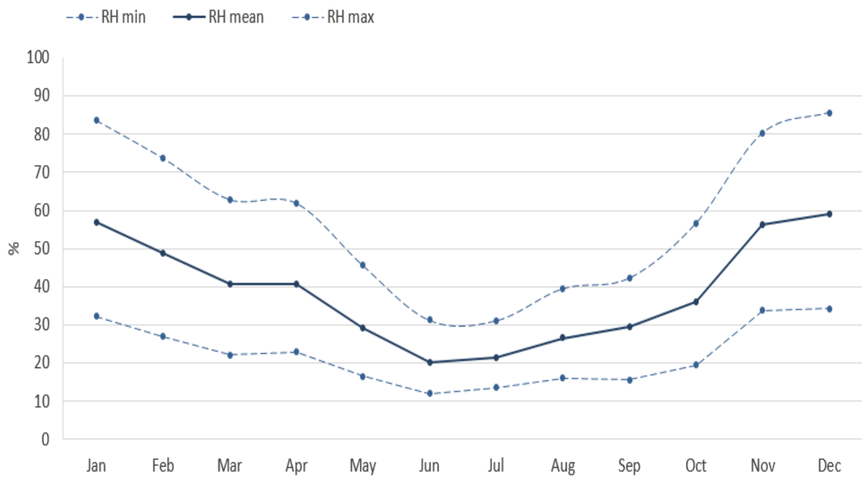

Figure 3.22. Average monthly reltive humidity for Taif (author generated from Meteonorm 7.0)

In the summer, humidity ranges from 20 to 30%, while in winter it is 50-60%.

Precipitation

Rain falls in most months, with May having the highest maximum precipitation at 35mm. The annual average is 171 mm (National centre of Meteorology, 2021).

Wind

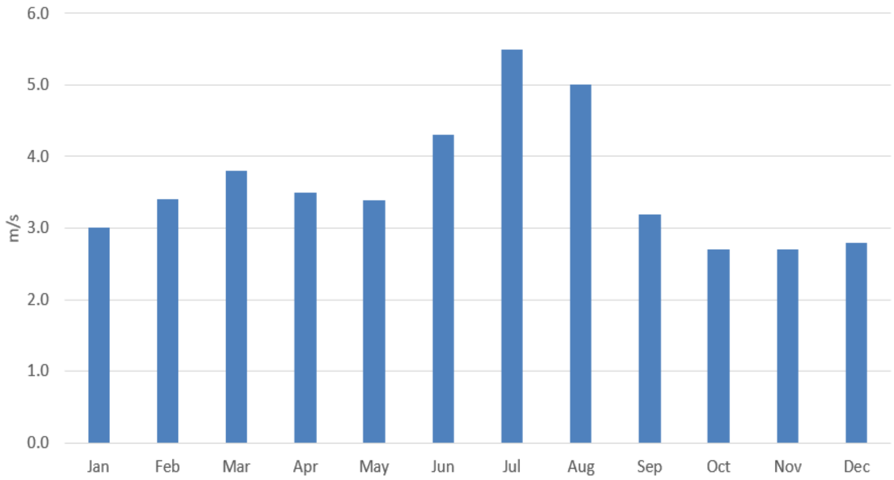

Figure 3.23. Average monthly wind velocity for Taif (author generated from Meteonorm 7.0)

Wind speed is 3-4m/s in the first five months of the year, rising to 4-5m/s in summer, and falling to 3 m/s in winter.

3.2. Thermal comfort

Under ASHRAE 55 (American Society of Heating, Refrigerating and Air Conditioning Engineers), thermal comfort is described where the thermal environment is satisfactory, and is evaluated subjectively. Two models; the predicted mean vote (PMV) and the adaptive model are commonly employed, and generally respected (Djamila, 2017). PMV monitors thermal comfort by measuring skin temperature and perspiration levels – specifically sweat secretion. If these two factors come within predetermined ranges of acceptability, conditions are deemed comfortable. Thermal comfort as experienced by individuals is a subjective category and cannot be comprehensively expressed solely in degrees. Although it is a personal experience influenced by several criteria, it is socially determined and defined by social norms and expectations. Notions of comfort change over time, place and season (Nicol & Roaf, 2017). It is open to the government to educate consumers to adjust their concept of thermal comfort and thereby change social norms by changing public expectations of thermal comfort and encourage consumers to become more frugal.

The availability of global standards for measuring thermal comfort and for the appraisal of thermal environments makes it possible to trust and uphold standards; these are set out in ISO 7730-2005, ASHRAE 55-2013 and EN 15251-2007 (Rupp et al., 2015). Frontczak & Wargocki carried out a literature survey to investigate how human comfort is impacted by a building's indoor environment. The study concluded that thermal comfort is the most vital element when it comes to overall satisfaction relating to indoor environmental quality, when compared with visual and acoustic comfort or even indoor air quality (2011). Since people spend an increasing amount of time indoors, this aspect is important, and it is necessary to take into account the fact that people spend 80-90%

of their days inside buildings when plans are being made to boost the user's environmental comfort through architectural design or engineering efforts (Rupp et al., 2015).

Thermal equilibrium is said to be achieved when a person's internal heat production is in balance with their heat loss. Thermal comfort is influenced internally by physical activity and clothing insulation, and externally by the thermal environment. The ability to find different temperatures acceptable depends on the access to opportunities to modify conditions (Nicol & Roaf, 2017). .Given that thermal comfort is defined as a condition of the mind , it is unsurprising that when house dwellers have the freedom to control indoor temperature by for example, adjusting natural ventilation using windows, it helps reduce their reliance on air conditioning

The variables which impact thermal comfort include environmental factors such as air temperature, air movement, humidity and radiation, and personal factors such as metabolic rate, clothing, health and acclimatization. Additionally, secondary factors such as food and drink consumed, body shape, subcutaneous fat, age and gender can also play a role. Under thermal comfort standards, key variables have been established. Firstly, air temperature is the leading environmental factor, since it determines convective heat dissipation. Second is air movement, which speeds up convection, causing a physiological cooling effect due to greater skin evaporation. Thirdly, there is medium relative humidity (30-65% being acceptable), as this level would not impact thermal comfort to a great extent. Fourthly, radiation exchange, which is decided by the temperature of the nearby surfaces based on mean radiant temperature (MRT). This cannot be calculated directly, and can only be measured using a black glove thermometer evaluating glove temperature reacting to radiant heat inputs together with air temperature. In situations where air velocity is zero, MRT=GT, but $\mathrm{MRT} = \mathrm{GT}\ (1 + 2.35\sqrt{V}) - 2.35 * \mathrm{DBT}\sqrt{V})$ can be used to correct for air movement. The impact of MRT is also related to clothing, and is considered twice as important as DBT. For comfort, it is necessary that DBT and MRT should not have more of a difference than 3K. The fifth key variable is metabolic rate related to activity level, using the Met unit. Lastly, the sixth main variable is clothing, acting as thermal insulation for the body, calculated in 'clo' units. It should also be noted that acclimatization and habit have significant physical as well as mental effects (Szokolay, 2014, p.17).

3.2.1. Predict mean vote (PMV) model

The PMV model was first developed by Fanger, and was intended for use in temperate climate zones. This model has since become a recognised international standard in ISO 7730 and ASHRAE 55. The PMV model was created using the fundamentals of thermal heat balance combined with the physiology of thermoregulation. The PMV model is able to accurately forecast comfort temperatures within a controlled environment, particularly in cold conditions (Djamila, 2017). PMV is an index that predicts the mean value of the responses of a group of house dwellers on a seven-point thermal sensation scale (Djamila, 2017).

Comfort in reality is a much more multidimensional system than is assumed in the steady-state PMV-type indices. The development of the science of comfort from its 20th century origins arising from the needs of the heating, ventilation and air-conditioning (HVAC) industry is revealing. The modern concept of comfort was reformulated to make it responsive to the solutions offered by the ventilation and air-conditioning industries; if engineers could input "target conditions into their HVAC equipment" to obtain a comfortable or neutral environment for any group, they could establish a causal connection between HVAC and achieving thermal comfort, thereby making their product indispensable. It was Fanger who first "repositioned and redefined comfort' as a product sold by the HVAC industry" (Fanger, 1970). The perspective around comfort had changed; the HVAC industry therefore needed to define 'comfort' in terms that opened the physical variables to manipulation using the HVAC system. The emphasis of the definition was on achieving a thermal balance between the environment and the typical consumer. An obvious weakness was the assumption that this thermal environment is constant. Another weakness is its understated psychological or social dimension perhaps related to measurement of PMV data in climate chambers (and not in a lived-in home) (Nicol and Roaf 2017).

The ASHRAE Standard 55 and Standard ISO 7730 are two prominent standards. Firstly, the ASHRAE Standard 55 suggests comfort ranges of ∼20–24 °C for winter clothing (1 clo) and ∼23.5–27 °C for summer clothing (0.5 clo), at 1.1 met and 0.1 m/s air velocity (Mishra et al., 2016). Secondly, Standard ISO 7730 offers the indices predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) to forecast the mean thermal sensation and satisfaction related to thermal conditions within a group of people. This methodology of appraising thermal conditions uses heat exchange of the human body and its surrounding environment as its foundation (Frontczak & Wargocki, 2011).

Once the PMV is calculated, the PPD, or index that establishes a quantitative prediction of the percentage of people who feel too warm or too cool - otherwise known as thermally dissatisfied - can be determined. The predicted percentage of dissatisfied calculates the percentage of people predicted to feel local discomfort. Although PMV therefore predicts the thermal sensation of a population, it does not portray the level of thermal comfort of occupants in a place. Fanger therefore developed an equation to relate the PMV to the predicted percentage of dissatisfied occupants. On the other hand, optimal thermal sensation is neutral according to the PMV model (Van Hoof et al., 2010).

3.2.2. Adaptive thermal comfort (ATC) model

The adaptive model is another methodology used when researching thermal comfort. It is based on the theory of a causal link between outdoor climate and indoor comfort because people can adapt to different temperatures in the course of the seasons. The adaptive model applies to situations where people actively respond to thermal conditions, whereas the PMV model is applied to passive responses to the thermal environment. One fundamental difference between the two models is that PMV can be used with air-conditioned buildings but the adaptive model can only be applied to buildings with passive thermal systems. Simply put, the Predicted Mean Vote calculates a comfort score ranging from cold [-3] through neutral [0] to hot [3] for mechanically ventilated buildings, whereas for naturally ventilated buildings, the adaptive thermal comfort model calculates an indoor design temperature, around which a range is defined as comfortable for 80% or even 90% of people.

The adaptive model uses a number of different field studies, which allowed for linear regressions on indoor operative temperatures (acceptable ranges) and prevailing outdoor air temperatures to be determined. In relation to Fanger's theory, this was a significant change (Rupp et al., 2015). Three key aspects of the adaptive model are not accounted for by the predicted mean vote and the predicted percentage of dissatisfied (PMV-PPD). These aspects are psychological (e.g. comfort expectation and habituation with regards to indoor and outdoor climate), behavioural (e.g. opening windows and the use of blinds, fans and doors) and physiological (e.g. acclimatization) (Nguyen et al., 2012). Numerous adaptive comfort models exist, such as ASHRAE 55-2004 and EN15251 (Nguyen et al., 2012). The adaptive model continues to be reliable and accurate for use in naturally ventilated as well as air-conditioned modes of operation in mixed mode building environments (Manu et al., 2016).

3.2.3. Comparison between PMV and ATC models

In 1972, Nicol and Humphreys put forward a counter argument to the heat balance comfort theory. They suggested the phenomenon of adaptation by the occupant, and felt that the steady state comfort theory was limited in its application to built environments (Nguyen et al., 2012). For naturally ventilated structures, comfort temperatures are clearly affected by behavioural, physiological, and psychological adaptive processes, but these aspects are not taken into account under the PMV model. Adaptation occurs when occupants interact with their environment, as they are not static beings. Also, the differences seen in the subjects' mental state is overlooked in the PMV model, while peoples' longer-term adaptations are not accounted for under the Fanger model. (Djamila, 2017; Nguyen et al., 2012). The adaptive comfort concept unlike the steady state PMV model, accounts for shifts in the range of temperatures considered acceptable. This reassessment of expectations of what constitutes comfort extends the temperature range in which occupants feel comfortable and encourages consumers to reflect upon their A/C settings to conserve what is, after all, a finite resource. On the other hand, there might be longer-term sustainability problems, related to the thermal range of building occupants being maximised under the adaptive approach (Halawa & van Hoof, 2012).

The difference between the two approaches goes beyond their different experimental approaches; there is a subtle difference of values between the two approaches. The 'index' approach sees the role of thermal comfort as the constructor of comfortable environments, but the adaptive approach extends choice to building occupants by encouraging them to explore the range of conditions they would like. PMV uses the climate chamber to accurately measure a range of four physical variables and two 'personal' variables. However, other variables which contribute to thermal comfort can be measured and recorded. These include climate, season, socio-cultural influences and even variations in age or gender. None of these factors can be excluded from how people experience, interpret and interact with the environment (Raw & Oseland, 1994).

To conclude, the adaptive approach is a more dynamic interpretation of thermal comfort. It is based on the assumption that occupants take conscious actions in addition to the body's involuntary physiological responses (sweating, shivering etc) to achieve thermal comfort. The adaptive model is suitable when trying to reduce energy usage in hot climatic conditions. The adaptive model has become popular because it is considered to be more straightforward and user-friendly than the PMV model. Also, outdoor air temperature values are the only requirements needed to estimate the comfort range (Djamila, 2017).

Comfort is a much more multidimensional system than is assumed in the steady-state PMV-type indices. The criteria associated with conventional comfort theories based on the PMV model are more appropriate to controlled buildings. However, these criteria fail to account for the adaptive behaviour of the occupants to enhance the thermal conditions they actually experience. The continual sensory feedback received by the thermoregulatory system contributes to the creation of several optimal states, and not merely one single state, depending on “time-related physical and psychological contexts”. To avoid the wasteful use of energy and to achieve thermal comfort, the European Energy Performance of Buildings Directive (EPBD) stated that officially recommended indoor temperatures should be displayed alongside the actual measured temperature to discourage the unnecessary use of air-conditioning and ventilation systems” (Nicol & Pagliano, 2007). However, this discussion pivots on the chosen definition of thermal comfort. In 2005, the International Standard EN ISO 7730 was revised to recognise the importance of adaptation mechanisms: clothing, body posture and decreased activity are difficult to measure but “can result in the acceptance of higher indoor temperatures”.

There is a large comfortable temperature range under adaptive thermal comfort, meaning energy usage from the cooling and heating system can be lowered effectively (Mishra et al., 2016). However, the heat balance model is suggested when it comes to mechanical system buildings. Also, it should be noted that the occupants' comfort level in buildings with air conditioning is often underestimated under the static model of thermal comfort.

3.2.4. Psychrometric charts

A central tenet of energy efficient design is that building must be construction in harmony with their specific environments. Hence, architects, contractors, and homeowners must all appreciate how local climates influence the optimal designs for housing (Milne et al., 2010). The initial stage of the bioclimatic design methodology involves an investigation of the chosen climate to link climatic conditions to human needs. This can be achieved using the psychometric chart which displays the comfort zone in diagram form, together with the climate at hand (Szokolay, 2014, p.57). The unique climatic traits of any given region can be discerned from bioclimatic charts. Moreover, psychometric charts can used to ascertain the combined impact of temperature and humidity at any chosen time. These charts can be utilized to assist in the determination of construction guidelines designed to optimise interior comfort in the absence of air conditioning. The charts focus on the so-called human comfort zone. This comprises the range of climatic variation within which most humans experience no thermal discomfort (Givoni, 1992).

To support indoor comfort conditions, design strategies are necessary for regulation. These can include passive or mechanical measures. The software program used to produce the psychometric chart was Climate Consultant 6.0 developed by UCLA department of architecture and build environment (Climate Consultant, 2020). Climate consultant typically employs psychometric chart, in accordance with the work of Givoni and Milne (Givoni, 1976; Cowan, 1991; Givoni, 1994; Givoni, 1998; Milne et al., 2010). The chart contains multiple dots, each one denoting the combined temperature and humidity of the 8760 hours in each year. Furthermore, the chart specifically indicates the interior and exterior air conditions and their impact on human comfort levels. This allows the relationship between temperature and humidity to be illustrated graphically so that climate data and human comfort conditions can be accurately appreciated. Each of the sixteen zones in this chart correlates with different design strategies. Thus, the most beneficial passive heating and cooling strategies can be determined by the number of hours the fall within each zone. The psychometric data produced by climate consultant analysis enables a bespoke list of design guidelines to be established for every location (Milne, 2017), as shown in Figures 3.12 to 3.15. A sustainable building design must, in the early stages of the design, take into account energy efficient design strategies. Unfortunately, many architects still rely on simplified analysis and visually attractive design techniques. This analysis was deemed to be particularly significant as it indicated the amount of time that a building could be run with/without the input of a mechanical ventilation system.

- **Makkah**

Through the analysis of Makkah climate data, it was shown that when passive approaches were taken into account, the most effective design strategies were sun shading of windows (34.3 % of the year), two stage evaporative cooling (16.1 % of the year) and fan driven ventilation cooling (15.3 % of the year) for passive interventions. In addition, natural ventilation would manage 10.4 % of the hours of the year and high thermal mass with night time ventilation would manage 9.9 %.

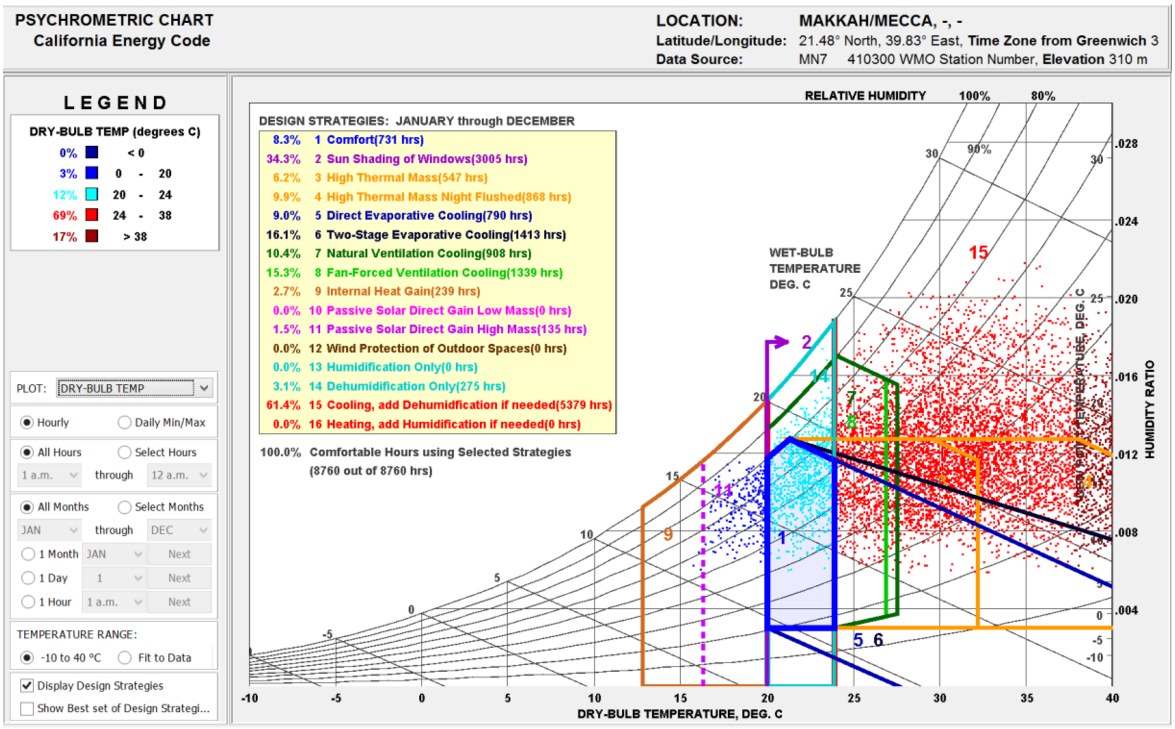

Figure 3.12. Psychrometric chart with environmental strategies overlays for Makkah

- **Jeddah**

In the case of Jeddah, the analysis of climate data showed that amongst passive interventions, the most effective strategies for extending the comfort range were sun shading of windows (34.3% hours of the year), natural ventilation (23.5% hours of the year) and fan-driven ventilation (22.2% hours of the year). High thermal mass with night time ventilation and high thermal mass alone were recommended for 9.3 % and 6.7 % hours of the year, respectively.

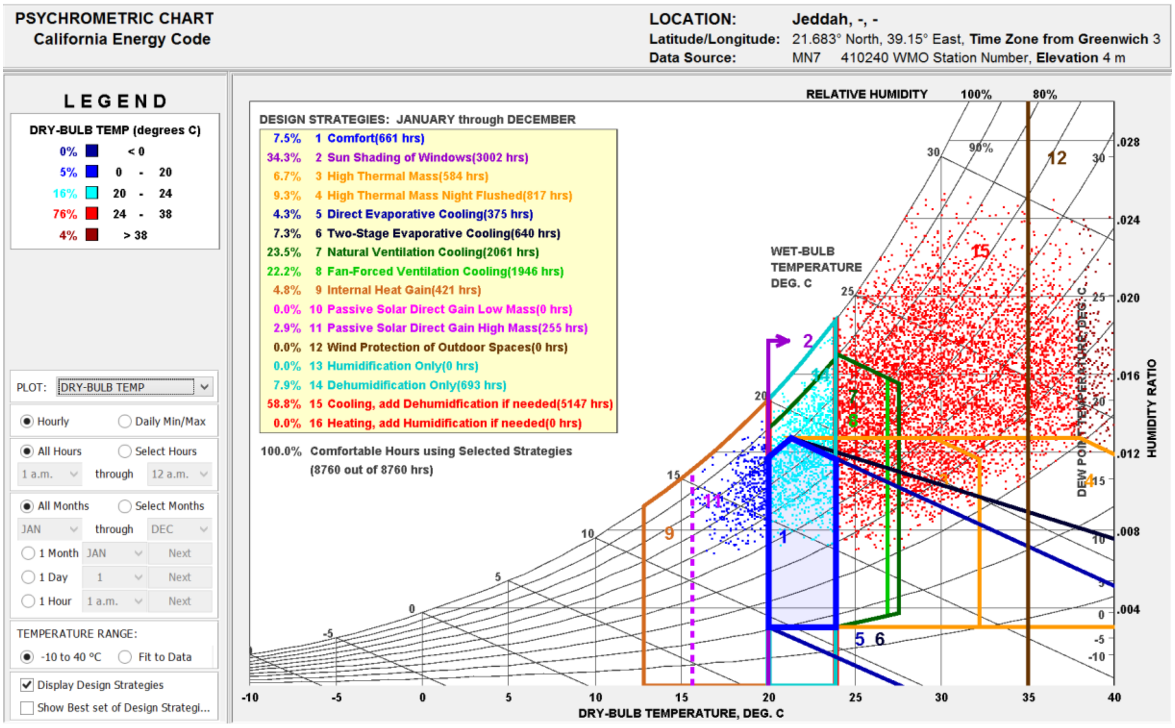

Figure 3.13. Psychrometric chart with environmental strategies overlays for Jeddah.

- **Riyadh**

In the case of the Riyadh climate data, when passive approaches were taken, the most effective design strategies for extending the comfort range were two stage evaporative cooling (60.1 % hours of the year), direct evaporative cooling (46.2 % hours of the year) and sun shading of windows (30.5 % hours of the year). In winter, internal heat gain was put forward for 18.7 % of the year, and solar gain with high thermal mass was suggested for 12.7 % of the year.

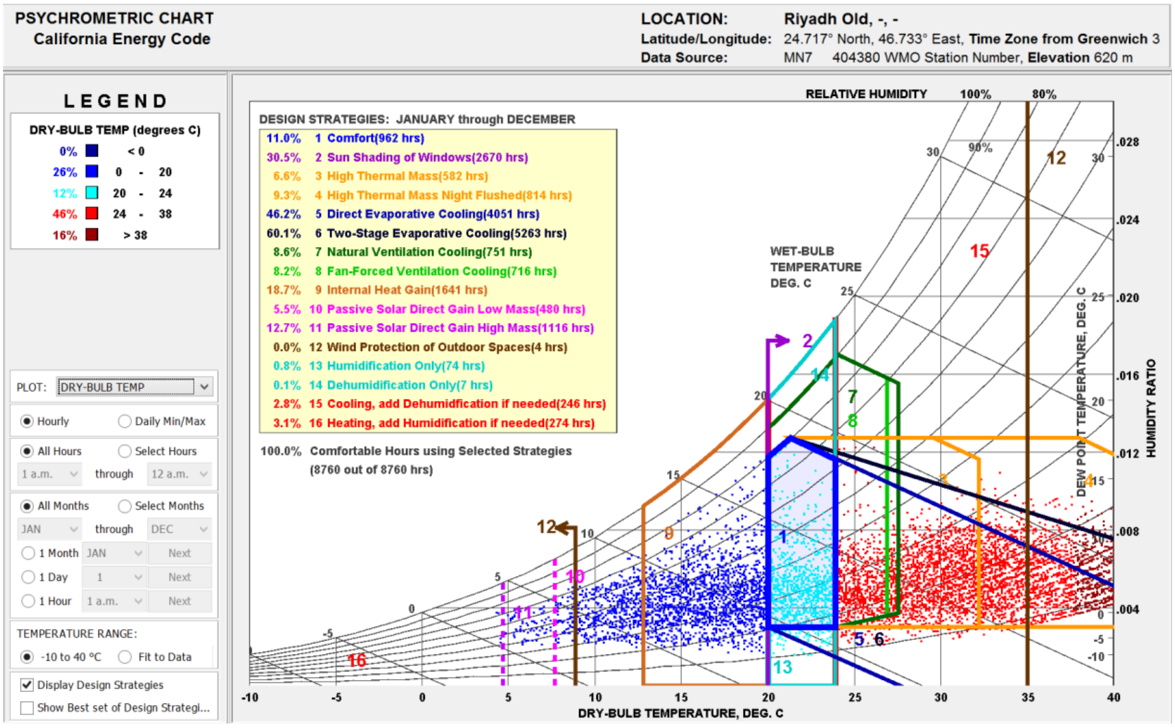

Figure 3.14. Psychrometric chart with environmental strategies overlays for Riyadh

- **Taif**

In the case of the Taif climate data, when passive approaches were taken, the most effective design strategies were two stage evaporative cooling (48.5 % hours of the year), direct evaporative cooling (47.5 % hours of the year) and sun shading of windows (30.1 % hours of the year); these were potentially the most advantageous passive interventions in the extension of the comfort range. High thermal mass with night time ventilation and high thermal mass by itself covered 20.5 % and 14.6 % hours of the year, respectively. In winter, internal heat gain accounted for 24.7 % and solar gain with high thermal mass at 16.7 %.

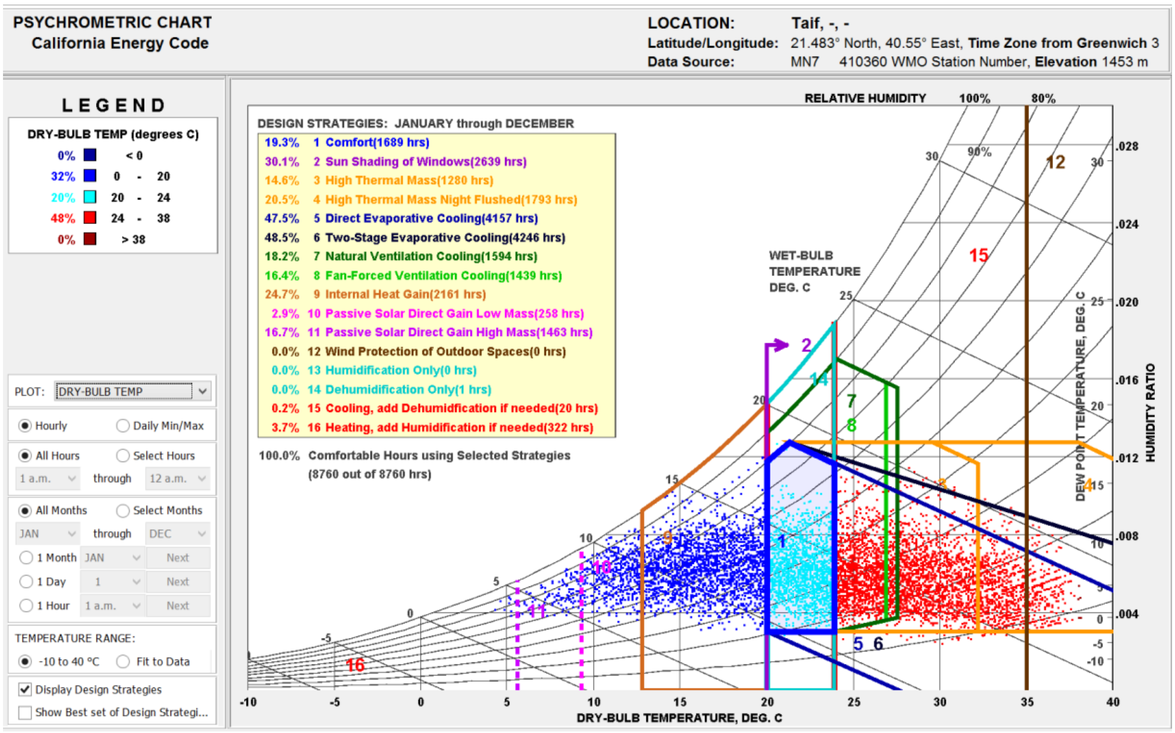

Figure 3.15. Psychrometric chart with environmental strategies overlays for Taif.

The air conditions can be easily observed through the psychometric chart, since they are linked with the climate in question and the thermal comfort of occupants. Also, the environmental design strategies used to achieve thermal comfort are portrayed. However, the design strategies represented in the Psychrometric charts above are preliminary strategies to gain an idea before planning the designing phase and they require further analysis to determine their applicability. Moreover, it is concluded that mechanical cooling systems could be replaced by evaporative cooling in many cases, particularly in climates such as that of Riyadh and Taif. However, this approach is not presented in the current research as a design option, as Saudi Arabia does not have natural water features, as groundwater and water from desalination plants are the country's two sources of water. Indeed, desalination uses vast amounts of energy, and there are concerns that Saudi Arabia's groundwater is a finite resource with a limited lifespan of more than 13 years. In turn, an evaporative cooling strategy is considered to potentially offer benefits throughout Taif and Riyadh. However, this is not usable in the current context due to the lack of water in the Gulf region and especially Saudi Arabia (Sheffield, 2016).

Chapter 4

Thermal performance of buildings and architectural design strategies for hot regions

4. Thermal performance of buildings and architectural design strategies for hot regions

One of the primary reasons for the significant use of electrical energy in buildings across the Kingdom is identified as mechanical cooling systems. To this end, a reduction in consumption through design is seen as one of the most effective strategies, and one that could go a long way to enhancing the thermal performance of residential buildings.

4.1. Thermal components of buildings

The numerous heat inputs and outputs in a building are components of its thermal system. This system can be described as below (Szokolay, 2014):

$\Delta S = Q(i) +- Q(c) + Q(s) +- Q(v) + Q(e)$

Where; ΔS = change in heat stored in the building. Q(i) = internal heat gain, Q(c) = conduction heat gain/loss, Q(s) = solar heat gain, Q(v) = ventilation heat gain/loss, and Q(e) = evaporative heat loss.

In cases where the sum of these heat flows is zero, the system is said to be in thermal balance. On the other hand, when ΔS is more than zero, the structure's internal temperature is increasing. If it reads less than zero, then the building temperature is dropping (Szokolay, 2014).

Two major external climatic forces - air temperature and solar radiation - heavily influence heat flow of a building. . Givoni states that reducing a building's cooling load through architectural design is to limit solar and envelope heat gain (1994).

Solar heat gain is affected by various elements, such as the type of a surface (opaque or transparent), shape, and building orientation. When it comes to passive regulation, window size, material, shading equipment and direction are the most influential variables (Szokolay, 2014).

Conversely, conductive heat gain can be affected by other variables, including building shape and outline, the ratio of surface to volume, and the envelope’s insulation ability.

Furthermore, ventilation heat gain can impact heat flow, and in turn this variable is based on openings, their orientation in relation to wind, methods of closing, and how airtight the envelope is (Szokolay, 2014). As it can be seen in such severe climate as in Saudi Arabia, the most significant energy input into a building is solar radiation (Szokolay, 2014, p.35). Therefore, reducing the solar and envelope heat gain in residential buildings will reduce the cooling load – the amount of heat energy that needs to be dissipated to maintain an acceptable temperature

4.2. Architectural design approaches for hot climates

Chapter two describes how traditional Saudi architecture is based upon a sophisticated response to climate that employs passive techniques for the cooling and heating of urban spaces and buildings (St Clair, 2009). The pre-industrial build environment was dictated by natural climatic conditions and socio-cultural needs. Indeed, the scientific principles applied in the modern passive-solar house are in the tradition of the construction principles used for dwellings by Jeddah merchants (Johnson, 1995). In naturally ventilated buildings where the mechanical option was not available , the relationship between indoor and outdoor temperature was mainly decided by the form and materials of the building in which the occupants used clothing and other features to passively adjust to the building in contrast to using A/C to adjust building temperature (Nicol & Roaf, 2017).

Chapter two explains the transition from the traditional houses in older Saudi towns to the suburban sprawl and decentralization of modern cities. The transformation in the course of 40 years which moved Saudi citizens from clay-brick houses with basic amenities to fully air-conditioned suburban homes linked by new transport infrastructure was in many ways impressive. But in the 1950's what may have seemed to be simple decisions about density, shading, zoning and the use of space lacked long-term vision and understanding of the dwellings being created. In place of funnelled breezes through narrow alleyways and compact floor plans which contained perimeter courtyards and balcony indents, the modern iteration restricted the building footprint to 60% of the site, mandated a minimum of two metres setback on all sides of the building and limited building heights to eight metres. The effect was to create an unnecessarily large and energy inefficient envelope (Al-Said, 2003). Too often therefore, the outcome was a decentralised sprawl of detached homes exposed to harsh sunlight. The newfound wealth in the 1950's was used to build bigger detached homes because non-traditional western building materials and methods were being imported for the first time and air conditioning was an indispensable part of the design (Mubarak, 2004). Subsequent excessive demand and profligate use of air-conditioning driven by its negligible cost has created a need for the design of energy efficient buildings. Air conditioning was new and soon became indispensable. Why would building design incur the cost of incorporating passive cooling into their plans when air conditioning was almost free to use?

Building energy performance is determined by building envelope design, air-conditioning and lighting system design, occupancy patterns, operating schedules, and meteorological conditions (Ahmad, 2004). The building envelope in particular has a significant impact on the energy performance of residential buildings (Ahmad, 2004; Melo et al., 2015). Heat flow is affected by the characteristics of the building fabrics, wherein appropriate building design lessens the heating and cooling requirement (Melo et al., 2015). Efficiently designed envelopes enhance thermal performance greatly, particularly for envelope load dominated building. Envelope load dominated buildings are the opposite of the compact closely packed traditional dwellings of one hundred years ago. Their low thermal mass made them vulnerable to outdoor conditions. Another influence on energy requirements is wall and roof insulation and orientation and placement (Al-Homoud, 2004b).

Mechanical cooling systems can have their run-time or size changed through climate-based design approaches. By establishing a suitable cooling strategy for specific structures in the schematic design stage means that three key elements must be clear, namely : climate, building type and pattern of operation (Kwok & Grondzik, 2007). Solar and heat control, heat amortization and heat dissipation are passive cooling methods used in different situations. Modulation of heat gain manages thermal storage capacity of buildings , whereas heat dissipation methods are related to the ability of a building to dispose of excess heat to an environmental sink of a lower temperature, such as the ground, water, and ambient air or sky (Santamouris & Kolokotsa, 2013). Passive strategies boost the occupants' comfort levels, while limiting energy usage. Low energy buildings are established by making specific choices regarding a passive design approach in line with the climate at hand, to provide the intended indoor comfort (Etzion et al., 1997; Akande, 2010; Rabah, 2005).

Through superior thermal performance, a building could require less extensive use of air conditioning. This can be achieved through different strategies, including reduced glazed areas, greater levels of thermal mass and naturally ventilated buildings. Moreover, other architectural features influencing interior environment and energy consumption, including external shading devices, double skin facades, glazing type, resistive insulation, green roof systems, and the orientation of the building (Chan, 2012). Furthermore, Tuhus-Dubrow & Krarti (2010) argue that a number of design properties impact a building envelope's energy efficiency, such as building shape, wall and roof construction, foundation type, insulation levels, window type and area, thermal mass, and shading. Certain strategies like having enough controlled thermal mass in line with the insulation, window design and analysis of overall building permit sizing of building features can be beneficial in this respect. These can be implemented through choosing efficient external system options, such as windows and doors to use natural daylighting and ventilation. These changes can boost building design and provide greater indoor comfort and lower running costs (Rabah, 2005). Harvey (2009) states that external insulation together with improved thermal mass and night ventilation are especially efficient for hot-dry climates. A building's thermal performance is affected by numerous elements, including design parameters (shape - fabric - fenestration - ventilation), material properties (heat capacity – heat density – reflectance - absorbance – emittance), weather data (air temperature – solar radiation – humidity – wind – participation) and the activity inside the structure (Szokolay, 2014).

4.2.1. Orientation and form

Optimal orientation is a vital early design step for reducing energy consumption, while also being the most straightforward passive solar design aspect (Morrissey et al., 2011 and Elghamry & Azmy, 2017). Building orientation is defined as the position a building takes on a site, and where its windows, rooflines, and other features are placed. Ideal orientation will rotate the structure to make best use of the sun and wind energy around it, while limiting energy loads in cold as well as hot climates. (Yeshwanth & Siddhartha, 2015; Friess & Rakhshan, 2017 and Elghamry & Azmy, 2017). Latitude and the high solar radiation level experienced in the Gulf Region generate maximum solar radiation exposure on west facing walls during the summer period, whereas the maximum exposure during the winter months is on south facing walls. Therefore, the optimum building orientation is for the main facades and glazed area to have a north south orientation (St Clair, 2009).

The directionality of solar radiation according to the path of the sun denotes that east and west facing walls in summer will have greater exposure to the sun through the glazing of a building with that orientation, therefore raising solar heat gain (Friess & Rakhshan, 2017). Solar gain linked to orientation will be based on additional factors, including the shade provided by the proximity of nearby buildings or trees. In cases where ideal orientation is implemented, energy requirements will fall, meaning that energy costs and greenhouse gas emissions will both be lower. In order to achieve effective solar orientation, the sun's paths related to the particular site must be clearly comprehended, for all periods of the year (Yeshwanth & Siddhartha, 2015).

Apart from the structure's fundamental properties, there are many variables impacting a building's thermal performance as mentioned, such as climatological factors, building shape and the surrounding urban environment (Friess & Rakhshan, 2017). The essential laws governing building orientation requires horizontal surfaces to be exposed to optimal solar radiation. Vertical surfaces on the east receive the most solar radiation in the morning, whilst those vertical surfaces facing west receive the maximum solar radiation in the afternoon. North and south facing vertical surfaces receive far less solar radiation (Koch-Nielsen, 2002). Orientation becomes increasingly important based on the quantity of glass and the glazing system used, and whether large solar heat gains can be achieved (Haase & Amato, 2009).

In the work of Aboul-Naga et al., (2000), the value of urban patterns are denoted with regards to building orientation, for the reduction of energy use. Their study compared the energy consumption of four detached two storey villas with different orientations in hot dry climate conditions (Al-Ain in UAE). Their work found that window location at different elevations could boost the energy necessary for cooling. In turn, they found that carefully positioned windows in to two building elevations, energy use could be lowered by roughly 55%.

In Yeshwanth & Siddhartha's (2015) study, a mid-rise four floor office building in Bangalore is the focal point. This structure is modelled with different geographical orientations, and simulations allow the ideal building orientation to be established, where cooling and ventilation energy expenditures are the lowest they can be. Their study concludes that buildings cannot achieve their optimal energy efficiency levels unless they match orientation to prevailing geographic conditions. For example, , north-south orientation is considered suitable for most climates, with the long facade facing the equator and reducing facade areas which face east and west (Haase & Amato, 2009). In the work by Elghamry & Azmy (2017), optimal orientation for maximum energy saving in a hot dry climate is investigated, using Cairo, Egypt as a case study. They saw that a western-facing facade has the highest yearly energy consumption, which is 26% greater than a southern facade. For a two-facade building, north-south orientation is shown to have the least energy consumption. Furthermore, Elhadad, Baranyai, & Gyergyák (2018) evaluate a New Minia City building's energy performance (again in Egypt), using various different orientations. In cases where the building would face north, energy consumption has the potential to drop by 5.8%. The best and worst building orientations are north and south respectively, and they showed a 7.5% difference in energy consumption between them.

There is no consensus opinion when it comes to how effective building orientation is in the current context. The majority of researchers conclude that, putting aside the important variable of location, orientation has a substantial effect on buildings. Nonetheless, research conducted by Taleb (2015) sought to determine whether modifying the orientation of the villa in the study would lessen the interior mean temperature and cooling load. The results found that there were no differences in either the mean temperature or the cooling load. Specifically, the wind circulation projections generated by the CFD simulation indicated that, whilst changing wind direction within the spaces related to the location and orientation of the building, this was not enough to significantly change the interior temperatures. It was suggested that this finding could be attributed to the layout of the building. For example, irrespective of whether the building had a north or north-east orientation, there was insufficient wind flow within the interior of the building. Specifically, warm air cannot be directed from the interior to the exterior when rooms are not open to each other since this does not allow for cross-ventilation. Moreover, there were only minimal differences in wind speed between the two orientations examined in the study and both orientations permitted warm air to enter the building. Thus, both orientations ultimately resulted in comparable air temperatures.

It is also considered that geometrical forms can reduce energy use in buildings (Steadman et al., 2014). Making the envelope surface area smaller for specific enclosed volumes or floor area should be a priority when trying to maximise a building's energy efficiency. A geometric relationship exists between a structure's envelope surface area and its internal volume. In turn, certain building forms have greater intrinsic efficiency than others, without taking into account the materials used. On the other hand, certain other aspects of a building envelope – such as passive strategies for natural ventilation or lowering cooling loads - clearly impact energy consumption and general building sustainability (D’Amico & Pomponi, 2019).

D’Amico & Pomponi, (2019) examined how envelope surface and indoor spaces of buildings are related to define the forms with greater inherent sustainability. Envelope surface (walls plus roof) are taken as the major property which establishes a building's shape and is also the key variable for thermal transfer with the outdoors, which produces energy demand and carbon emissions. In addition, there is a need for plenty of materials created using finite natural resources, and these scarce resources are renewed numerous times in the building's service life (D’Amico & Pomponi, 2019). Along the same lines, Steadman, Hamilton, & Evans (2014) conducted an empirical study to show that there was a robust link between exposed building surface area and gas/electricity use. In the work of Rashdi & Embi (2016), the relationship of optimum building form was examined in the context of reducing cooling load. Their findings stated that that the selection of compact materials and low ratios of building surface to volume offer a passive reduction in cooling load.

AlAnzi et al., (2009) undertook a simplified analysis to forecast the relationship between a building’s shape and yearly energy output. They showed that building shape impacts the overall building energy consumption based on three key elements; relative compactness, the window-to-wall ratio, and glazing type defined by its solar heat gain coefficient. Furthermore, Ourghi et al., (2007) undertook a simplified analysis method to forecast the effect office building shape has on its annual cooling, and overall, energy use. Their analysis showed a robust link between shape and energy consumption in commercial structures.

4.2.2. Thermal insulation

The building envelope is defined as the connection of the interior of the building with its outdoor environment. Components of the envelope can be walls, roof, and foundations. The building envelope is vital as a thermal barrier in controlling interior temperatures, establishing how much energy is necessary for maintaining a consistent level of thermal comfort. Limiting the building envelope's heat transfer is required to make the building space's heating and cooling more efficient. For colder conditions, the building envelope is able to limit how much energy is needed for heating, whereas hot climates can benefit by lowering the energy needs for cooling. How much energy is released, or held, through walls and roofs is affected by the design and materials involved. The location of windows and doors is dictated primarily by the size and design of the building, which all impact energy use and can help limit losses. Choosing the most suitable material is a complex task, as the overall wall's energy properties are impacted by the design. Crucially, material choice and wall insulation substantially affect a building's thermal characteristics (Yeshwanth & Siddhartha, 2015).

Insulated building walls are components of the building envelope, and they shield the space inside them from various weather conditions, and limit wide variance in temperature. In most cases, this is achieved by raising the envelope's thermal resistance (R-value), and subsequently lowering transmission loads. In turn, the inclusion of thermal insulation is considered vital, especially in areas which have extreme climates (Al-Sanea, Zedan, & Al-Hussain, 2012). Szokolay asserts that the envelope's thermal insulation is a critical means of control, particularly in environments where heating or cooling is necessary (2014, P.59). Kharseh, Al-Khawaja, & Hassani (2015) examine the effect of using thermal insulation when it comes to the lower cooling load of residential structures in Qatar. Their findings denote that, when implementing under 2 cm of polyurethane to the external walls, cooling requirements can fall by as much as 27%. Also, Ahmad (2004) compares the energy consumption of a typical house built with different types of masonry materials using analysis program DOE-2.1E. The model house investigated in this study is located in Dhahran, Saudi Arabia. It was found that insulating (walls and roof) the best case of the house with 50 mm of extruded polystyrene causes a significant 42% reduction of the annual electrical energy consumption when compared to the base case without insulation. The best case has 153 kWh/m2 of total annual energy consumption and 109 kWh/m2 of it is from the cooling load. On the other hand, Research by Melo et al., (2015) examined energy performance in commercial buildings, in accordance with the thermal insulation material employed in building envelopes, in three cities in Brazil. The research revealed that the potential of the application of insulating material to building surfaces to increase annual cooling loads depended upon prevailing weather conditions. Thus, isolated surfaces impeded the dissemination of interior gains to the exterior, leading to an increased need for air conditioning. However, this study is for commercial buildings where internal gains are high due to the equipment, lighting and people.

A building envelope's thermal insulation thickness and placement are the most critical elements taken into account in this regard. When it comes to insulation location, Alshaikh & Roaf (2016) state that the mass should be insulated externally for best performance, but this is not practised in Saudi Arabia. In line with this, Ozel (2014) argues that ideal thermal performance is achieved when insulation is exterior to a wall, according to their analysis of insulation location impact and thickness. Their study examined a building wall's heat transfer properties and optimization of insulation thickness, in steady periodic conditions, employing climatic data from Elazığ in Turkey. The findings highlighted the fact that minimum temperature fluctuations at the inner surface of a wall occur in instances where insulation is on the exterior of walls. However, Al-Sanea and Zesan (2001) investigated the way insulation location affected a building's wall with respect to heat transfer characteristics. On average, heat transmission of air-conditioning operation in walls with inside insulation was roughly one-third of that with outside insulation. Thus, it is suggested that spaces requiring air-conditioning systems (used intermittently) should have inside insulation. However, Al-Sanea and Zedan (2011) researched optimum thickness and placement of a thermal insulation layer (s) under steady periodic conditions using climatic data from Riyadh. In their study, a wall with three identical layers of insulation on the outside, middle and inside had the best performance, and performed better than one layer of inside insulation. The precise thickness required for wall and roof insulations in order to lessen heat transfer is determined by building orientation and type, the efficiency of air conditioning and many others but in particular is the climatic conditions of the building (Melo et al., 2015). Al-Sanea and Zedan (2011) examined the ideal thickness and position of the thermal insulation layer (s), with steady periodic conditions using climatic data from Riyadh.

It was found that ideal total insulation thickness was 7.8 cm. Also, Ozel (2014) examined the impact of insulation positioning and thickness on heat transfer in building walls, and optimization of insulation thickness under steady periodic conditions using climatic data from Elazığ in Turkey. They concluded that ideal insulation thickness was 8.2 cm. Heat transmission load is lower without a limit when insulation thickness is greater, but the rate of this decrease drops rapidly as the thickness increases. It is suggested that the designer chooses an insulation material which has the smallest potential thermal conductivity with the greatest thickness that is within the owner's budget. On the other hand, insulation costs rise according to its thickness, and there is a level that all insulation materials reach where the additional cost of the material is not countered by reduced energy consumption.

The work of Yeshwanth & Siddhartha (2015) and Shafigh et al., (2018) agree that thermal mass is a structure's capacity to maintain and absorb heat for an extended timeframe, before releasing it, according to the nature of the material used in its construction. The distinct feature of thermal mass buildings is their gradual energy absorption and ability to maintain and store this energy for long periods of time, meaning that the structure does not require as much cooling or heating, and has more consistent indoor temperatures. Thermal mass efficiency is considered adequate when diurnal variation of ambient temperatures is more than 10K. Using the location of the case study houses, weather conditions varied more than 10k in their monthly mean maximum and minimum temperature, across the year. In cases where there are significant diurnal temperature changes, the excess heat can be stored through heat input control and timing systems, before releasing it when necessary. Szokolay (2014) echoed this sentiment, stating that mass effect is a critical passive control approach for hot and dry climates experiencing substantial diurnal temperature differences. This allows indoor conditions to remain consistently comfortable in the day when temperatures are potentially too high for occupants, with no requirement for mechanical cooling systems.

Weather conditions in Saudi Arabia show monthly mean temperatures which exceed the recognized thermal comfort levels. Monthly mean outdoor temperatures in Makkah, Jeddah, Riyadh and Taif are more than 25 °C for 11, 10, 7 and 5 months of the year respectively, in excess of the agreed thermostat setting for air conditioning as recommended by the Saudi code for residential buildings. Thermal mass is not suggested for all building fabrics in the current study, as the new Saudi building code standards recommend the use of low U-value external building fabrics. This means that resistive thermal insulation is a more suitable choice in place of capacitive insulation. Additionally, thermal mass affects the area and speciousness of rooms and also because residential buildings in Saudi Arabia are air conditioned most of the time.

4.2.3. Window system

Some consider the window to be the house envelope's weakest part, and is affected by many variables including the glazing, frame material (e.g. metal, wood), thickness of the material, and exposure. Szokolay (2014) states that a closed double glazing component, with a coating on the interior, could help limit thermal transfer to a large degree, and filling it with low-pressure inert gases including krypton and argon could bring about lower conductive transfer.

Numerous studies have attempted to find the ideal glazing type. Alaidroos and Krarti (2015) found that the most suitable glazing type for lowering energy usage in hot climates is argon-filled double-pane and colored low-glazing made up of low Solar Heat Gain Coefficient (SHGC) and U-values. It was shown that low SHGC glazing could substantially limit radiant heat increases and is considered essential in hot areas of the world. On the other hand, the cooling load becomes less through smaller U-values, as a result of their benefit to heat transfer through windows. In Saudi Arabia, the most extreme solar radiation is experienced on the east and west façades but in winter, this occurs on the south walls. Therefore, windows should ideally be oriented to the north and the south.

4.2.4. Shading devices

In order to avoid solar input, shading design is undertaken, which is geometry-based. Compared to internal devices, the external shading device is considered to be a more effective option, due to the fact that the internal device takes in solar heat and dissipates it to the interior (Kim et al., 2012). There are three categories of devices, which are vertical, horizontal, and egg-crate (Szokolay, 2014). Firstly, vertical devices have a horizontal shadow angle (HAS) and are most effective when the window and sun are unidirectional. Secondly, horizontal shading has vertical shadow angles (VSA) and performs at its best when the shaded window is facing a southerly direction. Lastly, egg-crate devices have features from the other two categories, as they are unable to be specific through one particular angle.

Passive shading systems reduce a building's heat gain , thereby diminishing the need for cooling systems (Pacheco et al., 2012). A suitable external shading approach to lowering solar heat gains provides substantial energy saving capabilities (Friess et al., 2012). Shading systems are crucial for the prevention of solar access to a building, and should be positioned externally to mitigate heat within that space (Brotas & Nicol, 2016). Neighbouring buildings can produce additional shade. Nikoofard et al., (2011) found that nearby structures, or even tree foliage can impact annual heating and cooling energy needs in Canadian houses by as much as 10% and 90%, respectively.

On the other hand, as the glazing size of low-rise buildings is smaller than in their high-rise equivalents, the window-to-wall ratio must be maintained at its lowest possible value. Shading devices have greater efficiency with larger windows compared to smaller windows (Alaidroos& Krarti, 2015).

4.2.5. Natural ventilation

Employing natural ventilation in structures allows for the less frequent use of mechanical cooling systems (Stavroula et al., 2016). During the natural ventilation system's planning, the direction and velocity of the wind must be taken into account, as well as temperature differences (Taleb, 2014). Szokolay (2014) showed that the three key aims of natural ventilation are to boost fresh air supply, extract internal heat when the temperature inside (T_i) is higher than the temperature outside (T_o), and, lastly, to increase the dissipation of skin heat.

Building design is critical when encouraging natural (wind-driven) ventilation (Stavroula et al., 2016; Brotas & Nicol, 2016; Szokolay, 2014). Specifically, building design is able to bring about single-sided or cross ventilation, due to varying wind pressures being caused through the wind, or buoyancy-driven ventilation as a result of temperature differences. This, in turn, produces a vertical flow of air through atriums, chimney or stairwells (Stavroula et al., 2016). On the other hand, Brotas & Nicol

(2016) put forward the notion that wind-driven ventilation in Saudi Arabia would not be effective, since the outdoor dry bulb temperatures are in excess of the thermal comfort ranges, especially in the summer.

On the other hand, night-time ventilation could bear significant potential for energy savings (Artmann, Manz, & Heiselberg, 2008). Nighttime thermal comfort is maintained through night cooling with a thermally medium to heavy weight building and without mechanical cooling, according to the work of Brotas and Nicol (2016). There has been growing interest in night ventilation as a design strategy. Night ventilation comprises a passive or semi-passive approach to cooling that harnesses the external temperature swing and thermal mas of the building to pre-cool the building via increased external night-time airflow. At night, when the outdoor air temperature is lower than the indoor temperature, the increased airflow cools down the mass, letting it to release the heat stored during the previous day. During the next day, the cooler mass operates as a heat sink to absorb and store the heat in the space from solar and internal loads (Landsman et al., 2018; Artmann et al., 2008). However, the potential of this night ventilation approach is dependent upon air flow rates, the thermal capacity of the building, and the right mixture of the thermal mass and the air flow (Santamouris et al., 2010).

Due to average daily temperatures surpassing standard comfort limits in some regions, night ventilation can assist with heat dissipation. On the other hand, this requires nighttime temperature variance of roughly 10°C, as denoted by Szokolay (2014) and Givoni (1994). Stavroula et al. (2016) state that night ventilation is able to assist in lowering indoor diurnal air temperature by 1.5-2.0°C, regardless of air temperature fluctuations (even up to 8.4°C difference). From this perspective, Stavroula et al put forward the notion that night ventilation is preferable to day-time ventilation due to the fact that opening windows and atriums at night substantially boosts air change rate and indoor diurnal temperature variance. In turn, this brings about higher convective heat loss from mass elements, adding to heat dissipation. Night ventilation can successfully reduce interior temperatures and extract heat in medium mass buildings in hot humid climates. However, this strategy alone was not enough to satisfy human comfort needs (Landsman et al., 2018).

The performance of night ventilation systems can be tested using simulations controlling different parameters. Research by Artmann et al., (2008) concluded that the most substantial impacting night ventilation method are climatic conditions and the air flow. Research by Taleb (2015) revealed that active cooling systems combined with natural passive ventilation delivered the most desirable results wherein temperatures were reduced, cooling loads were managed, and energy costs for residents were alleviated. Santamouris et al., (2010) examined energy data pertaining to 214 air-conditioned residential units in which night ventilation systems were used. The buildings in the study encompassed a range of cooling requirements and night air flow rates, with the study data being homogenized for comparable climatic and operational conditions. The results indicated that night ventilation had the potential to reduce cooling loads by 40kWh/m2/y, although the average reduction was 12kWh/m2/y.

4.3. Research on energy efficiency measures

In Saudi, enormous benefits can be delivered by energy efficiency measures. Yearly energy expenditure could be decreased substantially, assuming electricity production costs remain unchanged, with the majority of the savings made by residential buildings (Nachet & Aoun, 2015).

Aldossary, Rezgui, & Kwan (2017) suggested 3 low-carbon prototype houses, which involved Saudi Arabia's current architectural design, renewable energy strategies, and fabric. Prior to this, these researchers had initially evaluated the energy consumption definition standard related to Saudi Arabian residences. Aldossary and colleagues felt that their suggested prototypes could lower energy consumption by 71.6%. Also, it was seen that the energy usage of the suggested prototypes ranged from 77 kWh/m2 to 98 kWh/m2. They put forward the idea that ideal yearly energy usage for their prototypes could reach 77 kWh/m2/year, while different papers such as Aboul-Naga, Al-Sallal, & Diasty (2000) indicated that an average residential house's energy usage would potentially fall to 60kWh/m2/ year. This denotes that the aforementioned prototypes were unable to reach ideal energy usage levels.

However, prototype house number 1, which had the most efficient energy consumption per floor area of 77 kWh/m2/year, used the most energy of all three prototypes, probably because the house prototype is larger than the other two houses, and this way it was able to portray a typical Saudi house more realistically than its counterparts. Conversely, prototype house no. 2 was not as large as the traditional Saudi house. Lastly, prototype 3 did not take into account the socio-cultural aspects of Saudi housing design, as it is instead showed western culture characteristics. While the three prototypes showed slightly greater energy uses than the ideal values for residential buildings, they had shown a substantial positive development over those of the authors' previous study (Aldossary, Rezgui, & Kwan, 2014a). In that study, energy consumption for a typical house in Riyadh was roughly 127.6 kWh/m2/year.

Aldossary, Rezgui, & Kwan (2014a) take a multiple case study approach to investigate trends in energy usage across a number of traditional buildings in Riyadh (hot and dry climate location). Aldossary and colleagues pinpointed six dwellings, including three typical flats and three typical houses, and then examined the average domestic energy consumption of each, using monthly utility bills. Following this, IES-VE simulation software was used to imitate user behavior to highlight the housing design's weak points and define regionally replicable energy retrofitting choices. The study's findings indicated that efficient glazing, utilization of on-site renewable energy, shading devices and various retrofitting approaches brought about a 15-34% energy reduction. Along the same lines, these authors used this methodological approach again in a different study, this time examining the context of Jeddah. They found that using retrofitting solutions helped lower energy usage by 21-37% (Aldossary et al., 2014b). Table 4.1 illustrates examples of energy efficient measures used in other studies.

Table 4.1. Examples of energy efficient measures used in other studies

Author(s)	Description	Measures	Result
(Aldossary et al., 2017)	Low rise residential buildings in Riyadh using IES-VE	Architectural design, fabric and on-site renewable energy strategies	Energy consumption fell by 40%
(Aboul-Naga et al., 2000)	Typical low rise detached houses in Al-Ain in UAE using ENERFACE and electricity bill	Orientation and window placement	Energy consumption was 55% lower when windows were not exposed to two orientations
(Aldossary et al., 2014a)	Three houses and three flats in Riyadh using IES-VE, electricity bills and user behaviour	Shading devices, onsite renewable energy sources and more efficient glazing	Energy use was 34% lower
(Aldossary et al., 2014b)	Three houses and three flats in Jeddah using IES-VE, electricity bills and user behaviour	Shading devices, onsite renewable energy sources and more efficient glazing	Energy consumption was lowered by 37%
(Akbari, Morsy, & Al-Baharna, 1996)	Nine residential buildings in Bahrain using DOE- 2 computer program	Energy efficient air conditioners, insulating houses, improved infiltration, increasing thermostat settings for space cooling, efficient refrigerators and freezers, efficient water heaters, efficient clothes washers, and compact fluorescent lights	Residential electricity consumption was reduced by 32%
Morsy and Al-Baharna (1995) cited Akbari, Morsy, & Al-Baharna, 1996)	Nine air-conditioned residential buildings in Bahrain using DOE- 2 computer program	Improving building insulation, reducing infiltration rate, using double glazed reflective windows, and increasing thermostat cooling	Air condition electricity consumption fell by 67%

		setpoint from 22.2"C to 25.6"C	
(Kharseh et al., 2015)	Typical house in Qatar using Hourly analysis program (HAP).	Changes to U-value of the external walls, lighting efficacy and higher indoor set point temperature.	Cooling needs were reduced by 46%
(Kharseh & Al-Khawaja, 2016)	Typical house in Qatar using Hourly analysis program (HAP)	Changes to U-value of the external walls, higher indoor set-temperature, lighting efficacy, external walls colour, and window quality	Cooling needs were 53% lower.
(Taleb, 2014)	Typical house in Dubai using IES software	Using natural ventilation and reducing heat gain together with the use of efficient shading devices and double glazing	Annual energy use fell by 23.6%
(Alaidroos & Krarti, 2015)	Typical house in Riyadh, Jeddah, Dhahran, Tabuk, Abha using Energy Plus	Wall and roof insulation, window area and type, shading, and thermal mass	Energy reductions of 47.3%, 41.5%, 43.19%, 41.1% and 26% were seen in the five cities respectively
(Taleb & Sharples, 2011)	A typical house in Jeddah using IES software	Changes to thermal insulation of the external walls and roofs, more efficient glazing, using external shading devices and fitting energy-efficient fluorescent lighting	Energy consumption fell by roughly 32.4%.
(Al-Ragom, 2003)	Typical two storeys house in Kuwait using DOE-2.1E building simulation program	Roof & walls insulation, upgrade the glazing type and reducing window area	Energy usage was lowered by 46%

(P. H. Saleh, 2015)	Two flats in one case study building in Lebanon using TAS	Increase external walls, external shading the walls and increase the thermostat set point of the A/C from 24°C to 26°C.	Cooling needs were lowered by 48%
(Heravi & Qaemi, 2014)	Typical official building in Tehran using Design Builder	Roof thermal insulation, Materials Thermal Specifications, walls thermal insulation, external walls thickness, story height and window type	Reductions of 13.80%, 13.03%, 12.16%, 11.60%, 11.38% and 9.97% were seen in energy usage
(Hatamipour, Mahiyar, & Taheri, 2007)	Field study and computer program (BLC) in Iran (nonresidential)	Double glazed windows, change colour of exterior walls and roofs, external screen shading and wall insulation	Cooling needs were 40% less

Chapter 5

Research methodology

5. Research methodology

5.1. Introduction and research flow

This section sets out the aim of the fieldwork undertaken in four climatic zones, which is to generate useful data on the evaluation of indoor thermal performance and reduce energy consumption in residential buildings. The methodologies used included field monitoring and computer modelling. The choice of location is explained, and the case study is presented. Lastly, the equipment and a computer model used to examine the houses in question is described in-depth (See figure 5.1).

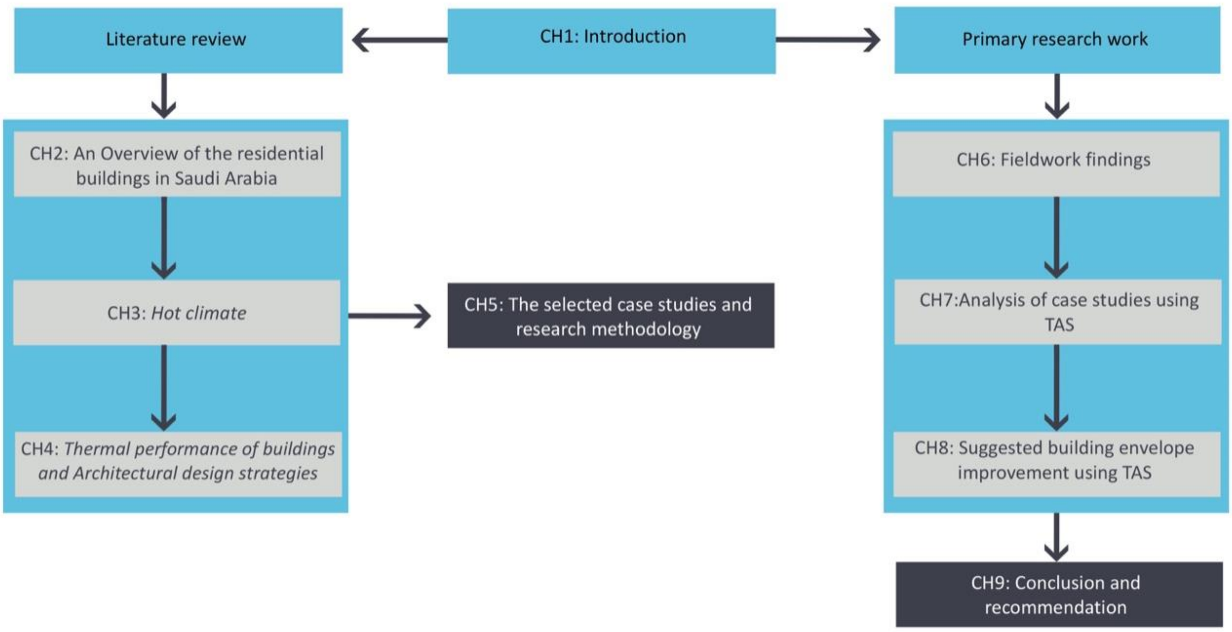

Figure 5.1. Outline of the Research Structure

5.2. Research design methodology

To address the principal research aim in this study, the research is divided into six stages, each of which necessitates a slightly different strategy.

First, the determinants affecting energy consumption must be identified in the building sector in Saudi Arabia and also case studies are chosen. Hence, a literature is required in conjunction with site visits. Secondly, the physical factors impacting energy consumption in residential buildings must be explored, using case studies focusing on different climatic zones within Saudi Arabia. Hence, a Meteonorm software was required to study the climatic conditions of several Saudi cities. This also required a site visit in order to inspect the architectural plans and materials linked to the buildings chosen as case studies. Thirdly, the most effective design techniques employed in relation to Saudi Arabia's climate must be evaluated via a literature review and the subsequent testing of multiple instruments. Fourth, it is essential to monitor the interior environmental conditions in the case studies buildings. This goal can be realised through the measuring of selected thermal environmental variables during two major fieldworks using instruments and computer modelling for both summer and winter periods. Fifth, the physical measurements and computer-modelling results must be verified using the calculated root mean square error (RMSE) and normalized mean bias error (NMBE) methods, wherein the results should lie between ±30% and ±10%, in respect of a model with hourly figures as per ASHRAE guidelines (ASHRAE, 2014). The sixth stage requires the identification of approaches to improve buildings' fabrics for the purposes of energy efficient residential buildings. The current study employs Thermal Analysis Software (TAS) to identify the most appropriate residential building materials for hot climates.

5.3. Selection of the case studies

Saudi Arabia has been selected for a number of reasons. Firstly, the few papers published regarding indoor thermal performance of residential buildings was a key motivation for the current study. Indeed, there is a general lack of related studies across any Gulf countries with a similar climate, not only Saudi Arabia. In addition, Saudi Arabia was the source of the research's funding, with the intention of the aforementioned problems being overcome. This study uses Makkah, Jeddah, Taif, and Riyadh as its four different climatic zones (Figure 5.2). The four cities vary in their climate to an extent, with extremely hot summers and warm winters in Makkah, hot summers and warm winters in Jeddah, extremely hot summers and cold winters in Riyadh, and hot summers and cold winters in Taif. The specific locations were selected because of their climate variation, and their status as four of the biggest cities in Saudi Arabia across the Makkah – Riyadh regions, where half the population of Saudi Arabia resides (General authority for statistics, 2010).

A number of research papers have investigated indoor thermal performance to discover solutions which can reduce cooling load in Saudi residential buildings, with surveys and computer models often being used. On the other hand, this research is innovative due to its use of physical measurements in low-rise residential buildings, to provide an accurate portrayal of indoor thermal performance and the impact of building fabrics with regards to cooling load. A computer model is used to process these measurements. The generated findings can be used throughout Saudi Arabian cities, as well as any other cities worldwide which have similar climates.

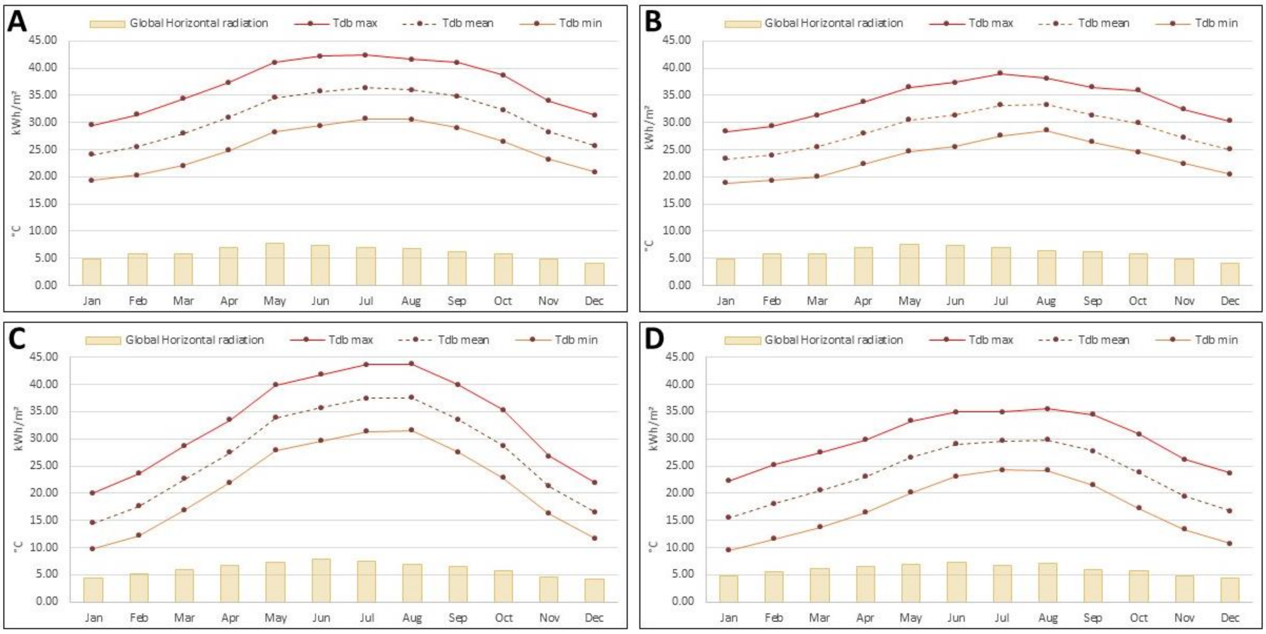

Figure 5.2. Monthly average climate condition of the four chosen cities: A. Makkah, B. Jeddah, C. Riyadh, and D. Taif.

The houses chosen were the common type of residential houses in Saudi Arabia (villas), and their indoor thermal performance was examined with field monitoring using instruments and thermal analysis software. Following this, the impact of different improvements to lower the cooling requirements of these buildings was evaluated.

There were certain differences in the four villas examined, namely the number of floors and types of dwelling. As a result, a contrast can be established amongst all the residential buildings with regards to varying indoor thermal performance. The two buildings in Makkah and Jeddah are three floor buildings, while the building in Riyadh is two floors building and the Taif house is a one-floor structure. The Makkah, Jeddah and Taif buildings are detached, with the Riyadh home being semi-detached. In each house, two specific rooms are monitored. Figures 5.3, 5.4, 5.5 and 5.6, display illustrated drawings for the chosen rooms for each house.

Figure 5.3. Illustrated drawings for chosen rooms for the house in Makkah

Figure 5.4. Illustrated drawings for chosen rooms for the house in Jeddah

Figure 5.5. Illustrated drawings for chosen rooms for the house in Riyadh

Figure 5.6. Illustrated drawings for chosen rooms for the house in Taif

5.4. Time of conducting the fieldwork and preparation

This study attempted to produce useful research findings across winter and summer in the specified areas, which could provide a clear picture of the extreme weather of Saudi Arabia. Firstly, the literature on thermal performance and energy use in residential buildings was reviewed, exposing the existing research gap. Next, initial fieldwork was undertaken relating to the four case studies used, completed three months after the researcher's enrolment into a PhD course. Following this, the Ministry of Municipal and Rural Affairs was contacted to obtain the architectural plans and information on the building materials used in the houses under investigation. Photos of the structures were also obtained, and short interviews were held, to deepen existing knowledge regarding indoor thermal performance and the energy consumed during cooling processes. Once the 1st year interim assessment is completed, the 1st fieldwork can start through an identification and gathering of the necessary tools, with a visit to Saudi Arabia thereafter to complete a pilot study, in October 2017. The pilot study would then be analysed and conducted a second time, in order to improve on the mistakes found in the initial pilot study. Notably, Alaboud & Gadi (2019) include the published pilot study. Upon completion of these steps, all remaining instruments were purchased by the end of 2017, with an examination of the case studies afterwards. The occupants of the houses in question were contacted, in order to organise the first major fieldwork in February 2018. This initial fieldwork was conducted between 20th-28th February 2018, with the second fieldwork between 30th August - 9th September 2018. An analysis of the gathered data followed, with calibration and improvement achieved through TAS. Finally, a conference paper was produced in August 2019 as part of the of the 18th International Conference on Sustainable Energy Technologies (SET 2019) in Kuala Lumpur, Malaysia (Alaboud & Gadi, 2020b).

Permission to complete the required fieldwork was gained from every house involved, and data collection was completed during the monitoring phase, prior to this for the architectural drawings. It should be noted that the researcher received a warm welcome and plenty of cooperation from the house owners, who happily gave permission for their houses to be part of this study in the summer and winter of 2018.

5.5. Monitoring building performance

A number of different appraisal methods exist for assessing the thermal performance of buildings. Olivia & Christopher (2015) describe several different processes involved in monitoring building performance. An example of this is the in-use monitoring (internal) method, used during a building's operation to pinpoint potential areas where performance could be boosted. For practical settings, this is the most widely used monitoring approach, as it offers swift advantages for thermal performance. To raise the performance of a building, the circumstances must be examined, and its operation must be addressed, the end goal and number of resources at hand will dictate the duration of a building's appraisal be it short or long term. In the case of seasonal monitoring, either short or long-term contexts are applicable, as short-term procedures can be conducted in every season, while long-term monitoring of data can be split across the seasons. Also, a number of different methods exist for data gathering during the monitoring of a building's performance. By employing the appropriate methods, a building can be most effectively evaluated (Guerra-Santin & Tweed, 2015). For the current study, short-term measurements are used for building appraisal over the course of a specific timeframe.

Modelling and measuring are two approaches used for examining the thermal performance of a structure. Dynamic thermal modelling research is beneficial, but they are conducted using certain preconceptions regarding the full extent of the complexity of real buildings, and involve simplifications. On the other hand, direct observations can be achieved when estimating the indoor temperature of a building (Jones et al., 2016). Though the shortcomings of modelling can be overcome by calculating indoor temperatures, this is costly and time consuming to complete, and therefore is rarely used (Beizaee et al., 2013). When calculating human health risk and thermal comfort, indoor temperatures must be estimated. Also, this is a necessary step due to its relation to energy consumption within the created environment (Asumadu-Sakyi et al., 2019; Magalhães et al., 2016).

The work of Magalhães et al. (2016) examined indoor temperature properties of residential buildings in northern Portugal. They conducted monitoring to evaluate the indoor temperatures of 141 households, at 30 minute intervals, throughout winter 2013-2014, across four unique geographical locations and found that building properties had a strong impact on indoor room temperatures. Lee & Lee (2015) studied residential thermal conditions for two types of residences across 12 months. Their setting was Seoul, Korea, which has distinctive seasonal differences in its weather. Indoor temperature was evaluated over a 12-month period, together with three additional variables, to establish indoor thermal conditions in 14 residences. Their findings were that indoor thermal conditions could be beneficial when it comes to comprehending personal thermal exposure. The study by Wright et al., (2005) examined internal temperatures in the UK, using nine dwellings throughout the August 2003 heat wave. Their calculations provided beneficial data regarding internal conditions during a heat wave, for a number of different types of dwelling and locations. Martinez-Molina et al., (2018) investigated thermal environment problems within historic museum buildings. In their study, a Post-Occupancy Evaluation methodology was used, which included both quantitative and qualitative methods to collect data, with indoor microclimate parameter measurement and visitor questionnaires respectively. In their study, a case study building was examined across a 12-month timeframe. The thermal properties of the building's Indoor Environmental Quality (IEQ) were evaluated in the quantitative methodology, with a detailed environmental monitoring campaign conducted using indoor air temperature and relative humidity, together with external environmental characteristics. In the work of Wang et al., (2018), indoor environment quality was investigated using a passive residential building in order to ascertain whether the German passive house concept could be used successfully in the coldest areas of China. A post-occupancy appraisal of indoor environmental quality was used to establish the physical properties of the indoor thermal environment and its air quality, alongside a subjective occupant survey. A number of thermal environmental parameters were involved, which were indoor/outdoor air temperature, indoor/outdoor relative humidity, global temperature, air velocity and inner envelope surface temperatures of external wall.

5.6. Monitoring equipment

To choose the most appropriate tools from the wide range of options available, specific criteria were applied to make the best choice. These criteria include resolution, price and accessories at hand. A number of sites linked to different firms were examined, and a number of these were based on the UK or overseas. It was the intention to use those based in the UK market, in order to not incur any customs, or extensive delivery times. Regardless, two of the products were from overseas, due to their lack of availability in the UK: the anemometer and Pyranometer measuring tools. The specific tools involved various elements, including reputation, cost, availability, features, accuracy and provided accessories (See figure 5.7 and table 5.1 for the instruments used and their data).

Figure 5.7. Instruments used.

Table 5.1: Instruments data

Name	Type	Parameter	Range	Accuracy	Note
Temperature Data logger	Elitech URC5	Indoor air temperature	-30 °C to +70°C	±0.5 °C(-20°C~+40°C); others, +1 ℃	Continuous test
Infrared Thermometer Temperature	ANGGO	Surface temperature	-50°C to +420°C	± 1.5°C	Site test
Globe Thermometer	Extech HT30	Indoor air temperature and (globe temperature)	0 to 50ºC and (0 to 80°C)	±1.0°C and (±2°C)	Site test
Hot Wire Anemometer	Tecpel AVM 714	Air velocity	0.2 ~20.0 m/s	± 3% + 1 digit	Site test
Pyranometer	MP-100 Apogee	Solar radiation	Less than 1 % up to 1750 W m2	directional errors less than ± 5 % at a solar zenith angle of 75	Site test

5.6.1. Temperature Data logger

Using the temperature data logger seen in figure 5.8, temperature values can be collected efficiently and without difficulty, across large timeframes. The tool used provides a large array of potential temperatures, from -30˚C to +70˚C with ± 0.5°C instrumental error. Its memory can store up to 3200 readings held for six months, with the record interval set at 15 minutes. The current study used the 15 minute recording interval, so the measurements were taken four times every hour, and the analysis used the average of each hour. Data management software is included in the data logger, data is easily downloaded through a USB port. The software offers data analysis through tables and graphs which can be exported as images. The data can be searched, stored, printed and exported in Word/Excel/TXT/PDF formats. Furthermore, the software offers the ability to adjust 'the record' interval as the user wishes, from 10 seconds to 24 hours. For the current fieldwork, four of these tools were used to monitor the buildings simultaneously, with two data loggers in each building. This allowed freedom of use for the required 48 hours of monitoring (Elitech, 2015). For more information see appendix A.

Figure 5.8. Elitech URC5 Temperature and Data logger

5.6.2. Infrared Thermometer Temperature

The small infrared thermometer shown in Figure 5.9 uses a dual laser, and offers rapid and reliable non-contact measurements across a wide range of surface temperatures. This is beneficial when it comes to surfaces that cannot be read, and measures temperatures between -50˚C to +420˚C, with ± 1.5°C instrumental error. Furthermore, measurements can be taken in ˚C or ˚F. Measurements are quick, and are available to the user within 500 milliseconds (Anggo, 2020). For more information see appendix B.

Figure 5.9. Anggo infrared Thermometer Temperature

5.6.3. Globe Thermometer

This tool is used to measure globe temperature (radiant temperature) and it monitors the impact of direct solar radiation on exposed surfaces (Figure 5.10). Measurements can be made in ˚C or ˚F, and can be used for indoor and outdoor conditions. It offers an In/Out function for use in either environment, which means the tester can be used with, or without, direct sun exposure. Temperatures measured range from 0˚C to +80˚C, with ± 2°C instrumental error (Extech, 2019). For more information see appendix C.

Figure 5.10. Extech HT30 Heat Stress WBGT Meter

5.6.4. Hot Wire Anemometer

With the hot wire anemometer, used for extremely low air velocity measurements, the RS 232 PC serial interface is used, and can measure air flow in m/s, km/h, ft/min, knots, and mile/h (Figure 5.11). The portable anemometer offers reliable readings quickly, while being especially convenient due to its separate remote probe. Both hot wire and standard thermistors are provided, offering accurate readings even with low air velocity. This tool has a large LCD and dual function meter display, allowing both temperature and velocity to be read simultaneously. Additional functions include the ability to record max and min readings, a recall function, auto power off to save battery life, and optional PC software (TECPEL, 2020). For more information see appendix D.

Figure 5.11. Tecpel AVM 714 Hot Wire Anemometer

5.6.5. Pyranometer

With both a log and sample mode, this tool can record an integrated daily total (Figure 5.12). Sample mode allows a maximum of 99 manual measurements, while log mode switches the meter on and off to measure values every half a minute. The meter will create an average of sixty 30 second measurements every half an hour and save these averaged values to its memory. In turn, the meter can store a maximum of 99 such values, and once it exceeds this number, the oldest measurements are replaced with the new inputs. For this study, an integrated daily total will be recorded from the 48 averaged measurements, which constitutes a 24-hour timeframe. The sample and log measurements taken are shown through its LCD display, or through a computer once the data is downloaded. Notably, the integrated daily total is exclusively readable on a computer (Apogee, 2020). For more information see appendix E.

Figure 5.12. MP-100: Pyranometer Integral Sensor with Handheld Meter

5.7. Energy modelling simulation

A structure's thermal performance is affected by a few elements, including design parameters, material characteristics, weather and inside activity. All these variables can be examined using a variety of analysis tools. Thermal modelling programs can be found in the market, including simpler approaches involving steady-state calculations and more complicated offerings employing advanced calculation methods for dynamic thermal response.

After the measurements were collected, the house simulations were analysed. This was done to validate the validity of the simulation and related measurement outcomes, but also to pinpoint problems in current residential buildings. Additionally, this could boost the thermal performance of buildings, by recommending a number of energy efficiency changes.

EDSL TAS version 9.4.2 was the thermal analysis software used to model the buildings of the current study. This software was produced by Environmental Design Solutions Limited, providing thermal analysis software for buildings and can be used to simulate thermal performance. Primarily, the software offers evaluations of environmental performance and energy consumption. To simulate the thermal performance of a structure, TAS employs a fundamental approach closely tied with dynamic simulation. This way, the building's thermal state is followed across several hourly snapshots, offering the user an in-depth view of the structure's performance throughout an average 12-month period. In turn, the modelling process is clarified as the user comprehends the building model's different thermal processes. There are three modules in the TAS software: the 3D modeller, the building simulator and the results viewer. Firstly, the 3D modeller produces building models for the building simulator module, where the model can be simulated through an evaluation of the impacts of conduction, convection, advection, long-wave radiation, solar radiation, casual gains and plants with radiative and convection portions. The outcomes of this simulation are analysed through the results viewer, at which point the user-selected set of properties, using any area or surface can be shown and contrasted against results in other sections. Following this, the findings can be exported for use in third-party programmes such as Microsoft Excel, which allows for deeper user-defined analysis (EDSL TAS, 2020).

The EDSL TAS software is used to configure the thermal simulation, and allow the physical measurements of the fieldwork to be authenticated. In order for the simulated energy model to accept the calculated root mean square error (RMSE) and normalised mean bias error (NMBE), they should be within ±30% and ±10%, respectively, for a model involved with hourly figures using ASHRAE guidelines (ASHRAE, 2014). This research used hourly temperature readings, estimating RMSE as well as NMBE. The recorded data was categorised under winter or summer, and the values of the entire monitored temperature range were calculated for the monitored hours.

Numerous research papers have been published regarding measurement and simulation result calibration. In the work of Saleh (2015), thermal performance in two apartments within a single building in Lebanon was analysed, with concurrent monitoring of indoor air temperature using data loggers. The EDSL TAS software was used to configure the thermal simulation, before the author began parametric studies.

Alves et al., (2016) appraised thermal performance and comfort within residential buildings within certain climate change contexts in São Paulo. A total of three case study buildings were monitored, and then the measurements were compared with a computer simulation conducted with EDSL TAS. The intention of this monitoring was to calibrate the computational model in order to fit with the local climate conditions. In the case of the empirical environmental data, the environmental variables measured were air temperature, relative humidity, globe temperature and air velocity. In the case of the external database, the IAG-USP meteorological station was used to collect meteorological data. The air temperature, mean radiant temperature and relative humidity were used in the model calibration, then contrasted against the same period's measured data.

Additionally, an in-depth appraisal of a University of Reading library is presented in Leong and Essah (2017). In-situ measurements and building simulation modelling were the methods employed, with the former intending to gather IEQ parameter data and outdoor conditions. Temperature and relative humidity (RH) were measured internally and externally, such as air velocity and noise. Experimental results and the monitored yearly energy use were used to authenticate and configure the simulated results.

5.7.1. Criteria of energy modelling simulation tool

The wide range of energy modelling simulation tools available means that matching tool selection to the context at hand requires prior investigation. The software available includes simplified solutions, and more complicated offerings. For steady-state type calculations, simple programs are used, whereas advanced choices use 'admittance procedure', in line with the dynamic thermal response. Certain criteria have been outlined below to choose the ideal computer modelling tool.

Accuracy of tool

Accuracy is of great importance in this type of research, and the results collected in the current study would need to be in-depth and reliable. An energy modelling simulation tool was not used independently, and an additional method was used to produce similar results of a different type.

The accuracy of the tools in question was constantly evaluated, pinpointing the thermal analysis calculation method that the tool was built on, and taking into account various disadvantages. Certain software employs simple approaches, which produce unreliable results, which could then be used in other studies where accuracy was not critical. In addition, the amount of modelling detail required by the tool in its input data was an element requiring evaluation as well. Without exception, input data is required in order to generate an output. In turn, with less input, there is a smaller amount of output. On this note, input depth would dictate its accuracy, and for specific tools, their input data is either fixed or not visible by the user. In the current research, the key thermal elements of the construction materials used must be accessible to the researcher so that updates and corrections can be controlled and edited using the data input interface.

Depth of software and self-learning access

Technological tools are only as good as the data they hold. Gathering and inputting complex data into simulation programs is a time-consuming process. The learning curve for unfamiliar digital tools, especially energy simulation tools, is steep. How easily the curve is negotiated depends on the quality of the user manual, user-friendly input procedures and an easily accessed support system to solve teething problems and answer questions.

All four case studies required simulation, and it was considered that the computer programme would need to be straightforward enough to ensure ease of use for the intended purposes, while maintaining a level of detail and ease of use is extremely difficult to obtain in the context of building thermal simulation. Eventually, TAS was considered a suitable balance between data accuracy, the level of detail and the ease of use.

Required outputs

The required outputs are the most valuable element when it comes to deciding the optimal tool. Currently, a large number of tools under energy modelling simulation programs exist. The critical variable when deciding a thermal modelling tool is the ability the tool has to manage the application in question and generate the required outputs. For the current study, the selected tool needed to be able to predict internal conditions such as temperatures and heat conduction. In addition, cooling load must be calculable, and the performance of alternative constructions leading to superior indoor thermal environments and lower cooling consumption should be analyzable within.

5.8. Summary

The wide variety of tools available makes the selection of the ideal tool difficult. The choice is made from a shortlist of highly developed and widely applied reliable tools. The simulation in question will dictate the selection, and since the current study is reliant on the accuracy of results, a large amount of software could immediately be excluded. TAS was considered capable of undertaking the intended simulation with sufficient accuracy, and to be able to produce output with sufficient quality, especially when it comes to independently calculating the heat loss/gain of every part of the building. Also, TAS uses a calculation method considered to have greater accuracy than other software and the construction database provides an in-depth data. On the other hand, TAS' input processes are complicated and time consuming. Also, it does not offer a free student license choice, meaning that the researcher is obliged to buy a license on a yearly basis. Overall, TAS was considered the ideal choice for this study despite its shortcomings, due to its depth, accuracy, and its ability to simulate the thermal performance of buildings through a fundamental approach using dynamic calculation in line with the response factor method. TAS and Meteonorm licenses were purchased for the simulation, where the latter allows for historical weather data to be collected from the four cities involved in the study.

Chapter 6

Environmental internal condition (Monitored)

6. Environmental internal condition (Monitored)

6.1. Introduction

This chapter provides a description of each buildings selected. It will highlight several variables including indoor and outdoor dry bulb temperature, floor, roof and external walls surface inner temperatures, outdoor solar heat gain and air velocity. All these variables have been monitored using equipment introduced in the previous chapter. Air temperature in particular is considered as the most significant ambient factor affecting thermal comfort levels, leading to the use of air conditioning to control indoor climate conditions. This part will take into consideration the internal environmental condition as it is and is illustrated with the results obtained from the measurement during the field study.

Employing tools to calculate environmental properties is an approach used throughout the current study. The site monitoring data was analysed to rate current building design strategies to establish indoor thermal performance. Most of the data collected was made up of indoor air temperature values, through data loggers recording every 15 minutes, across a two-day period (minimum), in all buildings, for both winter and summer. The loggers were positioned at a height of 1m to 2m from the floor surface level and in locations away from direct solar radiation and other heat sources. The aim of this analysis was to ascertain how indoor air temperature relates to building fabric properties. The intention was to investigate the thermal performance of the four houses, across the different climate zones described within Saudi Arabia, and so two rooms in each residential building were investigated during winter and summer seasons in 2018. The monitoring period of IAT was 74, 57, 50 and 51 consecutive hours respectively for the houses in Makkah, Jeddah, Riyadh and Taif in winter 2018. For the summer period, the monitoring period of IAT was 71, 49, 46 and 97 consecutive hours respectively for the houses in Makkah, Jeddah, Riyadh and Taif. For every house, two loggers were placed in the two rooms, for concurrent data collection, to allow for simultaneous recording of IAT in the four case study homes. However, only four data loggers were used in total, and as the buildings were in different cities, it was not possible to collect all measurements simultaneously. As a result, it was decided that data loggers would complete a minimum of 48 hours of monitoring in each season. This would allow for prevailing patterns to emerge in the absence of an AC system for the two rooms in each building. For the Riyadh building, only 46 hours of data was collected during the summer season. Also, the A/C was used during various periods in the Riyadh building, across both seasons.

When this monitoring was taking place, specific environmental variables were being recorded on-site. Spot measurements of indoor air temperature (IAT), outdoor air temperature (OAT), globe temperature (TG), surface temperature of internal floor (FIST), surface temperature of internal roof (RIST) and internal surface temperature of external walls (ISTEW), outdoor solar radiation and outdoor air velocity were taken at particular areas relative to the case study buildings. Certain rooms were selected in each building for coherence, for one day in winter and one day summer, with three main intervals for measurement: 9:00 am, 12:00 pm and 3:00 pm. It was intended that by using these specific times, minimum and maximum temperatures could be recorded, thus denoting the extremes of the outdoor conditions and how the internal conditions were affected. Building envelope properties were analysed through this spot data, in relation to the thermal performance of the buildings. Finally, measuring the surface temperature of internal floor (FIST) and surface temperature of internal roof (RIST) are two of the methods which can predict the amount of conducted heat through the ground floor and roof respectively. 12 spots were measured then an average taken for each surface for three chosen times for the chosen rooms in the case studies buildings.

6.2. Microclimate of the house in Makkah

6.2.1. Indoor air temperature (continuous test)

All the rooms monitored are free running during the monitoring allowing time for the surfaces to act freely and naturally, and the two rooms have no internal heat gain. The ground floor guest room (GR) has a floor area of 23.2 m2, while the first-floor bedroom (BR) is slightly larger with a floor area of 26.8 m2. The bedroom is directly above the guest room and both have double external walls orientated south and west. The bedroom is exposed to the outdoor from the roof. There are two single glazed windows in each room with external shutters which blocked solar heat gain during the entire time of monitoring. Using world weather online, external temperature data were obtained from the nearest weather station, a small airport east of Makkah (OEMK) (world weather online, 2020). Two locations in the building were identified for the positioning of temperature data loggers to enable the data collection process (Figure 6.2).

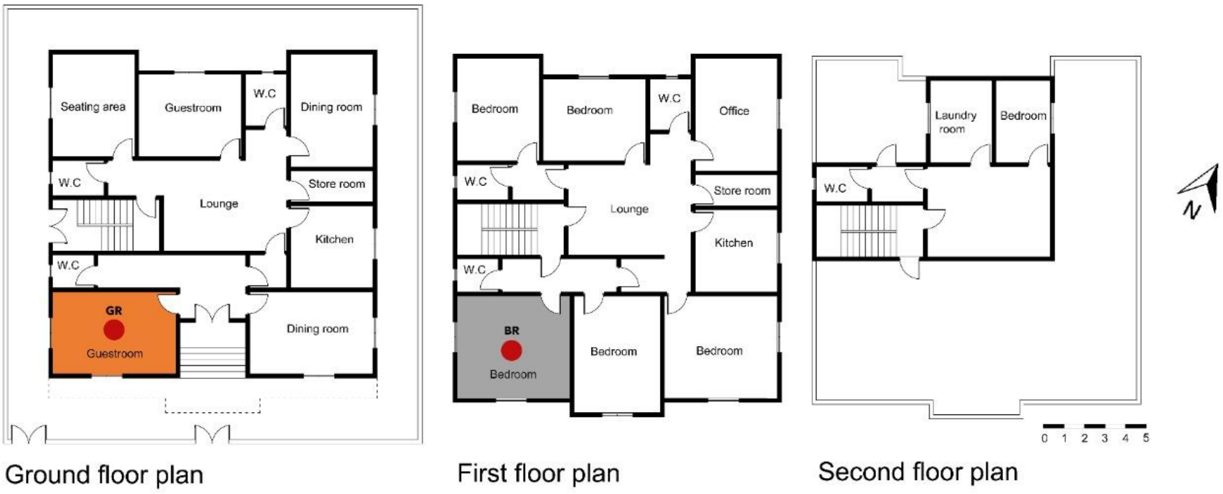

Figure 6.2. Temperature data loggers Location set up of the house in Makkah

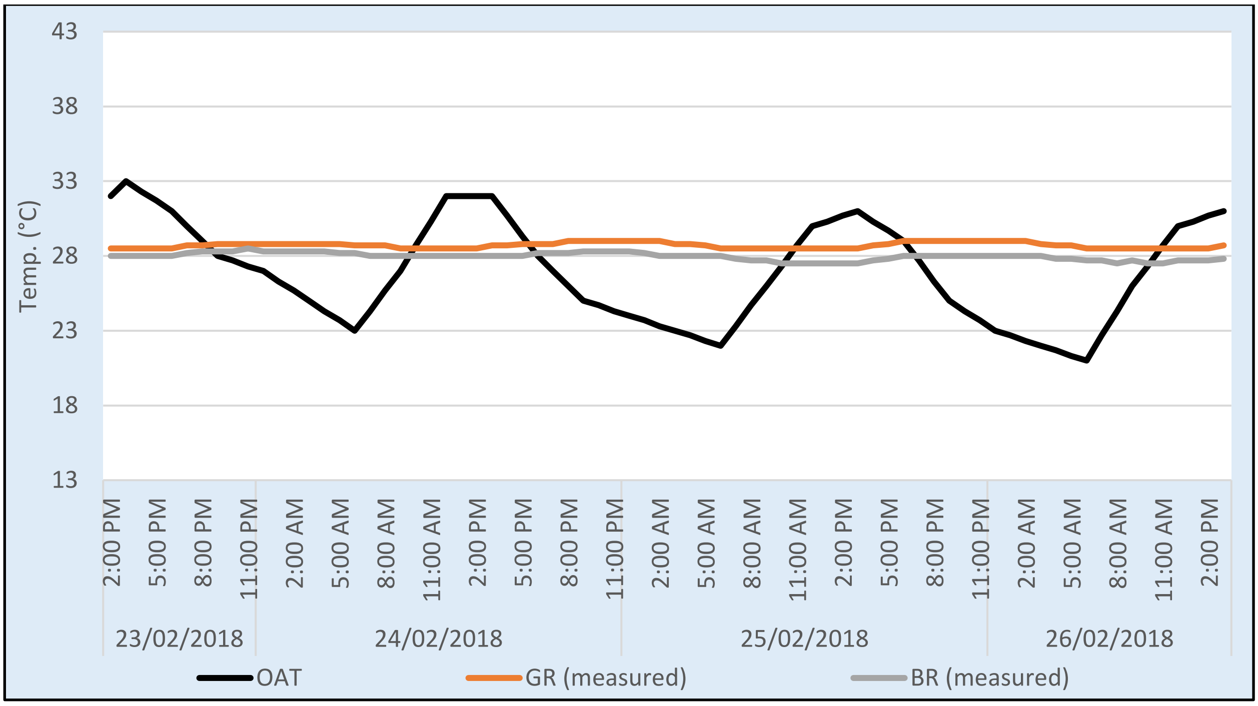

Figure 6.2.1: Outdoor and indoor air temperature of the selected rooms of the house in Makkah in winter recorded by Data-logger (°C)

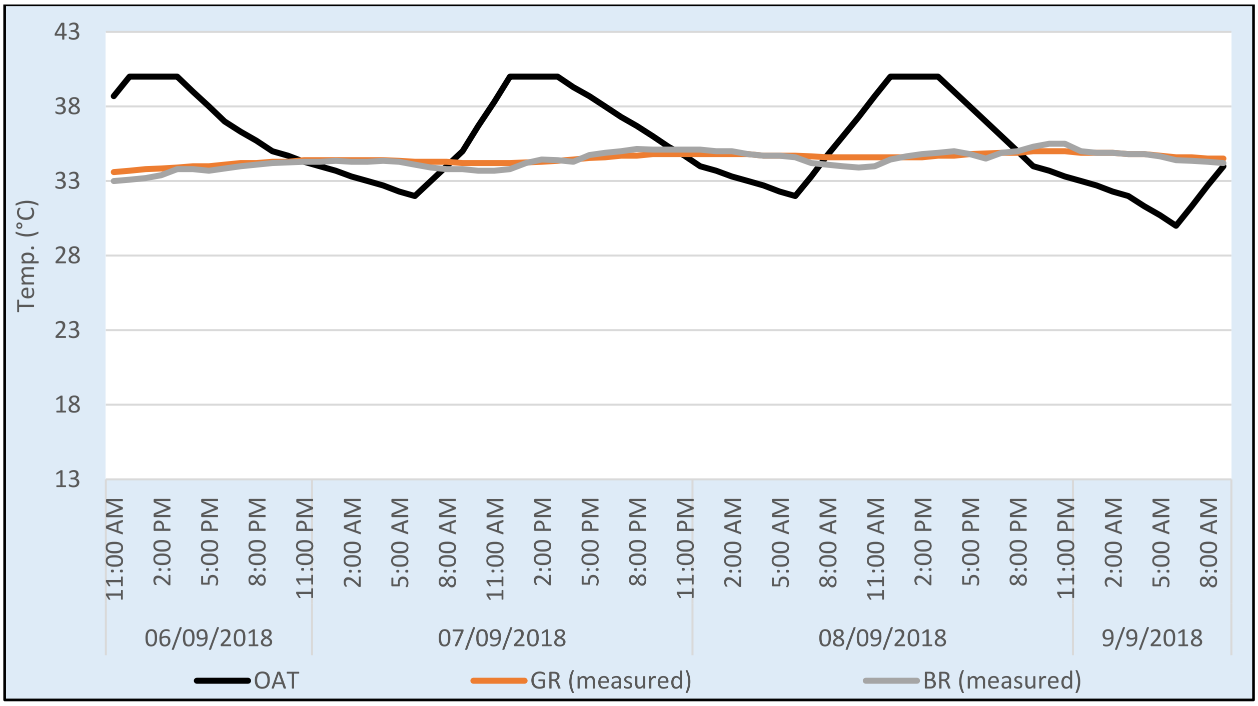

Figure 6.2.2: Outdoor and indoor air temperature of the selected rooms of the house in Makkah in summer recorded by Data-logger (°C)

An analysis of air temperature monitored data is presented with respect to the indoor thermal conditions of the case study building in Makkah. A summary of the main recorded data is presented in figure 6.2.1 for winter days and in figure 6.2.2 for summer days.

In winter, a review of the recorded data indicated that the outdoor air temperature (OAT) - ranged between 21 °C and 33°C. Typically, OAT peaked in the afternoon (11:00 to 16:00), with the lower extremes recorded during the early morning period (2:00 to 8:00).Diurnal OAT – the difference between daily maximum and minimum temperatures - ranged from 9 to 10 °C. Indoors, the temperatures for the two rooms ranged between 27.5°C and 29°C and the difference between them is minor (1 °C). The lowest indoor air temperature (IAT) was recorded in the bedroom (BR) in the late morning and early afternoon of 25th February and in the early morning of 26th February whereas the highest IAT was recorded in the guest room (GR) from around sunset until after midnight of 24th and 25th of February. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in both rooms which had diurnal temperature swings of around 1°C.

In summer, a review of the recorded data indicated that OAT ranged between 30 ◦C and 40◦C. Typically, OAT peaked in the afternoon (11:00 to 17:00), with the lower extremes recorded during the early morning period (12:00 to 9:00). Furthermore, diurnal OAT was 8 ◦C. indoors, the temperatures for the two rooms ranged between 33 ◦C and 35.5 ◦C and the difference between them is minor (2.5◦C). The lowest indoor air temperature (IAT) was recorded in the bedroom (BR) in the late morning period of 6th September, whereas the highest IAT was recorded in the bedroom (BR) on 7th September from after sunset until midnight. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in both rooms, which had diurnal temperature swings of around 1◦C.

Overall, the variation of IAT was limited and constant. This is attributed to the harsh climate conditions. This can be considered as one of the main reasons for not achieving lower IAT. Finally, internal temperatures in both summer and winter are over the upper temperature limit of thermal comfort level required by SBC.

6.2.2. Environmental variables (spot measurements)

Spot indoor/outdoor air temperature, floor/roof indoor surface temperature and globe temperature readings were recorded (see figure 6.2.3). Additionally, outdoor observation and measurements were taken (see table 6.2.1). The main aim was to establish the impact of the building envelope characteristics on the variation of temperature indoors.

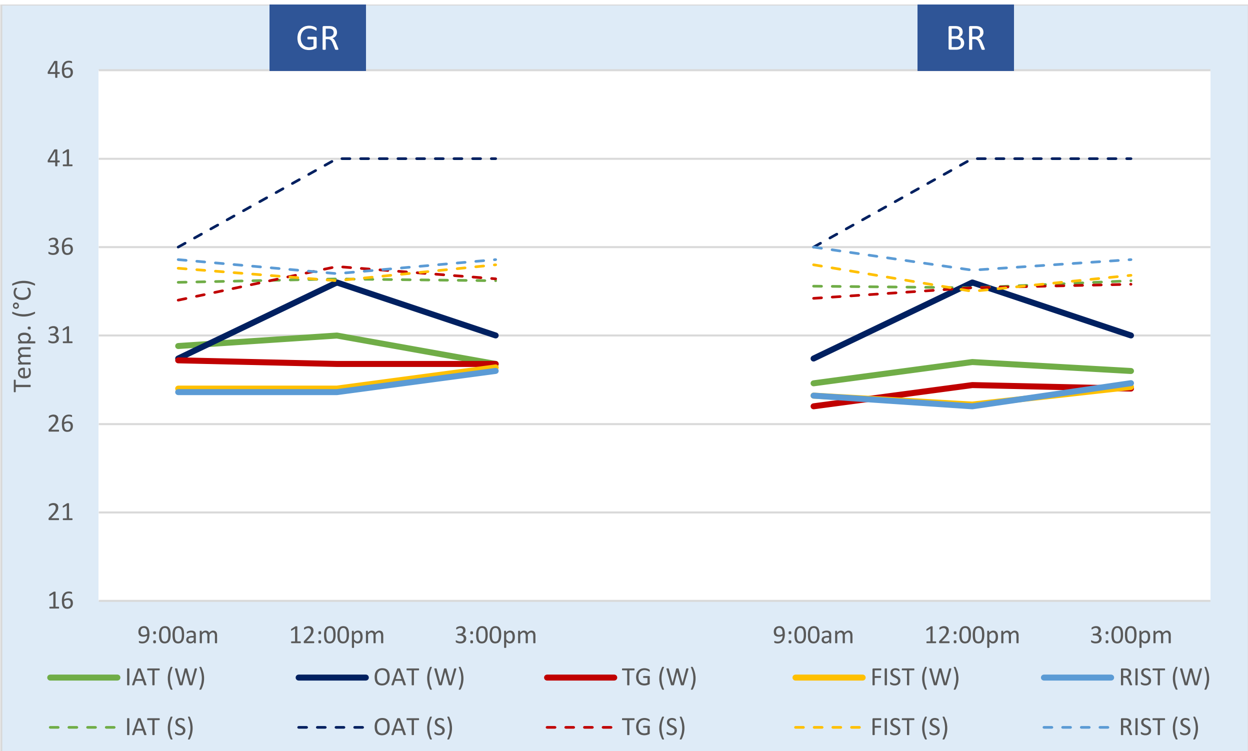

Figure 6.2.3. Indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings recorded in typical winter day (26th February 2018) and typical summer day (7th September 2018) (˚C).

Table 6.2.1: Spot measurements of environmental variables of outdoor conditions

Typical winter day (26th February 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Clear	509	0.9
12:00	Scattered cloud	990	0.3-2.5 m/s
15:00	Partly cloudy	369	0.3-2 m/s
Typical summer day (7th September 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Partly cloudy	567	0.2-0.6
12:00	Clear	813	0.3-0.8
15:00	Clear	446	0.1-0.2

In winter, the outdoor air temperature rises at 12:00 midday by more than 4 °C compared to the first measurement taken and drops around 15:00 to 31 °C due to the partly cloudy sky conditions later in the afternoon. Indoor air temperature (IAT) for the guest room (GR) shows a consistent level at around 30.5 °C in the ground floor room at 9:00 and 12:00 while at 15:00 IAT drops by 1 °C consistent with the drop in OAT. Globe temperature (TG) has a strong correlation with IAT but it is around 1 °C less than IAT. The floor and roof internal surface temperatures (FIST-RIST) have identical figures at all the times; at 9:00 and 12:00 (27.8°C) and they both rise by 1.2 °C at 15:00. FIST and RIST are more than 3 °C lower than IAT at 9:00 and 12:00 but at 15:00 all the variables including TG have the same temperature (29 °C). For the bedroom (BR), IAT follows the same pattern as OAT as it rises from 28 °C in the morning to 29.5°C in the afternoon, then drops to 29 °C later in the afternoon. Globe temperature follows the IAT but it is around 1 °C less than IAT. The floor and roof internal surface temperature have identical figures for all the times; at 9:00 (27.5°C) and 12:00 (27°C) and they both rises by 1 °C at 15:00. FIST and RIST are 3 °C lower than IAT at 12:00 but at 9:00 and 15:00 they are slightly lower than IAT.

In summer, there is a noticeable variation in the temperatures compared to winter. This is comprehensible owing to the OAT swing. The outdoor air temperature rises at 12:00 and 15:00 by 5 ◦C compared to the first measurement taken, due to the afternoon high intensity solar radiation. The two rooms had quite similar patterns in all the variables. The single most striking observation to emerge from the data comparison is the RIST of the bedroom was 3 ◦C higher than the IAT at 9am and the same as OAT then continue to be higher than the other indoor variables during the whole time of monitoring and this is due to the vertical position of the sun. The RIST of the bedroom was higher at 9am compared to the other two times in the afternoon due to the effect of thermal mass of the roof construction where it absorbs and stores heat during the day then release it later on when it becomes cooler.

In summary, the bedroom has a slight decrease in all the variables compared to the guest room probably because rooms adjacent to the guest room are free running while the corridor and rooms close to the bedroom are air conditioned. FIST and RIST starts to increase later in the afternoon in the two rooms regardless of the indoor and outdoor temperatures due to the massive amount of heat being transferred during the daytime through the two external walls in both rooms and from the roof in the bedroom.

Measuring the inner surface temperature of external walls (ISTEW) is one of the methods which can predict the amount of conducted heat through the external wall (opaque element). Four levels and 12 points for each wall were selected with appropriate attention. Then, the average for every hour is taken in figure 6.2.4. Four external walls for the two selected rooms were identified for the surface temperature measurements to enable the data collection process (Figure 6.2.5).

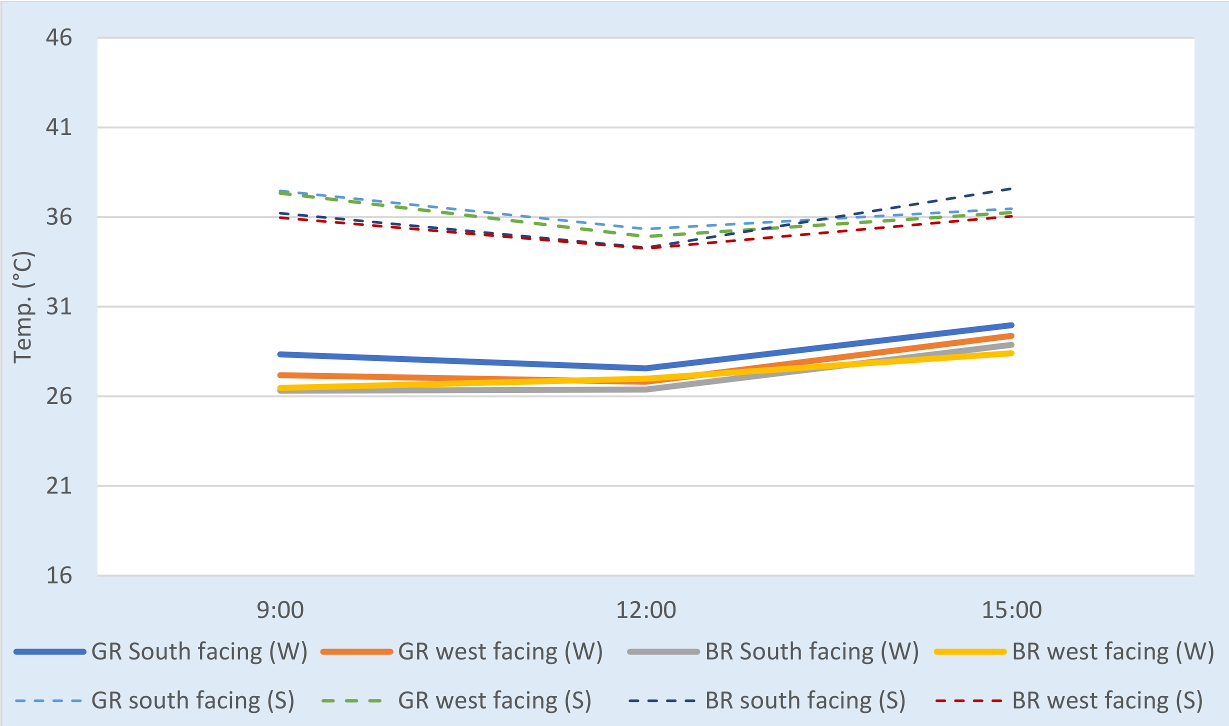

Figure 6.2.4. Inner surface temperature of the external walls of the guest room and the bedroom in winter and summer (˚C).

Figure 6.2.5. Highlighted external walls orientation of the house in Makkah

In winter, the inside wall surface temperature for the guest room (GR) rose by about 1.5 °C for both walls between measurements taken at 9:00 compared to 15:00. The rise in inside wall surface temperature is expected as outdoor air temperature, which showed big increases from early morning due to the high intensity of solar radiation, were always higher than the indoor surface temperature. There are similarities in the way both walls perform as both have the same trend at an average of 27.5 °C, 27.5 °C and 29.5 °C for the times 9:00, 12:00 and 15:00 respectively. For the bedroom (BR), the inside wall surface temperature rises by more than 2 °C for the south facing wall and about 1 °C for the west facing wall from the first measurements taken at 9:00 compared to 15:00. There are similarities in the way both walls perform as both have the same trend at an average of 26 °C, 26 °C and 28 °C for the times 9:00, 12:00 and 15:00 respectively for the south facing wall, while the west facing wall has an average of 26.5 °C, 26.5 °C and 28.5 °C for the times 9:00, 12:00 and 15:00 respectively.

In summer, there are similarities in the way both walls perform at the two rooms as at 9:00, the ISTEW is similar to the measurements taken at 15:00, but at 12:00, the temperature dips by 2 °C. ISTEW is always higher than the other environmental variables discussed earlier and that due to the walls being exposed to high intensity of solar radiation.

6.3. Microclimate of the house in Jeddah

6.3.1. Indoor air temperature (continuous test)

Over the monitoring period, all the rooms were free running during the monitoring time the surfaces could act freely and naturally. Neither of the two rooms have internal heat gain. The ground floor guest room (GR1) has a floor area of 45 m2 while the first-floor bedroom (BR1) is smaller with a floor area of 20m2. The guest room has double external walls (facing east and north) and four windows (two on each wall surface) while the bedroom has only one external wall (facing west) and one window. The two rooms are not exposed to the outdoor from the roof. The windows are self-shaded by a horizontal overhang of the façade (above and side of the windows). All of them are single glazed with internal curtains. External temperature data were obtained from Weather Underground every hour from the nearest weather station located in King Abdul-Aziz airport in Jeddah (Weather Underground, 2020a). Two locations in the building were identified for the positioning of temperature data loggers to enable the data collection process (Figure 6.3).

Figure 6.3. Temperature data loggers Location set up of the house in Jeddah

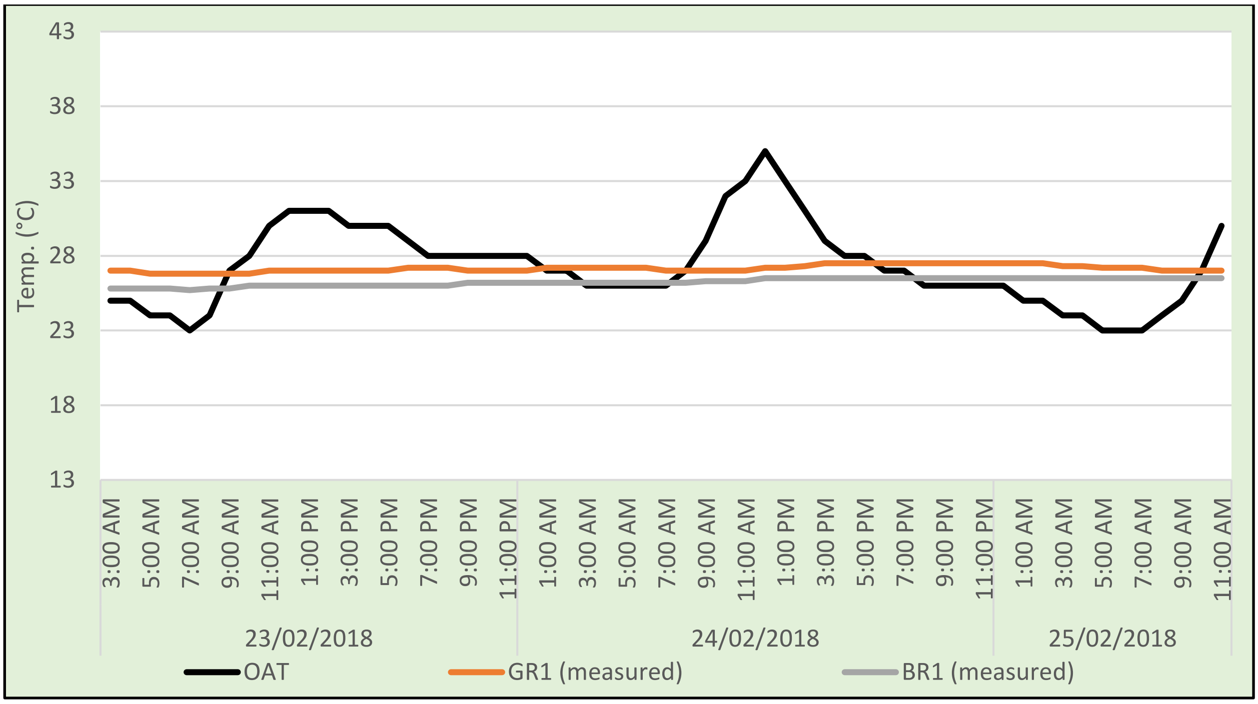

Figure 6.3.1: Outdoor and indoor air temperature of the selected rooms of the house in Jeddah in winter recorded by Data-logger (°C)

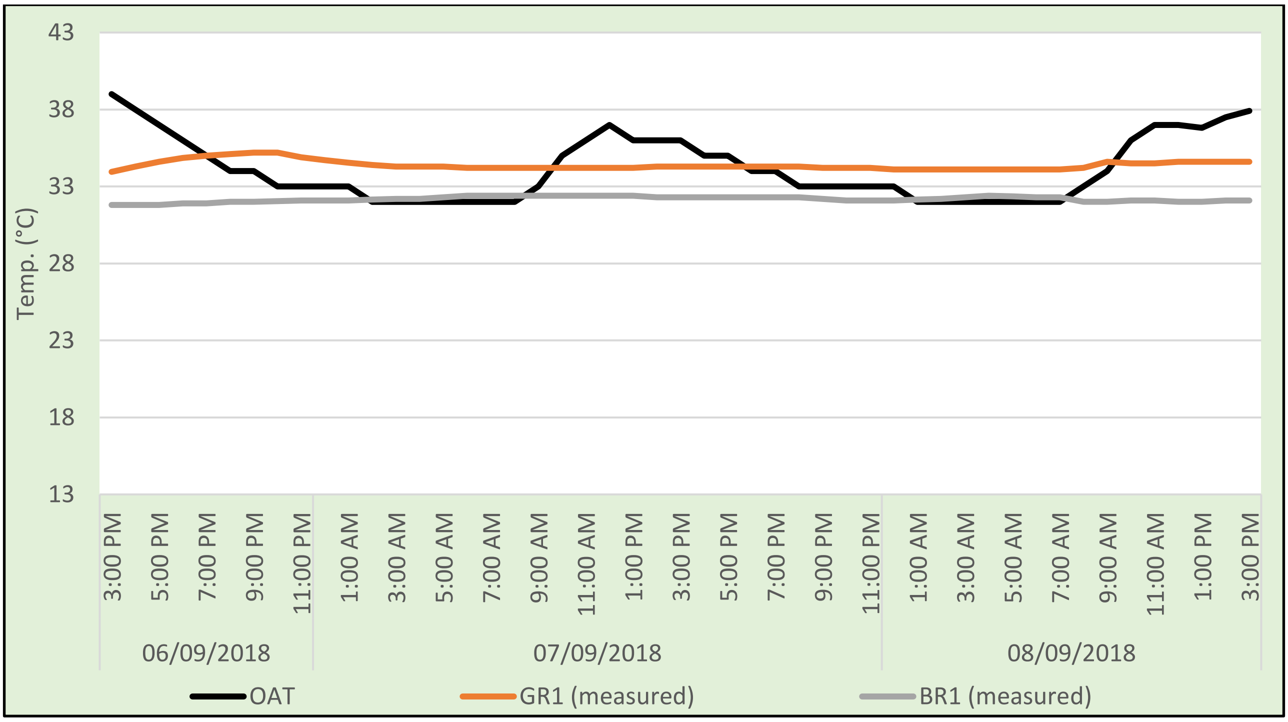

Figure 6.3.2: Outdoor and indoor air temperature of the selected rooms of the house in Jeddah in summer recorded by Data-logger (°C)

An analysis of air temperature data is presented with respect to the indoor thermal conditions of the case study building in Jeddah. A summary of the main recorded data is presented in figure 6.3.1 for winter days and in figure 6.3.2 for summer days. In winter, a review of the recorded data indicates that the outdoor air temperature (OAT) ranged between 23°C and 35°C. Typically, OAT peaked in the afternoon (11:00 to 13:00), with the lower extremes recorded during the early morning period (3:00 to 7:00). Furthermore, diurnal OAT ranged from 8 to 9 °C. Indoors, the temperatures for the two rooms ranged between 25.8 °C and 27.5°C and the difference between them is minor (1 °C). The lowest indoor air temperature (IAT) was recorded in the bedroom (BR1) in the early morning of the first day of recording whereas the highest IAT was recorded in the guest room (GR1) from around sunset until after midnight of 24th and 25th of February. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in both rooms which had diurnal temperature swings of around 1°C.

In summer, a review of the recorded data indicates that OAT ranged between 32◦C and 39◦C. Typically, OAT peaked in the afternoon (11:00 to 15:00), with the lower extremes recorded during the early morning period (2:00 to 7:00). Diurnal OAT ranged between 5 to 6 ◦C. Indoors, the temperatures for the two rooms ranged between 31.8 ◦C and 35.2 ◦C and the notable difference between them was up to 3.2 °C. The lowest indoor air temperature (IAT) was recorded in the bedroom (BR1) for the first three hours of monitoring on 6th September, whereas the highest IAT was recorded in the guest room (GR1) on 6th September from after sunset until midnight. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in both rooms, which had diurnal temperature swings of around 1◦C.

Overall, the IAT was found to be constant for the two rooms. The bedroom had lower indoor temperature by 1 and 2 °C in winter and summer, respectively. This might be a consequence of the difference in floor size as the guest room is more than double the size of the bedroom, and also because of the larger area exposed to the outdoors as the guest room has two walls. Another reason is that the corridor and rooms near the bedroom were air conditioned during the monitoring period. Finally, internal temperatures in both summer and winter are over the upper temperature limit of thermal comfort set by the SBC.

6.3.2. Environmental variables (spot measurements)

Spot indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings were recorded (see figure 6.3.3). Additionally, observation and measurements were taken outdoor (see table 6.3.1). The main aim of this was to establish the impact of the building envelope characteristics on the variation of temperature indoors.

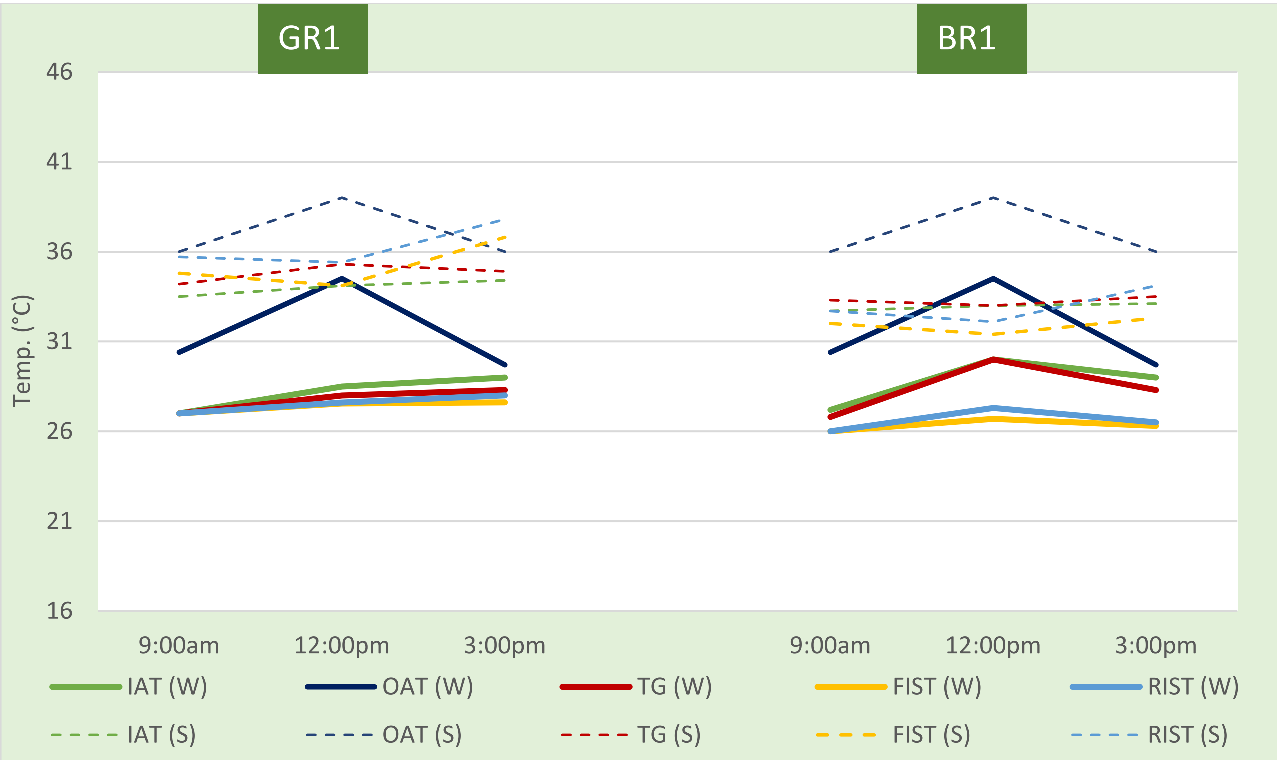

Figure 6.3.3. Indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings recorded in typical winter day (24th February 2018) and typical summer day (8th September 2018) (˚C).

Table 6.3.1: Spot measurements of environmental variables of outdoor conditions

Typical winter day (24th February 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Partly cloudy	505	0.6-3.2
12:00	Mostly cloudy	350	0.7-1
15:00	Mostly cloudy	170	1-2
Typical summer day (8th September 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Clear	516	0.2
12:00	Clear	843	0.8-2.2
15:00	Clear	481	0.6- 1.5

In winter, the outdoor air temperature rises at 12:00 by about 4 °C compared to the first measurement taken then drop at 15:00 to the lowest OAT due to the mostly cloudy sky condition and a little rain. The guest room (GR1) had quite similar pattern in all the variables. The single most striking observation to emerge from the data is that Indoor air temperature (IAT) for GR1 shows a gradual increase from 27.5 °C early in the morning to 29 °C later in the afternoon. For the bedroom (BR1), IAT follows the pattern as OAT when it rises from 27 °C in the morning to 30 °C at 12:00 and then it dropped for the last time the measurements taken to 29 °C. Globe temperature has identical figures with the IAT. The floor and roof internal surface temperature are mostly connected to IAT but not as fluctuated and with lower temperature and both have the same temperature at the three times the measurements were taken at an average of 27 °C.

In summer, the outdoor air temperature rises at 12:00 by 3 ◦C compared to the first measurement taken and it drops at 15:00 to 36 ◦C. For the guest room (GR1), the indoor air temperature has an average of 34 ◦C. Globe temperature follows the IAT but it is around 1◦C higher than IAT at 12:00. The floor and roof internal surface temperature had similar patterns all the times in which RIST was 1◦C higher than the FIST and for both variables, they drop slightly at 12:00 before rising by 2 ◦C at 15:00. Moreover, both FIST and RIST at 15:00 are not only higher than IAT but are also higher than OAT. For the bedroom (BR1), Globe temperature follows the IAT but it is slightly higher than IAT (from 0.4-0.6 ◦C). The floor and roof internal surface temperature had similar patterns all the time when RIST was around 1◦C higher at 9:00 and at 12:00 but at 15:00 it is 2◦C higher and for both variables, they drop slightly at 12:00 before rising at 15:00 by 1◦C for FIST and by 2 ◦C for RIST.

In summary, the bedroom has a slight decrease in all the variables compared to the guest room and that is probably because rooms nearby the guest room are free running, while for the bedroom, the corridor and nearby rooms are air conditioned.

Measuring the inner surface temperature of external walls (ISTEW) is one of the methods which can predict the amount of conducted heat through the external wall (opaque element). Four levels and 12 points for each wall were selected. Then, the average reading for every hour is taken in figure 6.3.4. Three external walls for the two selected rooms were identified for the surface temperature measurements to enable the data collection process (Figure 6.3.5).

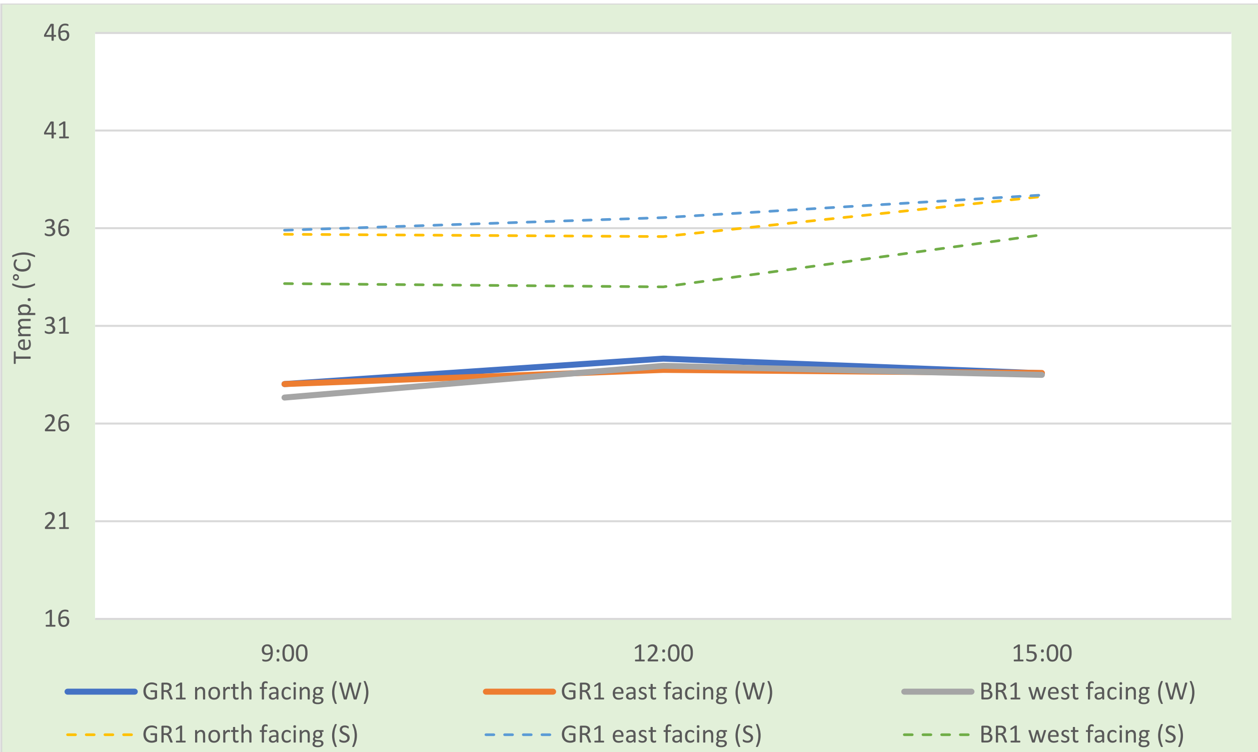

Figure 6.3.4. Inner surface temperature of the external walls of the guest room and the bedroom in winter and summer (˚C).

Figure 6.3.5. Highlighted external walls orientation of the house in Jeddah

In winter, the inside wall surface temperatures were at constant level for all the sport. There are similarities in the way both walls perform as both have the same trend at an average of 28 °C, 29 °C and 28 °C for the times 9:00, 12:00 and 15:00 respectively for both rooms.

In summer, there is no significant difference between the two rooms as at 9:00 and 12:00 but at 15:00, the ISTEW rises by about 2 °C. The rise in inside wall surface temperature is anticipated because it correlates to rising outdoor air temperature which exceeds indoor surface temperatures. The increase in inside wall surface temperature reflects the IAT for the two rooms. The walls in the guest rooms are up to 3 °C higher than the west wall in the bedroom.

6.4. Microclimate of the house in Riyadh

6.4.1. Indoor air temperature (continuous test)

The two rooms are free running during most of the monitoring time for the surfaces to act freely and naturally and have no internal gain. The 1st guest room (GR2) and the 2nd guest room (GR3) are on the ground floor and has a floor area of 20m2 and 14.5m2 respectively. The two rooms are not exposed to the outdoor from the roof and have only a single external wall facing south for GR2 and facing west for GR3, and there is one window for each wall and the windows are single glazed. Both rooms' windows have internal curtains during the monitoring period. Using Weather Underground, external temperature data were obtained every hour from the nearest weather station, which is located in King Khalid airport in Riyadh (Weather Underground, 2020b). Two locations in the building were identified for the positioning of temperature data loggers to enable the data collection process (Figure 6.4).

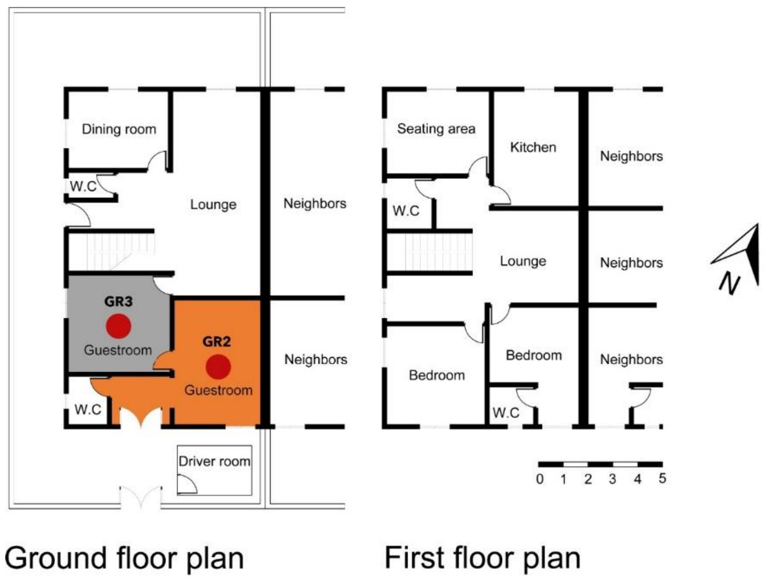

Figure 6.4. Temperature data loggers Location set up of the house in Riyadh

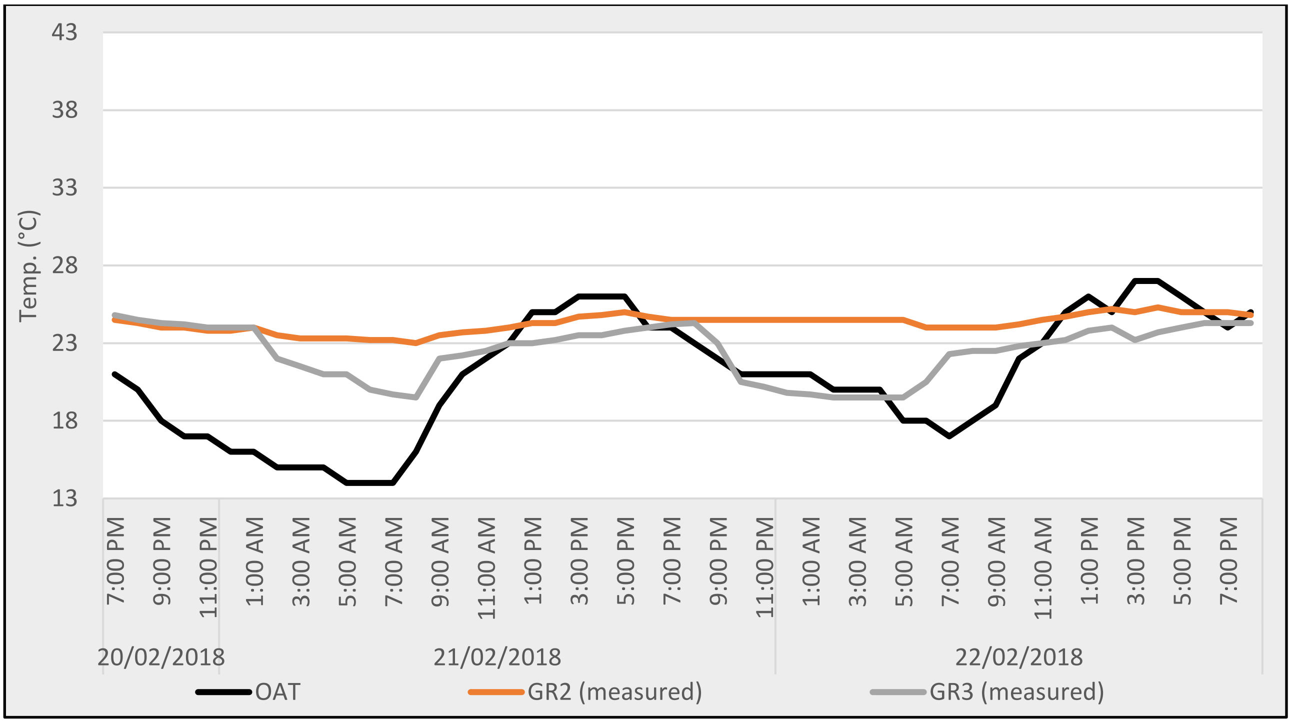

Figure 6.4.1: Outdoor and indoor air temperature of the selected rooms of the house in Riyadh in winter recorded by Data-logger (°C)

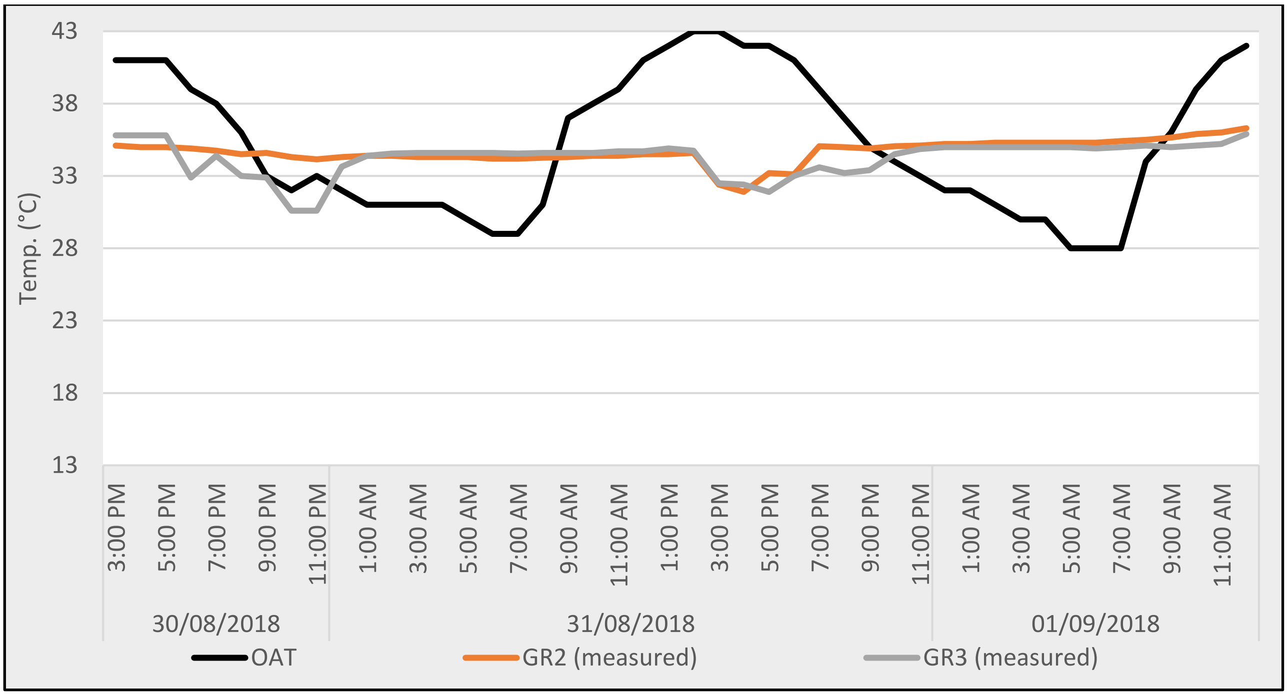

Figure 6.4.2: Outdoor and indoor air temperature of the selected rooms of the house in Riyadh in summer recorded by Data-logger (°C)

An analysis of air temperature monitored data is presented with respect to the indoor thermal conditions of the case study building in Riyadh. A summary of the main recorded data is presented in figure 6.4.1 for winter days and in figure 6.4.2 for summer days.

In winter, a review of the recorded data indicated that the outdoor air temperature (OAT) ranged between 14 °C and 27°C. Typically, OAT peaked in the afternoon (13:00 to 18:00), with the lower extremes recorded during the early morning period (4:00 to 8:00). Furthermore, diurnal OAT ranged from 10 to 12°C. Indoors, the temperatures for the two rooms ranged between 19.5°C and 25.3°C. and the difference between them is minor (1 °C) when the A/C is off. The lowest indoor air temperature (IAT) was recorded in the 2nd guest room (GR3) from 01:00 of the second day until 08:00 and from 21:00 of the second day until 06:00 of the third day and that due to turning on the air conditioner whereas the highest IAT was recorded in the 1st guest room (GR2) in the afternoon of 22nd February. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in 1st guest room which had diurnal temperature swings of around 2°C, while for the 2nd guest room, the fluctuations were more than 5°C because of using the A/C to control the climate condition.

In summer, a review of the recorded data indicated that OAT ranged between 28 ◦C and 43 ◦C. Typically, OAT peaked in the afternoon (13:00 to 19:00), with the lower extremes recorded during the early morning period (4:00 to 8:00).The diurnal OAT ranges were d around 14◦C. Indoors, the temperatures for the two rooms ranged between 30.6 ◦C and 36.3 ◦C and there was no significant difference between them when not using the A/C. The lowest indoor air temperature (IAT) was recorded in 2nd guest room (GR3) for the last two hours of the first day, whereas the highest IAT was recorded in 1st guest room (GR2) for the last day of monitoring from (2:00 to 4:00). Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in both rooms, which had diurnal temperature swings of around 1◦C when not using the A/C.

Overall, the variation of IAT was constant for the two rooms and matched each other when no A/C. was in use. This is attributed to the lack of natural ventilation. This can be considered as one of the main reasons for not achieving lower IAT overnight time even when OAT is far lower than indoors in winter. Also, the use of the A/C for four periods for GR3 and one period for GR2 shows that, even in winter, people prefer to control indoor climate conditions rather than open windows for natural ventilation, a view supported by Aldossary et al., (2015) who concluded that occupants were not content to use natural ventilation and/or fans. Finally, internal temperatures in winter are within the upper temperature limit of thermal comfort required by SBC, whilst for summer it is over the upper temperature limit.

6.4.2. Environmental variables (spot measurements)

Spot indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings were recorded (see figure 6.4.3). Additionally, observations and measurements were taken outdoors (see table 6.4.1). The main aim of this was to establish the impact of the building envelope characteristics on the variation of temperature indoors.

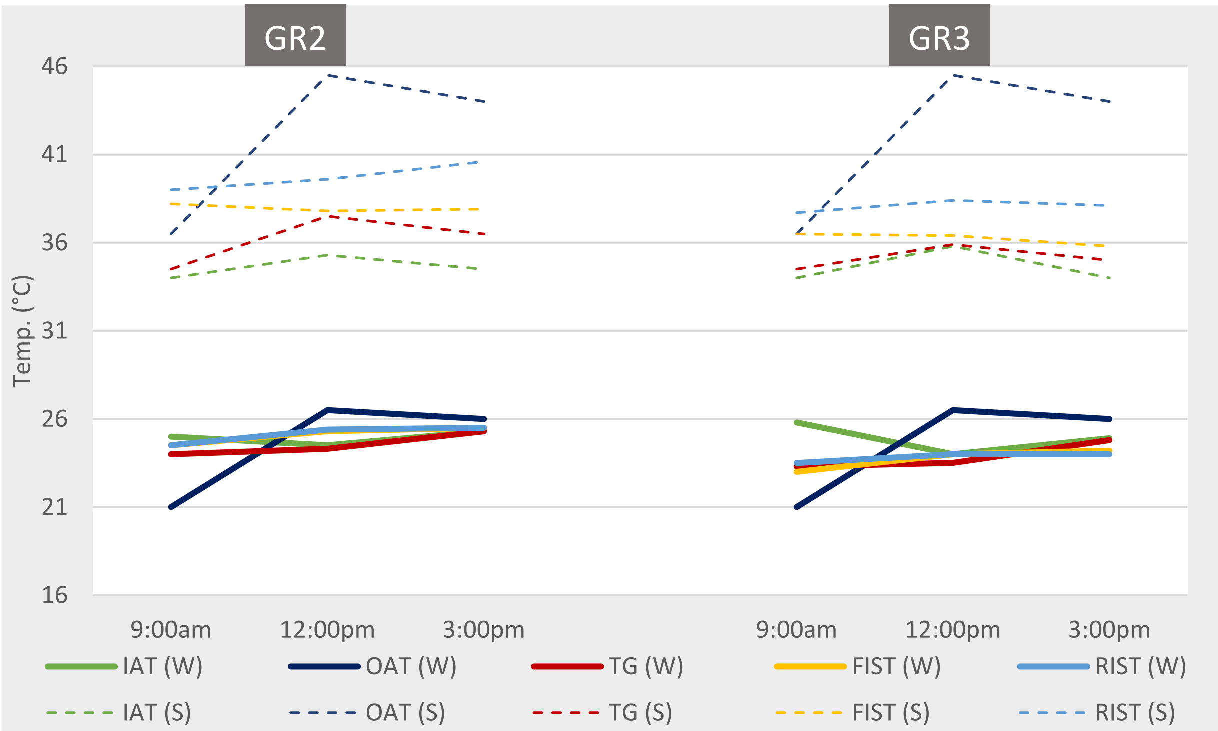

Figure 6.4.3. Indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings recorded in typical winter day (21st February 2018) and typical summer day (1st September 2018) (°C).

Table 6.4.1: Spot measurements of environmental variables of outdoor conditions

Typical winter day (21st February 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Widespread dust	410	2-11
12:00	Widespread dust	763	1-1.5
15:00	Widespread dust	372	1-5
Typical summer day (1st September 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Clear	970	0.4-2.1
12:00	Clear	940	0.3-1.6
15:00	Clear	719	3-5.5

In winter, the outdoor air temperature rises at 12:00 and 15:00 by about 5 °C compared to the first measurement taken due to the huge intensity of solar radiation. The two rooms have a similar pattern in all the variables. They show a constant level of around 25°C at all the times in the 1st guest room (GR2). For the 2nd guest room (GR3), the indoor air temperature is not as constant at the other room. IAT at 9:00 shows high figure at 26 °C then it drops to 24 °C for the other two times. Globe temperature, floor and roof internal surface temperature has an identical figure at 12:00 and 15:00 with the IAT but for 9:00, it is 2 °C less than IAT.

In summer, the outdoor air temperature rises at 12:00 by 9 ◦C compared to the first measurement taken and it drops at 15:00 to 44 ◦C. For the 1st guest room, globe temperature follows the same trend as the IAT at 9:00 but it is 2◦C or more than IAT at 12:00 and 15:00. The floor and roof internal surface temperature is higher than OAT at 9:00 and RIST is about 1◦C higher than FIST, Moreover, A steady rise of RIST from 39 ◦C at 9:00 to 40.6 ◦C late in the afternoon, while the FIST is constant at an average of 38 ◦C. The single most striking observation to emerge from the data comparison is the RIST was 6 ◦C higher than the IAT at 15:00. For the 2nd guest room, the same trend comparing to the first guest room occur but with a slight reduction in TG, FIST and RIST.

In summary, the floor inner surface temperature (FIST) and the roof inner surface temperature (RIST) in the summer season increases later in the afternoon in the two rooms regardless of the indoor and outdoor temperatures, and that is due to the massive amount of heat transferred during the day through the walls in both rooms.

Measuring the Inner surface temperature of external walls (ISTEW) is one of the methods which can predict the amount of conducted heat through the external wall (opaque element). Four levels and 12 points for each wall were selected with appropriate attention. Then, the average for every hour is taken in figure 6.4.4. Two external walls for the two selected rooms were identified for the surface temperature measurements to enable the data collection process (Figure 6.4.5).

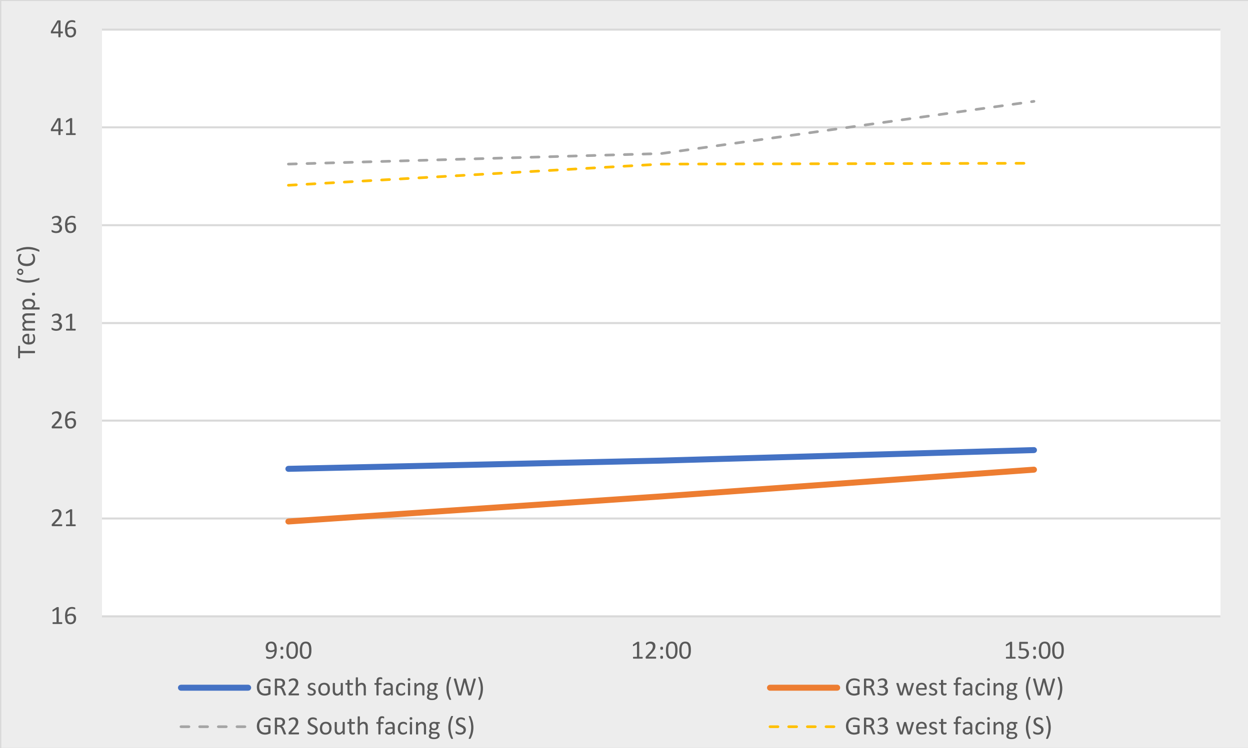

Figure 6.4.4. Inner surface temperature of the external walls of the 1st and 2nd guest rooms in winter and summer (˚C).

Figure 6.4.5. Highlighted external walls orientation of the house in Riyadh

In winter, the inside wall surface temperature for the 1st guest room (GR2) was at constant level for all the sport at an average of 24 °C at 9:00, 12:00 and 15:00. The inside wall surface temperature for the 2nd guest room (GR3) rises constantly from 21°C in the morning to 22 at 12:00 to 23.5 °C later in the afternoon. The rise in inside wall surface temperature is expected except at 9:00 as OAT has the same temperature as the average internal surface temperature of the external wall.

ISTEW for the 1st guest room follows the same trend to the other environmental variables discussed earlier, while for the 2nd guest room which is always less than the other variables discussed earlier also.

In summer, there are similarities in the way both walls perform at the two rooms as at 9:00 and 12:00 bur for 15:00, the 1st guest room rises by 3 °C. the ISTEW is always higher than the other variables discussed earlier in the previous section and that due to the walls being exposed to high intensity of solar radiation. The ISTEW for the two rooms have the same trend with RIST.

6.5. Microclimate of the house in Taif

6.5.1. Indoor air temperature (continuous test)

All the rooms are free running during the monitoring time for the surfaces to act freely and naturally and the two rooms have no internal heat gain. The 1st bedroom (BR2) and the 2nd bedroom (BR3) are in the ground floor and have an identical floor area of 19.2m2. The rooms are adjacent to one another and both are exposed to the outdoor from the roof. BR2 has one external wall orientated to the east, while BR3 has two external walls orientated to the east and the north. The east facing walls in the two rooms have one window; each of them is single glazed with internal curtains during the monitoring period. Using the online Weather Underground as a source, external temperature data were obtained from the nearest weather station, located in Taif international airport (Weather Underground, 2020c). Two locations in the building were identified for the positioning of temperature data loggers to enable the data collection process (Figure 6.5).

Figure 6.5. Temperature data loggers Location set up of the house in Taif

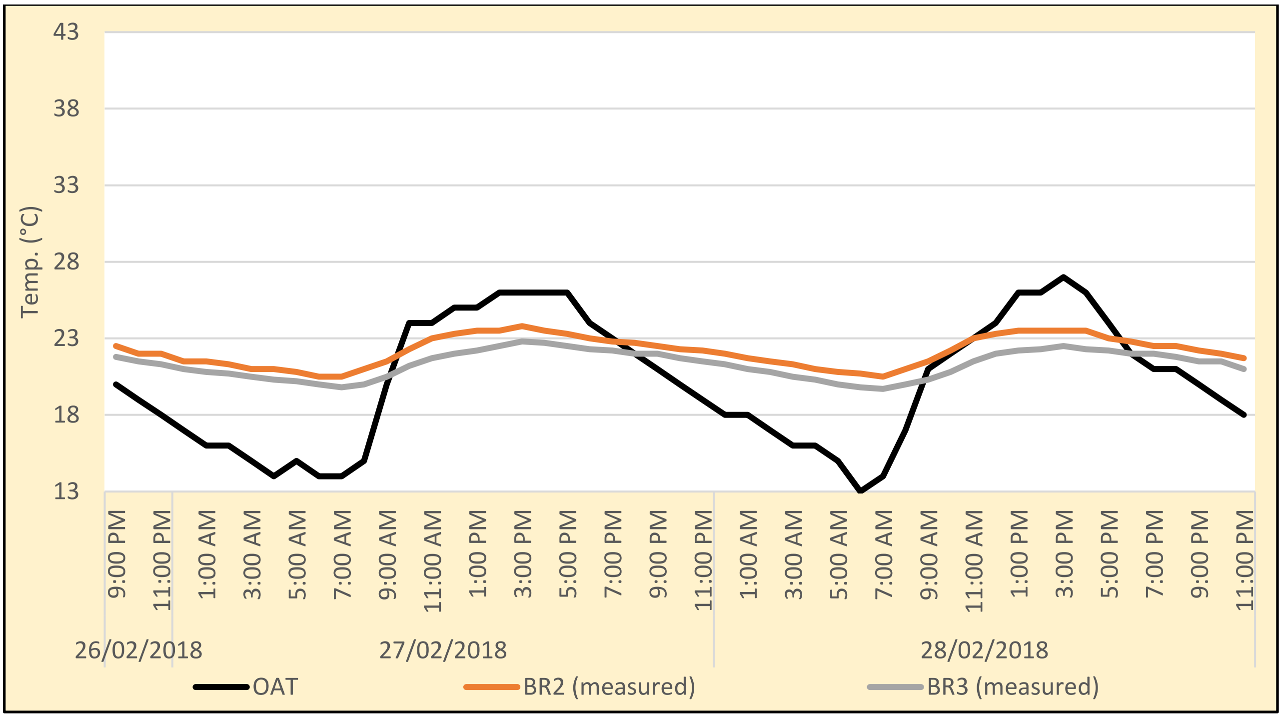

Figure 6.5.1: Outdoor and indoor air temperature of the selected rooms of the house in Taif in winter recorded by Data-logger (°C)

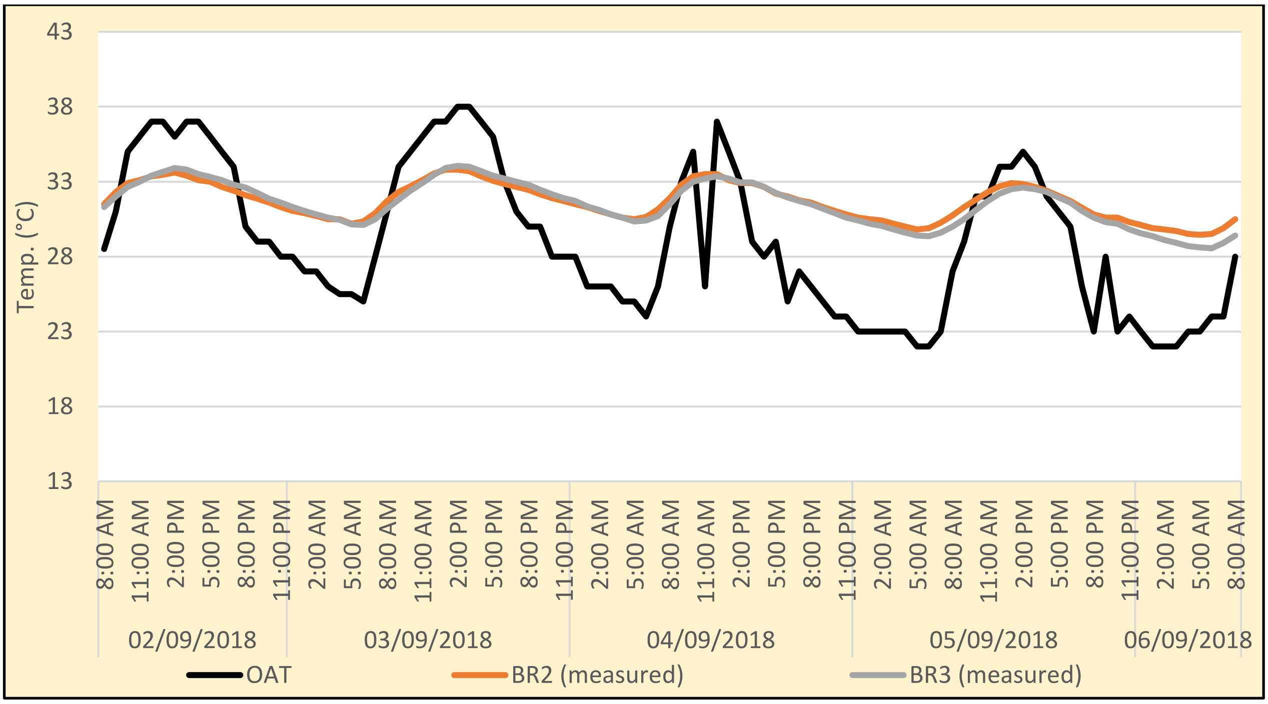

Figure 6.5.2: Outdoor and indoor air temperature of the selected rooms of the house in Taif in summer recorded by Data-logger (°C)

An analysis of air temperature monitored data is presented with respect to the indoor thermal conditions of the case study building in Taif. A summary of the main recorded data is presented in figure 6.5.1 for winter days and in figure 6.5.2 for summer days.

In winter, a review of the recorded data indicated that the outdoor air temperature (OAT) ranged between 13 °C and 27°C. Typically, OAT peaked in the afternoon (12:00 to 17:00), with the lower extremes recorded during the early morning period (3:00 to 8:00). Furthermore, diurnal OAT ranged from 12 to 14 °C. Indoors, the temperatures for the two rooms ranged between 19.7 °C and 23.8 °C and the difference between them is minor (1°C). The result shows BR2 has higher IAT than BR3 and that possibly contributed to heat loss of BR3 due to having two external walls.

The lowest winter indoor air temperature (IAT) was recorded in the 2nd bedroom (BR3) in early morning of 27th and 28th February, whereas the highest winter IAT was recorded in the 1st bedroom (BR2) from 13:00 to 17:00 of the second and third days of recording. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in the two rooms which had diurnal temperature swings of 3°C. This might be a consequence of low thermal performance from the building roof fabric.

In summer, a review of the recorded data indicated that OAT ranged between 21 ◦C and 38 ◦C. Typically, OAT peaked in the afternoon (10:00 to 16:00), with the lower extremes recorded during the early morning period (2:00 to 8:00). Furthermore, diurnal OAT ranged at 13 ◦C. Indoors, the temperatures for the two rooms ranged between 28.55 ◦C and 34.05 ◦C, showing a significant difference of 4.7◦C. The lowest indoor air temperature (IAT) was recorded in the 2nd bedroom (BR3) in the morning hours of the final monitoring day, whereas the highest IAT was recorded in the same room in the afternoon on 3rd September. Unlike the significant temperature fluctuations recorded outdoors, steady conditions were observed in both rooms, which had diurnal temperature swings of around 4◦C. Overall, the variation of IAT was found to be relatively limited for the two rooms; BR2 had a slightly higher IAT. This is attributed to having only one external wall compared to the other room. The swing in IAT was found to be 3◦C and 4◦C for winter and summer respectively, and that might be due to the poor roof construction. Also, the lack of natural ventilation can be considered as a reason for not achieving lower IAT at night time even when OAT is lower than indoors. Finally, internal temperatures in winter are within the upper temperature limit of thermal comfort levels required by SBC, whilst for summer it is over the upper temperature limit.

6.5.2. Environmental variables (spot measurements)

Spot indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings were recorded (see figure 6.5.3). Additionally, observation and measurements were taken outdoors (see table 6.5.1). The main aim of taking spot measurements was to establish the impact of the building envelope characteristics on the variation of temperature indoors.

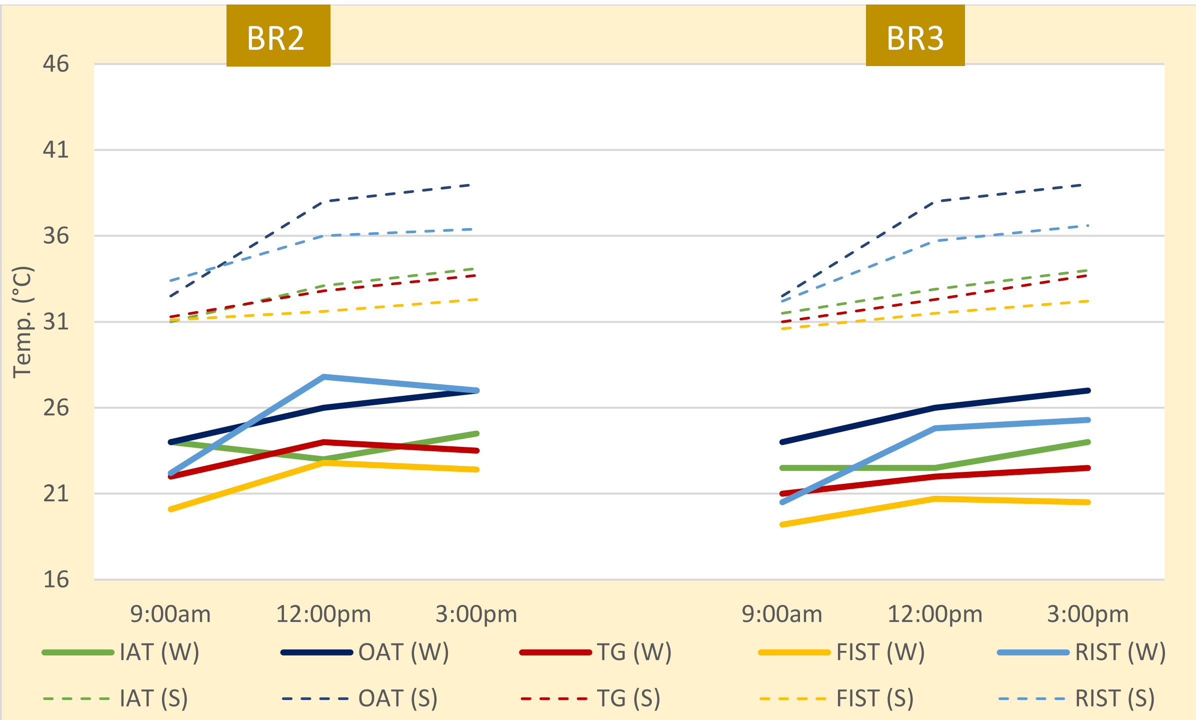

Figure 6.5.3. Indoor/outdoor air temperature, floor/roof indoor surface temperature, globe temperature readings recorded in typical winter day (27th February 2018) and typical summer day (3rd September 2018) (˚C).

Table 6.5.1: Spot measurements of environmental variables of outdoor conditions

Typical winter day (27th February 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Clear	575	0.1-0.5
12:00	Clear	890	0.5-1.5
15:00	Scattered cloud	680	0.5-1.9
Typical summer day (3rd September 2018)			
Time	Sky condition	Solar radiation (W/m2)	Air velocity (m/s)
9:00	Clear	705	0.2
12:00	Clear	882	0.5-1
15:00	Clear	711	0.3-1

In winter, the outdoor air temperature rises constantly from 24 °C in the morning to 27 °C later in the afternoon. The indoor air temperature shows a constant level at an average of 24 °C at all the times in the 1st bedroom (BR2), while Globe temperature has similar figures at 12:00 and 15:00 with the IAT but for 9:00, it is a about 2 °C less than IAT. Floor and roof internal surfaces temperature have a noticeable difference to the other temperatures. First of all, the difference between FIST and RIST can be up to 5 °C. Secondly, the RIST at 15:00 is the same or even higher than the OAT at 12:00. Thirdly, the floor inner surface temperature at 9:00 is 4 °C lower than IAT, and the roof inner surface temperature is 2 °C lower than IAT. These differences are linked to the high thermal conductance of the roof material. For the 2nd bedroom (BR3), the indoor air temperature shows a constant level at 22.5 °C for 9:00 and 12:00 but later in the afternoon, it rises to 24 °C. Globe temperature, FIST and RIST have an identical pattern with the 1st bedroom's figures (BR2) but slightly less.

In summer, the outdoor air temperature rises at 12:00 by more than 5 ◦C compared to the first measurement taken and it rises again at 15:00 to 39 ◦C. Globe temperature follows the IAT at all the time for both rooms. The floor and roof internal surface temperature for the two rooms have the same pattern in which both rises from 9:00 to 15:00 but the difference between them can be as much as 4 ◦C. RIST follows the OAT and is more than 3 ◦C higher than the other variables.

Measuring the Inner surface temperature of external walls (ISTEW) is one of the methods which can predict the amount of conducted heat through the external wall (opaque element). Four levels and 12 points for each wall were selected with appropriate attention. Then, the average for every hour is taken in figure 6.5.4. Three external walls for the two selected rooms were identified for the surface temperature measurements to enable the data collection process (Figure 6.5.5).

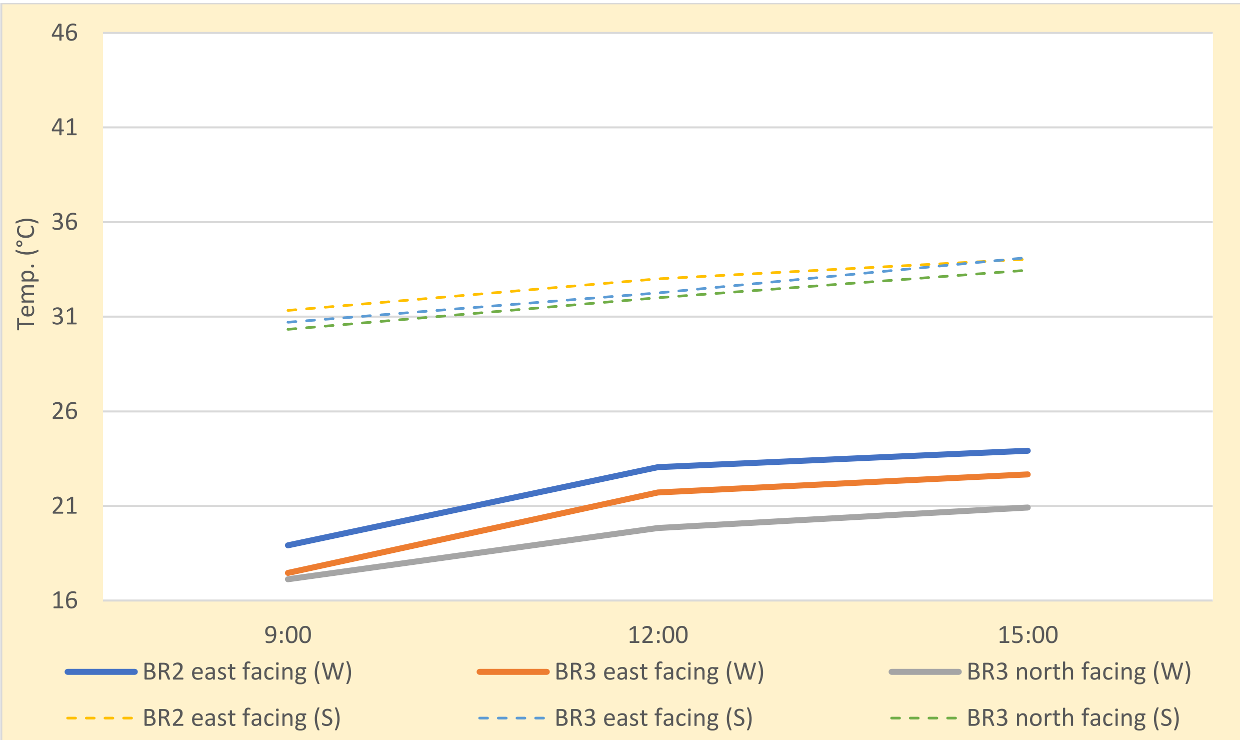

Figure 6.5.4. Inner surface temperature of the external walls of the 1st and 2nd bedrooms in winter and summer (˚C).

Figure 6.2.5. Highlighted external walls orientation of the house in Taif

In winter, the inside wall surface temperature increases massively from the morning until late afternoon. The rise in inside wall surface temperature is anticipated because both rooms face east. There are similarities in the way all walls perform as temperatures rise by about 4 °C from 9:00 to 12:00 and increase again by 1°C at 15:00.

In summer, there are similarities in the way all the walls in the two rooms perform, as both increase gradually from early in the morning until late in the afternoon. ISTEW has the same trend with GT and IAT at the same time which was discussed earlier.

6.6. Summary

This chapter a description of each buildings selected. It highlights several variables including indoor and outdoor dry bulb temperature, floor, roof and external walls surface inner temperatures, outdoor solar heat gain. All these variables were monitored using the equipment introduced in the previous chapter. This part took into consideration the internal environmental condition as it is and illustrated the results obtained from the measurement during the field study.

The house in Makkah: the variation of IAT was found to be quite limited and constant. Also, internal temperatures in both summer and winter are over the upper temperature limit of thermal comfort level required by SBC. In terms of environmental variables, IAT can be more than 3˚C higher than Inner surface temperature of the external walls (ISTEW) of the guest room early in the morning but later in the afternoon it decreases to even lower than ISTEW in winter. In summer, the reverse happens, as the IAT was 3 and 2˚C lower than the ISTEW in the morning and later in the afternoon.

The house in Jeddah: the variation of IAT was found to be constant for the two rooms. Also, the bedroom had lower indoor temperature than the guest room by 1 and 2 °C in winter and summer, respectively. This might be a consequence of the difference of the rooms' areas as the guest room is more than double the size of the bedroom, and also because of the bigger exposure area to the outdoor from the external walls, as the guest room has two walls. Another reason is that the corridor and nearby rooms adjacent to the bedroom were air conditioned during the monitoring period. Finally, internal temperatures in both summer and winter are over the upper temperature limit of thermal comfort level required by SBC.

The house in Riyadh: the variation of IAT was found to be constant for the two rooms and match each other when there is no A/C. Also, the use of the A/C for four periods for GR3 and one period for GR2 show that even in winter people prefers to control the indoor climate condition rather than opening the window for natural ventilation. Finally, internal temperatures in winter are within the upper temperature limit of thermal comfort level required by SBC, whilst for summer it is over the upper temperature limit.

The house in Taif: the variation of IAT was found to be quite limited for the two bedrooms with the BR2 had slightly less IAT. This is attributed to having only one external wall compared to the other room which has two external walls. The swing in IAT was found to be 3◦C and 4◦C for winter and summer respectively and that might be due to the poor roof construction. Finally, internal temperatures in winter are within the upper temperature limit of thermal comfort levels required by SBC, whilst for summer it is over the upper temperature limit.

The outcomes are in line with the findings from Artmann et al., (2008) which showed the effect of solar heat gains on different orientations of external façades. In the summer, solar irradiation is highest on the east and west façades. West-oriented rooms tend to overheat most because there is a coincidence in the afternoon between high ambient temperature and high solar irradiation.

Chapter 7

Environmental internal condition using thermal analysis software

7. Environmental internal condition using thermal analysis software

This chapter details the second phase of the evaluation of thermal conditions within residential buildings using thermal analysis software (EDSL TAS version 9.4.2). TAS was used to test the impact of the existing external walls, roofs and floors on the indoor air temperature, heat conduction and cooling load. Exploring thermal trends within the modelled homes is necessary to predict the thermal conditions within the residential buildings and to examine alternate enhancements for achieving better indoor thermal environments and energy efficient houses. Thermal performance for the houses during winter and summer is assessed. Also, comparisons between the fieldwork results (physical measurements) and the computer modelling results (TAS), is conducted and discussed. The findings related to heat conduction through external building fabrics are also presented. The accurate measurement of heat gain and loss through the walls and roof can be used to optimize the envelope characteristics based on a combination of input data and the building geometry. However, it is important to remember the importance of considering the weather conditions and the building and system characteristics (Melo et al., 2015).

For the simulated energy model to be acceptable, calculation of the root mean square error (RMSE) and normalised mean bias error (NMBE) should be in the range of 30% and 10% respectively for a model that deals with hourly figures based on ASHRAE guidelines (ASHRAE, 2014). This study recorded hourly dry bulb temperature which is a measure of air temperature. It is called dry-bulb temperature because the thermometer bulb is dry to avoid variation in the recorded temperature caused by the moisture content of the air. While calculating both the RMSE and the NMBE, two methods were used: the first method consists of dividing the recorded data into winter and summer, while the second consists of calculating the values of the entire monitored temperatures during the total monitored hours.

Heat conduction in external opaque fabrics has been analysed to assist the proposal of improvements to the house's envelopes. This approach has been selected because a building’s exposed surfaces to the outdoors plays a major role in determining the internal conditions as revealed through the fieldwork. This topic is discussed in Chapter 8. Heat loss/gain through any specific surface can be calculated separately by TAS through Surface Filter outputs. This ability was utilized to analyze the thermal performance of various building elements, where heat flow was calculated for external opaque surfaces i.e. walls, roofs and floors.

Cooling load is also predicted in these houses which represent different climatic zones along with investigation for parameters that could affect the cooling load such as floor level. The analysis results of each house are presented and discussed in detail. Then the results presented in this chapter discussed later for applying fabrics modification.

7.1. The house in Makkah

7.1.1. Dry bulb temperature

The same rooms chosen for the fieldwork are chosen here for the same days and hours. The case study building is modelled (figure 7.1) using thermal analysis software (EDSL TAS version 9.4.2).

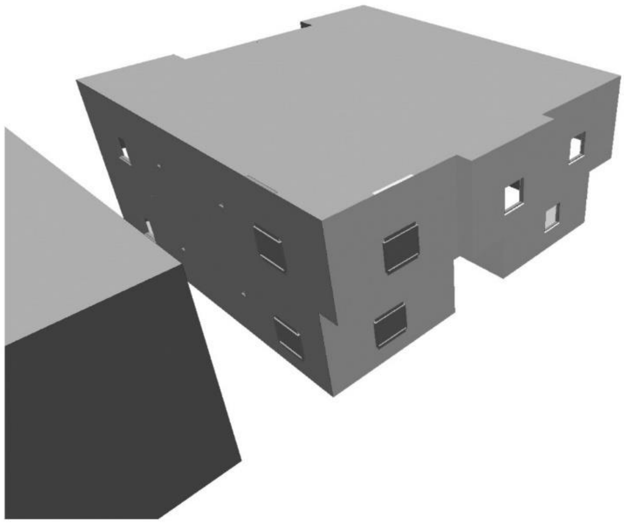

Figure 7.1. Snapshot of the house 3D model in TAS.

The calibration results achieved very similar internal temperature behaviours for the guest room and bedroom (see figures 7.1.1 and 7.1.2). In winter, peaks and troughs are the same for the first two days with slightly high temperatures. In summer, peaks and troughs are the same with relatively high temperatures in the first day; nevertheless, they become around 1 K higher on the second and third days in the bedroom (BR). The reason for plotting the simulated results in this way was to verify and calibrate the analytic work. The root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods were calculated in table 7.1.1. The NMBE was lower than the 10% limit and the RMSE was lower than the 30% limit set by ASHRAE. It is thus safe to assume that the simulated results are within the acceptable range.

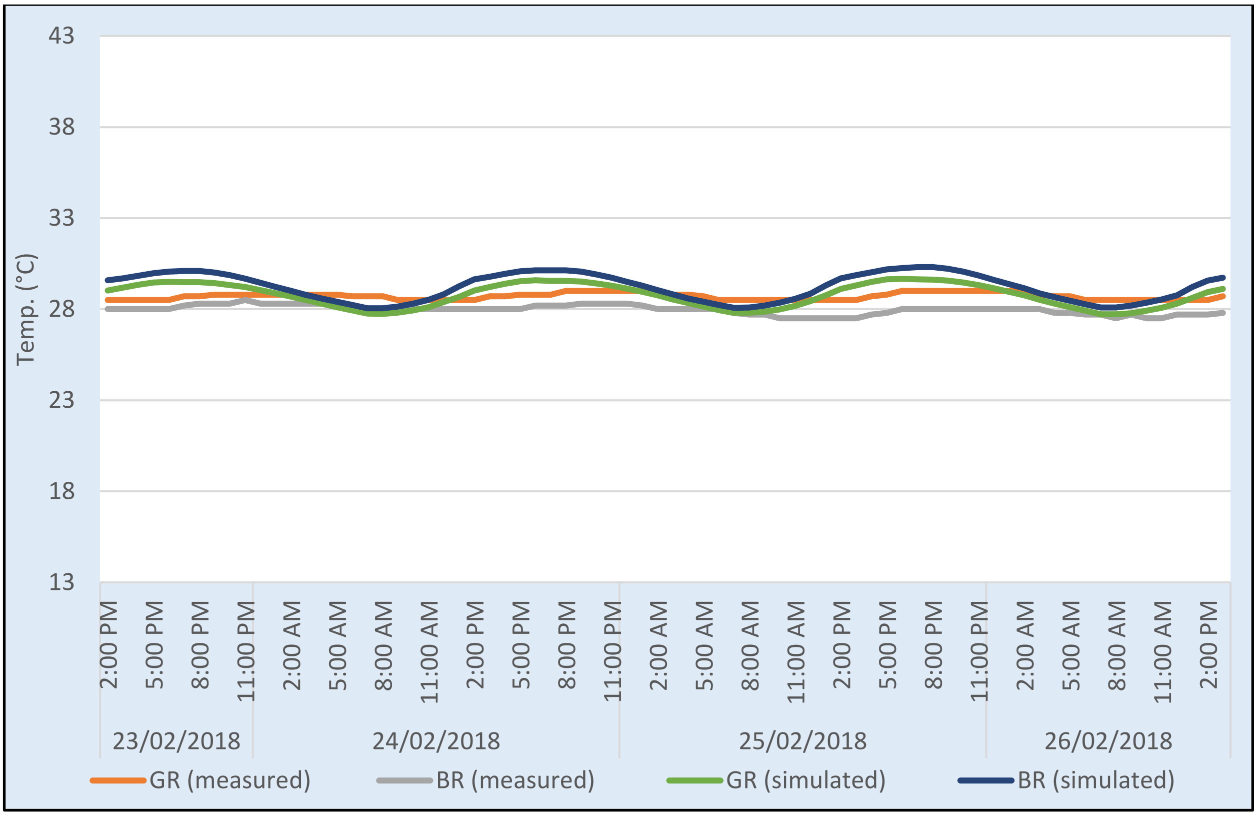

Figure 7.1.1. Measured and simulated DBT temperature of the house in Makkah's selected rooms in winter (˚C)

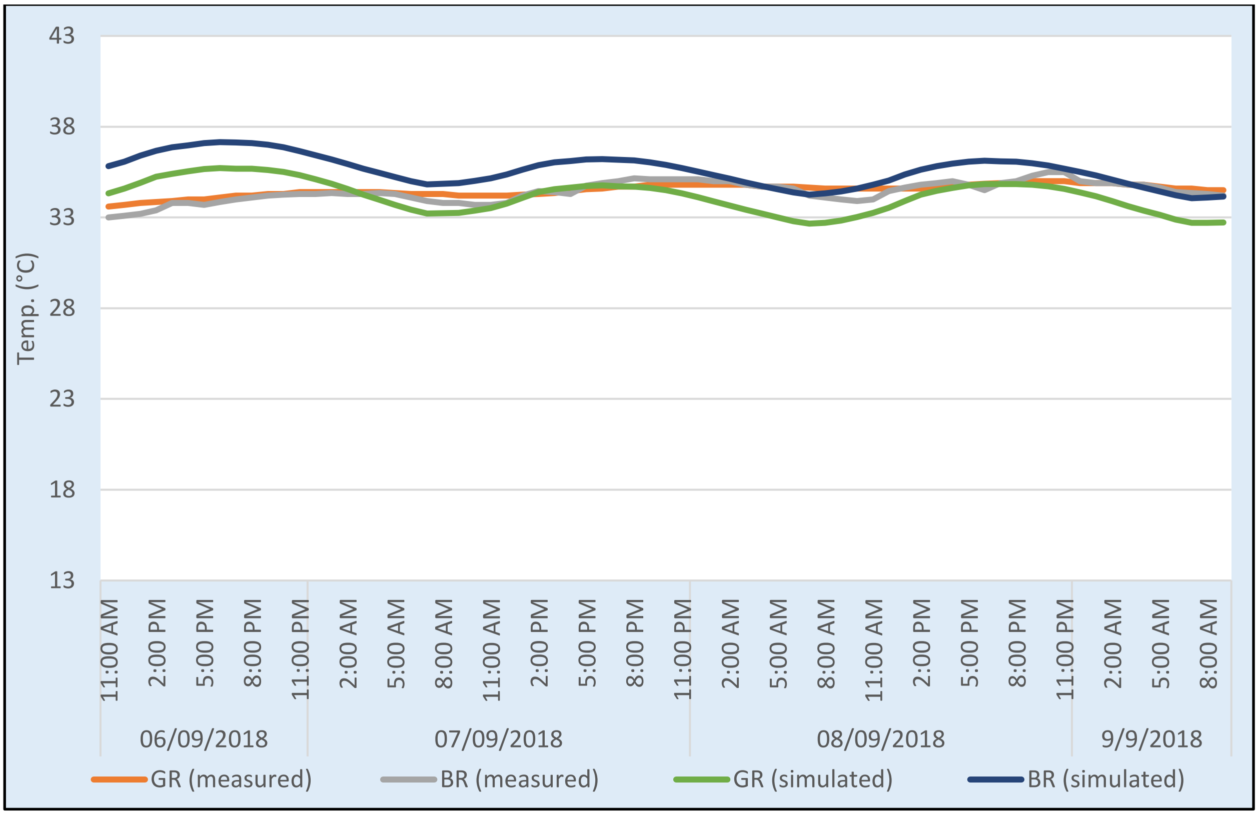

Figure 7.1.2. Measured and simulated DBT temperature of the house in Makkah's selected rooms in summer (˚C)

Table 7.1.1. Calculated the root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods.

room	Season	RMSE	Average RMSE	NMBE	Average NMBE
Guest room	Winter	0.5	1.6	-0.1	0.2
	Summer	2.8		0.6	
Bedroom	Winter	10.7	10.3	-3.3	-2.8
	Summer	9.9		-2.4	

7.1.2. Heat conduction through fabrics

Figure 7.1.3 illustrates heat loss/gain through the floor, roof and external walls components in the guest room and the bedroom as it is on the ground floor and the first floor over the course of both a summer and a winter day. Heat loss/gain through the floor component in the guest room on the ground floor during both a summer and a winter day shows relatively small amount of heat gain and heat loss. In winter, the thermal analysis revealed that heat gain through the floor occurs constantly, where it is quite stable all the time. This means that the internal surface temperature of the floors is lower than the external surface temperature of the floors (i.e. the surface which is exposed to the soil). This could be explained by the fact that, in winter, the temperature of the ground is higher than the external air temperature. Heat flow through floor differs between summer and winter, as heat loss takes place through floors most of the time in summer. This could be explained by the summer temperature of the ground being lower than the external air temperature.

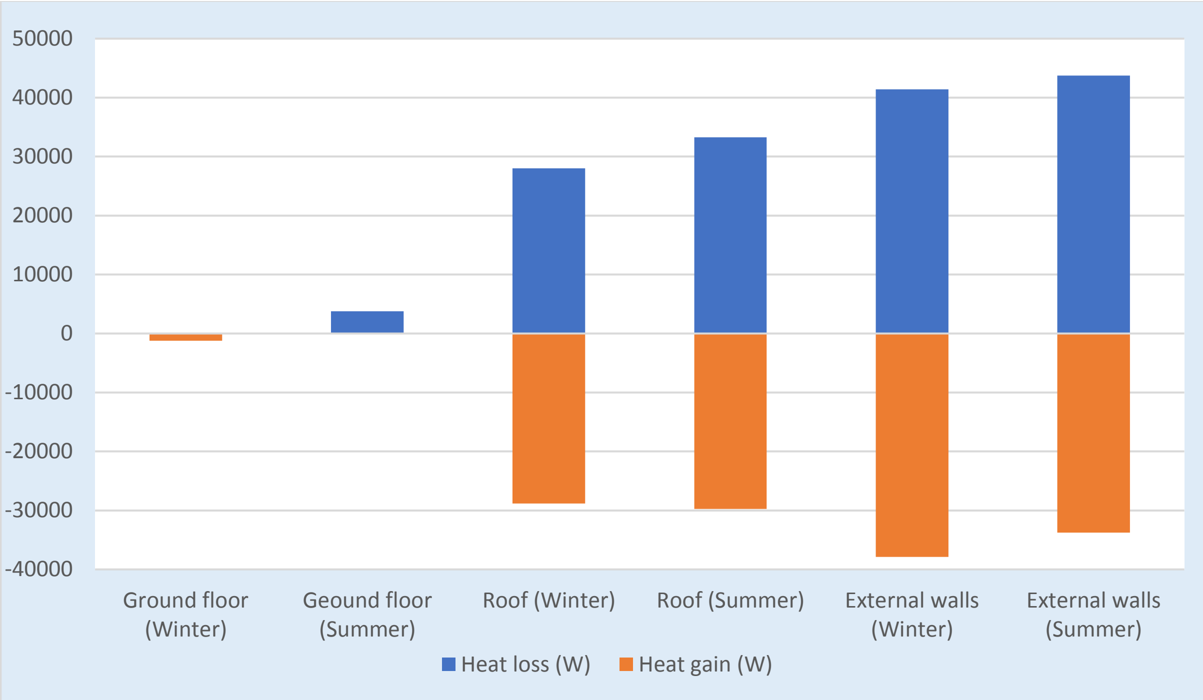

Figure 7.1.3. Heat conduction through building fabrics (floor, roof and external walls) in the guest room and bedroom in winter and summer (W)

Heat loss/gain through the roof component in the bedroom on the 1st floor, as it is exposed to the outdoor, during both a summer and a winter day shows relatively large amount of heat gain and heat loss. Heat gain through roof starts early in the morning as the roof exposes to solar radiation and ends later in the afternoon; then heat loss takes place as the outside temperature falls in both winter and summer. The external solar gain in both seasons has similar figures and starts to increase significantly from early in the morning to reach its peak at 12:00 (figure 7.1.4). A positive correlation was found between TAS and monitored variables. As stated in Chapter six the bedroom roof had the highest inner surface temperatures among the other variables measured.

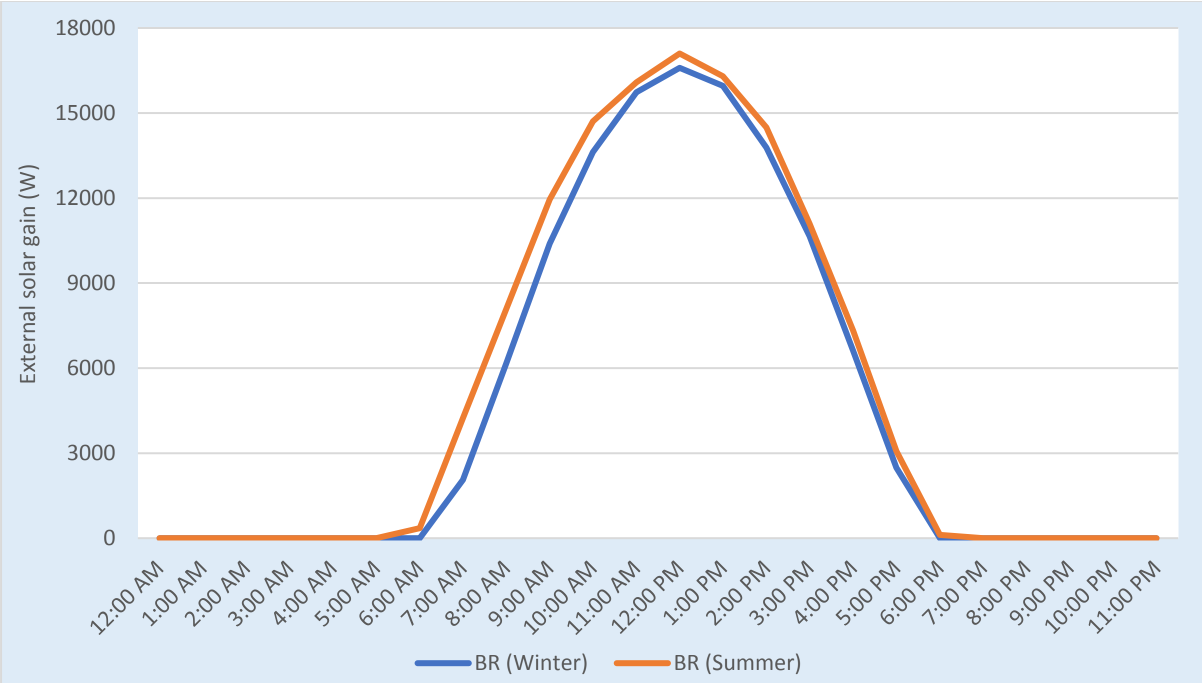

Figure 7.1.4. Externa solar gain on fabric (roof) of the bedroom in winter and summer (W)

Finally, heat loss/gain through the external walls' components in the guest room and bedroom of both a summer and a winter day shows larger amount of heat gain and loss than all the other building components. This explained in detail in figures 7.1.5 and 7.1.6 which illustrate heat loss/gain through every external walls' components in the guest room and bedroom of both a summer and a winter day. In winter, the thermal analysis reveals that heat gain through walls increases gradually from early in the morning, reaching its peak at midday for the south facing walls, then declines and ends approximately later in the afternoon. In summer, the trend of heat conduction through walls is quite similar to that in winter. Heat conduction in the external walls was greater in winter than in summer. This is attributed to the lower angle of the sun, which enables its direct radiation to reach the external walls in an orthogonal angle. This has resulted in massive heat conduction through the external wall which, perhaps, leads to increase in indoor condition. To confirm this, the sun bath diagram of Makkah for the two chosen days for the fieldwork and the simulation which represent winter and summer (26th February and 7th September) at the three set times (9:00 - 12:00 and 15:00) is presented in figure 7.1.7. The result produced by grasshopper software emphasises the claim that the solar angle of the sun in winter has up to a 15° lower altitude. The altitude angles for all the six readings are taken manually from the software and presented in table 7.1.2.

Table 7.1.2. The altitude angles for all the six times in Makkah

Times	9:00	12:00	15:00
winter	29°	57.9°	42.6°
summer	39.5°	73.5°	47.8°

Furthermore, the south facing walls in both rooms have the maximum heat gain by conduction during the daytime, and also has the maximum heat loss later in the evening. A positive correlation was found between TAS and monitored variables. As presented in Chapter six, south-facing walls have slightly higher inner surface temperatures than west facing walls in both rooms. In both summer and winter, there is major heat conduction through the roof. However, it is much less on external walls when considering opaque surfaces only.

Finally, the external solar gain on the external walls follows the same pattern of the heat conduction in both seasons as south walls are exposed to more solar gain. Also, the bedroom's solar gain has slightly higher figures due to its location on the first floor compared to the guestroom in the ground floor (see figures 7.1.8 and 7.1.9).

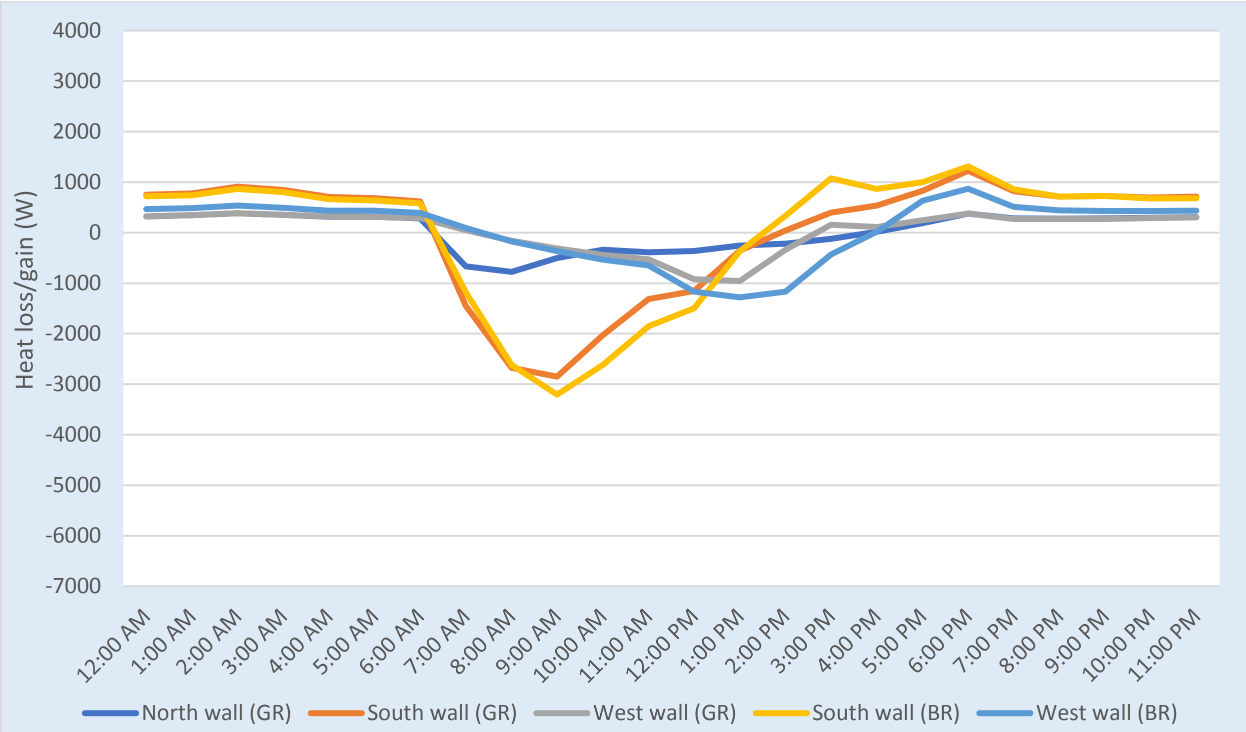

Figure 7.1.5. Heat conduction through fabric (walls) in the guestroom and bedroom in winter (W)

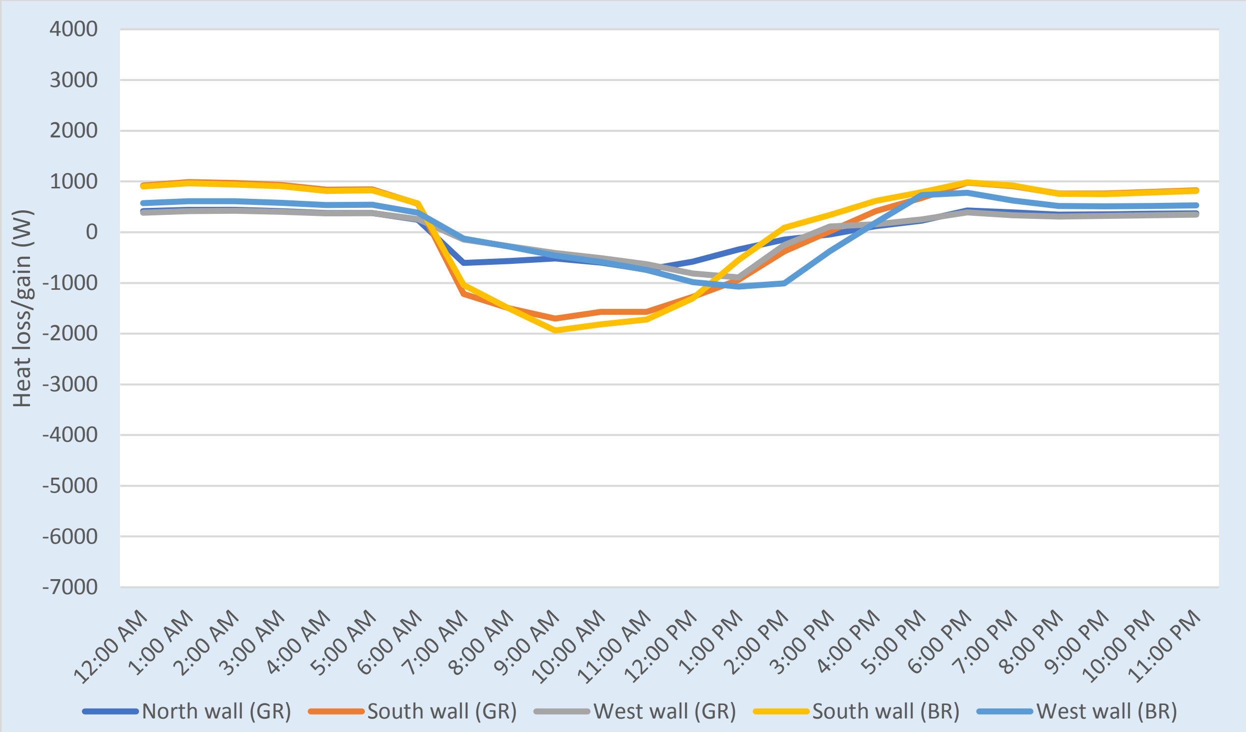

Figure 7.1.6: Heat conduction through fabric (walls) in the guestroom and bedroom in summer (W)

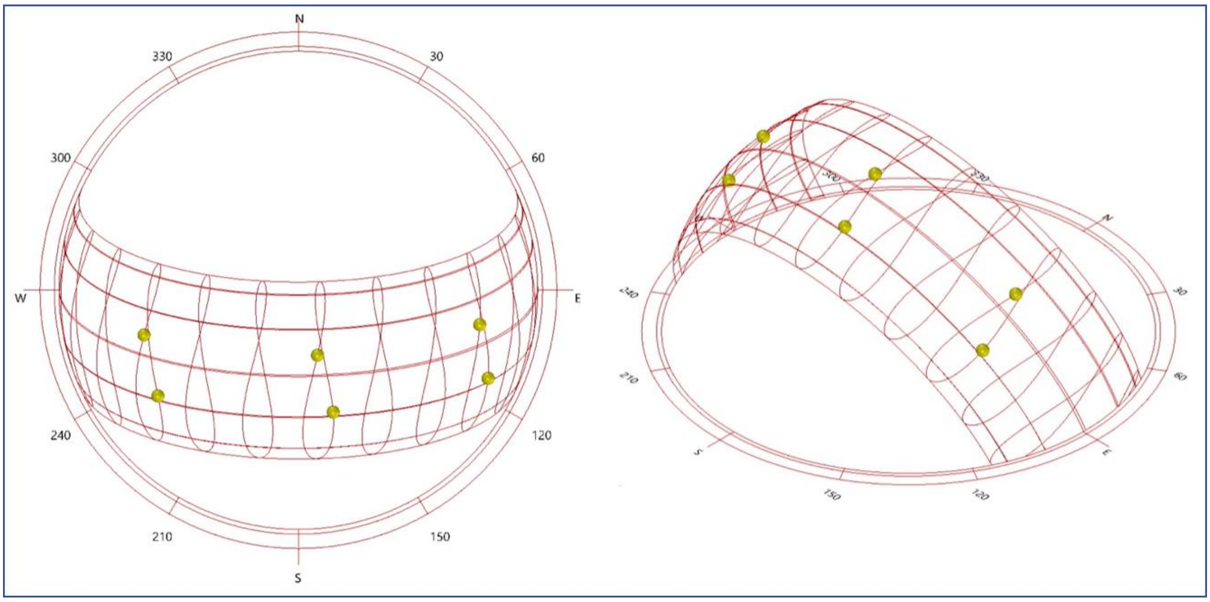

Figure 7.1.7. The sun path diagram of Makkah (Author generated from grasshopper software) (grasshopper, 2020)

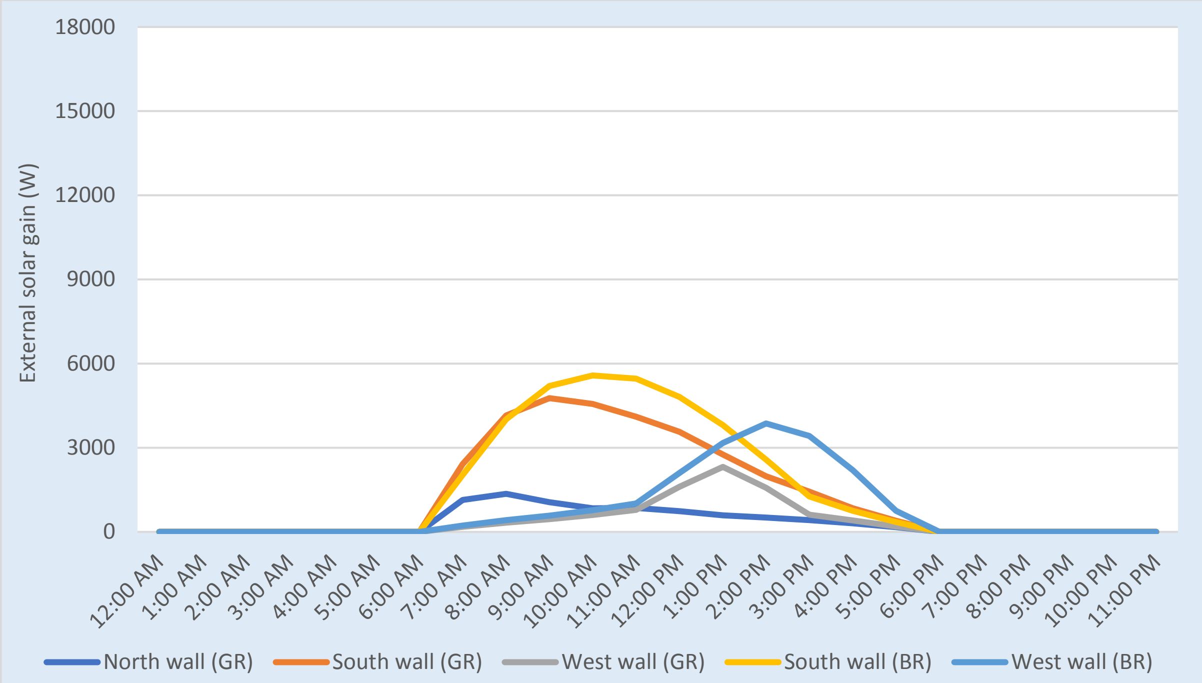

Figure 7.1.8. External solar gain on fabric (walls) in the guestroom and bedroom in winter (W)

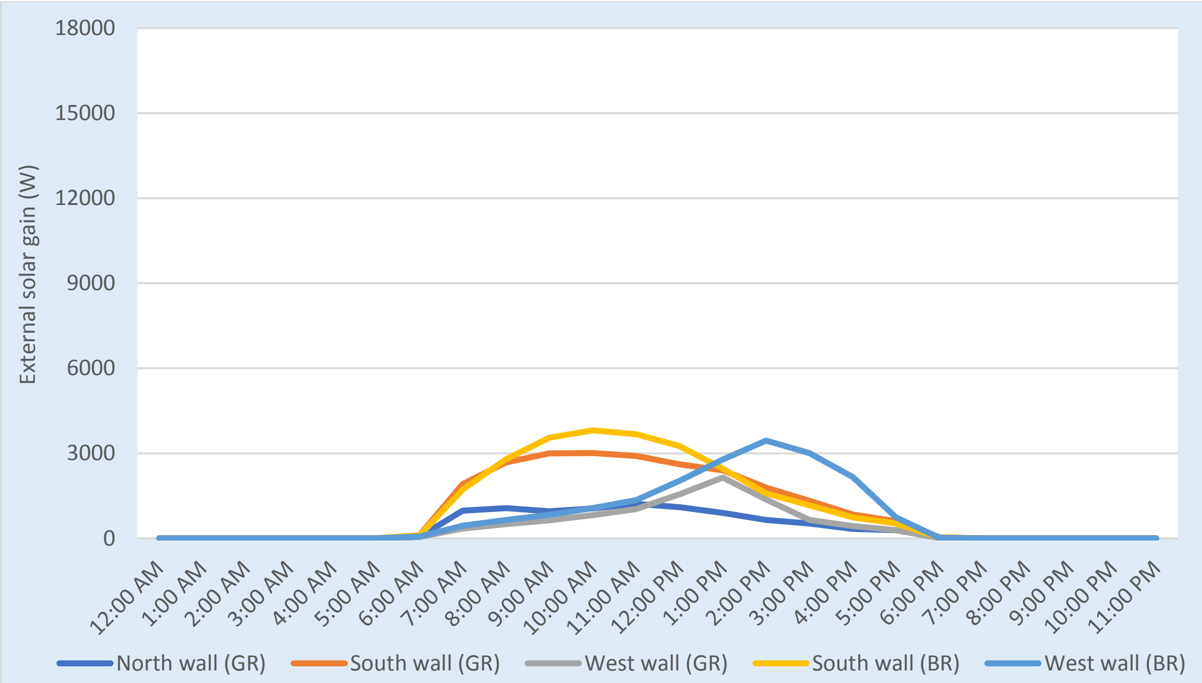

Figure 7.1.9. External solar gain on fabric (walls) in the guestroom and bedroom in summer (W)

7.2. The house in Jeddah

7.2.1. Dry bulb temperature

The same rooms chosen for the fieldwork are chosen here for the same days and hours. The case study building is modelled (figure 7.2) using thermal analysis software (EDSL TAS version 9.4.2).

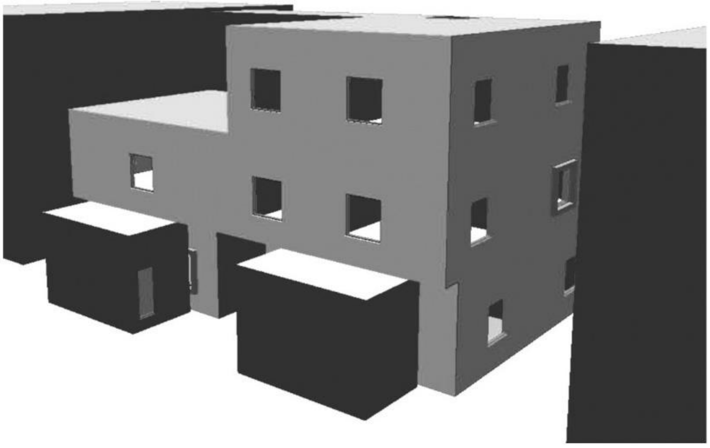

Figure 7.2. Snapshot of the house 3D model in TAS

The readings indicated similar internal temperatures for the guest room and bedroom (see figures 7.2.1 and 7.2.2). In winter, peaks and troughs are the same for the whole days monitored. In summer, peaks in the guest room are the same with relatively low temperatures, while troughs are up to 2 k lower than the measured result. The most striking point is bedroom which has higher simulated temperature of over 2 ˚C the whole time. This because the nearby rooms and the corridor during the fieldwork were air conditioned. The root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods were calculated in table 7.2.1. The NMBE was lower than the 10% limit and the RMSE was lower than the 30% limit set by ASHRAE. It is thus safe to assume that the simulated results are within the acceptable range.

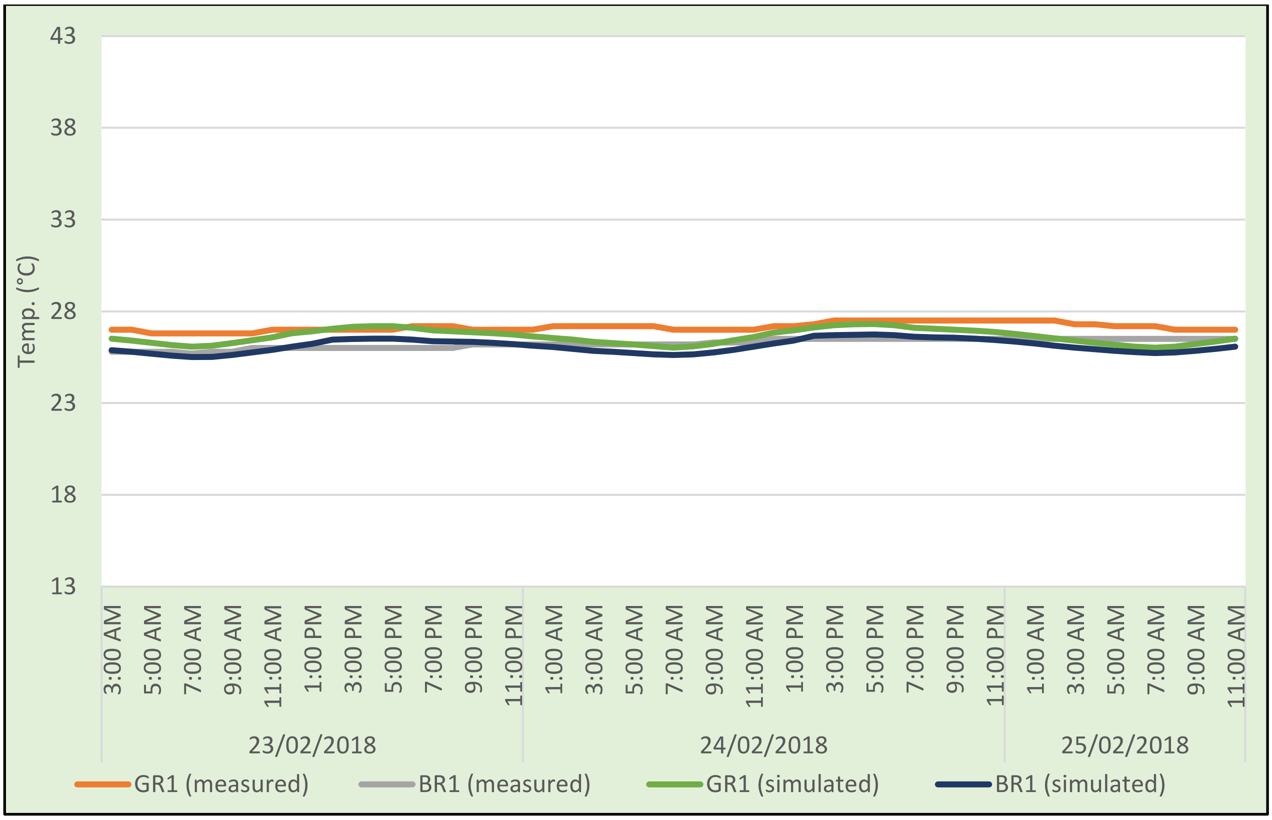

Figure 7.2.1. Measured and simulated DBT temperature of the house in Jeddah's selected rooms in winter (˚C)

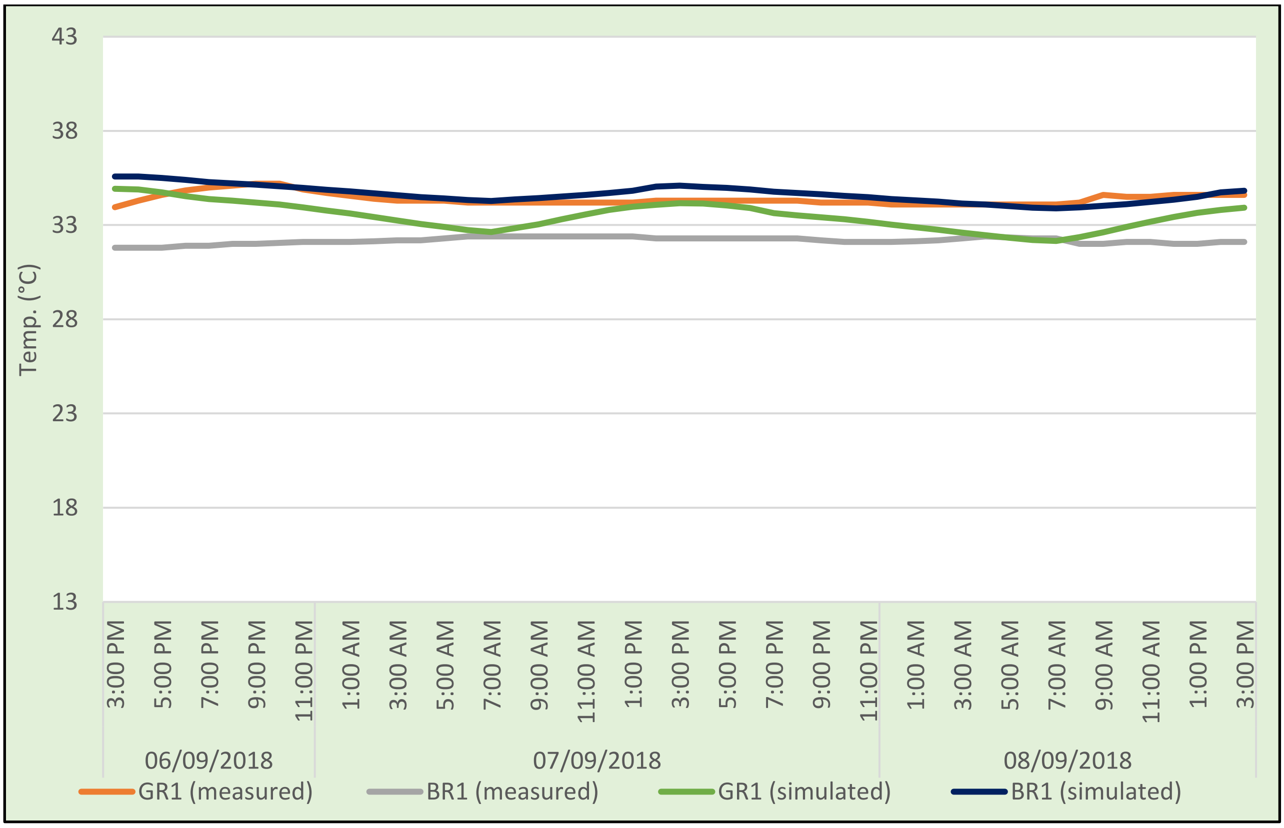

Figure 7.2.2. Measured and simulated DBT temperature of the house in Jeddah's selected rooms summer (˚C)

Table 7.2.1. Calculated the root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods.

room	Season	RMSE	Average RMSE	NMBE	Average NMBE
Guest room	Winter	3.9	5.2	1.1	1.2
	Summer	6.4		1.3	
Bedroom	Winter	0.9	9.1	0.2	-1.7
	Summer	17.2		-3.7	

7.2.2. Heat conduction through fabrics

The top floor (2nd floor) of the house in Jeddah were removed in the simulation mainly to quantify the heat conduction through the roof above the bedroom on the 1st floor. Figure 7.2.3 provides heat loss/gain through the floor, roof and external walls components in the guest room and the first floor as it is on the ground floor and the 1st floor during both a summer and a winter day.

Heat loss/gain through the floor component in the guest room on the ground floor during both a summer and a winter day shows relatively small amount of heat gain and heat loss. In winter, the thermal analysis revealed that heat gain through floor occurs all the time, where it is quite stable all the time. This means that the internal surface temperature of the floors is lower than the external surface temperature of the floors (Le. the surface which is exposed to the soil). This could be explained by the fact that, in winter, the temperature of the ground is higher than the external air temperature. In summer, heat flow through floor differs from that in winter, as heat loss takes place through floors most of the time in summer. This could be explained by that, in summer, the temperature of the ground is lower than the external air temperature.

Heat loss/gain through the roof component in the bedroom on the 1st floor, as it is exposed to the outdoor, during both a summer and a winter day. illustrates a relatively huge amount of heat gain and heat loss through the roof. Heat gain through roof starts in the morning as the roof exposes to solar radiation and ends late in the afternoon; then heat loss takes place as the outside temperature falls in both winter and summer.

Figure 7.2.3. Heat conduction through building fabrics (floor, roof and external walls) in the guest room and bedroom in winter and summer (W)

Finally, heat loss/gain through the external walls' components in the guest room and bedroom of both a summer and a winter day shows larger amount of heat gain and loss than all the other building components. This explained in detail in figures 7.2.4 and 7.2.5 that provide heat loss/gain through each external walls' components in the guest room and bedroom during both a summer and a winter day. In winter, the thermal analysis revealed that heat gain through walls increases gradually from early in the morning reaching its peak at the midday for the north wall in the guest room, then declines and ceases in late afternoon. In summer, the trend of heat conduction through walls is quite similar to that in winter. North wall heat conduction has greater figures compared to the other walls and that due to its bigger area exposure (23.8 m2) compared to the other east and west walls in the same room (GR1) and the west wall in the bedroom (BR1) which have 16.3 m2, 7.4 m2 and 11.6 m2 respectively.

Furthermore, the north wall in the guest room has the maximum heat gain by conduction during the daytime and the maximum heat loss late in the evening. A positive correlation was found between TAS and monitored variables. As stated in Chapter 6 that north-facing wall was alongside the east wall in the guest room has slightly highest inner surface temperatures than the west facing wall in the bedroom. It can be revealed that in both summer and winter, heat conduction through the roof is major. However, it is slightly less than external walls when considering opaque surfaces only.

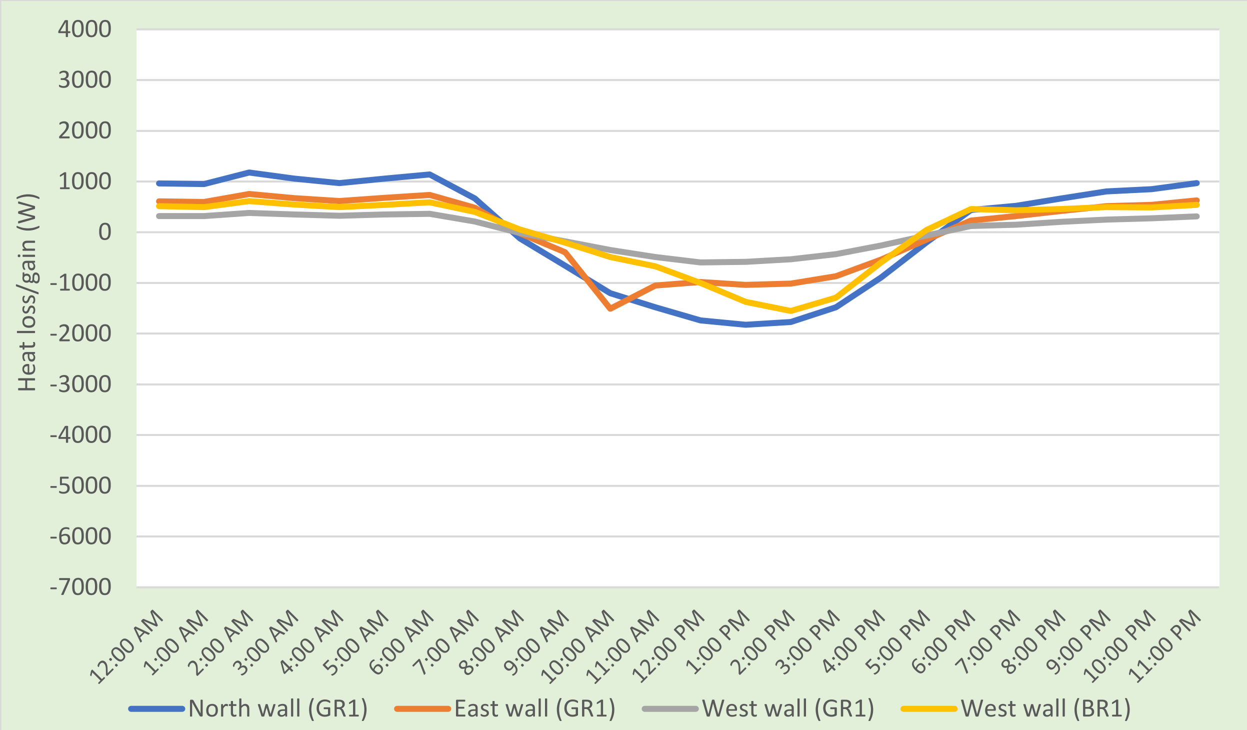

Figure 7.2.4. Heat conduction through fabric (walls) in the guestroom and bedroom in winter (W)

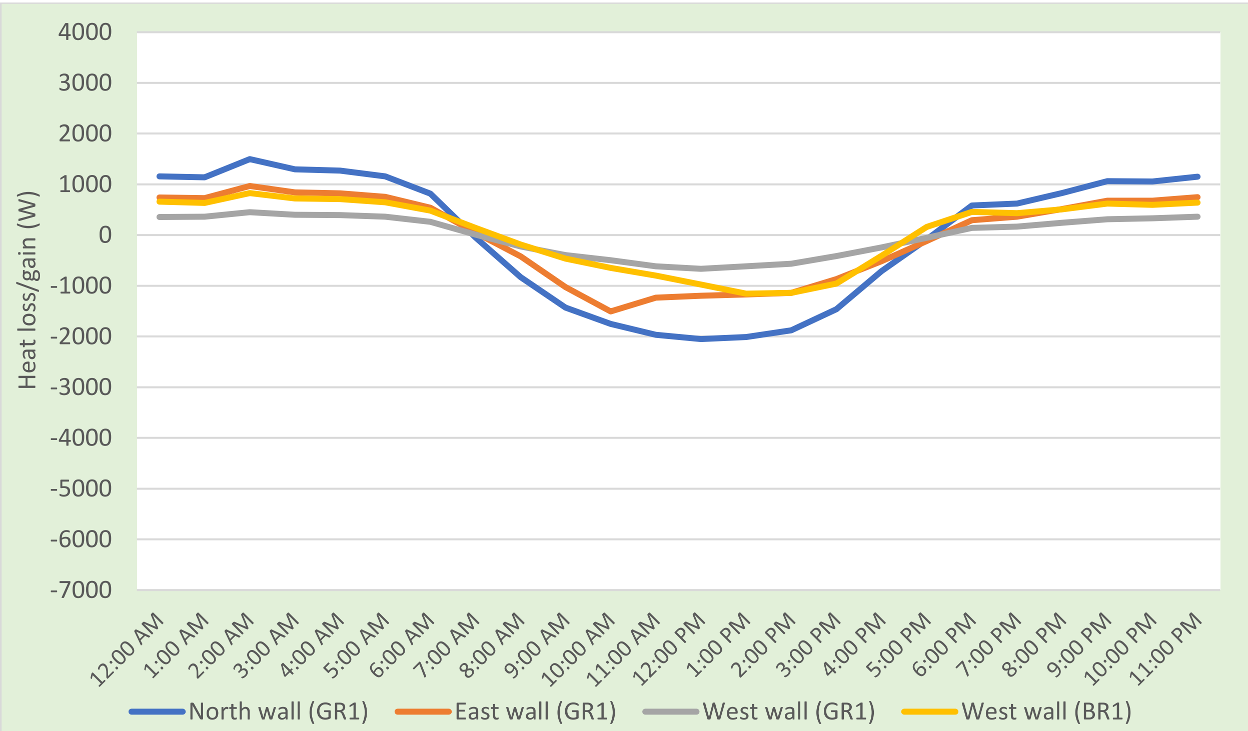

Figure 7.2.5. Heat conduction through fabric (walls) in the guestroom and bedroom in summer (W)

7.3. The house in Riyadh

7.3.1. Dry bulb temperature

The same rooms chosen for the fieldwork are chosen here for the same days and hours. The case study building is modelled (figure 7.3) using thermal analysis software (EDSL TAS version 9.4.2).

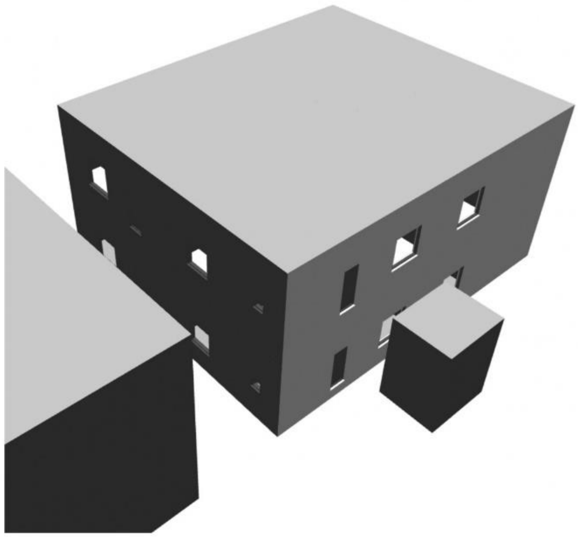

Figure 7.3. Snapshot of the house 3D model in TAS

The results indicate similar internal temperatures behaviours for the 1st guest room and 2nd guest room (see figures 7.3.1 and 7.3.2). In winter, peaks and troughs have relatively lower temperatures of around 2 k than the measured result. In summer, peaks and bottoms are the same for the whole monitoring days. The most striking point is the use of the A/C in four periods for the 2nd guest room and one period for the 1st guest room which cause the differential figures. The root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods were calculated in table 7.3.1. The NMBE was lower than the 10% limit and the RMSE was lower than the 30% limit set by ASHRAE. It is thus safe to assume that the simulated results are within the acceptable range.

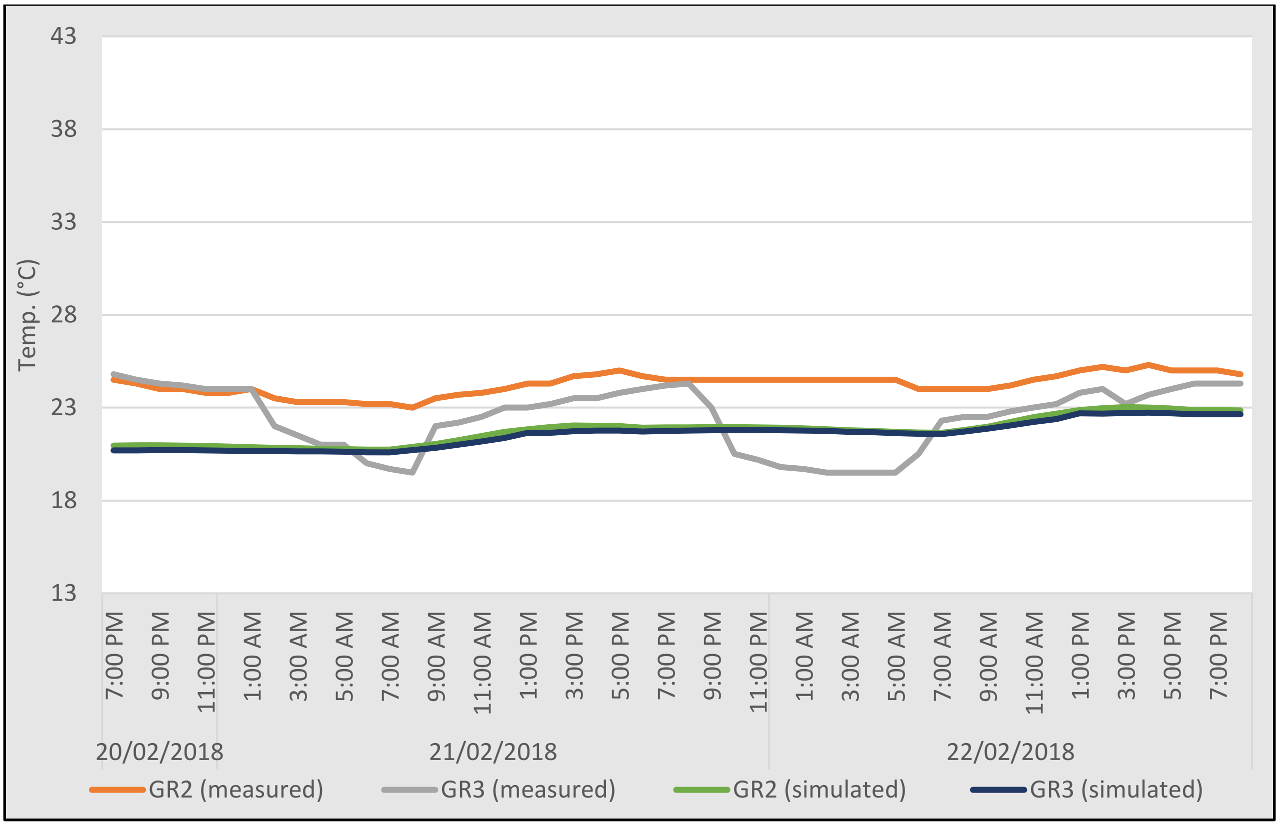

Figure 7.3.1. Measured and simulated DBT temperature of the house in Riyadh's selected rooms in winter (˚C).

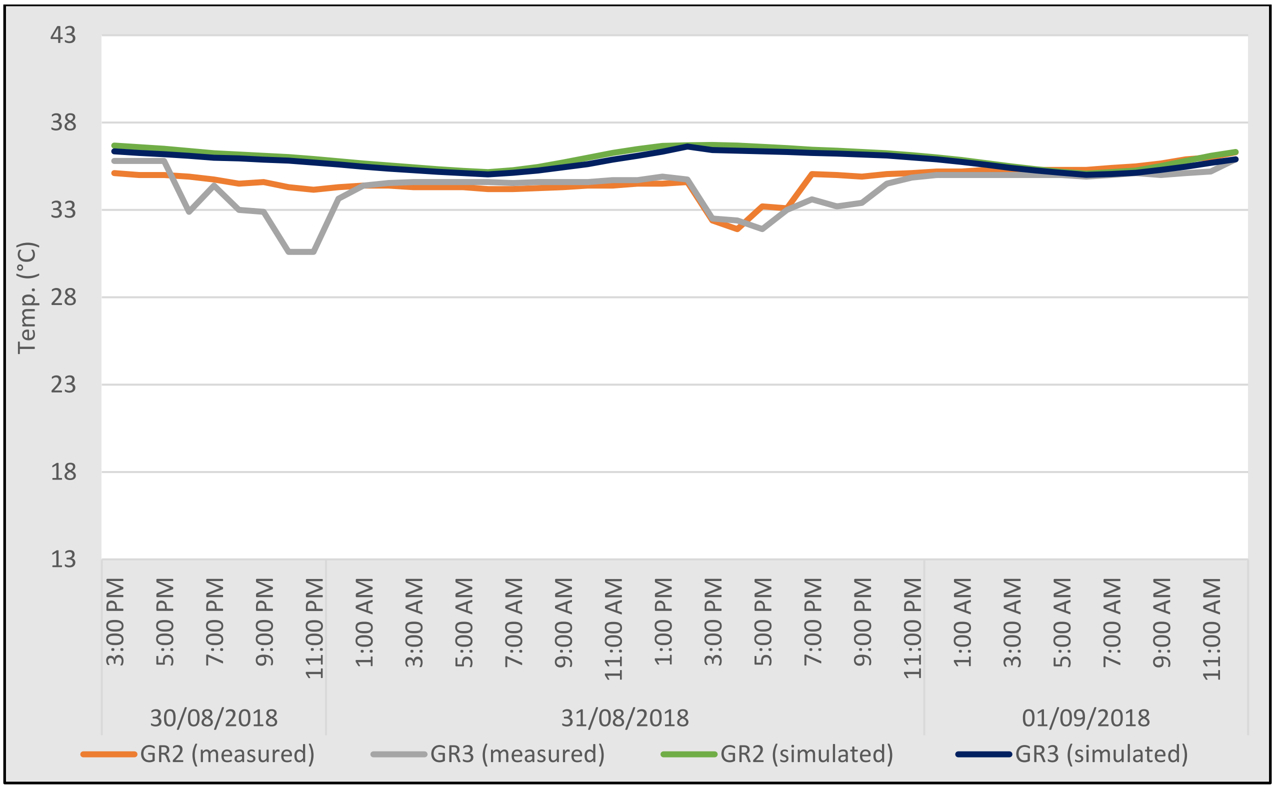

Figure 7.3.2. Measured and simulated DBT temperature of the house in Riyadh's selected rooms in summer (˚C).

Table 7.3.1. Calculated the root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods.

room	Season	RMSE	Average RMSE	NMBE	Average NMBE
1st guest room	Winter	17.73	13.23	5.16	1.72
	Summer	8.73		-1.70	
2nd guest room	Winter	6.39	8.26	2.01	0
	Summer	10.13		-2	

7.3.2. Heat conduction through fabrics

The top floor (1st floor) of the house in Riyadh was removed in the simulation mainly to quantify the heat conduction through the roof above the two guest rooms on the ground floor. Figure 7.3.3 provides heat loss/gain through the floor, roof and external walls components in the guest rooms as it is on the ground floor during both a summer and a winter day. Heat loss/gain through the floor component in the guest rooms on the ground floor during both a summer and a winter day shows relatively small amount of heat gain and heat loss. In winter, the thermal analysis revealed that heat gain through floor occurs all the time, where it is quite stable all the time. This means that the internal surface temperature of the floors is lower than the external surface temperature of the floors (Le. the surface which is exposed to the soil). This could be explained by the fact that, in winter, the temperature of the ground is higher than the external air temperature. In summer, heat flow through floor differs from that in winter, as heat loss takes place through floors most of the time in summer. This could be explained by that, in summer, the temperature of the ground is lower than the external air temperature. Heat loss/gain through roof component in the guest rooms shows the highest amount of heat gain and heat loss through any other building fabrics, while heat flow through external walls components come second after the roof components. The roof and external walls heat conduction will be explained in detail in the following figures.

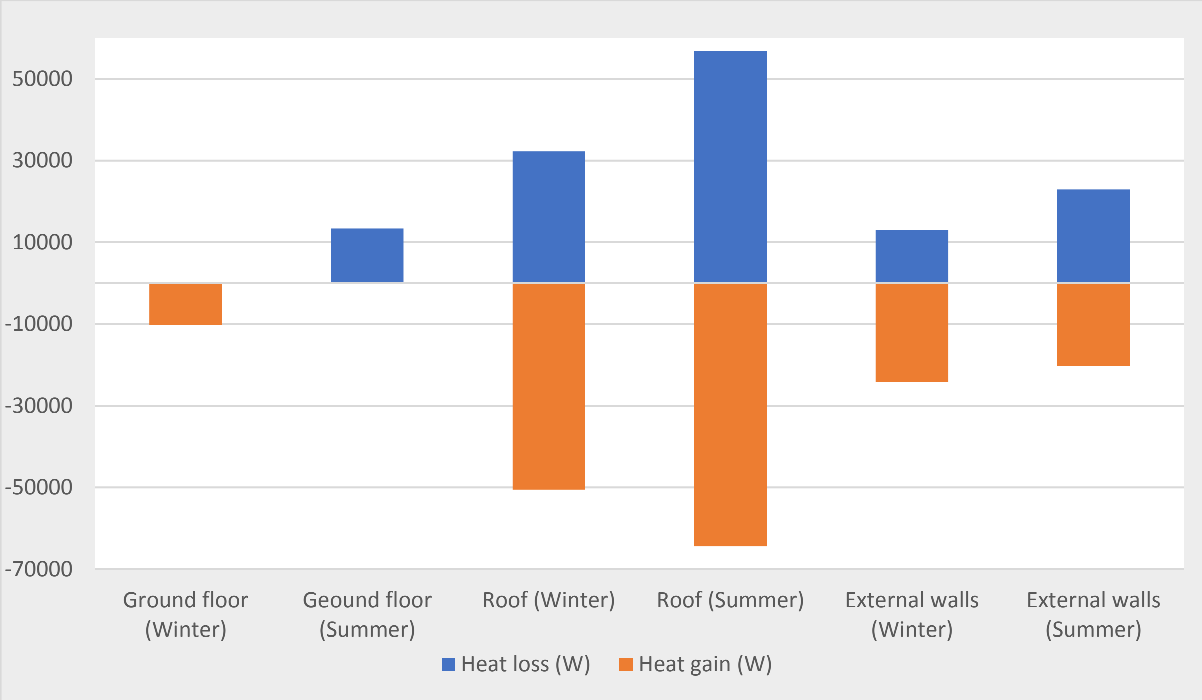

Figure 7.3.3. Heat conduction through building fabrics (floor, roof and external walls) in the 1st and 2nd guest rooms in winter and summer (W)

Figure 7.3.4 provides heat loss/gain through the roof component in the 1st and 2nd guest rooms, as it is exposed to the outdoor, during both a summer and a winter day. There is relatively huge amount of heat gain and heat loss through the roof. Heat gain through roof starts in the morning (at 7:00hr) as the roof exposes to solar radiation and ends in the afternoon (at 15:00hr); then heat loss takes place as the outside temperature falls down in both winter and summer. The first guestroom (GR2) has greater heat flow than the other room and this could be explained by the fact that the second guestroom (GR3) is smaller in the area (14.6 m2) than the first guestroom (20.3 m2).

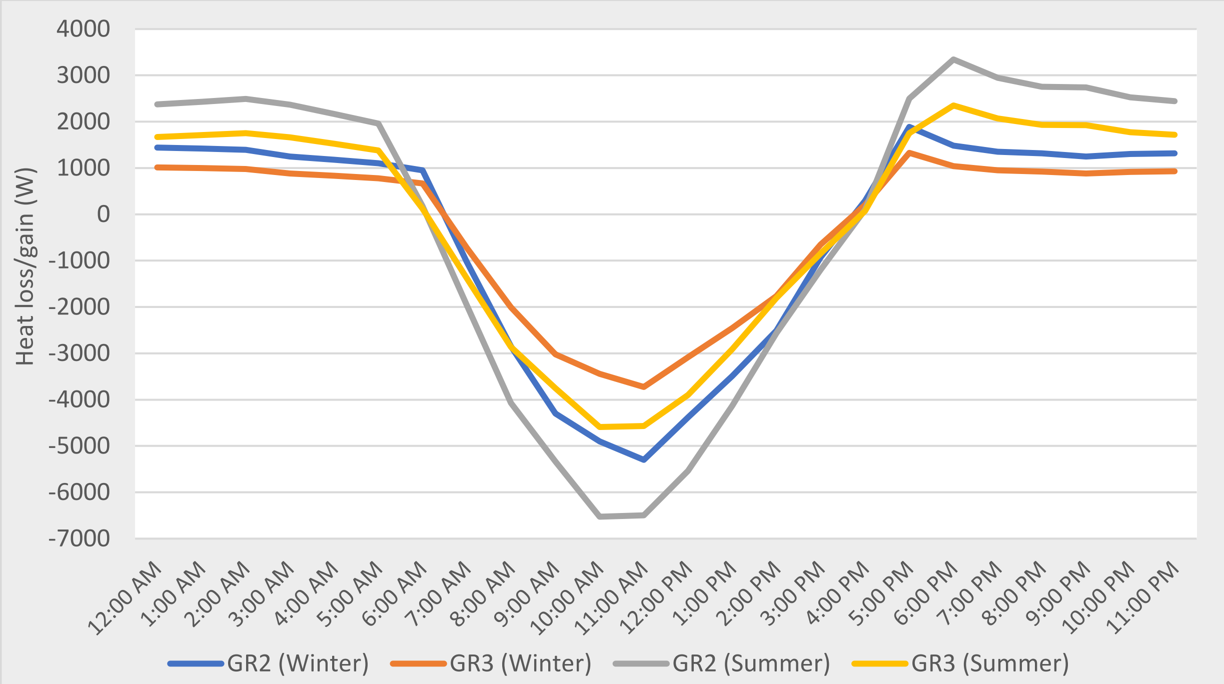

Figure 7.3.4. Heat conduction through fabric (roof) in 1st and 2nd guest rooms in winter and summer (W)

Figures 7.3.5 provides heat loss/gain through the external walls' components 1st and 2nd guest rooms during both a summer and a winter day. In winter, the thermal analysis revealed that heat gain through walls increases gradually from early in the morning reaching its peak at the mid of the day for the south wall in the 1st guest room, then declines and approximately ends later in the afternoon. In summer, Trend of heat conduction through walls is quite similar to that in winter.

South facing wall heat conduction was slightly greater in both seasons compared to the west wall and that because the south facing orientation receives huge amount of solar radiation. Also, during winter, heat conduction for the walls is greater than summer. This is attributed to the lower angle of the sun, which enables its direct radiation to reach the external walls in an orthogonal angle. This has resulted in massive heat conduction through the external wall which, perhaps, leads to increase in indoor condition. To confirm this, the sun bath diagram of Riyadh for the two chosen days for the fieldwork and the simulation which represent winter and summer (21st February and 1st September) at the three set times (9:00 - 12:00 and 15:00) is presented in figure 7.3.6. The result which taken from grasshopper software emphasis the claim that solar angle of the sun in winter has up to 15° lower altitude. The altitude angles for all the six times are taken manually from the software and presented in table 7.3.2.

Table 7.3.2. The altitude angles for all the six times in Riyadh

Times	9:00	12:00	15:00
winter	33.1°	55.8°	35.6°
summer	44.8°	70.8°	40.8°

A positive correlation was found between TAS and monitored variables. As presented in Chapter six, the south-facing wall in the 1st guest room had slightly higher inner surface temperatures than the west facing wall in the 2nd guest room. In both summer and winter heat conduction through the roof is major. However, it is much less on external walls when considering opaque surfaces only.

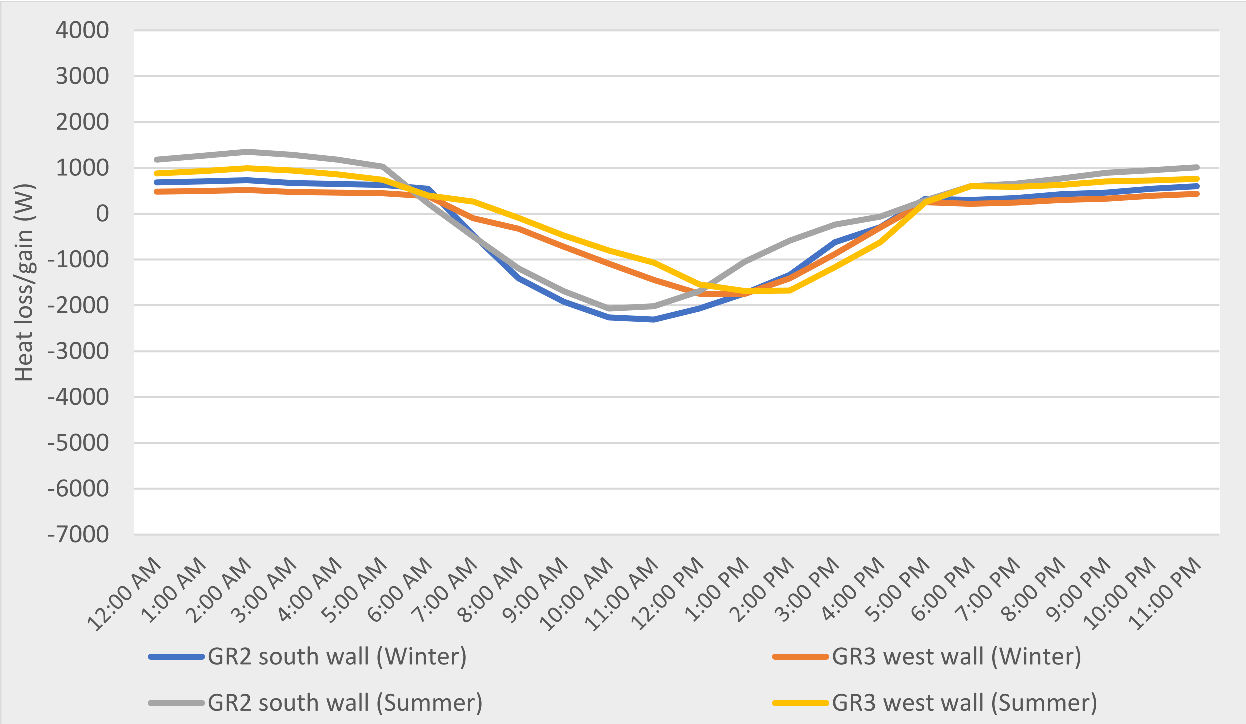

Figure 7.3.5. Heat conduction through fabric (walls) in 1st and 2nd guest rooms in winter and summer (W).

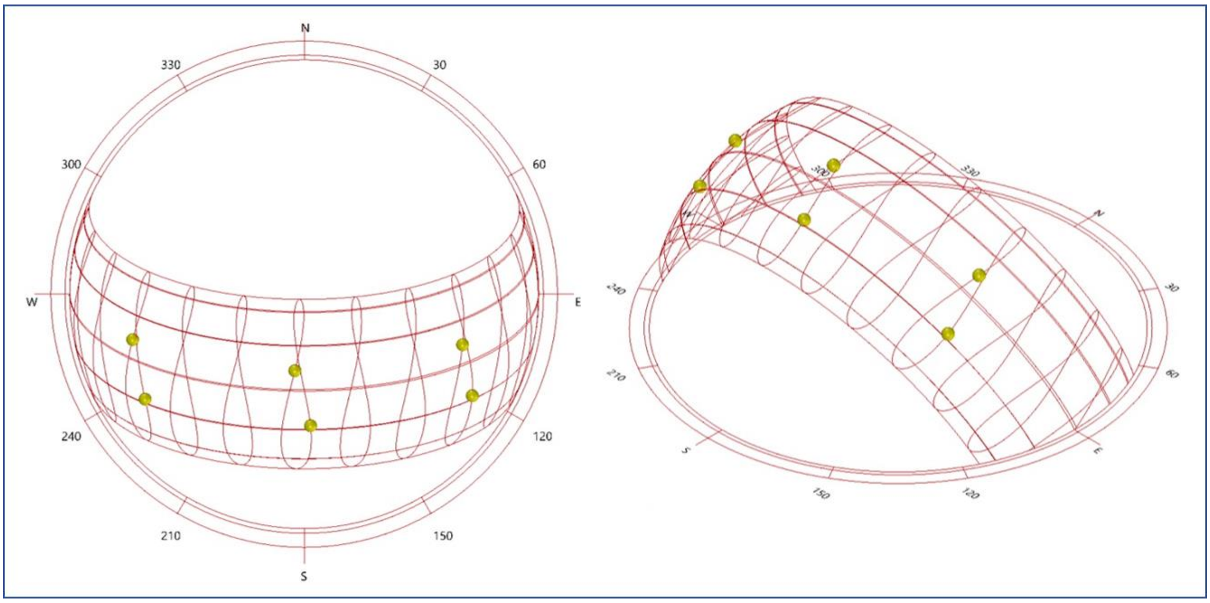

Figure 7.3.6. The sun path diagram of Riyadh (Author generated from grasshopper software) (grasshopper, 2020)

7.4. Calibration of the house in Taif

7.4.1. Dry bulb temperature

The same rooms chosen for the fieldwork are chosen here for the same days and hours. The case study building is modelled (figure 7.4) using thermal analysis software (EDSL TAS version 9.4.2).

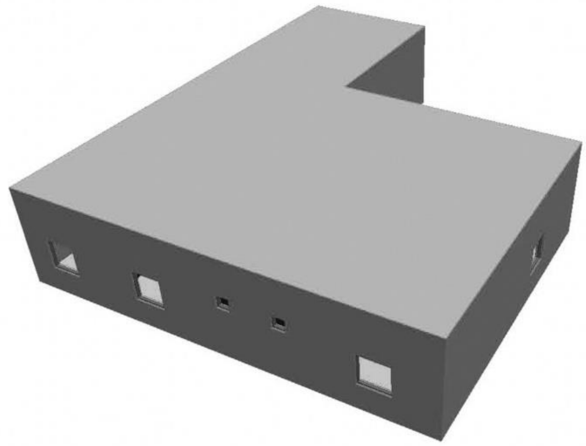

Figure 7.4. Snapshot of the house 3D model in TAS

The calibration results achieved similar internal temperatures behaviours for the 1st bedroom and 2nd bedroom (see figures 7.4.1 and 7.4.2). In winter, peaks and bottoms are the same for the first two days for the 1st bedroom but has slightly lower temperatures in the last 12 hours of monitoring, while the 2nd bedroom has the same temperatures for the first 12 hours of monitoring but later, the peak and troughs simulated results were up to 2 and 1 k higher than the measured ones respectively. In summer, peaks and troughs were constantly higher by 3 and 1.5 k respectively. The reason for plotting the simulated results in this way was to verify and calibrate the analytic work. The root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods were calculated in table 7.4.1. The NMBE+ was lower than the 10% limit and the RMSE was lower than the 30% limit set by ASHRAE. It is thus safe to assume that the simulated results are within the acceptable range.

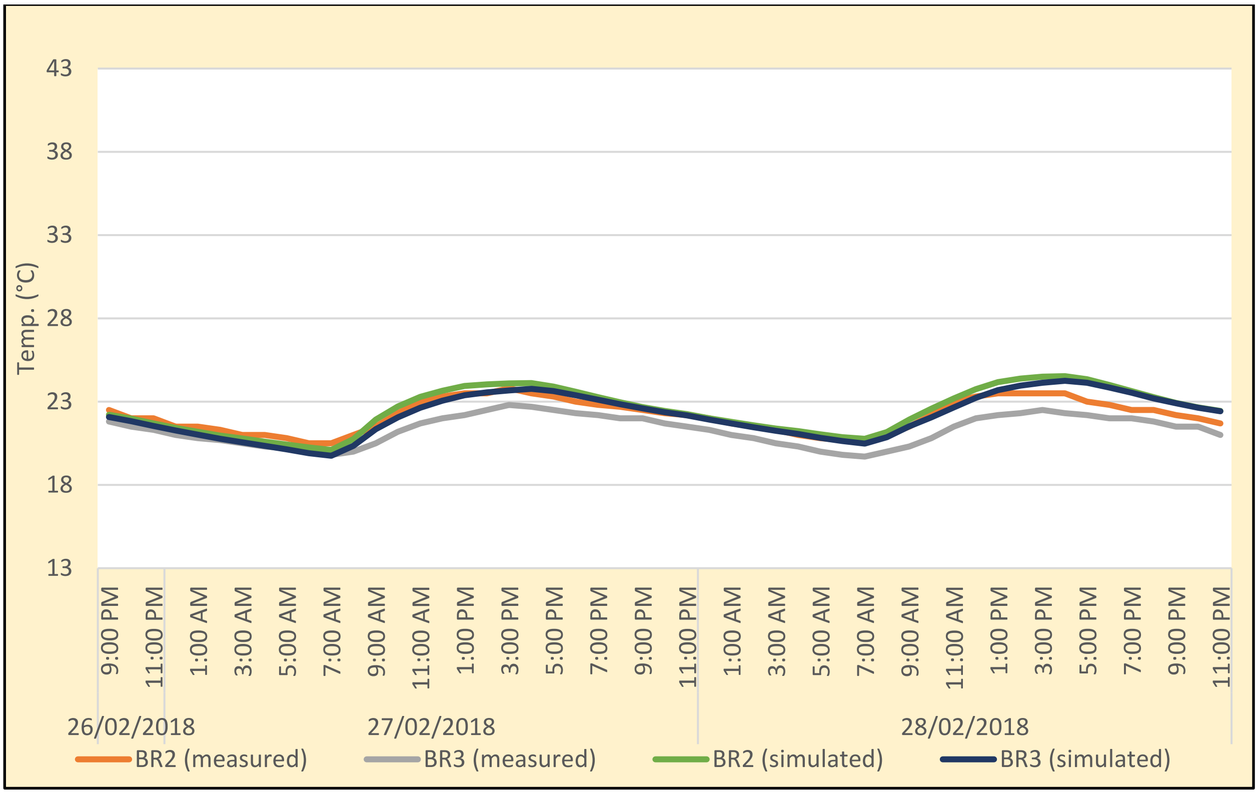

Figure 7.4.1. Measured and simulated DBT temperature of the house in Taif's selected rooms in winter (˚C).

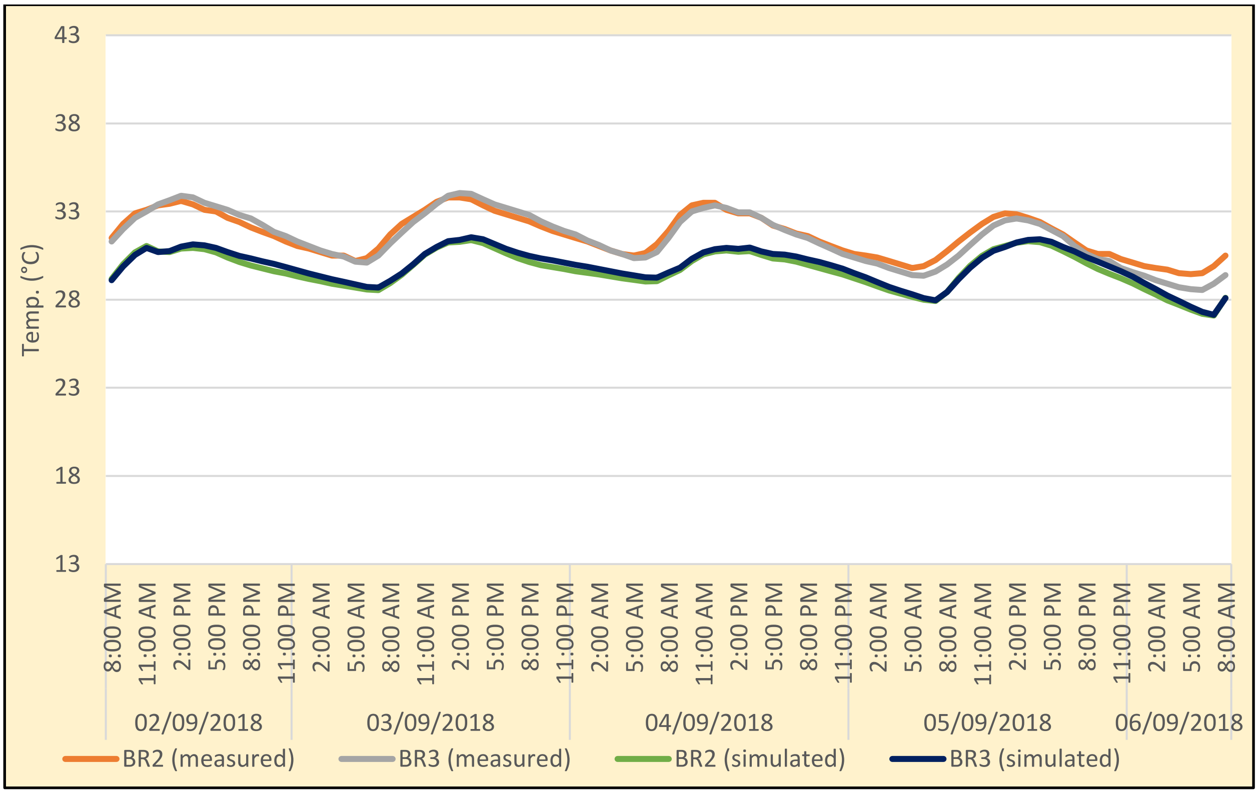

Figure 7.4.2. Measured and simulated DBT temperature of the house in Taif's selected rooms in summer (˚C).

Table 7.4.1. Calculated the root mean square error (RMSE) percentage and normalized mean bias error (NMBE) percentage using two methods.

room	Season	RMSE	Average RMSE	NMBE	Average NMBE
1st bedroom	Winter	2.1	10.6	-0.6	2.6
	Summer	19.2		5.9	
2nd bedroom	Winter	6.2	11	-2	1.4
	Summer	15.8		4.9	

7.4.2. Heat conduction through fabrics

Figure 7.4.3 illustrates heat loss/gain through the floor, roof and external walls components in the 1st and 2nd bedrooms in the course of both a summer and a winter day. Heat loss/gain through the floor component shows relatively small amount of heat gain and heat loss. In winter, the thermal analysis revealed constant minimal heat gain through the floor. This means that the internal surface temperature of the floors is lower than their external surface temperature (i.e. the surface exposed to the soil). This could be explained by the fact that, in winter, the ground temperature is higher than the external air temperature. In summer, heat loss occurs through floors most of the time. This could be explained by that, in summer, ground temperature is lower than the external air temperature.

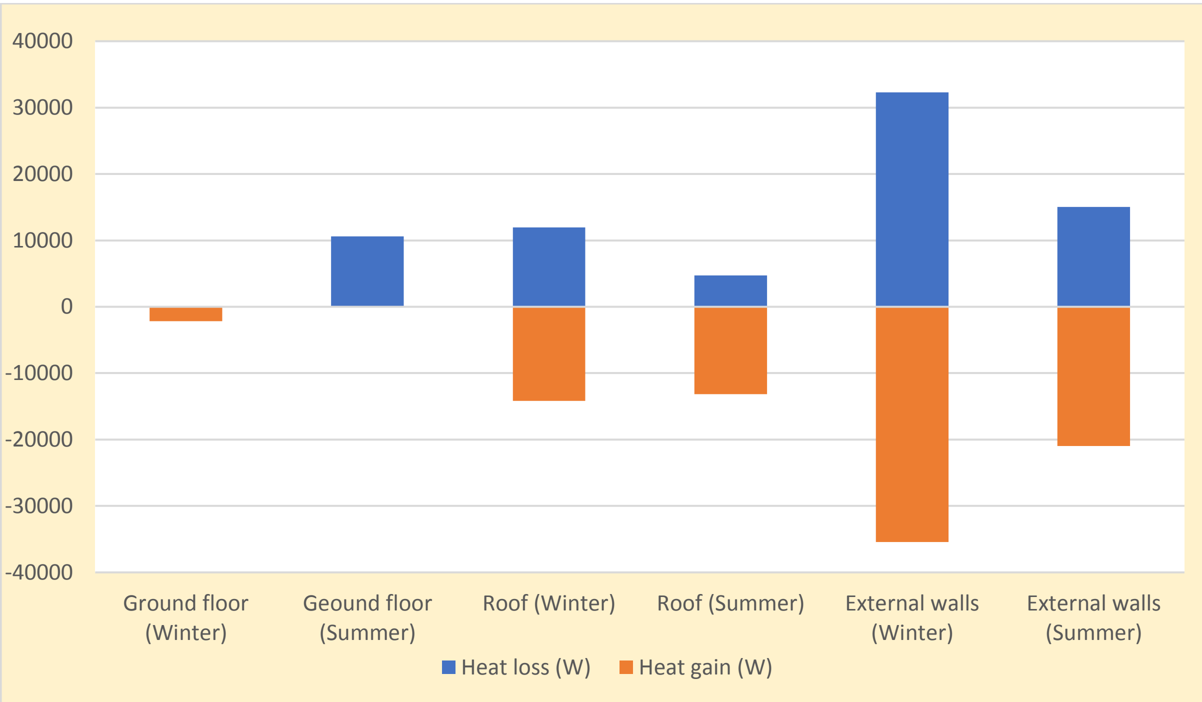

Figure 7.4.3. Heat conduction through building fabrics (floor, roof and external walls) in the 1st and 2nd bedrooms in winter and summer (W)

Heat loss/gain through the exposed roof component in the 1st and 2nd bedrooms, for both a summer and winter day shows high amount of heat flow. Heat gain via the roof commences in the morning and ceases later in the afternoon; then heat loss takes place as the outside temperature falls in both winter and summer. A positive correlation was found between TAS and monitored variables as discussed in Chapter six.

Finally, heat loss/gain through the external walls' components shows larger amount of heat gain and loss than all the other building components. This explained in detail in figures 7.4.4 and 7.4.5 that illustrate heat loss/gain through the external walls' components in the 1st and 2nd bedrooms in the course of a summer and winter day. In winter, the thermal analysis revealed heat gain through the walls increases gradually, reaching its peak (at 9:00hr) for the east walls, then declines and approximately ends later (at 17:00hr).

In summer, heat conduction through walls follows a similar trend to winter but has approximately half the heat gain compared to winter. This is attributed to the lower angle of the sun, which enables its direct radiation to reach the external walls in an orthogonal angle. This has resulted in massive heat conduction through the external wall which, perhaps, leads to increase in indoor condition. To confirm this, the sun bath diagram of Taif for the two chosen days for the fieldwork and the simulation which represent winter and summer (27th February and 3rd September) at the three set times (9:00 - 12:00 and 15:00) is presented in figure 7.4.6. The result, taken from grasshopper software, confirms the claim that the angle of the sun in winter is up to 15° lower altitude. The altitude angles for all the six times are taken manually from the software and presented in table 7.4.2.

Table 7.4.2. The altitude angles for all the six times in Taif

Times	9:00	12:00	15:00
winter	29.6°	58.1°	42.1°
summer	40.1°	73.7°	47.1°

Finally, the external solar gain on the external walls follows the same pattern of the heat conduction in both seasons as east facing walls are exposed to more solar gain (see figure 7.4.7 and 7.4.8). A positive correlation was found between TAS and monitored variables. As presented in Chapter 6, east walls have slightly higher inner surface temperatures than north facing wall. It can be revealed that in winter, heat conduction through the walls is major and double that of the roof considering opaque surfaces only.

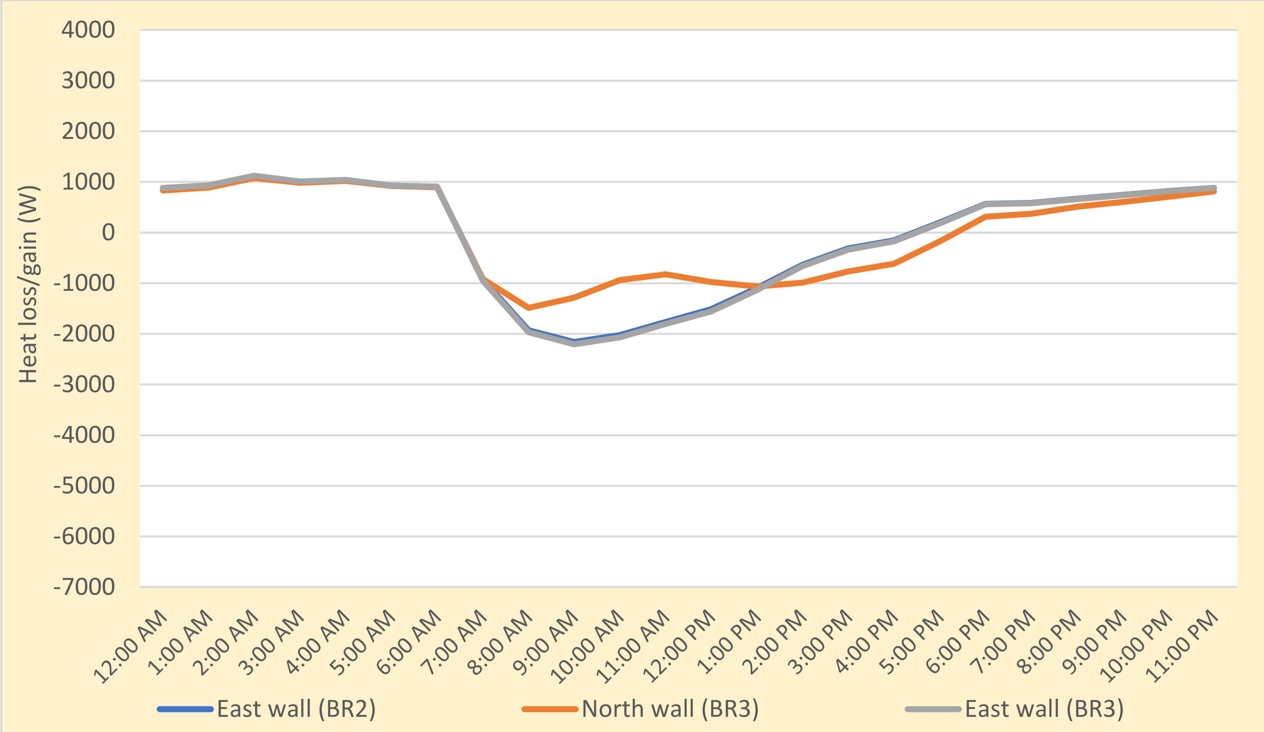

Figure 7.4.4. Heat conduction through fabric (walls) in the 1st and 2nd bedrooms in winter (W)

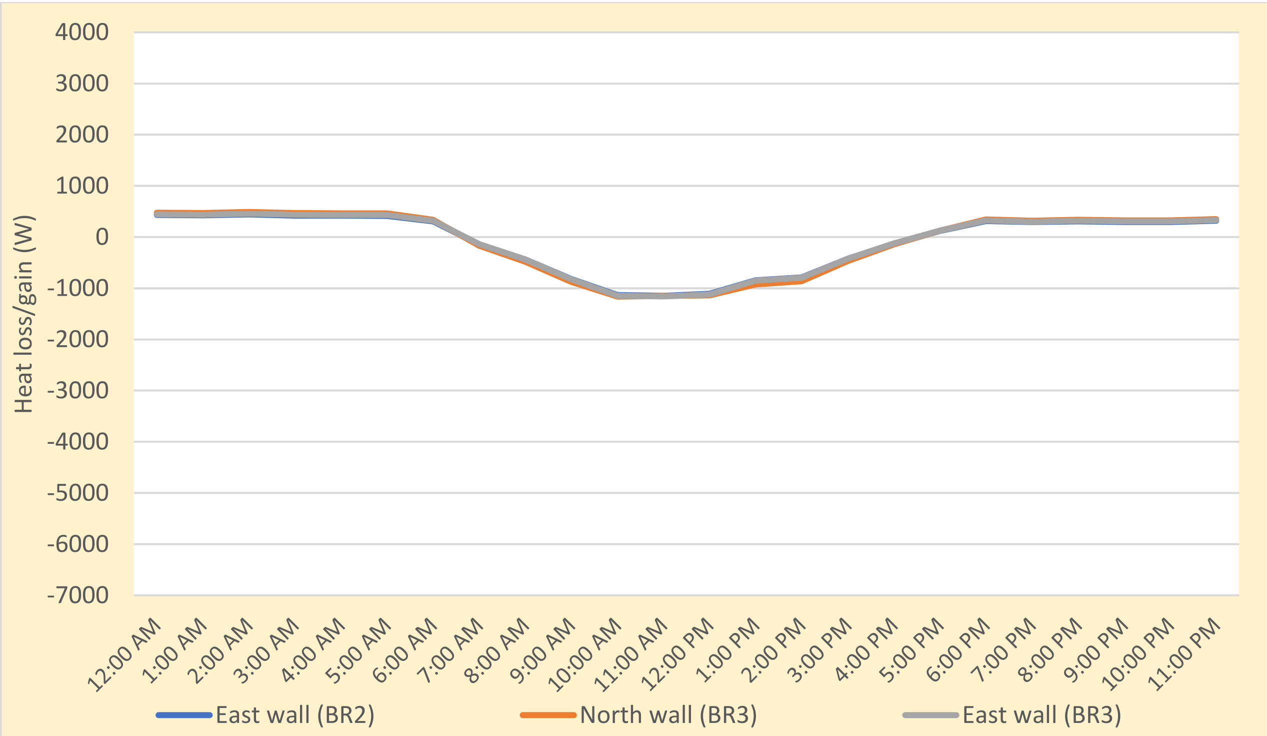

Figure 7.4.5. Heat conduction through fabric (walls) in the 1st and 2nd bedrooms in summer (W)

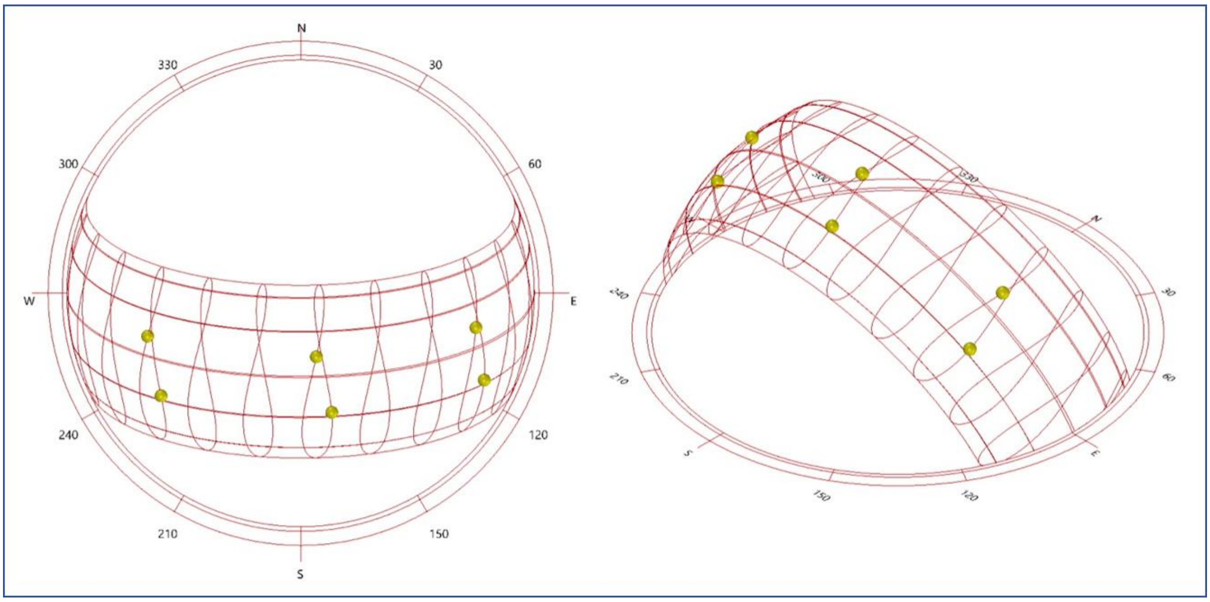

Figure 7.4.6. The sun path diagram of Taif (Author generated from grasshopper software) (grasshopper, 2020)

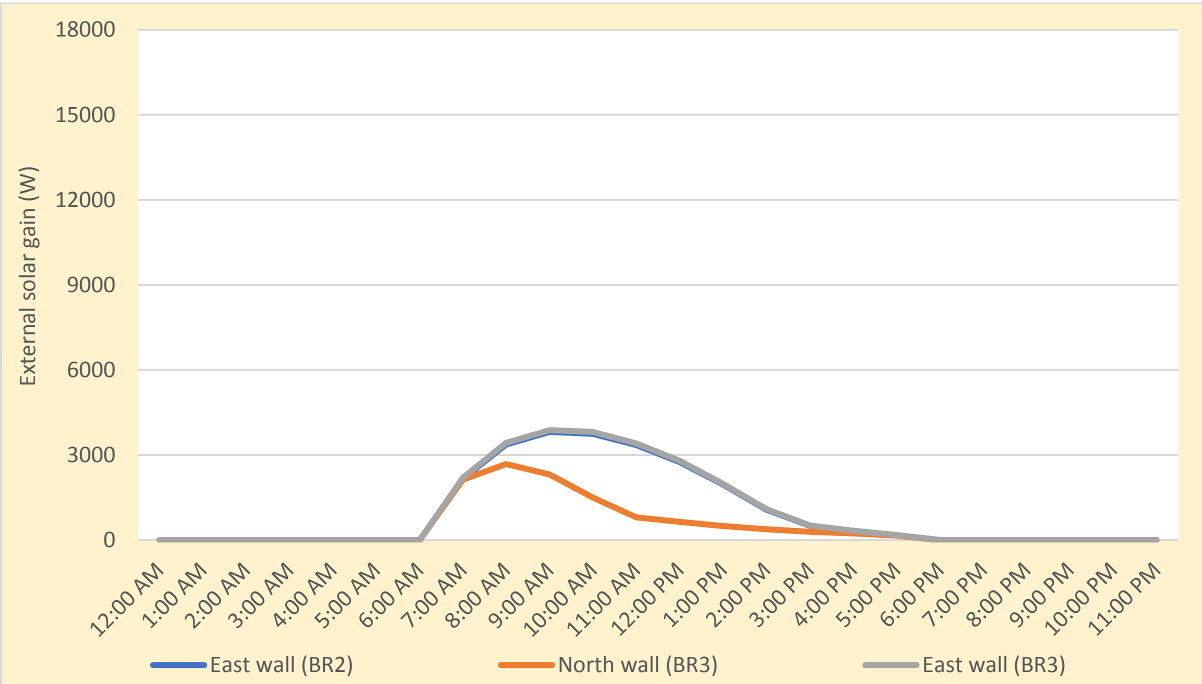

Figure 7.4.7. External solar gain on fabric (walls) in the 1st and 2nd bedrooms in winter (W)

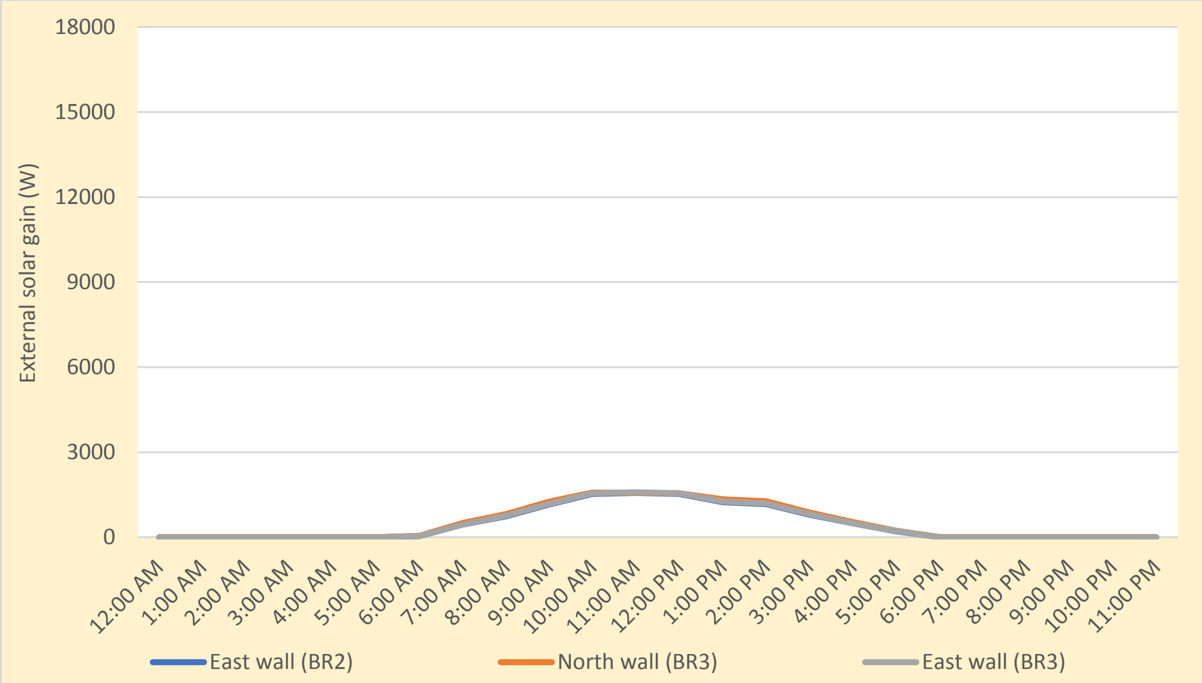

Figure 7.4.8. External solar gain on fabric (walls) in the 1st and 2nd bedrooms in summer (W)

7.5. Comparison of the cooling load benchmark in Saudi Arabia

One aim of this study is to obtain a clearer picture of how various fabrics on the building envelope affect the cooling load consumption and therefore optimize the intended measures to reduce energy consumption in residential buildings.

The cooling load is the amount of heat energy that would need to be removed from a space (cooling) to maintain the temperature in an acceptable range. The heating and cooling loads, or "thermal loads", take into account: the dwelling's construction and insulation. Its orientation and compactness are important features. How they are achieved will depend on how builders combine floors, walls, ceilings and roofs. The building's most adaptable feature is the windows. They can be adjusted for placement, size, shading and overshadowing, opening a variety of choices to get the best performance.

Lower thermal loads indicate that, relatively, the dwelling will require less heating and cooling to maintain comfortable conditions. The cooling load of the chosen houses has been simulated to estimate the annual cooling load. The houses are assumed to have air conditioning. The Saudi building code suggests that the air conditioning be set at 21.1°C in winter and 23.9°C in summer (SBC, 2018). However, the Saudi Energy Efficiency Centre recommends wider choice of A/C thermostat setting at between 23 and 25°C (SEEC, 2020). In this study, thermostat was set at 25°C due to the implied saving in cooling load compared to any lower indoor air conditioning temperature. Cooling is assumed to be available all year round, mainly to quantify the effect of energy efficiency measures on cooling load in the chosen buildings.

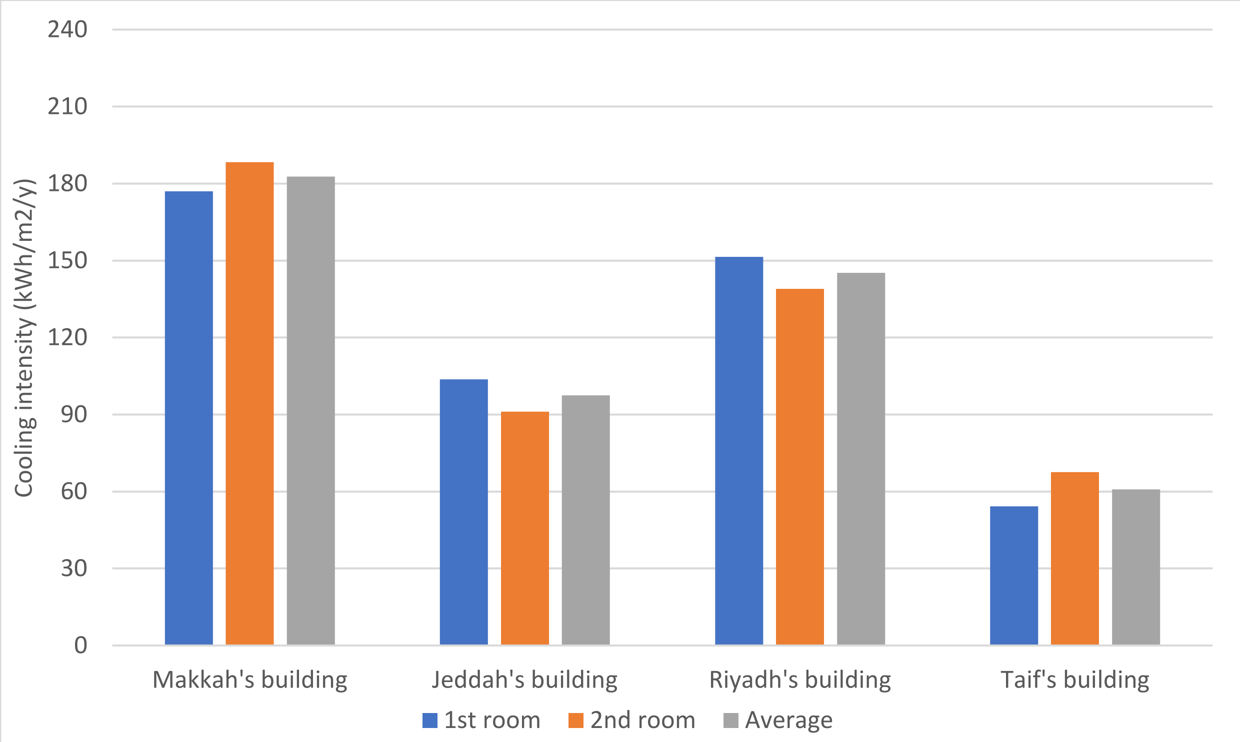

Figure 7.5.1. The current annual cooling load for the chosen houses in the four cities (kWh/m2/y)

The current average annual cooling loads are 182.7 for the house in Makkah, 97.4 for the house in Jeddah, 145.2 for Riyadh and 60.9 kWh/m2/y for Taif. The case study in Makkah has the highest cooling load and has similar figures to Alaboud and Gadi (2019) at 175 kWh/m2/y; Alaboud & Gadi (2020) which has 181.5 kWh/m2/y. The case study in Taif has the lowest cooling load and has similar figures to Alaidroos & Krarti (2015) for the city of Abha which has similar weather condtions to Taif and has 53 kWh/m2/y.

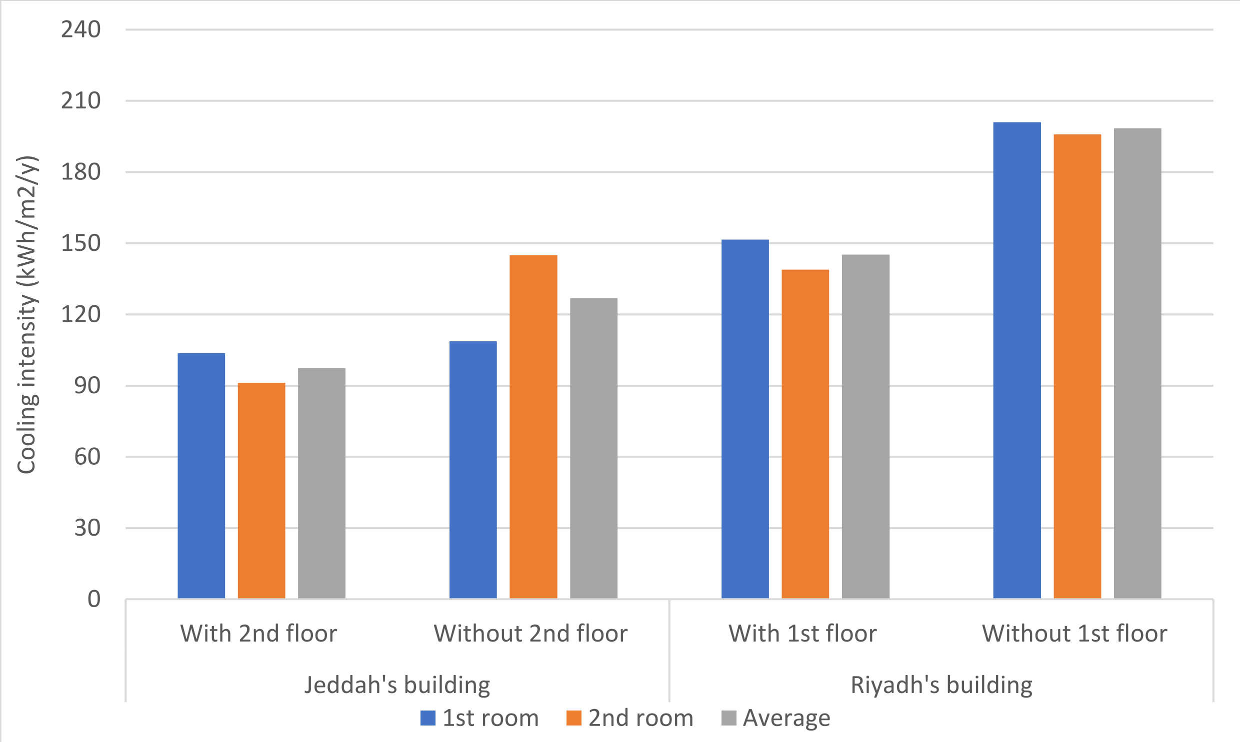

Figure 7.5.2. The proposed annual cooling load for the chosen houses in Jeddah and Riyadh (kWh/m2/y)

The two buildings in Jeddah and Riyadh were modelled without the top floors. This was done to quantify the cooling load and compare the effect of the roof exposure to solar radiation to the other two chosen houses in Makkah and Taif. The chosen rooms in Jeddah and Riyadh buildings are not exposed to solar radiation from the roof so the 2nd floor in the house in Jeddah was removed and modelled again in the simulation, same in the house in Riyadh, where the 1st floor was removed so the two rooms in the ground floor modelled within the ground floor only. The average cooling load in the case study in Jeddah increased from 97.4 to 126 kWh/m2/y due to the 2nd room (bedroom) being exposed to solar radiation from the roof. The average cooling load in the case study in Riyadh increased from 145.2 to 198.4 kWh/m2/y due to the two rooms exposure to solar radiation via the roof.

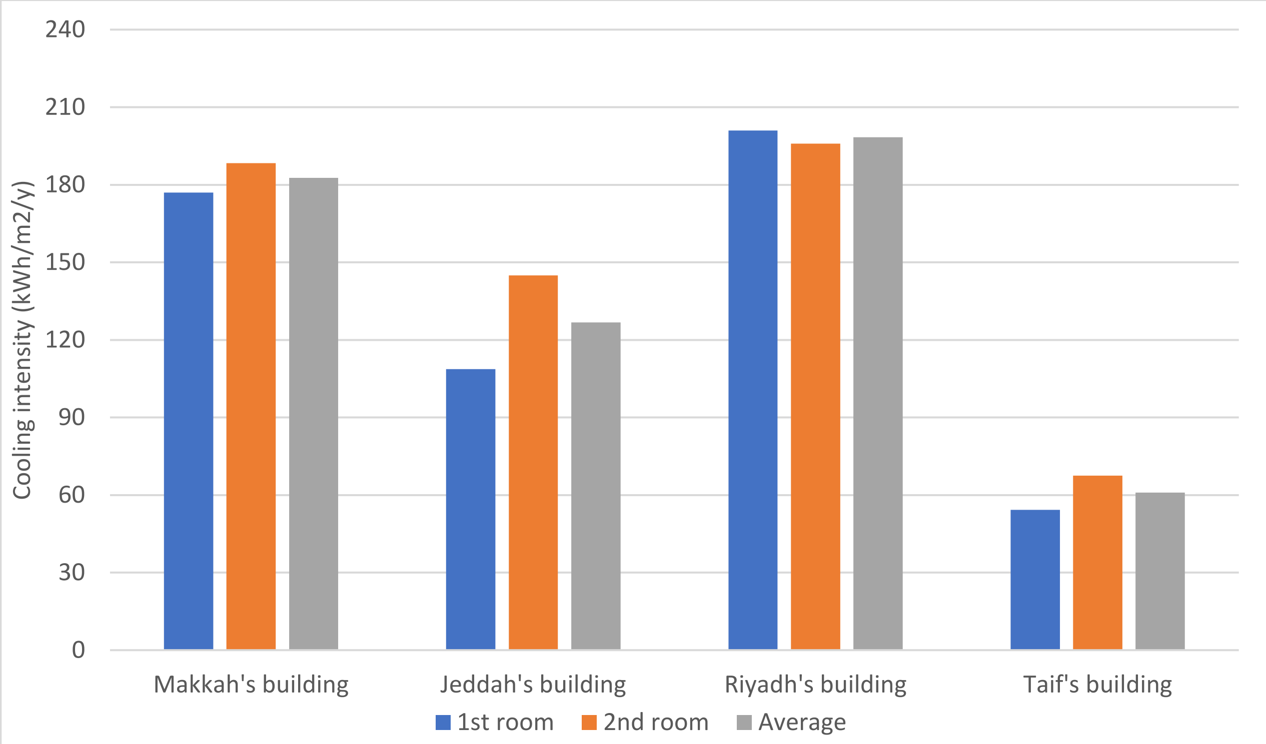

Figure 7.5.3. The proposed annual cooling load for the chosen houses in the four cities (kWh/m2/y)

The Jeddah case study has an average cooling load of 126 kWh/m2/y after removing the top floor. This result is in line with previous studies such as Alaidroos & Krarti (2015); Aldossary et al., (2014b) which has 161 and 138.6 kWh/m2/y respectively. The case study in Riyadh has the highest cooling load of 198.4 kWh/m2/y after removing the top floor, and shows similar figures to Alaidroos & Krarti (2015) and Aldossary et al., (2014) who recorded 148 and 103 kWh/m2/y respectively. Additionally, Ahmad (2004) compares the energy consumption of a typical house built with different types of masonry building materials using analysis program DOE-2.1E. The model house investigated in this study is located in Dhahran, Saudi Arabia. For the base case of the house, the calculated annual energy use intensity is 263 kwh/m2 and the required cooling load is 191 kWh/m2. The air conditioning uses 72% of the total annual energy consumed. Finally, these figures are kept as base cases discussed in the next chapter; Makkah's building (MB1), Jeddah's building (JB1), Riyadh's building (RB1), Taif's building (RB1).

7.6. Summary

This chapter analysed thermal performance and the annual cooling load of the selected houses in the four cities using a thermal modelling programme (EDSL TAS version 9.4.2). It also investigated the impact of the walls, floors and roofs on the chosen houses' thermal performance and cooling load.

The findings revealed that, in all houses, for the chosen rooms, the calibration of indoor dry bulb temperature simulated suggested similar internal temperature behaviours. It is thus safe to assume that the simulated results are within the acceptable range. Furthermore, the highest fabrics gain amongst the monitored fabrics in both summer and winter was via the roof for the houses in Makkah, Jeddah and Riyadh. For the house in Taif, the highest gain in both summer and winter amongst the fabrics monitored was via the external walls. This finding is supported by Koch-Nielsen (2002) Referring to a hot dry climate, he singled out the fabric which is exposed to the greatest amount of solar radiation – the roof – as one of the most important elements of the building envelope in a Saudi climate. Out of sight and difficult to access, it is also the most difficult component to protect

This study has set out to determine the annual cooling load of residential buildings, which consequently helped to understand the cooling consumption of the case studies. Understanding the cooling consumption of the case studies helped to develop a benchmark for comparison with research studies from the literature

and identify strategies for improving indoor thermal performance and reduce energy used for cooling in residential buildings. To accurately assess the annual cooling load, the existing houses is measured where the houses are assumed to have air conditioning. The average annual cooling loads are 182.7 for the house in Makkah, 126 in Jeddah, 198.4, for Riyadh and 60.9 kWh/m2/y for the house in Taif.

Chapter 8

Suggested building envelope improvement using thermal analysis software

8. Suggested building envelope improvement using thermal analysis software

8.1. Introduction

This chapter investigates how energy saving improvements to house envelopes can improve the indoor thermal environment of residential buildings. This approach to making improvements is taken for two reasons. The first reason is that the fabric loss/gain greatly influences the thermal performance of chosen houses. This impact is tracked by monitoring and by using thermal analysis software for the houses. The fieldwork data collection and the thermal simulation indicated that heat loss and gain occurred through all building fabrics but occurred especially via walls and roofs which are the most influence factors affecting indoor thermal performance and leading to higher cooling load use in summer and also winter. The second reason is that the quality of the existing residential building's fabrics can be improved to meet Saudi building code standards introduced in 2018 and will be enforced from mid-2021 on new buildings.

In this study, TAS was used for different external proposed houses' components including walls, roofs, floors, windows and shading. The proposed fabrics are applied on each house separately and the potential improvement to the indoor thermal environment throughout the whole year is investigated by altering each element separately. Afterwards, combinations of the proposed components are simulated to reflect the cooling load reduction achieved.

The market supplies many types of insulation materials which have different insulating properties. In this study, only one type of insulation is applied to the proposed building fabrics to be compared with. The chosen type of insulation is polyethylene board which has very low thermal conductivity (0.025 W/m.k) and is approved by Saudi Standards, for use in all types of buildings.

8.2. The house in Makkah

8.2.1. Proposed construction layers of external walls

To identify the best-case external wall which can improve the indoor thermal performance and achieve the lowest cooling load in all year, various types and thickness of walls were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed walls and compared with the base case of the existing walls. As far as the proposed walls types are concerned, thermal insulation was proposed because of it is ability to control the heat flow through the walls in both directions. Using thermal insulation could be appropriate in both winter and summer as heat gain through walls is second highest after heat gain from the roof as revealed by the thermal analysis of the house in Makkah. The effectiveness of the proposed walls was tested and simulated for the whole year to reflect the best case in relation to cooling load reduction. In view of the thermal analysis of the house in Makkah, three walls with different insulation thickness were proposed for the TAS simulation, where rooms IW1 to IW3 represent walls incorporating the thickness of thermal insulation materials. The simulation of the various proposed walls is aimed to stand on the different thermal performance using each type of wall. Furthermore, description for the proposed walls and the simulation results are provided in table 8.2.1 explaining their layers, thicknesses, U-value and thermal conductance. Additionally, existing external walls of the house in Makkah are presented in figure 8.2.1.

Figure 8.2.1. Highlighted existing external walls of the house in Makkah

Table 8.2.1: Characteristics of existing and proposed insulated walls

Walls	Wall type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing external walls used in Makkah's house	MW1 (main elevation)	40 mm limestone (outside) 20 mm external rendering 200 mm red hollow conc. block 20 mm internal plaster white paint (inside)	1.49	1.995
	MW2 (side elevation)	Paige paint (outside) 20 mm external rendering 200 mm red hollow conc. block 20 mm internal plaster white paint (inside)	1.549	2.102
Introducing thermal insulation	IW1	Paige paint (outside) 20 mm external rendering 100 mm red hollow conc. Block 20 mm polyurethane board 100 mm red hollow conc. block 20 mm internal plaster white paint (inside)	0.692	0.784
	IW2	Paige paint (outside) 20 mm external rendering 100 mm red hollow conc. Block 60 mm polyurethane board 100 mm red hollow conc. block 20 mm internal plaster white paint (inside)	0.328	0.348
	IW3	Paige paint (outside) 20 mm external rendering 100 mm red hollow conc. Block 100 mm polyurethane board 100 mm red hollow conc. block 20 mm internal plaster white paint (inside)	0.215	0.223

The existing walls (MW1, MW2): MW1 is only applied on the main elevation while MW2 is applied on external side elevations. This wall is commonly used in most Saudi residential buildings. It incorporates 20 mm internal plastering, 200mm red hollow concrete block, 20 mm external rendering and external painting.

1st case (MW2): The external and internal finishing used in MW2 is applied in all the proposed walls. Simply, the stone in the main elevation is removed and replaced by external painting.

Walls with thermal insulation (IW1 to IW3): Three types of the proposed walls incorporate cavity polyurethane board with different thickness (20mm, 60mm and 100mm). The highlighted wall has a U-value slightly less than the maximum value set by the SBC for Makkah's climate.

- **Cooling load saving with proposed external walls**

The energy savings of the proposed external walls is measured to estimate the annual cooling load assuming that the house in Makkah has air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.2.1.1 tabulates the annual cooling of the various walls in each case for both rooms in the Makkah house. Table 8.2.1.1 provides the percentage of cooling load savings compared with the existing walls.

Table 8.2.1.1. Percentage of reduction in annual cooling load for proposed walls compared with a base case of existing walls

Wall cases	Wall type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Base case	MW1 (main elevation)	182.6	-
	MW2 (side elevations)		
1st case	MW2 (main and side elevations)	176.9	3.1
2nd case	IW1	139.2	23.7
3rd case	IW2	122	33.1
4th case	IW3	116.4	36.2

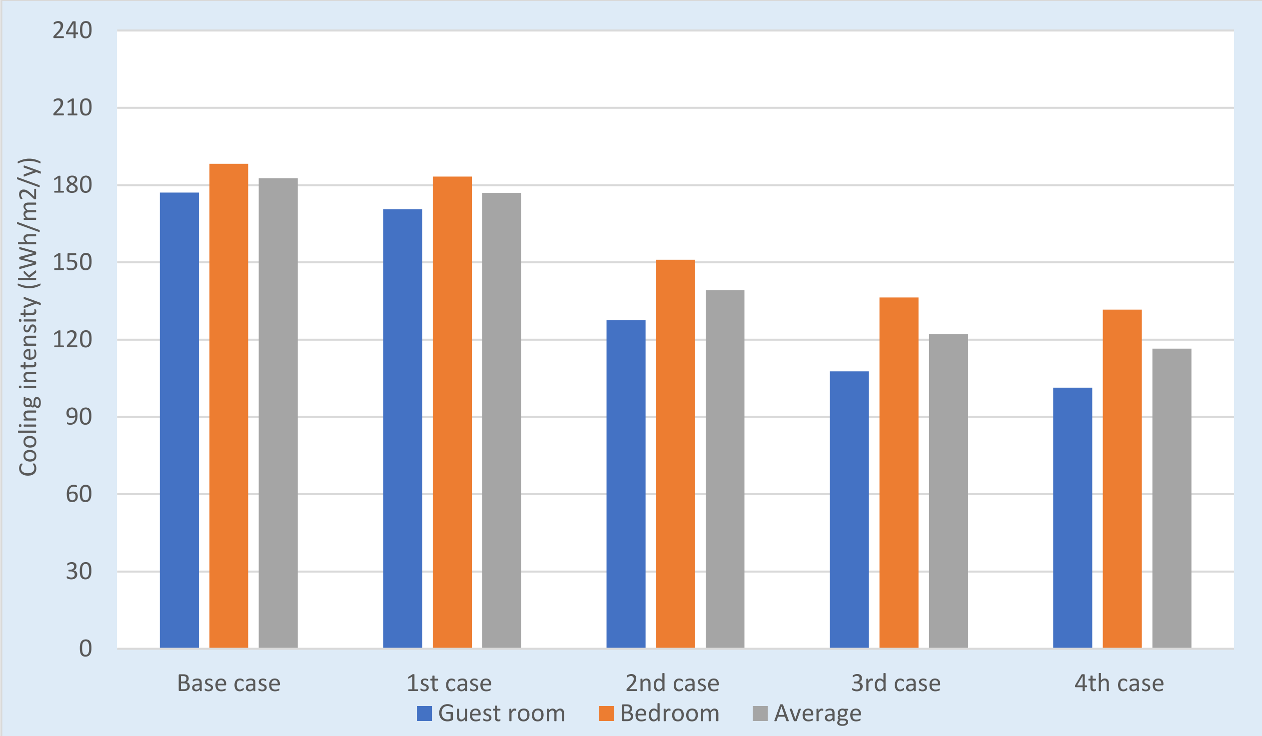

Figure 8.2.1.1: Annual cooling load for proposed walls (kWh/m2/y).

The results show that by implementing the proposed walls (2nd case to 4th case), potential cooling load savings of 23.7%, 33.1% and 36.2% are achieved in IW1, IW2 and IW3 respectively. However, there is a relatively small possible saving in the cooling loads in the 1st case at 3.1%. The results were obtained by incorporating insulation materials with various thicknesses - 20mm to 100mm - to achieve a possible decrease in cooling load the whole year. Overall, greater reduction in cooling load is attained by using thicker insulation material with low thermal conductance. Using 100mm insulation material in IW3 is the highest saving achieved in cooling load. However, increasing the thickness of the insulation materials is subject to the law of diminishing returns. Beyond a certain point, increasing insulation thickness has a diminished impact on cooling load savings. To compare between the three insulated walls, IW1 has a potential saving of 23.7% compared to the base case, while IW2 has a potential saving of 12.3% compared to IW1, finally, IW3 has a potential saving of 4.5% compared to IW2. Consequently, IW2 is chosen to improve indoor thermal environment for its potential saving of the cooling load and because it complies with the required Saudi building standards walls' u-value for the house in Makkah.

8.2.2. Proposed construction layers of Roof

To identify the best-case proposed roof which can improve the indoor thermal performance and achieve the lowest all year-round cooling load, various types and thickness of roofs were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed roofs and then compared with the base case roof. Heat gain through the roof is the highest in the Makkah house. Also, heat gain through the roof in summer and winter is higher than the heat lost via the roof. Therefore, various types of roofs, with lower thermal conductance than the existing roof, were proposed to minimize the heat gain. The use of additional thermal insulation was proposed for the roof. Table

8.2.2 sets out the proposed roofs explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.2.2: Characteristics of existing and proposed insulated roof

Roofs	Roof type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing roof used in Makkah's house	MR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.901	1.111
Introducing thermal insulation	IR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 25 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.474	0.526
	IR2	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 50 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.322	0.345
	IR3	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 100 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.196	0.204

The existing roof (MR1): is a common roof type used in most residential buildings. It incorporates 50 mm internal gypsum board with internal plaster and painting, 300 mm reinforced concrete slap, 170 mm sand, cement mortar and terrazzo tile. The external and internal finishing used in MR1 is applied in all the proposed roofs.

Roofs with thermal insulation (IR1 to IR3): Three types of the proposed roofs incorporate cavity polyurethane board with different thickness (25mm, 50mm and 100mm). The highlighted roof is the one with a little less U-value than the maximum value required by the SBC for Makkah's climate.

- **Cooling load saving with proposed roofs**

The energy savings of the proposed roofs is measured for the Makkah house to estimate the annual cooling load. The Makkah house is assumed to have air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.2.2.1 sets out the reduction in the annual cooling load achieved using the permutations the various roofs in each case for only the bedroom in the 1st floor in the house in Makkah. Table 8.2.2.1 tabulates the percentage of cooling load savings compared with the existing roof.

Table 8.2.2.1. Percentage of reduction in annual cooling load for proposed roofs compared with existing roof in the base case

Roofs cases	Roof type	annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	MR1	188.3	-
1st case	IR1	161	14.4
2nd case	IR2	150.9	19.8
3rd case	IR3	142.2	24.4

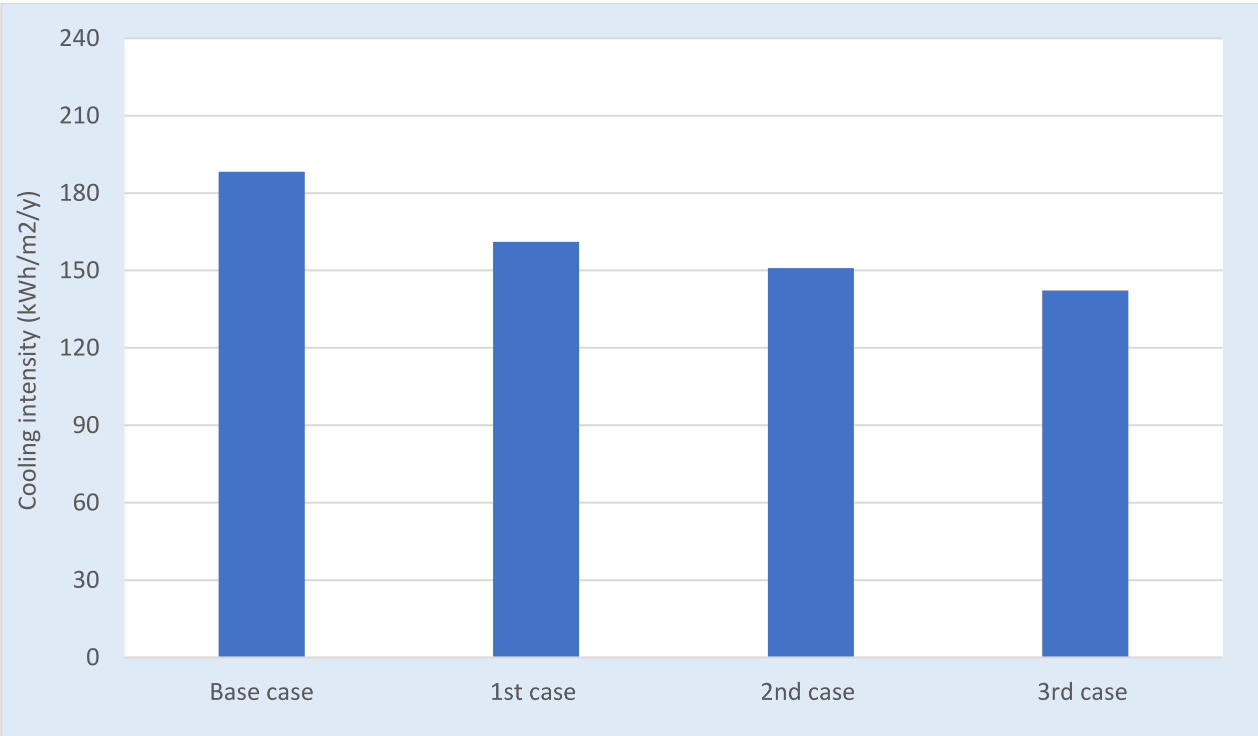

Figure 8.2.2.1: Annual cooling load for proposed roofs (kWh/m2/y).

Only the bedroom is chosen as it is on the 1st floor and is exposed to solar radiation. The results show that by implementing the insulated proposed roofs (1st case to 3rd case), the potential savings in the cooling loads ranging from 14.4%, 19.8% and 24.4 % are achieved in IR1, IR2 and IR3 respectively. The results revealed by incorporating insulation materials with various thicknesses, 25mm to 100mm, a possible decrease in cooling load could be obtained the whole year. Overall, greater decrease in cooling load is attained with greater thickness of the insulation material which has very low thermal conductance. Therefore, the highest saving in cooling load is achieved by using 100mm insulation material in IR3.

Additionally, increasing the thickness of the insulation materials does have a notable impact on saving cooling load. To compare between the three insulated roofs, IR1 has potential saving of 14.4 % compared to the base case, while IR2 has potential saving of 6.3% compared to IR1, finally, IR3 has potential saving of 5.7% compared to IR2. Consequently, IR3 is chosen to improve indoor thermal environment for its saving potential of the cooling load and because it complies with the required roofs u-value by Saudi building standards for the house in Makkah.

8.2.3. Proposed construction layers of floor

Two types of ground floors were proposed and simulated to improve the indoor thermal performance and achieve the lowest cooling load all year. The annual cooling load was estimated when the various proposed ground floors were implemented and compared with the base case of the existing floor.

Heat gain through the ground floors on a summer-day is lower than heat loss but heat gain on a winter-day is higher than heat loss. There is zero heat loss through the ground floor on a winter-day. Therefore, ground floors with various thickness and lower thermal conductance than the base ground floor were proposed to minimise heat loss in summer and heat gain in winter. Table 8.2.3 provides the proposed ground floors explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.2.3: Characteristics of existing and proposed insulated ground floor

Floors	Floor type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing floor used in Makkah's house	MF1	20 mm terrazzo tiles (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 150 mm soil	0.933	1.153
Introducing thermal insulation	IF1	20 mm terrazzo tiles (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 30 mm polyurethane board 150 mm soil	0.453	0.484
	IF2	20 mm terrazzo tiles (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 60 mm polyurethane board 150 mm soil	0.294	0.306

The ground floor (MF1) in Makkah is a commonly used floor type in most residential buildings. It is constructed from terrazzo tiles fixed on 150mm cement mortar and sand which are bedded on 300mm plain concrete.

Ground floors with thermal insulation (IF1 and IF2): two types of the proposed floors incorporate cavity polyurethane board with respective thickness of 30mm and 60mm. The highlighted ground floor is the one with a little less U-value than the maximum value required by the SBC for Makkah's climate.

- **Cooling load saving with proposed ground floors**

The energy savings delivered by the proposed ground floors has been calculated to estimate the annual cooling load. The assumption is that the Makah house has air conditioning The upper temperature for cooling is set at 25°C. Figure 8.2.3.1 sets out the annual cooling achieved by implementing the ground floor permutations in only the ground floor guest room in the house in Makkah. Table 8.2.3.1 provides the percentage of cooling load savings compared with the existing roof.

Table 8.2.3.1. Percentage of reduction in annual cooling load for proposed ground floors compared with existing floor in the base case

Floors cases	Floor type	annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	MF1	177.0	-
1st case	IF1	159.6	9.9
2nd case	IF2	154.4	12.8

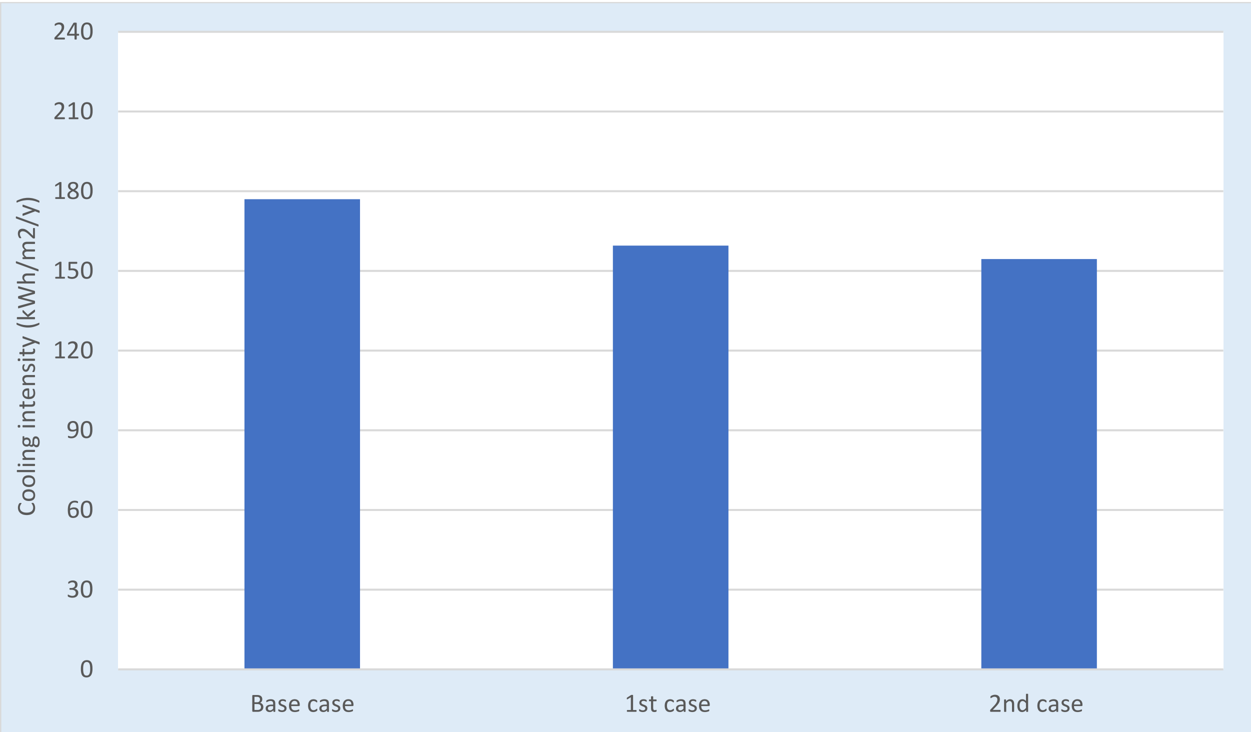

Figure 8.2.3.1: Annual cooling load for proposed ground floors (kWh/m2/y).

Only the guestroom is chosen because it is on the ground floor. The results show that by implementing the insulated proposed floor (1st case and 2nd case), the potential savings in cooling load are 9.9% and 12.8% achieved in IF1 and IF2 respectively. A possible reduction in cooling load could be obtained all year round by varying the thicknesses of insulation materials from 30mm to 60mm. The thicker the insulation material (low thermal conductance) the bigger the reduction in cooling load. Therefore, the biggest saving in cooling load is achieved by using 60mm insulation material in IF2.

Therefore, increasing the thickness of the insulation materials does not necessarily have a significant on saving cooling load. To compare between the two insulated ground floors, IF1 has potential saving of 9.9% compared to the base case, while IF2 has a potential saving of 3.2% compared to IF1. Consequently, IF1 is chosen to improve indoor thermal environment for its saving potential of the cooling load and because it complies with the ground floor u-value set by Saudi building standards for the house in Makkah.

8.2.4. Proposed construction layers of window and shading

Two types of window coupled with removing external shutters were proposed and simulated to improve the indoor thermal performance and achieve the lowest cooling load all year round. The annual cooling load was estimated by comparing with the implementation of the various proposed cases are compared with the base case of the existing windows and shading.

The thermal analysis of the Makkah house in the previous chapter showed that heat loss through windows is relatively slight compared with the total loss via fabrics in winter and summer. The least amount of solar heat gain amongst the fabrics is via the windows due to the external shutters. Therefore, single and double glazed windows without external shutters were proposed to evaluate the current external shutters in relation to the cooling load (see table 8.2.4).

Table 8.2.4: Characteristics of existing and proposed windows

Window and shading	Window type	Layers description	U-value (w/m².˚C)	Solar transmittance
Existing window and shading used in Makkah's house	MW1	Single glazing with internal blind and external shutter	5.5	0
Removing external shading	WW1	Single glazing with internal blind	5.5	0.080
	WW2	double glazing with internal blind	1.606	0.060

- **Cooling load saving with proposed windows**

The energy savings achieved by the proposed windows is measured to estimate annual cooling load. It was assumed the house in Makkah has air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.2.4.1 provides the annual cooling with the implementation of the various windows in both rooms in the house in Makkah. Table 8.2.4.1 provides the percentage of cooling loads savings comparing with the existing windows and shading.

Table 8.2.4.1. Percentage of reduction in annual cooling load for proposed windows compared with existing windows and shading in the base case

Windows and shading cases	window type	Average annual cooling (kWh/m²/y)	Increase of cooling load (%)
Base case	MW1	182.7	-
1st case	WW1	222.2	17.8
2nd case	WW2	223.8	18.4

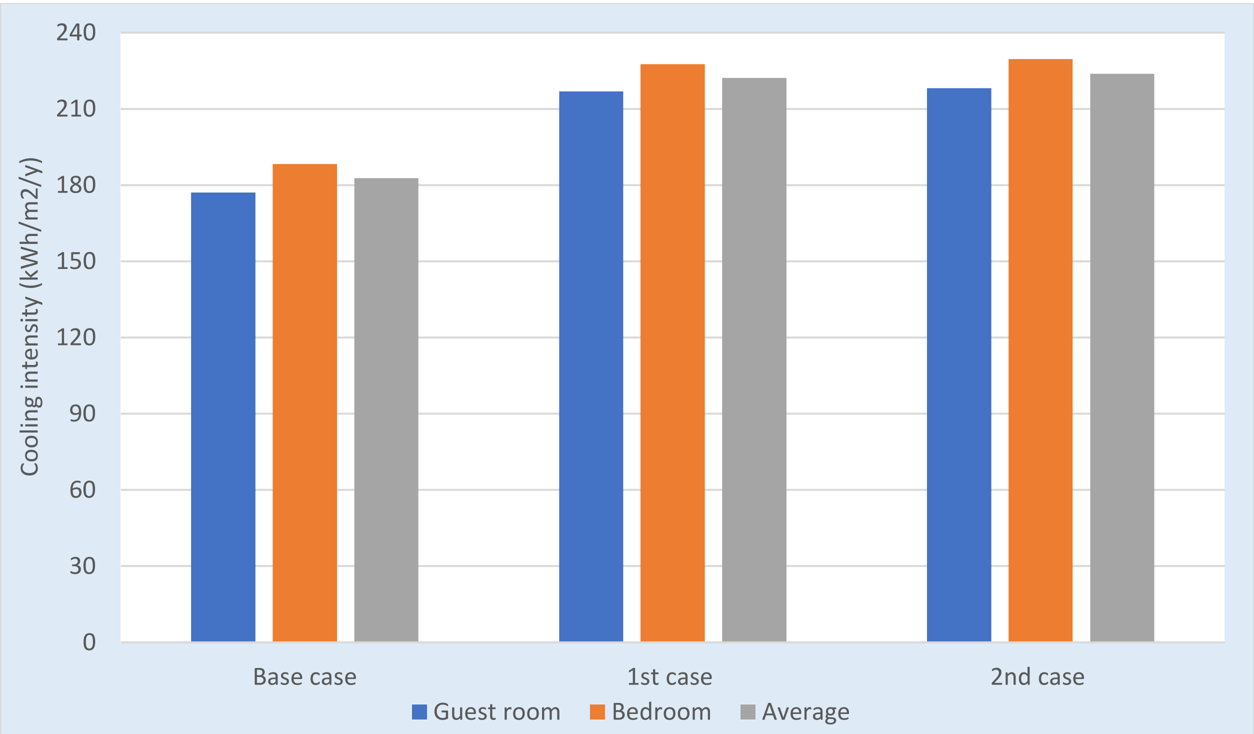

Figure 8.2.4.1: Annual cooling load for proposed windows (kWh/m2/y).

The results show that by removing the external shutters in the 1st and 2nd case, the potential increase in the cooling load, ranging from 17.8% and 18.4%, occurred in WW1 and WW2 respectively. The results also revealed no noticeable difference when upgrading the window type. Therefore, the highest saving in cooling load is achieved in the base case in MW1.

Consequently, MW1 is chosen to improve the indoor thermal environment for its saving potential of the cooling load even though it does not comply with the required window U-value.

8.2.5. Proposed combination of building fabrics

Combinations of the various proposed walls, roofs and ground floors were selected and simulated to ascertain the overall indoor thermal performance and achieve the lowest cooling load all year.

The annual cooling load was estimated with the implementation of the various combinations of fabrics and compared with a base model of existing fabrics. The potential cooling savings attained by applying these combinations of the house's envelope were calculated. Explanation for the selected combinations, the simulation results and the percentage of cooling load savings compared with the existing fabrics are provided in table 8.2.5.

All highlighted building fabrics discussed earlier in this chapter were selected and combined to achieve the best case. One proposed floor, one proposed wall and one of the proposed roofs were selected to form two combinations of fabrics. The 1st case is a combination of the proposed roof and walls but without the proposed floor, while the second case (best case) is a combination of roof, walls and floor. The selection was based on the annual potential improvement in cooling load.

The cooling savings of the proposed fabric combinations is measured to estimate the annual cooling load where the house is assumed to have air conditioning. The upper temperature is set at 25 °C. Figure 8.2.5 provides the annual cooling load with the implementation of the various combinations of fabrics the two rooms in the Makkah house. The results revealed that the fabric combination in the MC1 produced a potential saving of 49.7% in the cooling load, while the MC2 achieved the best case with a reduction of 56.5%.

Table 8.2.5: Characteristics of existing and proposed combinations of fabrics

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Base case	MB1	182.7	-
1st case	MC1 (roof, wall)	91.9	49.7
Best case	MC2 (roof, wall, floor)	79.7	56.4

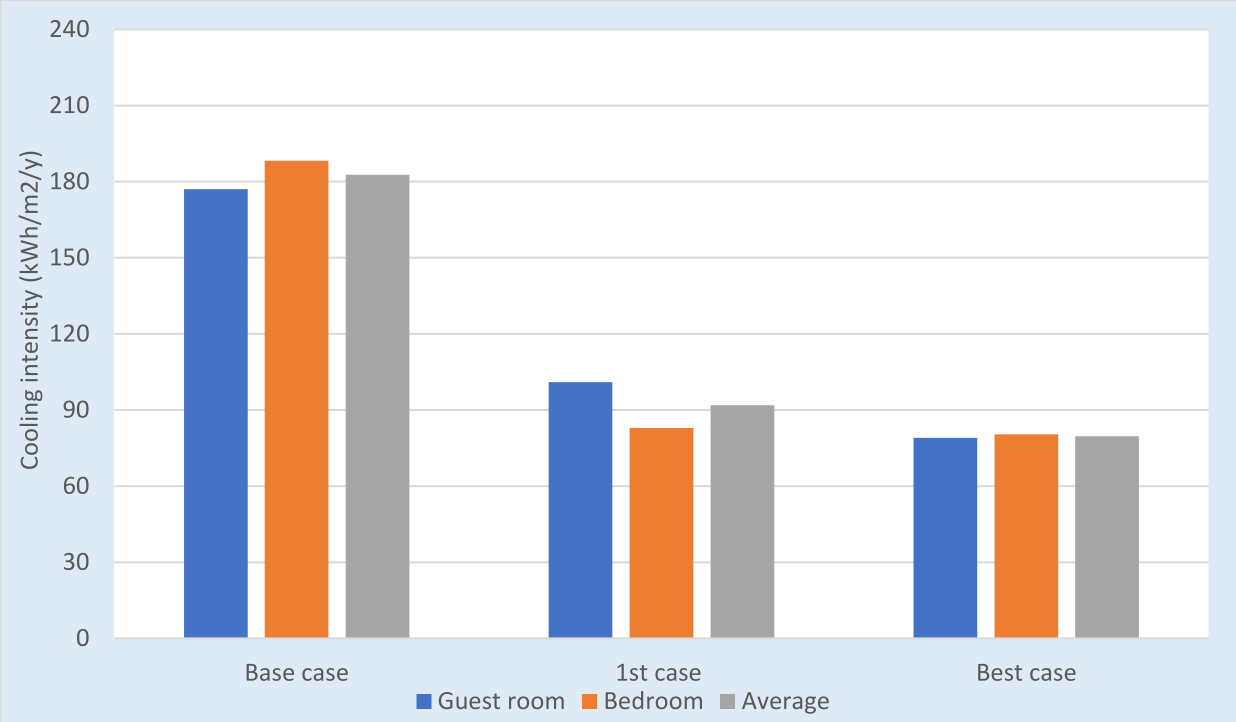

Figure 8.2.5: Annual cooling load for proposed fabrics' combination (kWh/m2/y).

- **The Effect of Revised Ventilation Strategy (mixed mode)**

As the outside temperature falls to the acceptable level of below 25 °C, night time ventilation was proposed for the studied rooms. The annual cooling load was estimated when applying the night ventilation whenever the outside temperature is less than 25 °C, along with the implementation of the best case recommended fabric combinations. The potential reduction in the percentage of cooling load compared the best case with the night time ventilation strategy (see table 8.2.5.1). The results reveal that by applying night time ventilation with the best case, a potential slight reduction in the 6.5 % of cooling load is achieved (see figure 8.2.5.1).

Table 8.2.5.1: Description of the best case and the proposed ventilation strategy

Combined cases	Combination type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Best case	MC2	79.7	-
1st case	MC3 (best case + NTV)	74.5	6.5

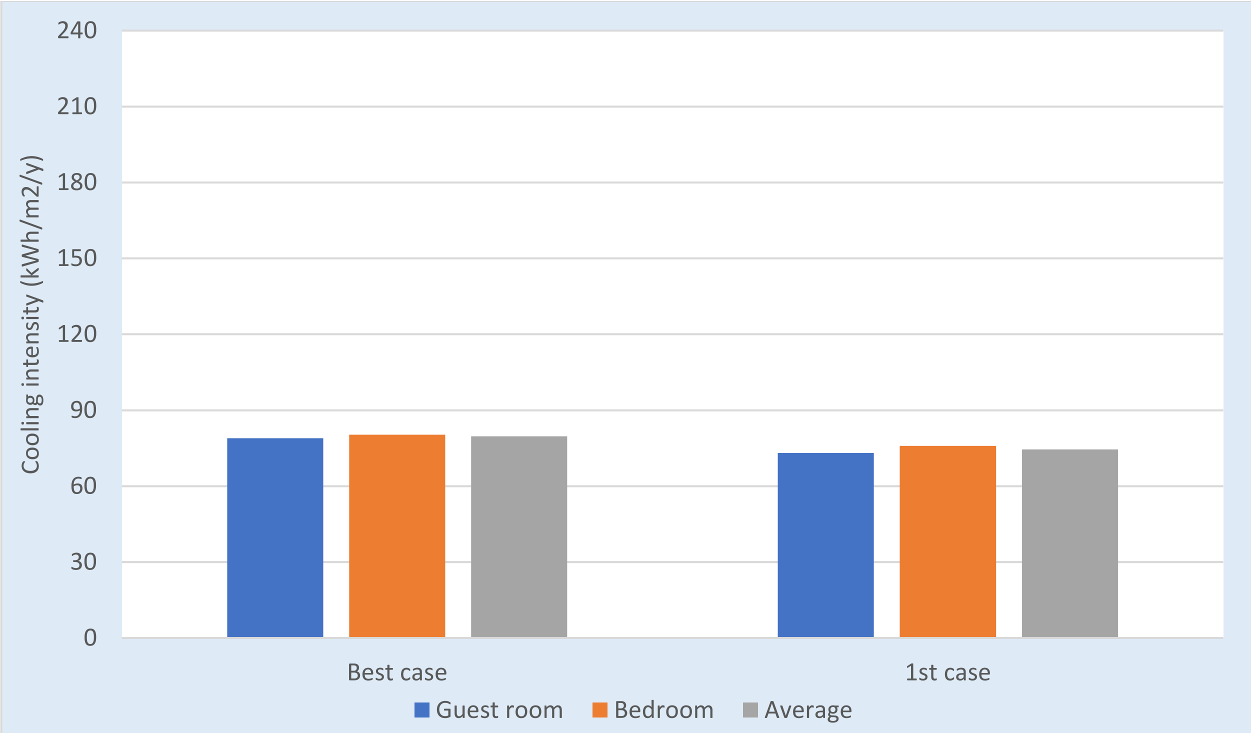

Figure 8.2.5.1: Annual cooling load for best case and the proposed ventilation strategy (kWh/m2/y).

- **The effect of set thermostat points of the A/C**

The potential cooling load saving by raising the A/C thermostat setting was proposed in the studied rooms. The annual cooling load was estimated when applying the different temperature degrees, along with the use of the most recommended fabrics combination (best case) which has set thermostat point kept at 25°C. The potential reduction in the percentage of cooling load comparing the conditions in the best case with the different degrees can be seen at table 8.2.5.2. The results revealed that by raising the A/C thermostat setting from 23.9 °C to 25°C, a potential 12.8 % reduction in the percentage of cooling load is achieved, while a noticeable reduction of 13.2% and 24.4% of the cooling load was also achieved when raising the temperature to 26°C compared to the best and 1st cases respectively (see figure 8.2.5.2).

Table 8.2.5.2: Description of the best case and the proposed set thermostat points of the A/C

Combined cases	Combination type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
1st case	MC4 (23.9˚C)	91.4	-
Best case	MC2 (25˚C)	79.7	12.8
2nd case	MC5 (26˚C)	69.1	24.4

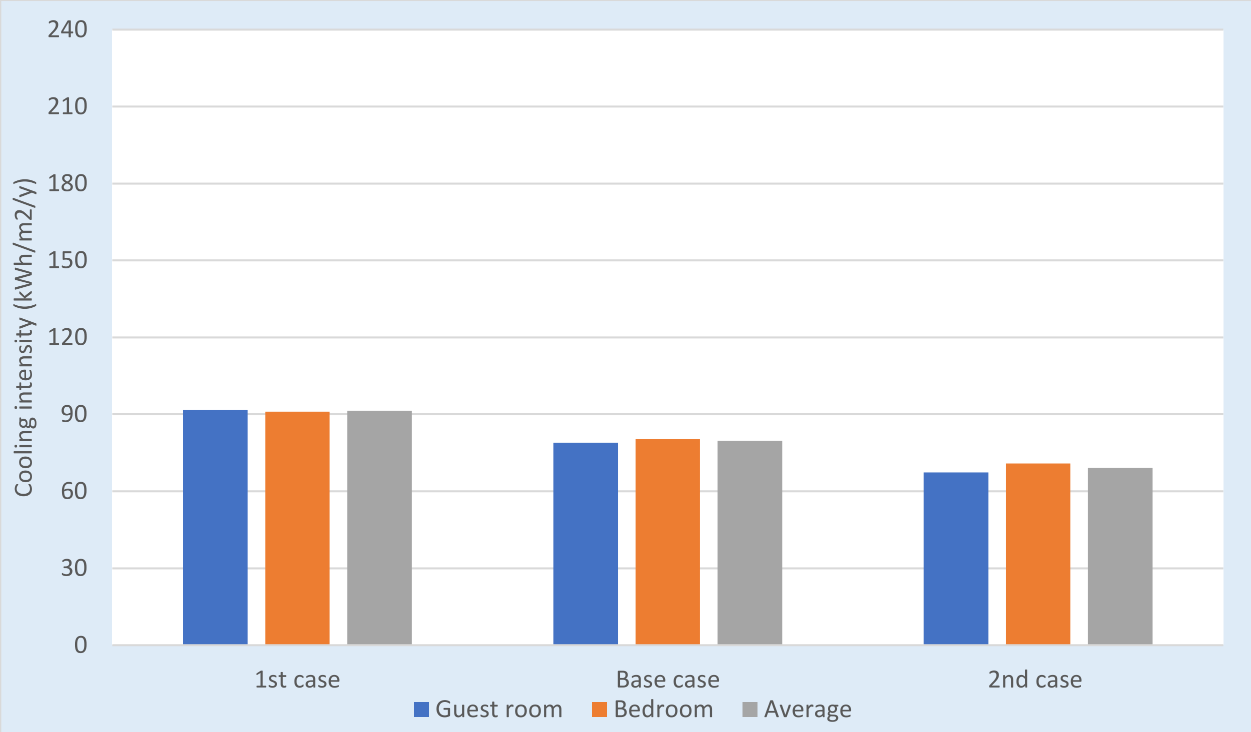

Figure 8.2.5.2: Annual cooling load for best case and the proposed set thermostat point of the A/C (kWh/m2/y)

8.3. The house in Jeddah

8.3.1. Proposed construction layers of external walls

To identify the best-case external wall which can improve the indoor thermal performance and achieve the lowest cooling load, various types and thickness of walls were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed walls and compared with the base case of the existing walls.

With reference to proposed walls types, one of the main factors affecting heat transfer is thermal insulation's capacity to control inward and outward heat flow through the walls. Using thermal insulation could be appropriate in both winter and summer as the heat gain through walls is the second highest in the Jeddah house. The effectiveness of the proposed walls was tested and simulated for the whole year to reflect the best case in relation to cooling load reduction.

In view of the thermal analysis of the house in Jeddah, three walls with different insulation thickness were proposed for the TAS simulation, where IW1 to IW3 represent walls incorporating thermal insulation materials. The simulation of the various proposed walls is aimed to stand on the different thermal performance that can be provided using each type of wall. Furthermore, description for the proposed walls and the simulation results are provided in table 8.3.1 explaining their layers, thicknesses, U-value and thermal conductance. Additionally, existing external walls of the house in Jeddah are presented in figure 8.3.1.

Figure 8.3.1. Highlighted existing external walls of the house in Jeddah

Table 8.3.1: Characteristics of existing and proposed insulated walls

Walls	Wall type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing external walls used in Jeddah's house	JW1 (main elevation)	30 mm marble stone (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	2.955	5.936
	JW2 (side elevation)	Paige paint (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	3	6.412
Existing external walls used in Makkah's house	MW2	Paige paint (outside) 20 mm external rendering 200 mm red hollow cone. block 20 mm internal plaster white paint (inside)	1.549	2.102
Introducing thermal insulation	IW1	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 20 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.692	0.784
	IW2	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 60 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.328	0.348
	IW3	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 100 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.215	0.223

The existing walls (JW1, JW2): JW1 is only applied on the main elevation of external walls, while JW2 is applied on external side elevations. This is a common wall type in Saudi residential buildings. It incorporates internal painting, 20 mm internal plastering, 200mm concrete block and 30 mm external rendering painting.

1st case (MW2): MW2 is the existing external wall used in the Makkah house and used here to test wall types different to the existing ones. This wall and its external and internal finishing is applied in all the proposed walls.

Walls with thermal insulation (IW1 to IW3): Three types of the proposed walls incorporate cavity polyurethane board with different thickness (20mm, 60mm and 100mm). The highlighted wall has slightly less U-value than the maximum value required by the SBC for Jeddah's climate.

- **Cooling load saving with proposed external walls**

To calculate the annual cooling load, the energy savings of the proposed external walls is measured where the Jeddah house is assumed to use air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.3.1.1 provides the annual cooling with the implementation of the various walls in each case for both rooms in the house in Jeddah. Table 8.3.1.1 provides the percentage of cooling load savings comparing with the existing fabrics.

Table 8.3.1.1. Percentage of reduction in annual cooling load for proposed walls compared with existing walls in the base case

Wall cases	Wall type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	JW1 (main elevation)	126.8	-
	JW2 (side elevation)		
1st case	MW2	116.3	8.2
2nd case	IW1	111	12.4
3rd case	IW2	108.8	14.1
4th case	IW3	108.2	14.6

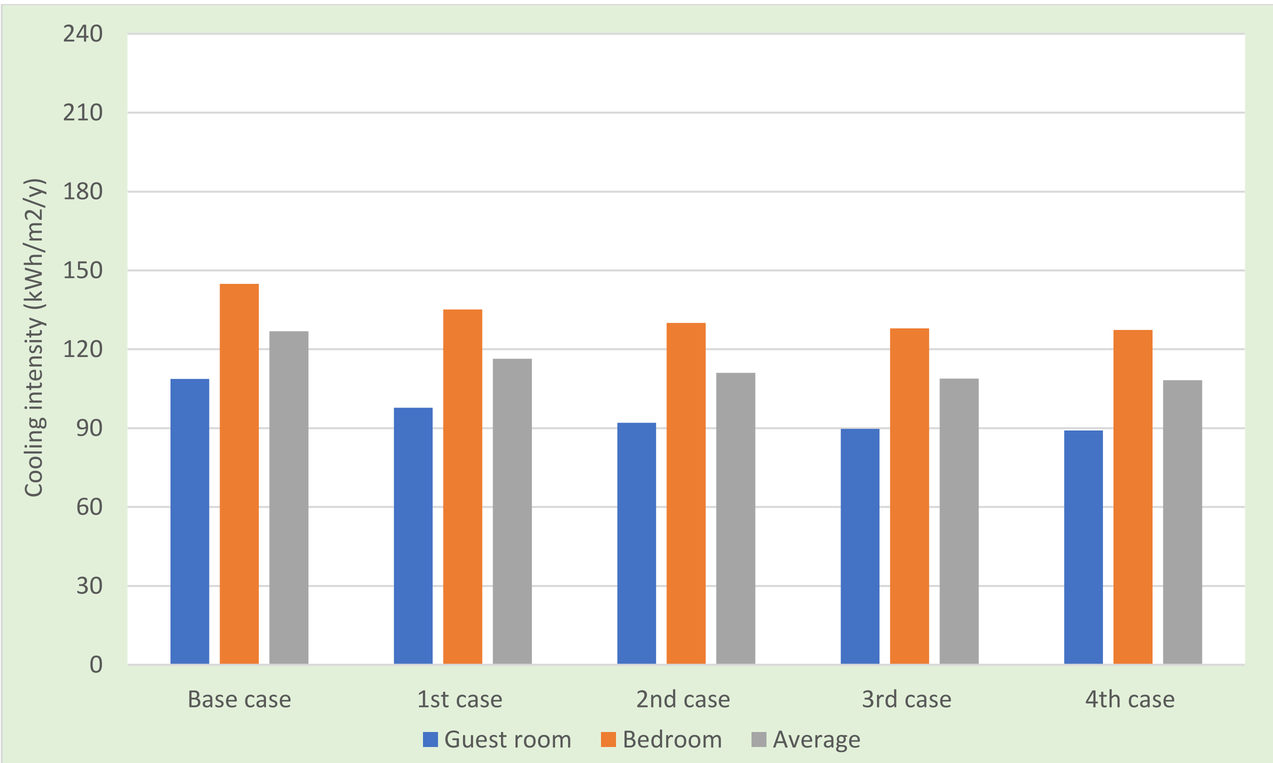

Figure 8.3.1.1: Annual cooling load for proposed walls (kWh/m2/y).

The results show that by implementing the proposed walls (2nd case to 4th case), the potential cooling load savings range from 12.4% in IW1, 14.1% IW2 and 14.6% in IW3 are achieved . However, by not using an insulated wall, there is still a considerable possible saving in the cooling load as in the 1st case at 8.2%. The results reveal by applying insulation materials with thicknesses between 20mm to 100mm, a possible all year reduction in cooling load could be obtained. Overall, the thicker the insulation material the bigger the reduction in cooling loads. The highest saving in cooling load is therefore achieved by using 100mm insulation material in IW3.

Therefore, , greater thickness of the insulation materials does not necessarily have the anticipated impact on saving cooling load. To compare between the three insulated walls, IW1 has a potential saving of 4.6% compared to the 1st case, while IW2 has potential saving of 1.9% compared to IW1, finally, IW3 has potential saving of 0.6% compared to IW2. Consequently, IW2 is chosen to improve indoor thermal environment for its potential saving of the cooling load and because it complies with the required walls u-value for the house in Jeddah.

8.3.2. Proposed construction layers of Roof

To identify the best-case proposed roof which can improve indoor thermal performance and achieve the lowest all year cooling load, various types and thickness of roofs were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed roofs and compared with the base case of the existing roof. Heat gain through the roof is the highest in the house in Jeddah, as revealed by the thermal analysis of the house in Jeddah in the previous chapter. Also, heat gain through the roof in summer and winter is higher than the roof loss. Therefore, various types of roofs, with lower thermal conductance than that of the existing roof, were proposed to minimize the heat gain. The use of additional thermal insulation was proposed for the roof. Table 8.3.2 and provides the proposed roofs explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.3.2: Characteristics of existing and proposed insulated roof

Roofs	Roof type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing roof used in Jeddah's house	JR1	20 mm terrazzo tiles (outside) 100 mm sand cement mortar 300 mm reinforced concrete slap 20 mm gypsum board and internal plaster white paint (inside)	1.395	1.972
Existing roof used in Makkah's house	MR1	20 mm terrazzo tiles (outside) 150 mm sand cement mortar 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.901	1.111
Introducing thermal insulation	IR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 25 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.474	0.526
	IR2	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 50 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.322	0.345
	IR3	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 100 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.196	0.204

The existing roof (JR1): is one of the most common roof types used in residential buildings. It incorporates 20 mm internal gypsum board with internal plaster and painting, 300 mm reinforced concrete slap, 120 mm sand, cement mortar and terrazzo tile.

1st case (MR1): is a common roof type in the country in residential buildings. MR1 is the existing roof used in Makkah's house and used here to test different type of roof than the existing one. This type of roof and its external and internal finishing is applied in all the proposed roofs.

Roofs with thermal insulation (IR1 to IR3): Three types of the proposed roofs incorporate cavity polyurethane board with different thickness (25mm, 50mm and 100mm). The highlighted roof in the table above is the one with a little less U-value than the maximum value required by the SBC for Jeddah's climate.

- **Cooling load saving with proposed roofs**

The energy savings of the proposed roofs is measured approximately where the house in Jeddah is assumed to have air conditioning so the annual cooling load could be estimated. The upper temperature for cooling is set at 25°C. Figure 8.3.2.1 tabulates the annual cooling when the various roofs were implemented for both rooms in the house in Jeddah. Table 8.3.2.1 provides the percentage of cooling load savings compared with the existing roof.

Table 8.3.2.1. Percentage of reduction in annual cooling load for proposed roofs compared with existing roof in the base case

Roofs cases	Roof type	annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	JR1	144.9	-
1st case	MR1	124.3	14.2
2nd case	IR1	107.4	25.8
3rd case	IR2	101.2	30.1
4th case	IR3	96.1	33.6

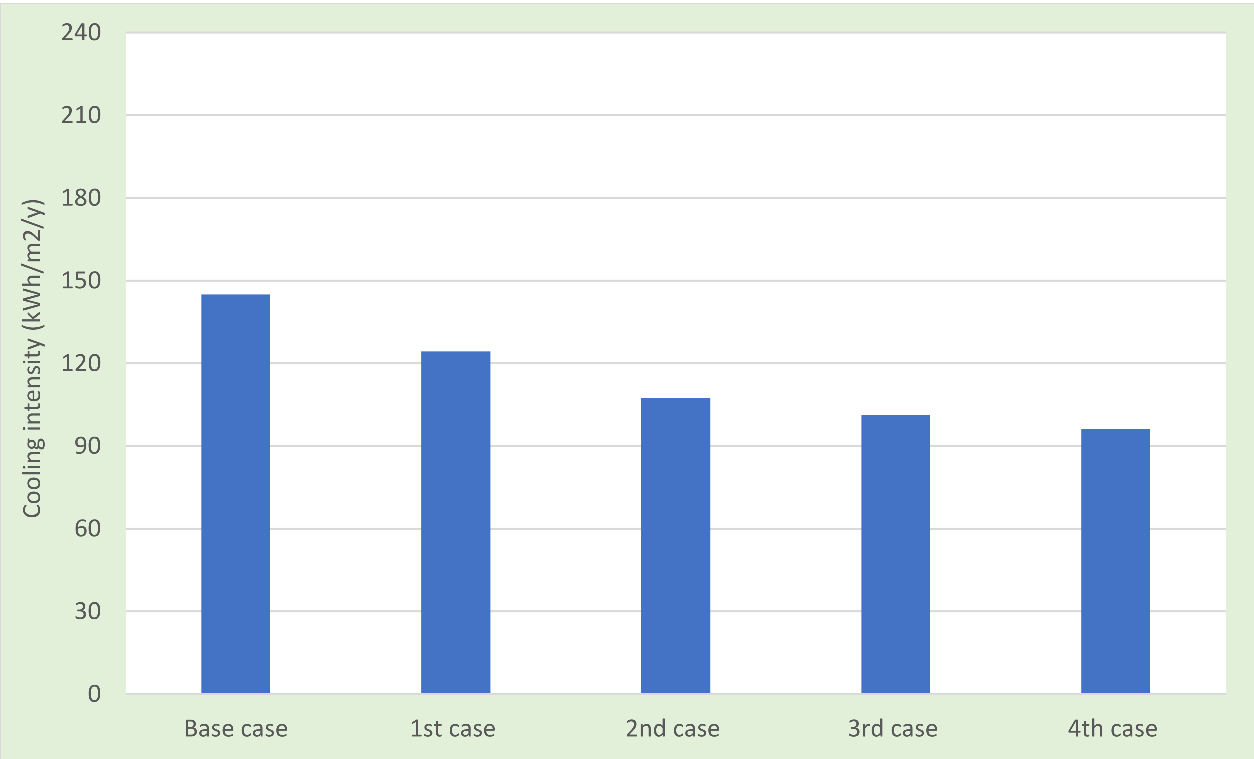

Figure 8.3.2.1: Annual cooling load for proposed roofs (kWh/m2/y).

Only the bedroom is chosen as it is on the 1st floor and is simulated without the 2nd floor to test its exposure to solar radiation. The results show that by implementing the insulated proposed roofs (2nd case to 4th case), the potential savings in the cooling load range from 25.8% in IR1, 30.1% in IR2 and 33.6 % in IR3. However, by not using an insulated roof, there is still a considerable potential saving in the cooling load as achieved in the 1st case at 14.2%.

The results revealed by incorporating insulation materials with thicknesses ranging from 25mm to 100mm, a possible decrease in cooling load could be obtained throughout the whole year. Overall, greater reduction in cooling load is attained by using thicker insulation material with low thermal conductance. Therefore, the highest saving in cooling load is achieved by using 100mm insulation material in IR3.

Additionally, using thicker insulation materials has an impact on saving cooling load. To compare between the three insulated roofs, IR1 has potential saving of 13.5 % compared to the 1st case, while IR2 has potential saving of 5.7% compared to IR1, finally, IR3 has potential saving of 5% compared to IR2. Consequently, IR3 is chosen to improve indoor thermal environment for its saving potential of the cooling load and because it complies with the required u-value according to Saudi building standards for the house in Jeddah.

8.3.3. Proposed construction layers of Floor

Three types of ground floors were proposed and simulated to improve the indoor thermal performance and achieve the lowest all year round cooling load. The annual cooling load was estimated following the implementation of the various proposed ground floors compared with the base case of the existing floor.

As revealed by the thermal analysis of the houses in the previous chapter, heat gain through the ground floors in a summer-day is significantly lower than heat loss. Also, ground floor heat gain on a winter-day is significantly higher than the zero heat loss. Therefore, various types of ground floors with various thickness and lower thermal conductance than the existing ground floor were proposed to minimise heat loss in summer and heat gain in winter. Table 8.3.3 sets out the proposed ground floors explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.3.3: Characteristics of existing and proposed insulated ground floor

Floors	Floors type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing floor used in Jeddah's house	JF1	20 mm terrazzo tile (inside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 100 mm soil	1.683	2.201
Existing floor used in Makkah's house	MF1	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 150 mm soil	0.933	1.153
Introducing thermal insulation	IF1	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 30 mm polyurethane board 150 mm soil	0.453	0.484
	IF2	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 60 mm polyurethane board 150 mm soil	0.294	0.306

The existing ground floor (JF1) is also a common floor type used in residential buildings. It is composed of terrazzo tiles fixed on 100mm cement mortar and sand which are bedded on 300mm plain concrete.

1st case (MF1): MF1 is the existing ground floor used in the Makkah house and used here to test modified floor types in contrast to the existing one. This ground floor and its external and internal finishing is applied in all the proposed floors.

Ground floors with thermal insulation (IF1 and IF2): Two types of the proposed floors incorporate cavity polyurethane board with different thickness (30mm and 60mm). The highlighted ground floor in the table above is the one with a little less U-value than the maximum value required by the Saudi building standards (SBC) for Jeddah's climate.

- **Cooling load saving with proposed ground floors**

The energy savings of the proposed ground floors is measured approximately where the house in Jeddah is assumed with air conditioning to estimate the annual cooling load. The upper temperature for cooling is set at 25°C. Figure 8.3.3.1 provides the annual cooling with the implementation of the various ground floors in only the guest room in the ground floor in the house in Jeddah. Table 8.3.3.1 provides the percentage of cooling loads savings comparing with the existing ground floor.

Table 8.3.3.1. Percentage of reduction in annual cooling load for proposed ground floors compared with existing floor in the base case

Floors cases	Floor type	annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	JF1	108.7	
1st case	MF1	100.9	7.2
2nd case	IF1	94.8	12.8
3rd case	IF2	93.0	14.4

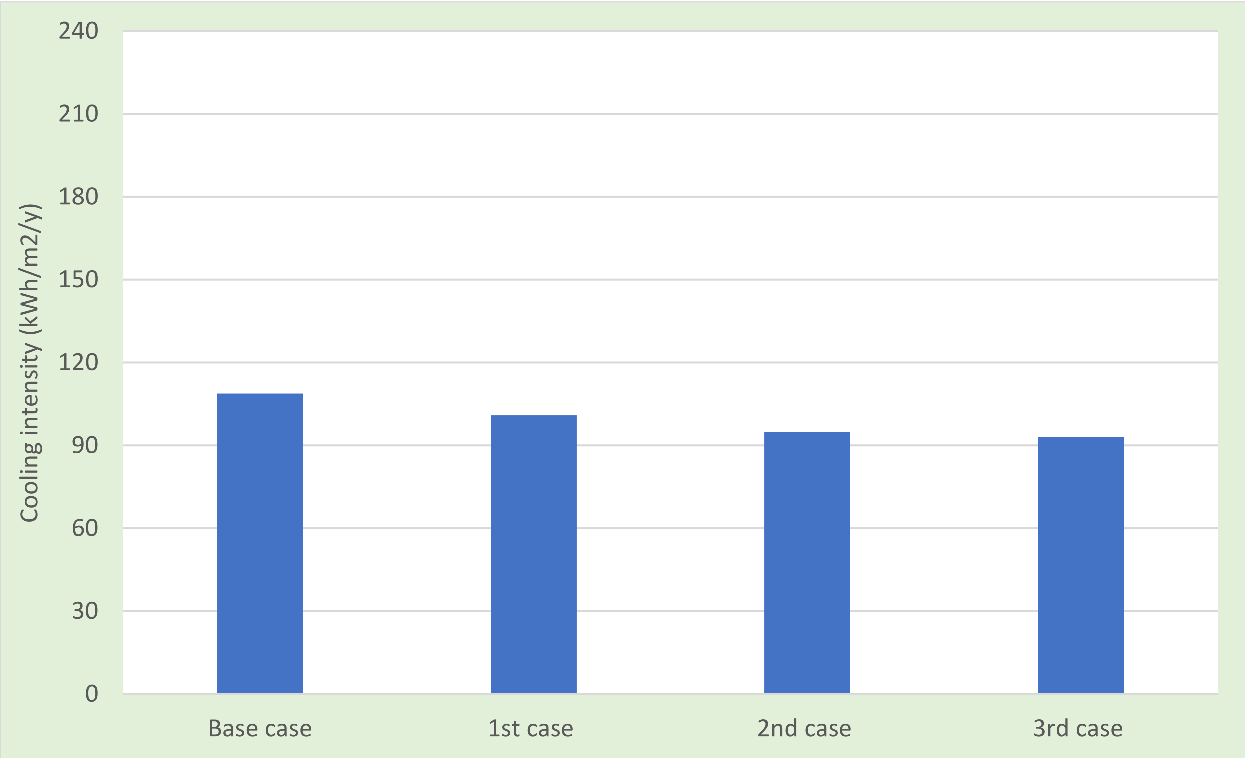

Figure 8.3.3.1: Annual cooling load for proposed ground floors (kWh/m2/y).

Only the guestroom is chosen for the simulation as it is on the ground floor. The results show that by implementing the insulated proposed floor (2nd case and 3rd case), the potential savings in the cooling loads ranging from 12.8% and 14.4% were achieved in IF1 and IF2 respectively. However, by not using an insulated floor, there is still a considerable possible saving in the cooling loads as it can be seen in the 1st case 7.2%.

Therefore, the highest saving in cooling load is achieved by using 60mm insulation material in IF2. Increasing the thickness of the insulation materials does not necessarily have a corresponding impact on saving cooling load. To compare between the two insulated ground floors, IF1 has potential saving of 6% compared to the base case, while IF2 has potential saving of 1.8% compared to IF1. Consequently, IF1 is chosen to improve indoor thermal environment for its cooling load saving and because it complies with the required ground floor u-value for the house in Jeddah.

8.3.4. Proposed construction layers of window and shading

One type of window coupled with removing external shutters was proposed and simulated to improve the indoor thermal performance and achieve the lowest cooling load. The annual cooling load was estimated when the implementation of the various proposed cases is compared with the base case of the existing windows and shading.

The thermal analysis of the house in Jeddah in the previous chapter showed that heat loss through windows is relatively slight compared with the total fabrics' loss in winter and summer. Besides, the solar gain through the windows is the least gain of the total fabrics in winter and summer due to the external shutters. Therefore, double glazed windows with external shading, single and double glazed windows without external shading were proposed to evaluate the current window and external shading in relation to the cooling load (see table 8.3.4).

Table 8.3.4: Characteristics of existing and proposed windows

Window and shading	Window type	Layers description	U-value (w/m².˚C)	Solar transmittance
Existing window and shading used in Jeddah's house	JW1	Single glazing with internal blind and external 200 mm horizontal overhang and 200 mm vertical two side shading	5.5	0.080
Upgrading window type	JW2	double glazing with internal blind and external 200 mm horizontal overhang and 200 mm vertical two side shading	1.606	0.060
Removing external shading	WW1	Single glazing with internal blind	5.5	0.080
	WW2	double glazing with internal blind	1.606	0.060

- **Cooling load saving with proposed windows**

To calculate the annual cooling load, the energy savings aligned with the proposed permutations for the windows has been measured assuming the Jeddah house has air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.3.4.1 provides the annual cooling with the implementation of the various windows in both rooms in the house in Jeddah. Table 8.3.4.1 provides the percentage of cooling load savings compared with the existing windows and shading.

Table 8.3.4.1. Percentage of reduction in annual cooling load for proposed windows comparing with existing windows and shading in the base case

Windows and shading cases	window type	Average annual cooling (kWh/m²/y)	Increase of cooling load (%)
Base case	JW1	126.8	-
1st case	JW2	132.3	4.1
2nd case	WW1	164.6	23.0
3rd case	WW2	167.8	24.4

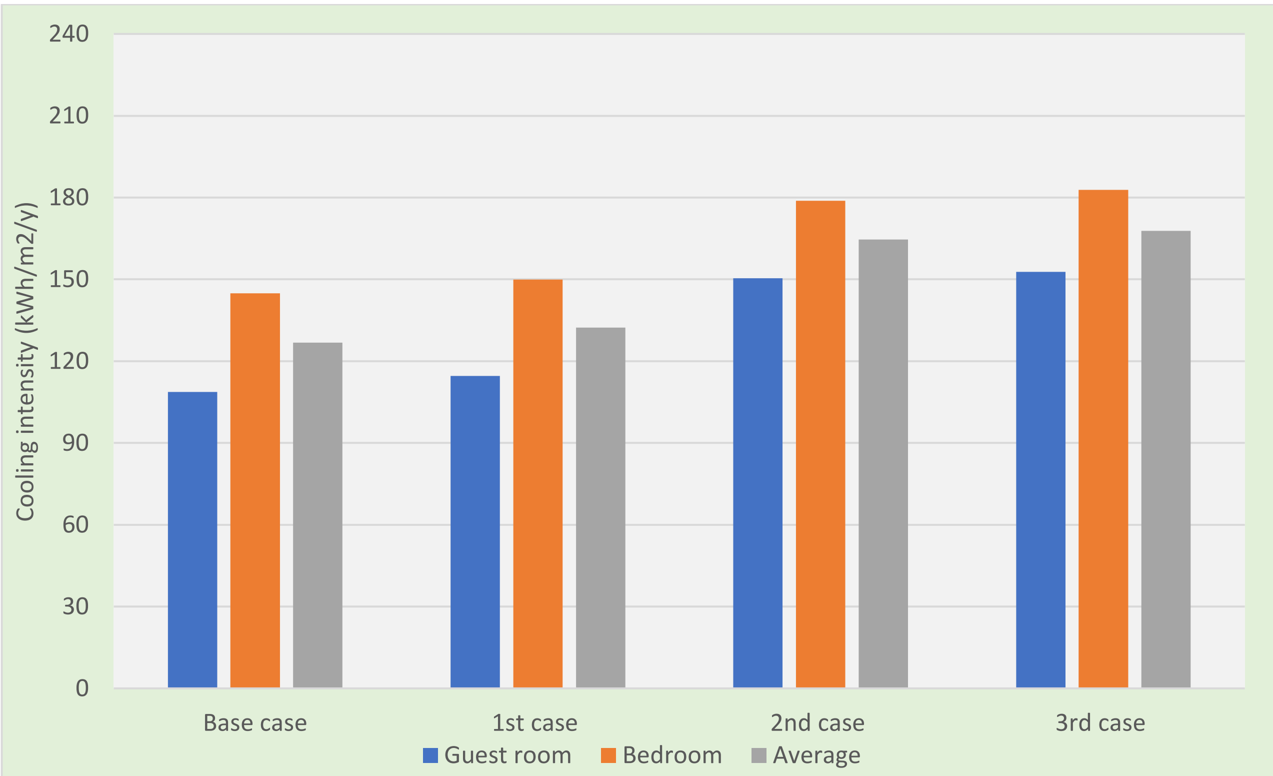

Figure 8.3.4.1: Annual cooling load for proposed windows (kWh/m2/y).

The results show that by removing the external shutters in the 2nd case and 3rd case, the potential increase in the cooling loads ranged from 23% and 24.4% and occurred in WW1 and WW2 respectively. The results also reveal a slight increase in the cooling load when upgrading the window type. Therefore, the highest saving in cooling load is achieved in the base case in JW1. Consequently, JW2 is chosen because it complies with the window U-value set by Saudi building standards.

8.3.5. Proposed combination of building fabric

Combinations of the various proposed walls, roofs, ground floors and windows were selected and simulated to find the best overall indoor thermal performance and achieve the lowest cooling load all year. The annual cooling load was estimated with the implementation of the various combinations of fabrics and then compared with the existing fabrics. The potential cooling savings attained by applying these combinations of the house's envelope were calculated. An explanation for the selected combinations, the simulation results and the percentage of cooling load savings compared with the existing fabrics, are provided in table 8.3.5.

All highlighted building fabrics discussed earlier in this chapter were selected and combined to achieve the best case. One of the proposed floors, one of the proposed walls, one of the proposed roofs and one of the proposed windows were selected to form three combinations of fabrics. The 1st case is a combination of the proposed roof and walls only, without the proposed floor and window, while the second case is a combination of roof, walls, floor and windows, while the third best case is a combination of roof, walls and floor. The selection was based on the annual potential improvement in cooling load.

To calculate the annual cooling load, the energy savings of the proposed fabric combinations has been measured on the basis that the house has air conditioning. The upper temperature is set at 25 °C. Figure 8.3.5 shows the annual cooling load with the implementation of the various fabric combinations for the two rooms in the Jeddah house. The results reveal that the combination of fabrics in the JC1 had a potential cooling load saving of 38.3% , while the JC2 achieved a 43.3% reduction of the cooling load achieved. Finally, JC3 achieved the best reduction of 47.3% of the cooling load.

Table 8.3.5: Characteristics of existing and proposed combinations of fabrics

Combined cases	Combination type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	JB1	126.8	-
1st case	JC1 (roof, wall)	78.2	38.3
2nd case	JC2 (roof, wall, floor, window)	72.0	43.2
Best case	JC3 (roof, wall, floor)	66.8	47.3

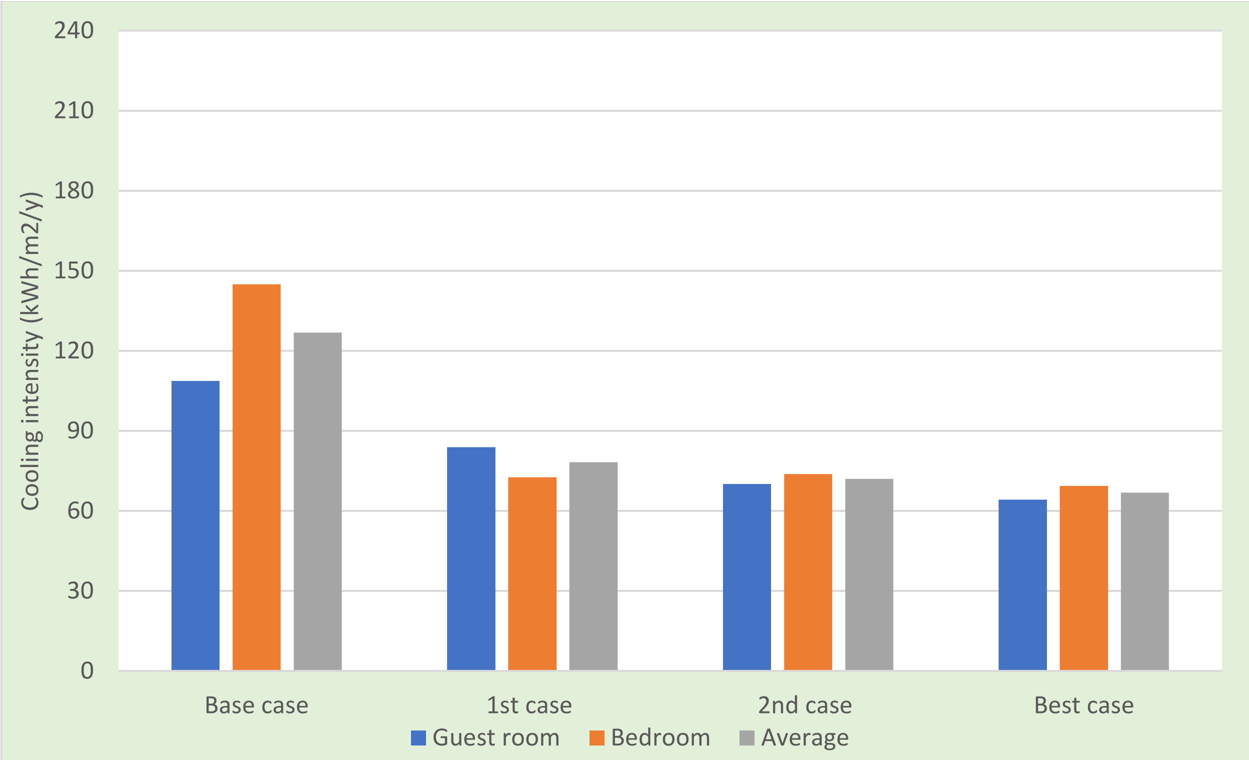

Figure 8.3.5: Annual cooling load for proposed fabrics' combination (kWh/m2/y).

- **The Effect of Revised Ventilation Strategy (mixed mode)**

As the outside night-time temperature falls to acceptable temperature levels (less than 25 °C), night time ventilation was applied in the studied rooms. The annual cooling load was estimated when applying the night ventilation whenever the outside temperature is less than 25 °C, along with the implementation of the most recommended fabric combination (best case). The potential reduction in the percentage of cooling load was compared with the best case conditions using the night time ventilation strategy (see table 8.3.5.1). The results revealed that by applying night time ventilation with the best case, a slight decrease in the percentage of cooling load of 8.8% was achieved (see figure 8.3.5.1).

Table 8.3.5.1: Description of the best case and the proposed ventilation strategy

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Best case	JC3	66.8	-
1st case	JC4 (best case + NTV)	60.9	8.8

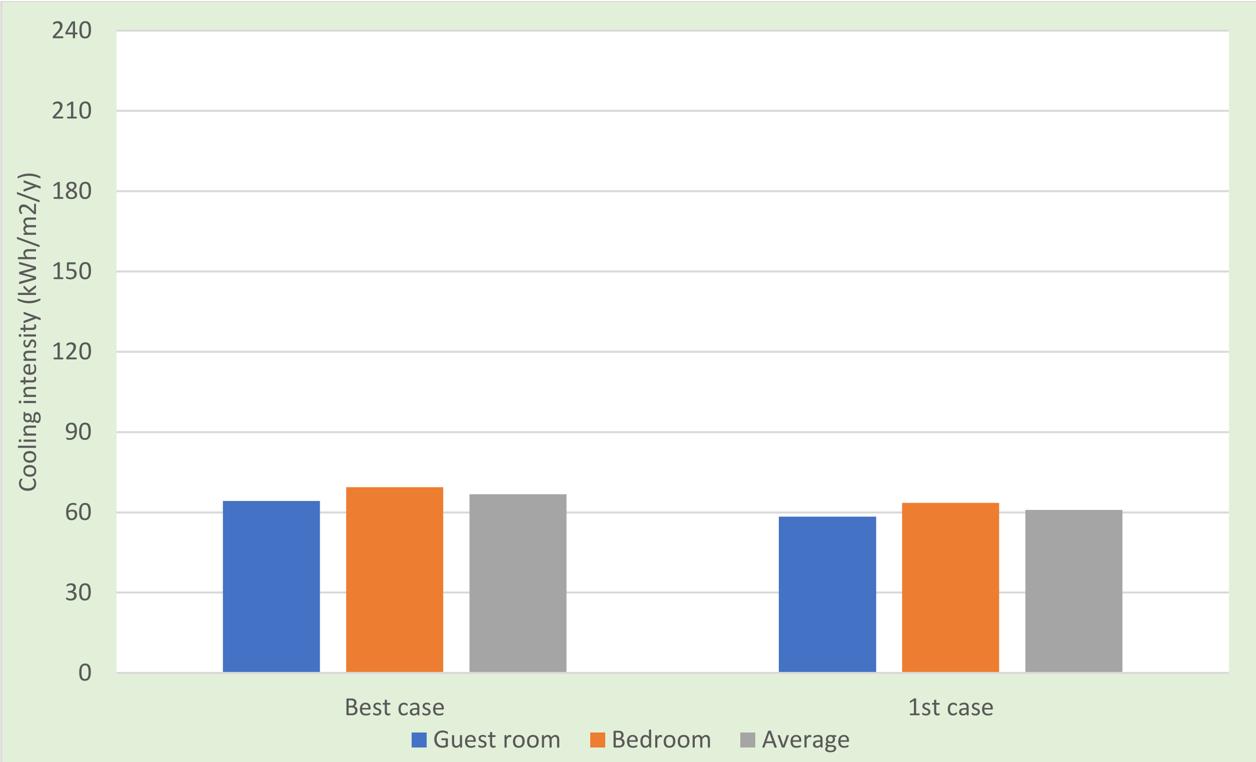

Figure 8.3.5.1: Annual cooling load for best case and the proposed ventilation strategy (kWh/m2/y).

- **The effect of set thermostat points of the A/C**

The potential saving of the cooling load as a result of raising the A/C thermostat setting was applied in the studied rooms. The annual cooling load was estimated when applying the different temperatures, along with the optimum fabric combinations best case which has set the thermostat point at 25°C. The potential reduction in the percentage of cooling load comparing the best case conditions with the different temperatures is illustrated at table 8.3.5.2. The results reveal that raising the A/C thermostat setting from 23.9 °C to 25°C, leads to a potential reduction in the cooling load of 16.7 %, when raising the temperature to 26°C a reduction of 16.9% compared to the best case and 30.8% compared to the 1st case of the cooling load was also achieved (see figure 8.3.5.2).

Table 8.3.5.2: Description of the best case and the proposed set thermostat points of the A/C

Combined cases	Combination type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
1st case	JC5 (23.9˚C)	80.3	-
Best case	JC3 (25˚C)	66.8	16.7
2nd case	JC6 (26˚C)	55.5	30.8

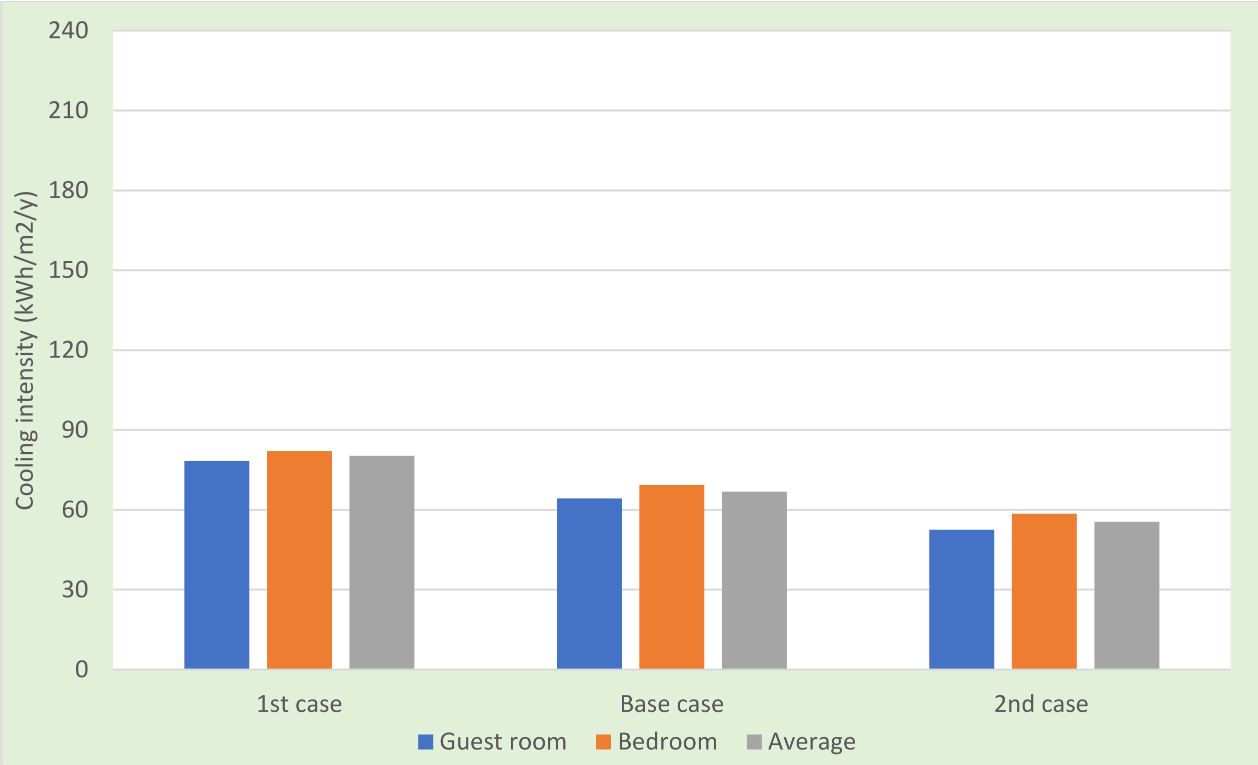

Figure 8.3.5.2: Annual cooling load for best case and the proposed set thermostat point of the A/C (kWh/m2/y).

8.4. The house in Riyadh

8.4.1. Proposed construction layers of external wall

To identify the best-case external wall which can improve indoor thermal performance and achieve a low cooling load, various wall types and thicknesses were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed walls and compared with the base case of the existing walls.

Regarding the proposed wall types and heat transfer, thermal insulation's capacity to control heat flow through the walls in both directions makes it suitable in winter and summer as the heat gain through walls is the second highest heat source in the Riyadh house. The effectiveness of the proposed walls was tested and simulated for the whole year to reflect the best case in relation to cooling load reduction.

In view of the thermal analysis of the house in Riyadh, three walls with different insulation thickness were proposed for simulation by TAS, where (IW1 to IW3) represent walls incorporating thermal insulation materials thickness. The simulation of the various proposed walls is aimed to stand on the different thermal performance that can be provided using each type of wall. Furthermore, description for the proposed walls and the simulation results are provided in table 8.4.1 explaining their layers, thicknesses, U-value and thermal conductance. Additionally, existing external walls of the house in Riyadh are presented in figure 8.4.1.

Figure 8.4.1. Highlighted existing external walls of the house in Riyadh

Table 8.4.1: Characteristics of existing and proposed insulated walls

Walls	Wall type	Layers description	U-value (w/m².°C)	Conductance (w/m².°C)
Existing external walls used in Riyadh's house	RW1 (main elevation)	30 mm limestone (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	2.897	5.708
	JW2 (side elevation)	Paige paint (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	3	6.412
Existing external walls used in Makkah's house	MW2	Paige paint (outside) 20 mm external rendering 200 mm red hollow cone. block 20 mm internal plaster white paint (inside)	1.549	2.102
Introducing thermal insulation	IW1	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 20 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.692	0.784
	IW2	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 60 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.328	0.348
	IW3	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 100 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.215	0.223

The existing walls (RW1, JW2): JW1 is only applied on the main elevation of external walls, while JW2 is applied on external side elevations. This wall is one of the most common wall types in Saudi Arabia and used in most of the residential buildings. It incorporates internal painting, 20 mm internal plastering, 200mm concrete block, 30 mm external rendering and external painting.

1st case (MW2): MW2 is existing external wall used in the Makkah house and used here to test different type of the wall than the existing ones. This wall and its external and internal finishing used is applied in all the proposed walls.

Walls with thermal insulation (IW1 to IW3): Three types of the proposed walls incorporate cavity polyurethane board with different thickness (20mm, 60mm and 100mm). The highlighted wall is the one with a little less U-value than the maximum value required by the SBC for Riyadh's climate.

- **Cooling load saving with proposed external walls**

To estimate the annual cooling load, the energy savings of the proposed external walls is measured in the Riyadh house which is assumed to have air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.4.1.1 provides the annual cooling when the various walls in each case for both rooms is implemented in the house in Riyadh. Table 8.4.1.1 provides the percentage of cooling load savings comparing with the existing fabrics.

Table 8.4.1.1. Percentage of reduction in annual cooling load for proposed walls compared with existing base case walls

Wall cases	Wall type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	RW1 (main elevation)	198.4	-
	JW2 (side elevation)		
1st case	MW2	168.3	15.1
2nd case	IW1	152.7	23
3rd case	IW2	146.1	26.3
4th case	IW3	144.1	27.3

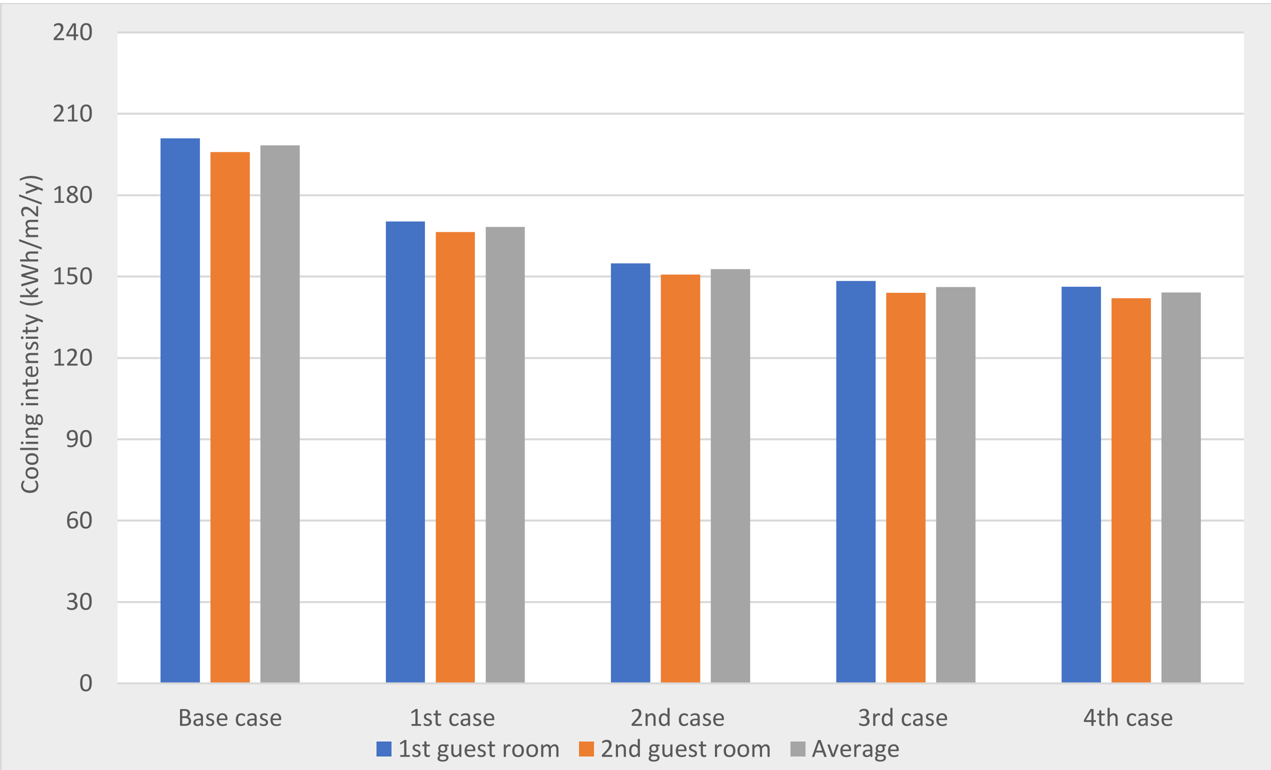

Figure 8.4.1.1: Annual cooling load for proposed walls (kWh/m2/y).

The results show that by implementing the proposed walls (2nd case to 4th case), the potential savings in the cooling loads ranged from 23% in IW1, 26.3% achieved in IW2 and 27.3% achieved in IW3. However, by not using an insulated wall, there is still a considerable possible saving in the cooling loads as in the 1st case 15.2%. The results reveal that incorporating insulation materials with thicknesses of between 20mm to 100mm, a possible all year reduction in cooling load could be obtained. Overall, a greater decrease in cooling load is attained with an increase in the thickness of the insulation material which has very low thermal conductance. Therefore, the highest saving in cooling load is achieved by using 100mm insulation material in IW3.

However, greater thickness of the insulation materials does not in this instance, have a big impact on saving cooling load. To compare between the three insulated walls, IW1 has potential saving of 9.2% compared to the 1st case, while IW2 has potential saving of 4.2% compared to IW1, finally, IW3 has potential saving of 1.3% compared to IW2. Consequently, IW2 is chosen to improve indoor thermal environment for its saving potential of the cooling load and because it complies with the required walls u-value by Saudi building standards for the house in Riyadh.

8.4.2. Proposed construction layers of Roof

To identify the best-case proposed roof which can improve indoor thermal performance and achieve the lowest all year cooling load, various types and thickness of roofs were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed roofs and compared with the base case of the existing roof. Heat gain through the roof is the highest in the house in Riyadh..Also, heat gain through the roof in summer and winter is higher than the roof loss. Therefore, various types of roofs, with lower thermal conductance than that of the existing roof, were proposed to minimize the heat gain. The use of additional thermal insulation was proposed for the roof. Table 8.4.2 provides the proposed roofs explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.4.2: Characteristics of existing and proposed insulated roof

Roofs	Roof type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing roof used in Riyadh house	JR1	20 mm terrazzo tiles (outside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 20 mm gypsum board and internal plaster white paint (inside)	1.395	1.972
Existing roof used in Makkah's house	MR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.901	1.111
Introducing thermal insulation	IR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 25 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.474	0.526
	IR2	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 50 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.322	0.345
	IR3	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 100 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.196	0.204

The existing roof (JR1): is one of the most common roof types used in Saudi residential buildings. It incorporates 20 mm internal gypsum board with internal plaster and painting, 300 mm reinforced concrete slap, 120 mm sand, cement mortar and terrazzo tile.

1st case (MR1): MR1 is the existing roof used in the Makkah house and used here to test different types of roof. This roof and its external and internal finishing is used in all the proposed roofs.

Roofs with thermal insulation (IR1 to IR3): Three types of the proposed roofs incorporate cavity polyurethane board with different thickness (25mm, 50mm and 100mm). The highlighted roof is the one with slightly less U-value than the maximum U-value recommended for Riyadh's climate.

- **Cooling load saving with proposed roofs**

The energy savings of the proposed roofs has been measured to estimate the annual cooling load while the Riyadh house is treated as having air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.4.2.1 provides the annual cooling with the implementation of the various roofs in each case for both rooms in the Riyadh house. Table 8.4.2.1 provides the percentage of cooling load savings compared with the existing roof.

Table 8.4.2.1. Percentage of reduction in annual cooling load for proposed roofs compared with existing roof in the base case

Roofs cases	Roof type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	JR1	198.4	-
1st case	MR1	178.8	9.8
2nd case	IR1	162.5	18.1
3rd case	IR2	156.5	21.1
4th case	IR3	151.4	23.6

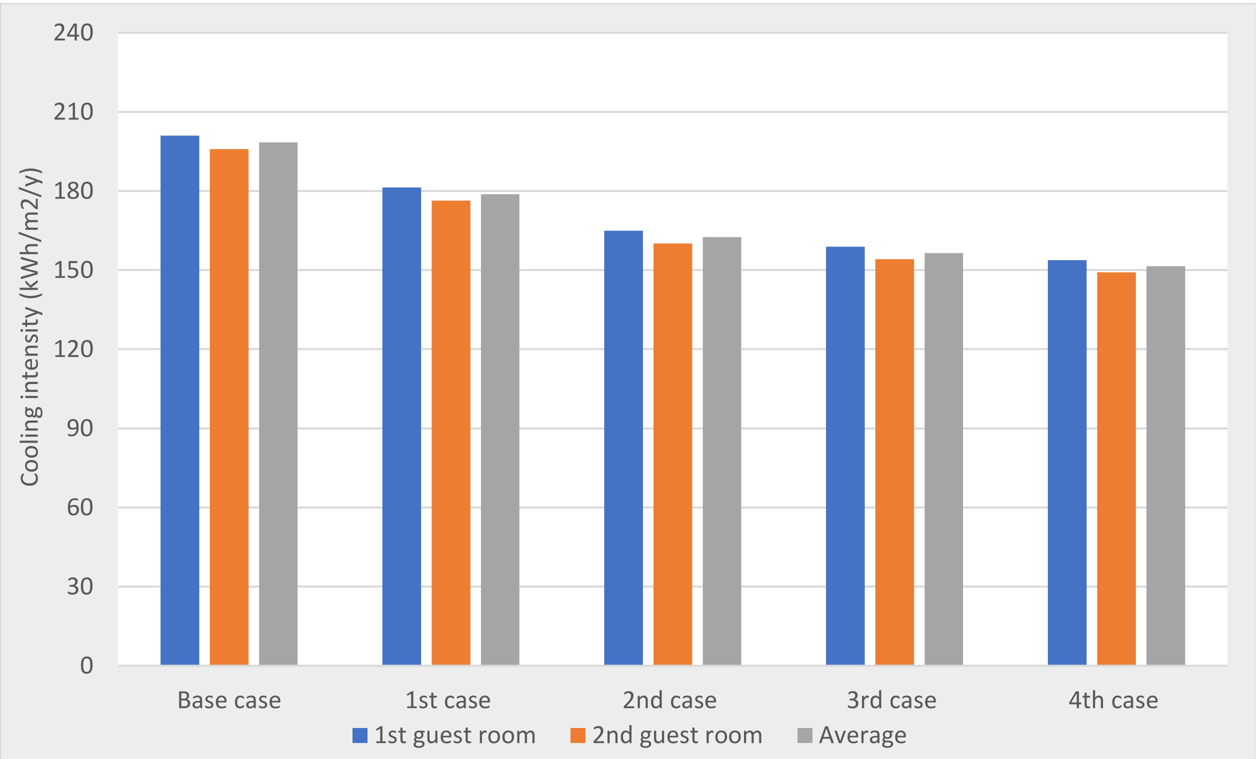

Figure 8.4.2.1: Annual cooling load for proposed roofs (kWh/m2/y).

The two rooms, excluding the 1st floor, have been simulated to test their exposure to solar radiation. The results show that by implementing the insulated proposed roofs (2nd case to 4th case), the potential cooling load savings ranged from 18.1% in IR1, 21.1% in IR2 and 23.6% in IR3 . However, by not using an insulated roof, there is still a considerable possible saving in the cooling load as seen in the 1st case at 9.8%.

The findings reveal that the use of insulation materials with various thicknesses between 25mm and 100mm can produce a possible reduction in cooling load the whole year. Overall, a greater reduction in cooling load is attained by increasing the thickness of the insulation material with its very low thermal conductance. Therefore, the highest saving in cooling load is achieved by using 100mm insulation material in IR3.

To compare between the three insulated roofs, IR1 has a potential saving of 9.1 % compared to the 1st case, while IR2 has potential saving of 3.6% compared to IR1, finally, IR3 has potential saving of 3.2% compared to IR2. Consequently, IR3 is chosen to improve the indoor thermal environment for its saving potential of the cooling load and because it complies with the required roofs u-value according to Saudi building standards for the house in Riyadh.

8.4.3. Proposed construction layers of Floor

Three types of ground floors were proposed and simulated to improve the indoor thermal performance and achieve the lowest cooling load in all year. The annual cooling load was estimated with the implementation of the various proposed ground floors and compared with the base case of the existing floor.

As revealed by the thermal analysis of the houses in the previous chapter, heat gain via the ground floors on a summer-day is significantly lower than the heat lost. Besides, heat gain through the ground floor on a winter-day is significantly higher than heat loss, which has zero heat loss through the ground floor in a winter-day. Therefore, various types of ground floors with various thickness and lower thermal conductance than the existing ground floor were proposed to minimise heat loss in summer and heat gain in winter. Table 8.4.3 provides the proposed ground floors, explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.4.3: Characteristics of existing and proposed insulated ground floor

Floors	Floors type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing floor used in Riyadh's house	JF1	20 mm terrazzo tile (inside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 100 mm soil	1.683	2.201
Existing floor used in Makkah's house	MF1	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 150 mm soil	0.933	1.153
Introducing thermal insulation	IF1	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 30 mm polyurethane board 150 mm soil	0.453	0.484
	IF2	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 60 mm polyurethane board 150 mm soil	0.294	0.306

The existing ground floor (JF1) is also a common floor type used in residential buildings. It is composed of terrazzo tiles fixed on 100mm cement mortar and sand, which are bedded on 300mm plain concrete.

1st case (MF1): MF1 is the existing ground floor used in the Makkah house and used here to test different types of floor. This ground floor and its external and internal finishing is applied in all the proposed floors.

Ground floors with thermal insulation (IF1 and IF2): Two types of the proposed floors incorporate cavity polyurethane board with different thickness (30mm and 60mm). The highlighted ground floor has less U-value than the maximum value required for Riyadh's climate.

- **Cooling load saving with proposed ground floors**

The energy savings of the proposed ground floors has been measured with the house in Riyadh assumed to have air conditioning to estimate the annual cooling load. The upper temperature for cooling is set at 25°C. Figure 8.4.3.1 provides the annual cooling with the implementation of the various ground floors in only the guest room in the ground floor in the house in Riyadh. Table 8.4.3.1 provides the percentage of cooling loads savings comparing with the existing ground floor.

Table 8.4.3.1. Percentage of reduction in annual cooling load for proposed ground floors compared with existing floor in the base case

Floors cases	Floor type	Average annual cooling (kWh/m²/y)	Increase of cooling load (%)
Base case	JF1	198.4	
1st case	MF1	199.6	0.6
2nd case	IF1	200.2	0.9
3rd case	IF2	200.4	1.0

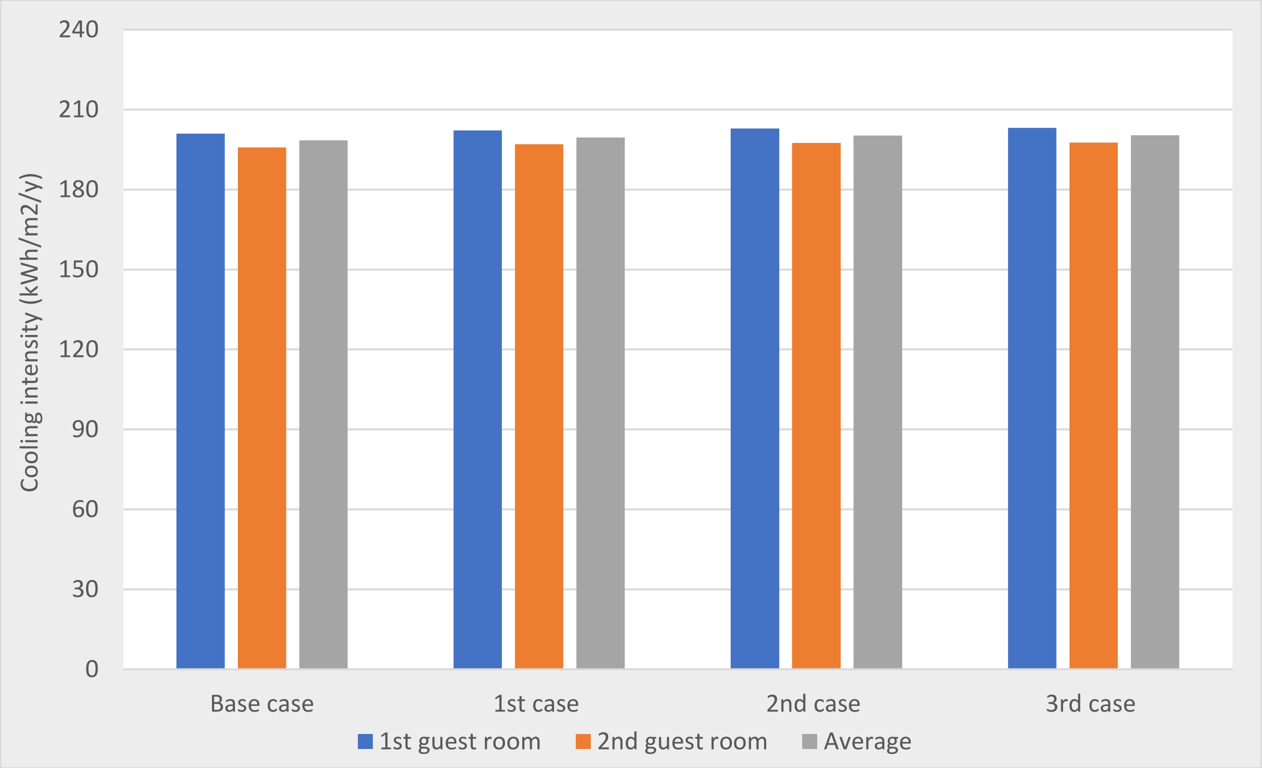

Figure 8.4.3.1: Annual cooling load for proposed ground floors (kWh/m2/y).

The results show that by implementing the insulated proposed floors (2nd case and 3rd case), there is no potential savings in the cooling loads in all cases. The results revealed by incorporating insulation materials with various thicknesses, 30mm to 60mm, a possible slight increase in cooling load could be obtained the whole year. IF1 is chosen because it complies with the required ground floors u-value for the house in Riyadh.

8.4.4. Proposed construction layers of window and shading

One type of window was proposed and simulated to improve indoor thermal performance and achieve the lowest all year cooling load. The annual cooling load was estimated with the implementation of the proposed case are compared with the base case of the existing windows and shading.

The thermal analysis of the house in Riyadh in the previous chapter showed that heat loss through windows is relatively slight compared with the total loss through fabrics in winter and summer. Also, the solar gain through the windows is the least gain of the total fabrics gain in winter and summer due to internal shading. Therefore, double glazed windows were proposed to assess if upgrading the window type has an effect on the cooling load (see table 8.4.4).

Table 8.4.4: Characteristics of existing and proposed windows

Window and shading	Window type	Layers description	U-value (w/m².°C)	Solar transmittance
Existing window and shading used in Riyadh's house	WW1	Single glazing with internal blind	5.5	0.080
Upgrading window type	WW2	double glazing with internal blind	1.606	0.060

- **Cooling load saving with proposed windows**

To estimate the annual cooling load, the energy savings using the proposed windows has been measured where the house in Riyadh is assumed to have air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.4.4.1 provides the annual cooling when windows are upgraded in both rooms in the Riyadh house. Table 8.4.4.1 provides the percentage of cooling load savings compared with the existing windows and shading.

Table 8.4.4.1. Percentage of reduction in annual cooling load for proposed windows compared with existing windows and shading in the base case

Windows and shading cases	Window type	Average annual cooling (kWh/m²/y)	Increase of cooling load (%)
Base case	WW1	198.4	-
1st case	WW2	198.9	0.3

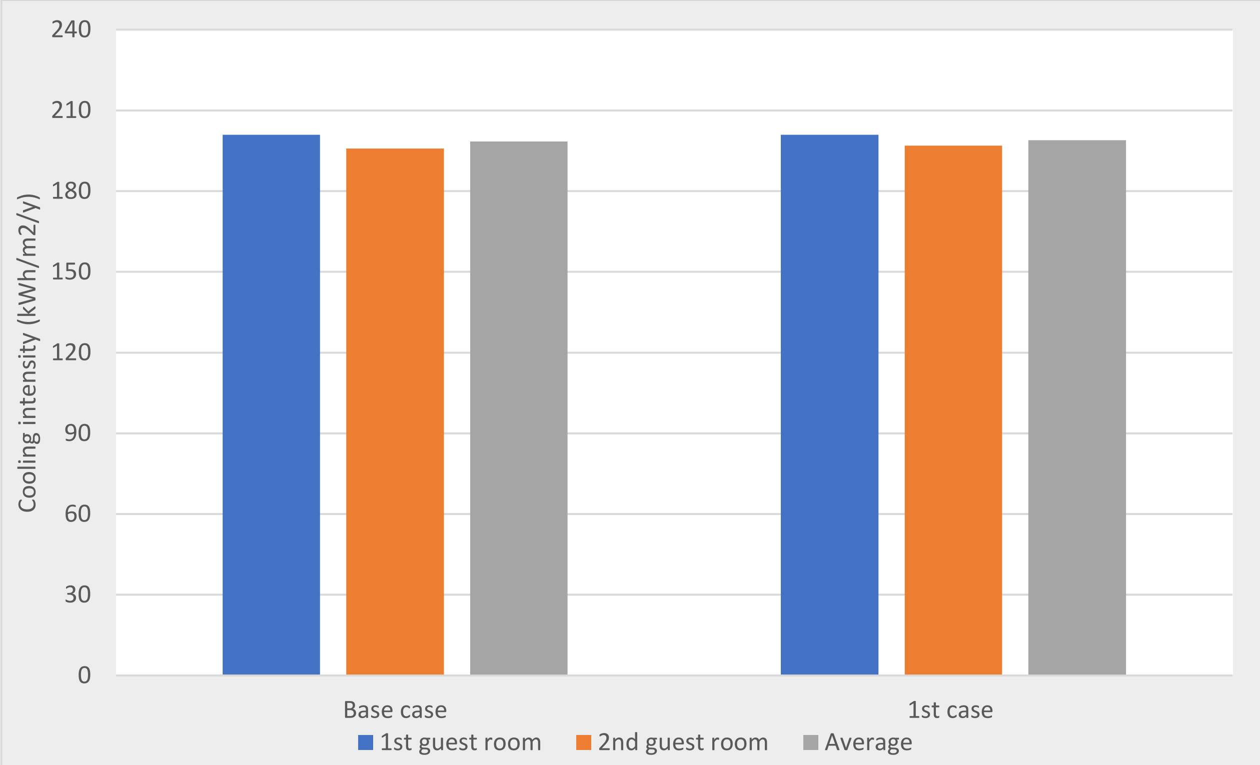

Figure 8.4.4.1: Annual cooling load for proposed windows (kWh/m2/y).

The results show that upgrading the window type has no effect on the cooling load. Therefore, the 1st case is chosen because it complies with the required window U-value assessed by Saudi building standards.

8.4.5. Proposed combination of building fabrics

Combinations of the various proposed walls, roofs, ground floors and windows were selected and simulated to ascertain the optimum overall indoor thermal performance and achieve the lowest cooling load all year. The annual cooling load was estimated when the various combinations of fabrics were applied and was compared with those of the base case. The potential cooling savings attained by applying these combinations of the house's envelope were calculated. Explanation for the selected combinations, the simulation results and the percentage of cooling load savings compared with the existing fabrics are provided in table 8.4.5.

All highlighted building fabrics discussed earlier in this chapter were selected and combined to achieve the best case. One of the proposed floors, one of the proposed walls, one proposed roof and the proposed windows were selected to form three combinations of fabrics. The 1st case is a combination of the proposed roof and walls only without the proposed floor and window, while the 2nd case is a combination of roof, walls and floor, while the third case (best case) is a combination of roof, walls, floor and windows. The selection was based on the annual potential improvement in cooling load.

To estimate the annual cooling load, the cooling savings using the proposed fabric combinations is measured where the house is assumed to have air conditioning. The upper temperature is set at 25 °C. Figure 8.4.5 provides the annual cooling load with the implementation of the various fabric combinations of the two rooms in the Riyadh house. The results reveal that implementing the fabric combination in RC1 delivers a potential saving of 54%, while using the fabric combination in RC2 delivers the second best case, achieving a reduction of 58%. Finally, RC3 delivers the best case with a reduction of 58.2% in the cooling load.

Table 8.4.5: Characteristics of existing and proposed combinations of fabrics

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Base case	RB1	198.4	-
1st case	RC1 (roof, wall)	90.7	54.3
2nd case	RC2 (roof, wall, floor)	83.4	58.0
Best case	RC3 (roof, wall, floor, window)	83.0	58.2

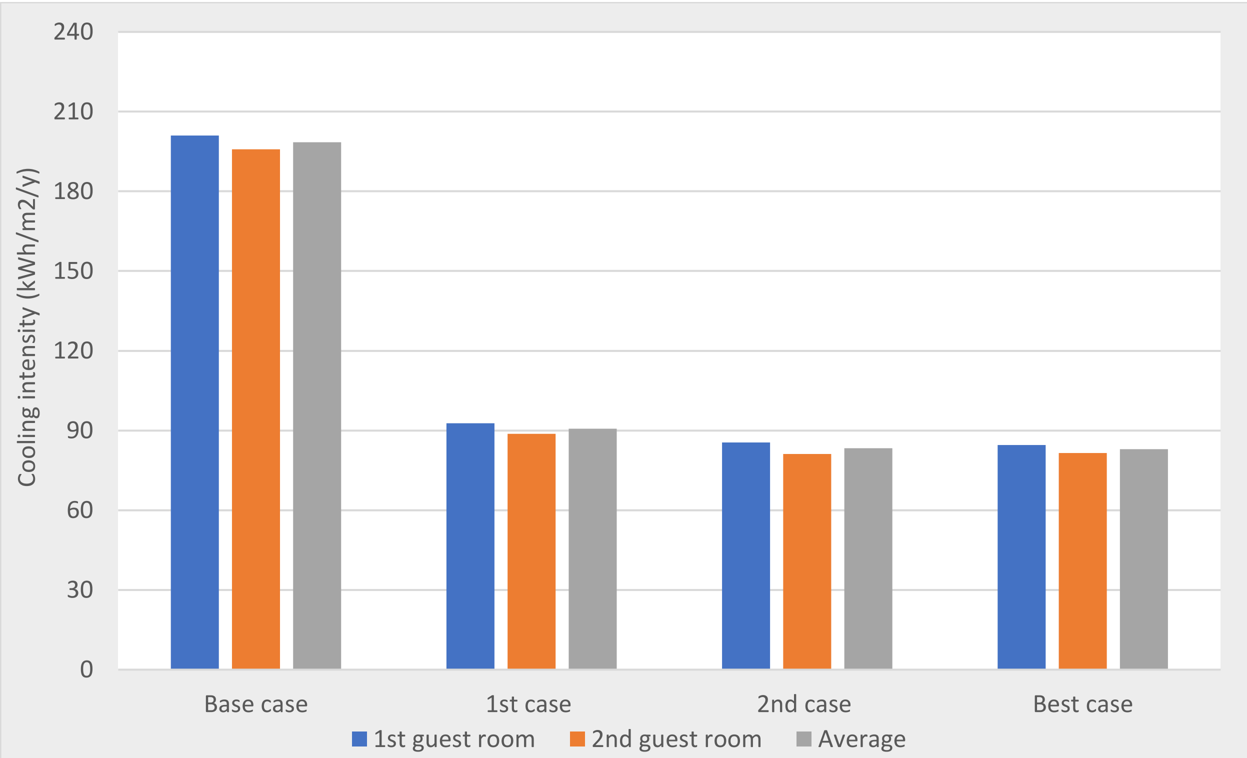

Figure 8.4.5: Annual cooling load for proposed fabrics' combination (kWh/m2/y).

- **The Effect of Revised Ventilation Strategy (mixed mode)**

As the outside night time temperature falls to acceptable temperature levels (less than 25 °C), a night time ventilation was proposed for the studied rooms. The annual cooling load was estimated when applying the night ventilation whenever the outside temperature falls below 25 °C, along with the enactment of the most recommended fabric combinations (best case). The potential reduction in the percentage of cooling load is compared with conditions in the best case with the night time ventilation strategy (see table 8.4.5.1). The results reveal that by applying night time ventilation with the best case, a slight potential reduction in the percentage of cooling load of 4.5 % can be achieved (see figure 8.4.5.1).

Table 8.4.5.1: Description of the best case and the proposed ventilation strategy

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Best case	RC3	83.0	-
1st case	RC4 (best case + NTV)	79.3	4.5

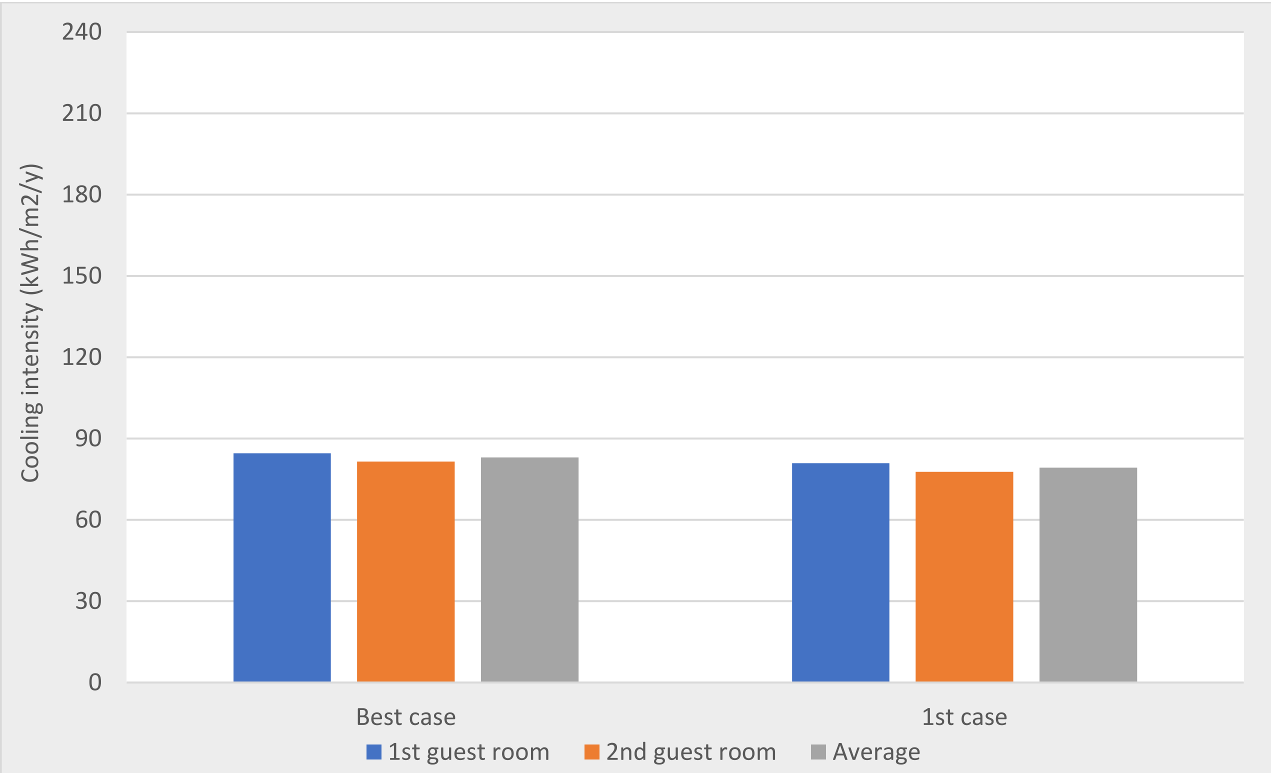

Figure 8.4.5.1: Annual cooling load for best case and the proposed ventilation strategy (kWh/m2/y).

- **The effect of set thermostat points of the A/C**

The potential saving of the cooling load as a result of raising the A/C thermostat setting was applied in the studied rooms. The annual cooling load was estimated when applying the different temperature readings, along with the best case fabric combinations which set the thermostat at 25°C.

The potential reduction in the percentage of cooling load comparing best case conditions with the different degrees can be seen at table 8.4.5.2. The results revealed that by raising the thermostat setting of the A/C from 23.9 °C to 25°C, a potential reduction in the percentage of 12.8 are achieved, while a noticeable reduction of 12.5% and 23.7% of the cooling load also achieved when raising the temperature to 26°C compared to the best and 1st cases respectively (see figure 8.4.5.2).

Table 8.4.5.2: Description of the best case and the proposed set thermostat points of the A/C

Combined cases	Combination type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	RC5 (23.9˚C)	95.1	-
Best case	RC3 (25˚C)	83.0	12.8
1st case	RC6 (26˚C)	72.6	23.7

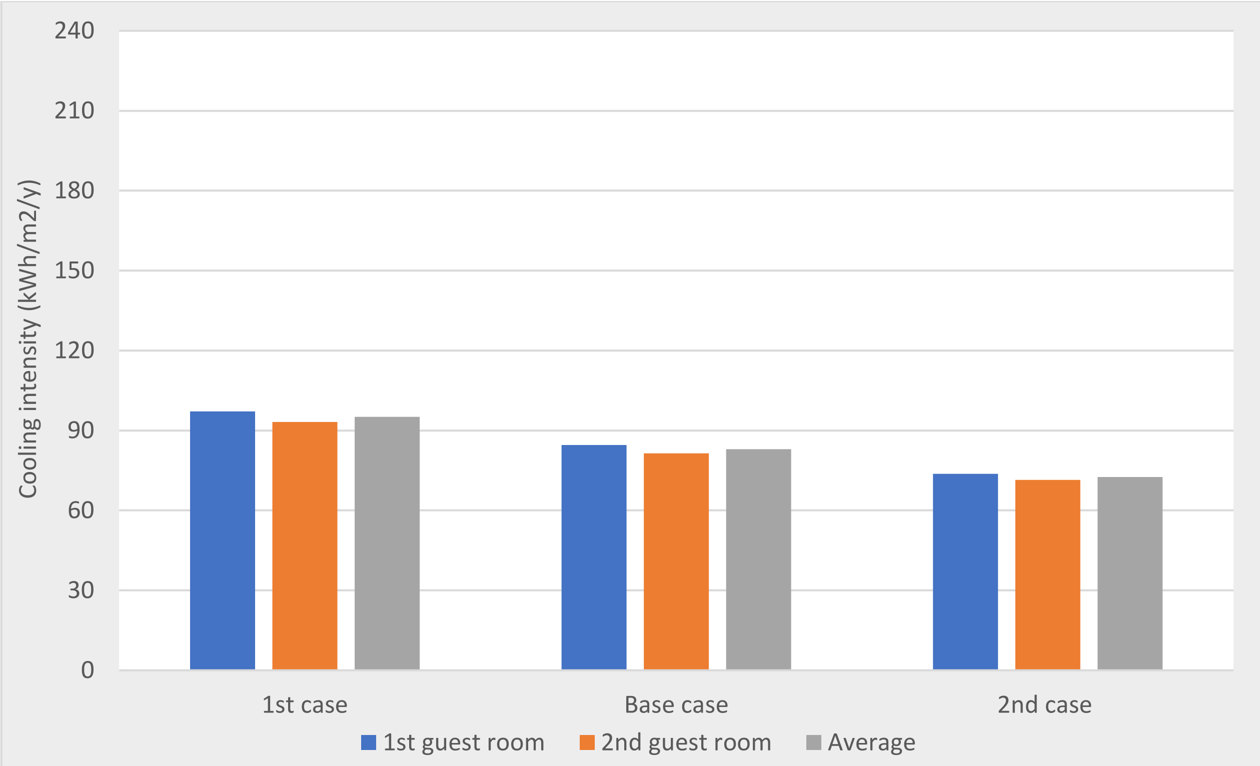

Figure 8.4.5.2: Annual cooling load for best case and the proposed set thermostat points of the A/C (kWh/m2/y).

8.5. The house in Taif

8.5.1. Proposed construction layers of external wall

To identify the best-case external wall for improving indoor thermal performance and achieving the lowest cooling load all year round, various wall types and thickness were proposed and simulated. The annual cooling load of the various proposed wall permutations was estimated and compared with the base case (JW2) of the existing walls. As far as the proposed walls types are concerned, the main factor affecting outdoor heat transfer is thermal insulation because of it is capacity to control heat flow through the walls in both directions. As the heat gain through walls is the highest in Taif, using thermal insulation in both winter and summer could be appropriate. The effectiveness of the proposed walls was tested and simulated for the whole year to establish the best case in relation to cooling load reduction. In view of the thermal analysis of the house in Taif, three walls with different insulation thickness were proposed for the TAS simulation, where (IW4 to IW6) represent walls incorporating thermal insulation thickness. The simulation of the various proposed walls is aimed to stand on the different thermal performance that can be provided using each type of wall. Furthermore, description for the proposed walls and the simulation results are provided in table 8.5.1 explaining their layers, thicknesses, U-value and thermal conductance. Additionally, existing external walls of the house in Taif are presented in figure 8.5.1.

Figure 8.3.1. Highlighted existing external walls of the house in Taif

Table 8.5.1: Characteristics of existing and proposed insulated walls

Walls	Wall type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing external walls used in Taif's house	JW2	Paige paint (outside) 30 mm external rendering 200 mm cone. block 20 mm internal plaster white paint (inside)	3	6.412
Existing external walls used in Makkah's house	MW2	Paige paint (outside) 20 mm external rendering 200 mm red hollow cone. block 20 mm internal plaster white paint (inside)	1.549	2.102
Introducing thermal insulation	IW4	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 25 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.608	0.678
	IW5	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 50 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.378	0.404
	IW6	Paige paint (outside) 20 mm external rendering 100 mm red hollow cone. Block 75 mm polyurethane board 100 mm red hollow cone. block 20 mm internal plaster white paint (inside)	0.274	0.288

The existing walls (JW2): JW2 is applied on all external elevations. This wall is one of the most common wall types in Saudi Arabia and used in most of the residential buildings. It incorporates internal painting, 20 mm internal plastering, 200mm concrete block, 30 mm external rendering and external painting.

1st case (MW2): MW2 is the existing external wall in the Makkah house and used here to test wall types different to the existing wall. This wall's external and internal finishing is applied to all the proposed walls.

Walls with thermal insulation (IW4 to IW6): Three types of the proposed walls incorporate cavity polyurethane board with varying thickness (25mm, 50mm and 75mm). The U-value of the highlighted wall is marginally below the maximum U-value set by the SBC for Taif's climate.

- **Cooling load saving with proposed external walls**

To estimate the annual cooling load, the energy savings using the proposed external walls are measured where the house in Taif is assumed to have air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.5.1.1 sets out the annual cooling for the house in Taif when in each case, the various layers of building materials are used in the walls for both rooms. Table 8.5.1.1 provides the percentage of cooling load savings compared with existing fabrics.

Table 8.5.1.1. Percentage of reduction in annual cooling load for proposed walls compared with existing walls in the base case

Wall cases	Wall type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	JW2	60.8	-
1st case	MW2	50.8	16.4
2nd case	IW4	43.1	29
3rd case	IW5	41.3	32
4th case	IW6	40.5	33.3

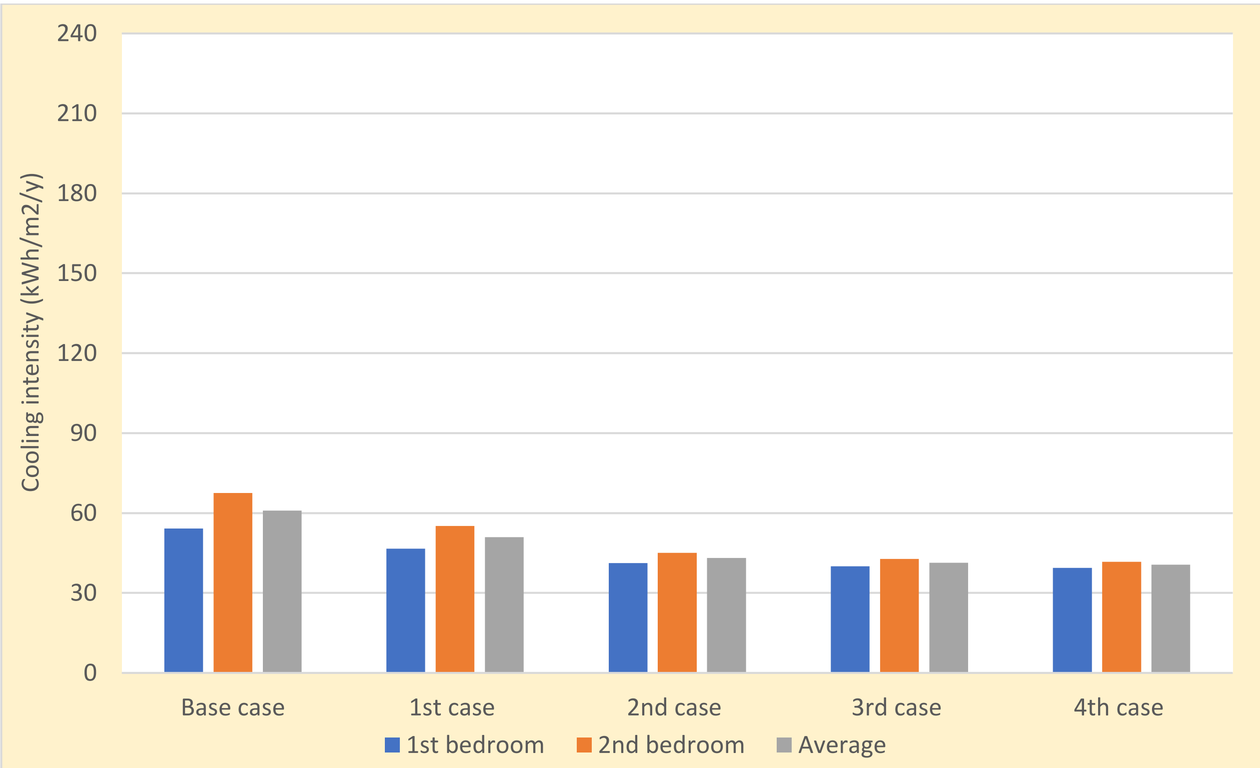

Figure 8.5.1.1: Annual cooling load for proposed walls (kWh/m2/y).

The results show that by implementing the proposed walls (2nd case to 4th case), the potential savings in the cooling loads ranging from 29%, 32% and 33.3% are achieved in IW4, IW5 and IW6 respectively. However, by not using an insulated wall, there is still a considerable possible saving in the cooling loads as is evident in the 1st case at 16.4%. The results revealed by incorporating insulation materials with various thicknesses, 25mm to 75mm, a possible cooling load reduction could be obtained all the year. Overall, greater decrease in cooling load is attained with greater thickness of the insulation material which has very low thermal conductance. Therefore, the highest saving in cooling load is achieved by using 75mm insulation material in IW6.

However, the greater thickness of the insulation materials does not in this instance, have a big impact on saving cooling load. To compare between the three insulated walls, IW4 has potential saving of 15.1% compared to the 1st case, while IW5 has potential saving of 4.1% compared to IW4, finally, IW6 has potential saving of 1.9% compared to IW5. Consequently, IW5 is chosen to improve indoor thermal environment for its saving potential of the cooling load and because it complies with the required walls u-value by Saudi building standards for the house in Taif.

8.5.2. Proposed construction layers of Roof

To identify the best-case proposed roof which can improve the indoor thermal performance and achieve the lowest cooling load in all year, various types and thickness of roofs were proposed and simulated. The annual cooling load was estimated with the implementation of the various proposed roofs and compared with the base case of the existing roof. Heat gain through the roof is the second highest in the Taif house. Also, heat gain through the roof in summer and winter is higher than heat loss via the roof. Therefore, various types of roofs, with lower thermal conductance than the existing roof were proposed to minimize heat gain. The use of additional thermal insulation was proposed for the roof. Table 8.5.2 provides the proposed roofs explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.5.2: Characteristics of existing and proposed insulated roof

Roofs	Roof type	Layers description	U-value (w/m².°C)	Conductance (w/m².°C)
Existing roof used in Taif's house	TR1	red paint (outside) 3.17 mm metal deck 1000 mm loft space 9.5 mm plasterboard (inside)	1	3.795
Existing roof used in Makkah's house	MR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.901	1.111
Introducing thermal insulation	IR1	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 25 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.474	0.526
	IR2	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 50 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.322	0.345
	IR4	20 mm terrazzo tiles (outside) 150 mm sand and cement mortar 80 mm polyurethane board 300 mm reinforced concrete slap 50 mm gypsum board and internal plaster white paint (inside)	0.232	0.244

The existing roof (TR1): is a roof type used in residential buildings. It incorporates 9.5mm internal plasterboard, 1000 mm loft space, 3.17mm metal deck and red painting.

1st case (MR1): MR1 is the existing roof in the Makkah house, used here to test different roof type to the existing one. This roof and its external and internal finishing is applied in all the proposed roofs.

Roofs with thermal insulation (IR1, IR2 and IR4): Three types of the proposed roofs incorporate cavity polyurethane board with different thickness (25mm, 50mm and 80mm). The highlighted roof has slightly less U-value than the maximum value set by the SBC for Taif's climate.

- **Cooling load saving with proposed roofs**

To estimate the annual cooling load, the energy savings of the proposed roofs has been measured based on the assumption that the house in Taif has no air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.5.2.1 provides the annual cooling with the implementation of the various roofs for both rooms. Table 8.5.2.1 provides the percentage of cooling load savings compared with the existing roof.

Table 8.5.2.1. Percentage of reduction in annual cooling load for proposed roofs comparing with existing roof in the base

Roofs cases	Roof type	Average annual cooling (kWh/m²/y)	Reduction of cooling load (%)
Base case	TR1	60.9	-
1st case	MR1	50.1	17.7
2nd case	IR1	43.1	29.2
3rd case	IR2	40.6	33.3
4th case	IR4	39.1	35.7

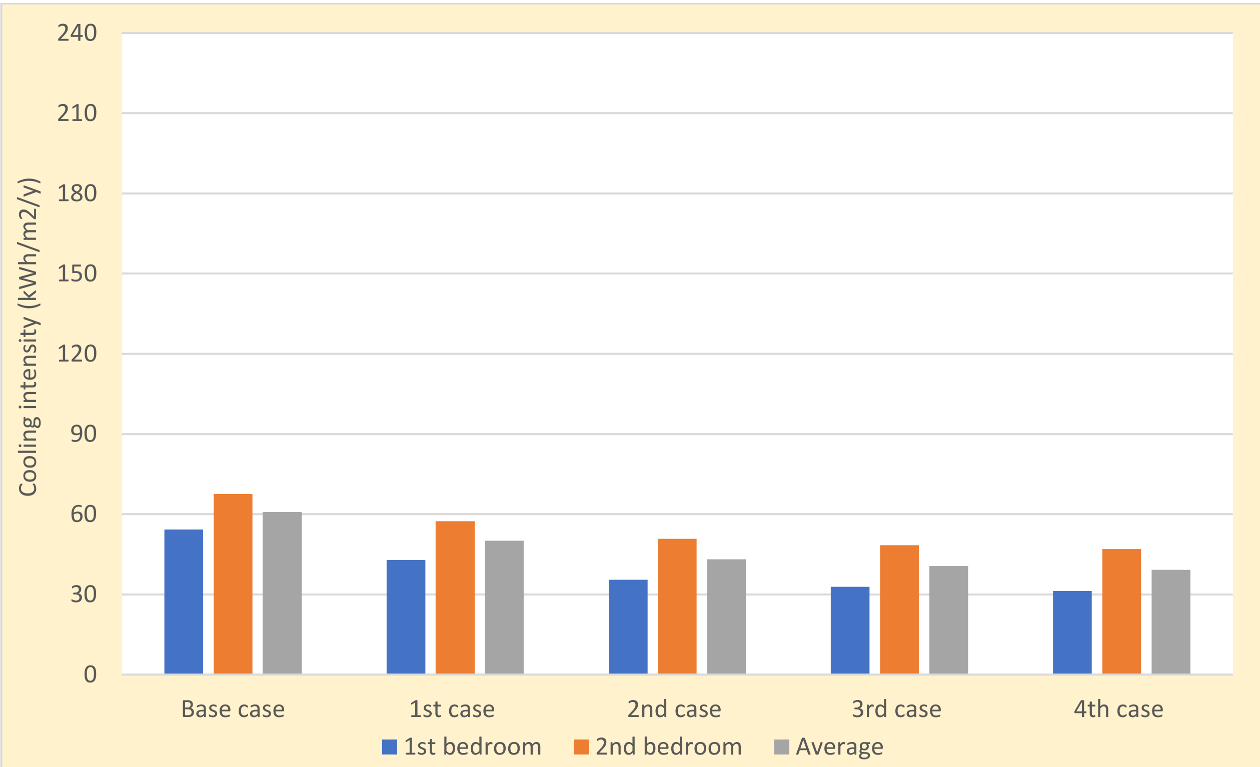

Figure 8.5.2.1: Annual cooling load for proposed roofs (kWh/m2/y)

The results show that the proposed insulated roofs (2nd case to 4th case), achieve savings in the cooling load ranging from 29.2%in IR1, 33.3% in IR2 and 35.7% in IR4 are achieved. However, by not using an insulated roof delivers a considerable cooling load saving as in the 1st case at 17.7%.

A possible all year-round cooling load reduction could be obtained by using insulation materials with thicknesses of 25mm to 80mm. Overall, bigger reduction in cooling load is attained using thicker insulation material with low thermal conductance. Therefore, the highest saving in cooling load is achieved by using 80mm insulation material in IR4.

To compare between the three insulated roofs, IR1 has potential saving of 13.9 % compared to the 1st case, while IR2 has potential saving of 5.8% compared to IR1, finally, IR4 has potential saving of 3.6% compared to IR2. Consequently, IR4 is chosen to improve indoor thermal environment for its saving potential of the cooling load and because it complies with the required roofs u-value by Saudi building standards for the house in Taif.

8.5.3. Proposed construction layers of Floor

Three types of ground floors were proposed and simulated to improve the indoor thermal performance and achieve the lowest all year cooling load. The annual cooling load was estimated with the implementation of the various proposed ground floors and compared with the base case of the existing floor.

Unsurprisingly, on a summer-day, heat gain via the ground floor is lower than heat loss. Conversely, on a winter-day, heat gain via the ground floor is significantly higher than heat loss which has zero heat loss through the ground floor in a winter-day. Therefore, various types of ground floors with various thickness and lower thermal conductance than that of the existing ground floor were proposed to minimise the heat loss in summer and the heat gain winter. Table 8.5.3 provides the proposed ground floors explaining their layers, thicknesses, U-value and thermal conductance.

Table 8.5.3: Characteristics of existing and proposed insulated ground floor

Floors	Floors type	Layers description	U-value (w/m².˚C)	Conductance (w/m².˚C)
Existing floor used in Taif's house	JF1	20 mm terrazzo tile (inside) 100 mm sand and cement mortar 300 mm reinforced concrete slap 100 mm soil	1.683	2.201
Existing floor used in Makkah's house	MF1	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 150 mm soil	0.933	1.153
Introducing thermal insulation	IF1	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 30 mm polyurethane board 150 mm soil	0.453	0.484
	IF2	20 mm terrazzo tile (inside) 150 mm sand and cement mortar 300 mm reinforced concrete slap 60 mm polyurethane board 150 mm soil	0.294	0.306

The existing ground floor (JF1) is also a common floor type used in residential buildings. It is made up of terrazzo tiles fixed on 100mm cement mortar and sand which are bedded on 300mm plain concrete.

1st case (MF1): MF1 is the existing ground floor used in the Makkah house and used in this instance to test different types of floor. This ground floor and its external and internal finishing is applied on all proposed floors.

Ground floors with thermal insulation (IF1 and IF2): Two types of the proposed floors incorporate cavity polyurethane board with different thickness (30mm and 60mm). The highlighted ground floor is the one with slightly less U-value than the Taif climate's maximum U-value level set by the SBC.

- **Cooling load saving with proposed ground floors**

To estimate the annual cooling load, the energy savings of the proposed ground floors has been measured where the house in Taif is assumed to have air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.5.3.1 provides the annual cooling with the implementation of the various ground floors in only the guest room on the ground floor in the house in Taif. Table 8.5.3.1 provides the percentage of cooling loads savings comparing with the existing ground floor.

Table 8.5.3.1. Percentage of reduction in annual cooling load for proposed ground floors compared with the base case existing floor

Floors cases	Floor type	Average annual cooling ($kWh/m^2/y$)	Increase of cooling load (%)
Base case	JF1	60.9	
1st case	MF1	67.6	9.9
2nd case	IF1	72.8	16.4
3rd case	IF2	74.5	18.2

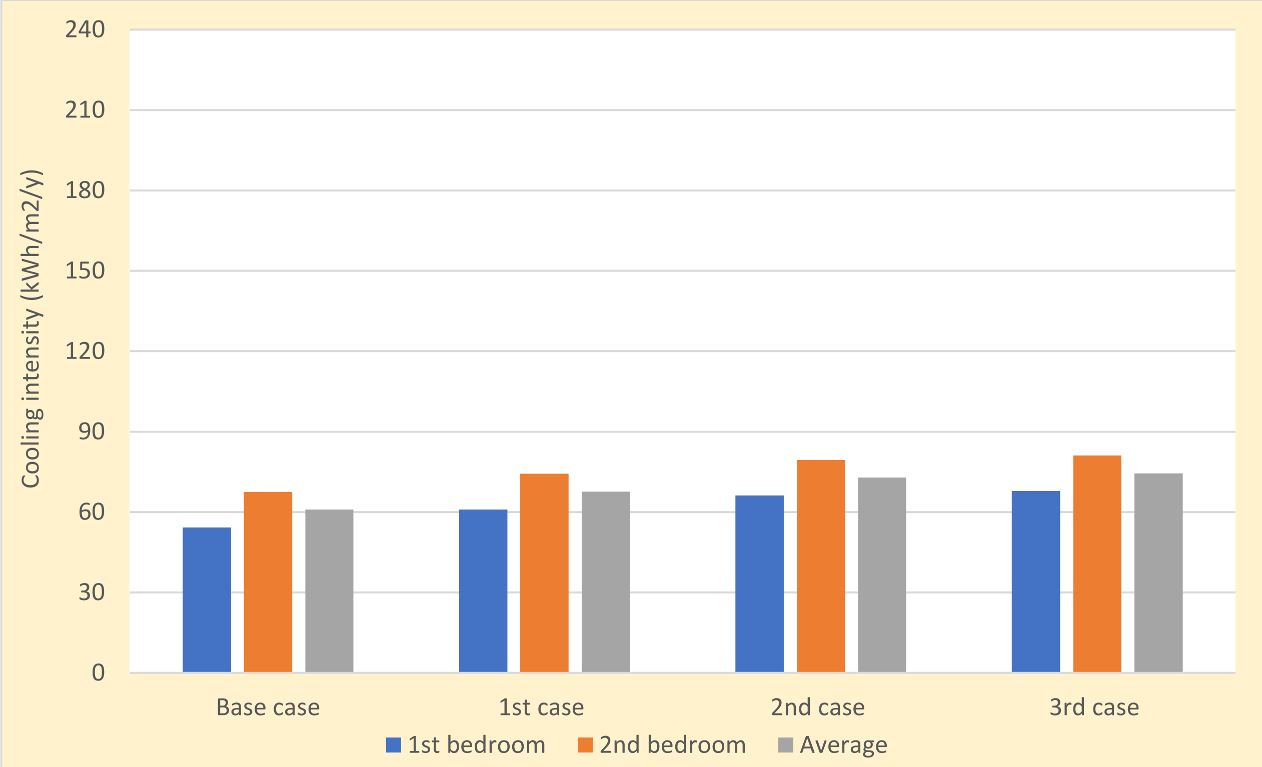

Figure 8.5.3.1: Annual cooling load for proposed ground floors (kWh/m2/y).

The results show that the implementation of the proposed insulated floors (2nd case and 3rd case), offers no potential cooling load savings in all cases. The results revealed by incorporating insulation materials with various thicknesses, 30mm to 60mm, an increase in cooling load could be obtained all year round. IF1 is chosen because it complies with the u-value set by Saudi building standards for the house in Riyadh.

8.5.4. Proposed construction layers of window and shading

One type of window was proposed and simulated to improve indoor thermal performance and achieve the lowest cooling load all year round. The annual cooling load is estimated by simulating the proposed case and comparing it with the existing base case windows and shading.

In the previous chapter, the thermal analysis of the house in Taif showed that heat loss through the windows in winter and summer is relatively slight compared with the total heat loss via other building fabrics. Besides, the solar gain through the windows is the least gain of all the gains via fabrics in winter and summer due to the internal shading. Therefore, double glazed windows were proposed to evaluate if upgrading the window type influences the cooling load (see table 8.5.4).

Table 8.5.4: Characteristics of existing and proposed windows

Window and shading	Window type	Layers description	U-value (w/m².˚C)	Solar transmittance
Existing window and shading used in Taif's house	WW1	Single glazing with internal blind	5.5	0.080
Upgrading window type	WW2	double glazing with internal blind	1.606	0.060

- **Cooling load saving with proposed windows**

To estimate the annual cooling load, the energy savings of the proposed windows has been measured on the assumption that the house in Taif has air conditioning. The upper temperature for cooling is set at 25°C. Figure 8.5.4.1 provides the annual cooling with the implementation of upgrading windows in both rooms in the house in Taif. Table 8.5.4.1 provides the percentage of cooling load savings compared with the existing windows and shading.

Table 8.5.4.1. Percentage of reduction in annual cooling load for proposed windows comparing with existing windows and shading in the base case

Windows and shading cases	Window type	Average annual cooling (kWh/m²/y)	Increase of cooling load (%)
Base case	WW1	60.9	-
1st case	WW2	62.4	2.4

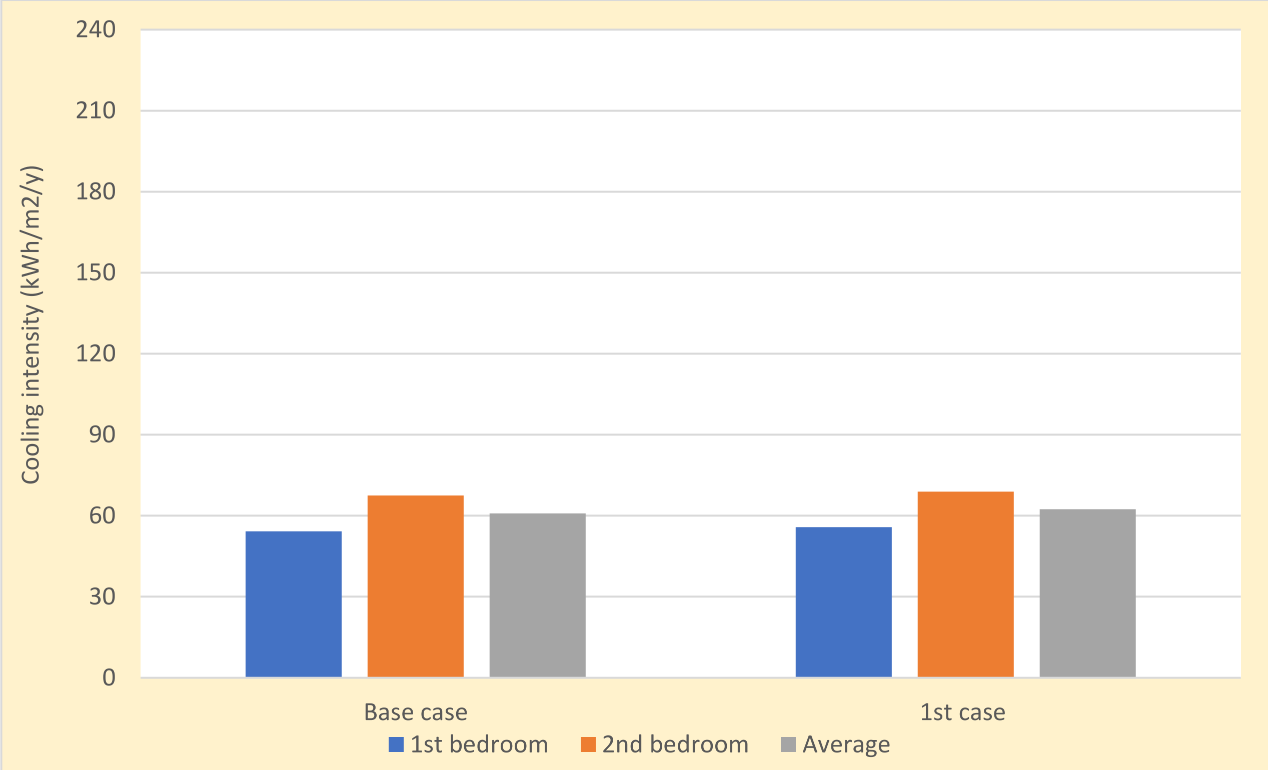

Figure 8.4.4.1: Annual cooling load for proposed windows (kWh/m2/y).

The results show that upgrading the window type has minor effect on the cooling load. Therefore, the 1st case is chosen because it complies with the required window U-value by Saudi building standards.

8.5.5. Proposed combination of building fabrics

Combinations of the various proposed walls, roofs, ground floors and windows were selected and simulated to calculate the overall indoor thermal performance and achieve the lowest all year round cooling load. The annual cooling load was estimated with the implementation of the various combinations of fabrics and compared with those of the existing fabrics. The potential cooling savings achieved by applying combinations of the house's envelope were calculated. Explanation for the selected combinations, the simulated results and the percentage of cooling load savings compared with existing fabrics is provided in table 8.5.5.

All highlighted building fabrics discussed earlier in this chapter were selected and combined to achieve the best case. One of the proposed floors, one of the proposed walls, one of the proposed roofs and the proposed windows were selected to form three combinations of fabrics. The 1st case is a combination of the proposed roof, walls, floor and windows, while the 2nd case is a combination of roof, walls and floor, while the best case (TC3) is a combination of roof and walls only, without the proposed floor and window. The selection was based on the annual potential improvement in cooling load.

The cooling savings of the proposed fabric combinations has been measured based on the assumption that the house assumed with air conditioning to estimate the annual cooling load. The upper temperature is set at 25 °C. Figure 8.5.5 provides the annual cooling load with the implementation of the various fabric combinations of the two rooms in the house in Taif. The results revealed that by implementing the fabrics combination in the TC1, potential saving of 62.6% in the cooling load, while the TC2 is the second-best case as reduction of 65.7% of the cooling load achieved. Finally, the best case is found in TC3 where a achieved a reduction of 79.6% of the cooling load.

Table 8.5.5: Description of existing and proposed combinations of fabrics

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Base case	TB1	60.9	-
1st case	TC1 (roof, wall, floor, window)	22.8	62.6
2nd case	TC2 (roof, wall, floor)	20.9	65.7
Best case	TC3 (roof, wall)	12.4	79.6

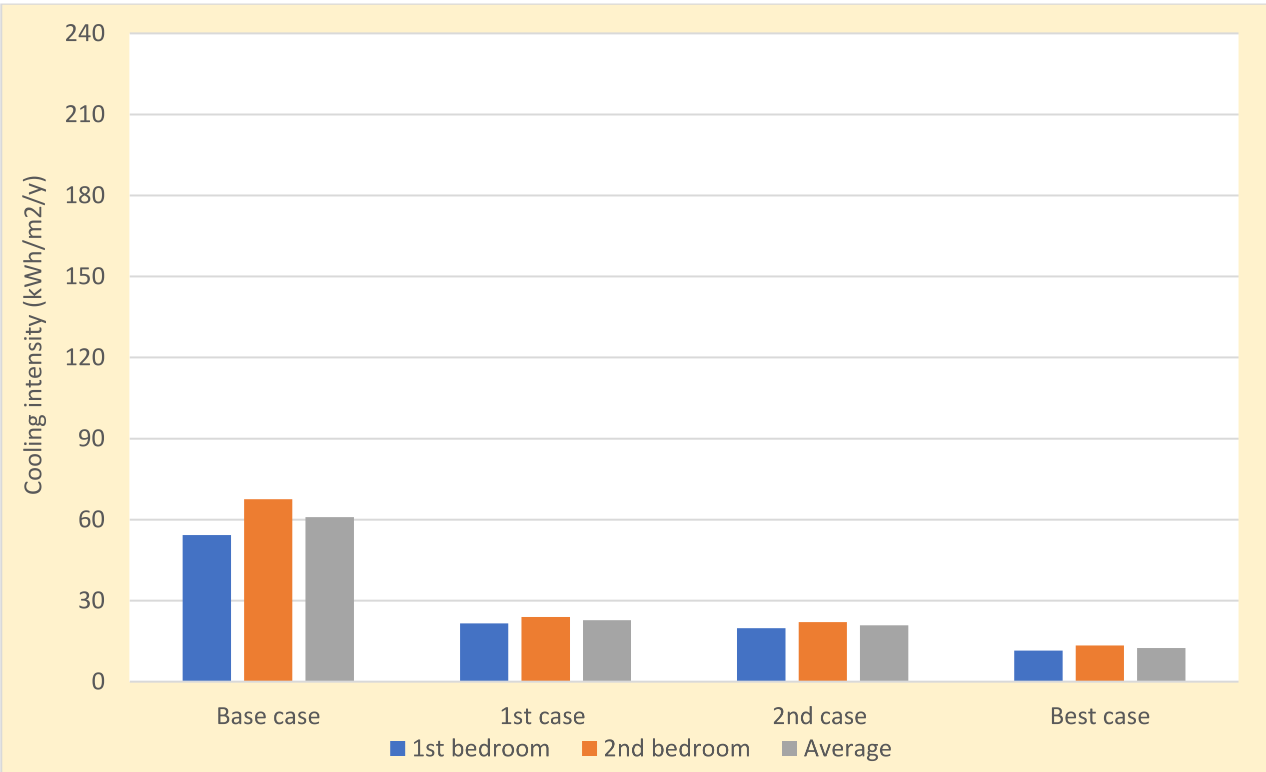

Figure 8.5.5: Annual cooling load for proposed fabrics' combination (kWh/m2/y).

- **The Effect of Revised Ventilation Strategy (mixed mode)**

As the outside night time temperature falls to acceptable levels (less than 25 °C), a night time ventilation was applied in the studied rooms. The annual cooling load was estimated when applying the night ventilation when outside temperatures fall below 25 °C, and when the most recommended fabric combination – the best case – was implemented. The potential reduction in cooling load percentage was calculated by comparing the best case conditions with the night time ventilation strategy (see table 8.5.5.1) revealing a potential decrease in the percentage of cooling load of about 20% (see figure 8.5.5.1).

Table 8.5.5.1: Description of the best case and the proposed ventilation strategy

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Best case	TC3	12.4	-
1st case	TC4 (best case + NTV)	10.0	19.3

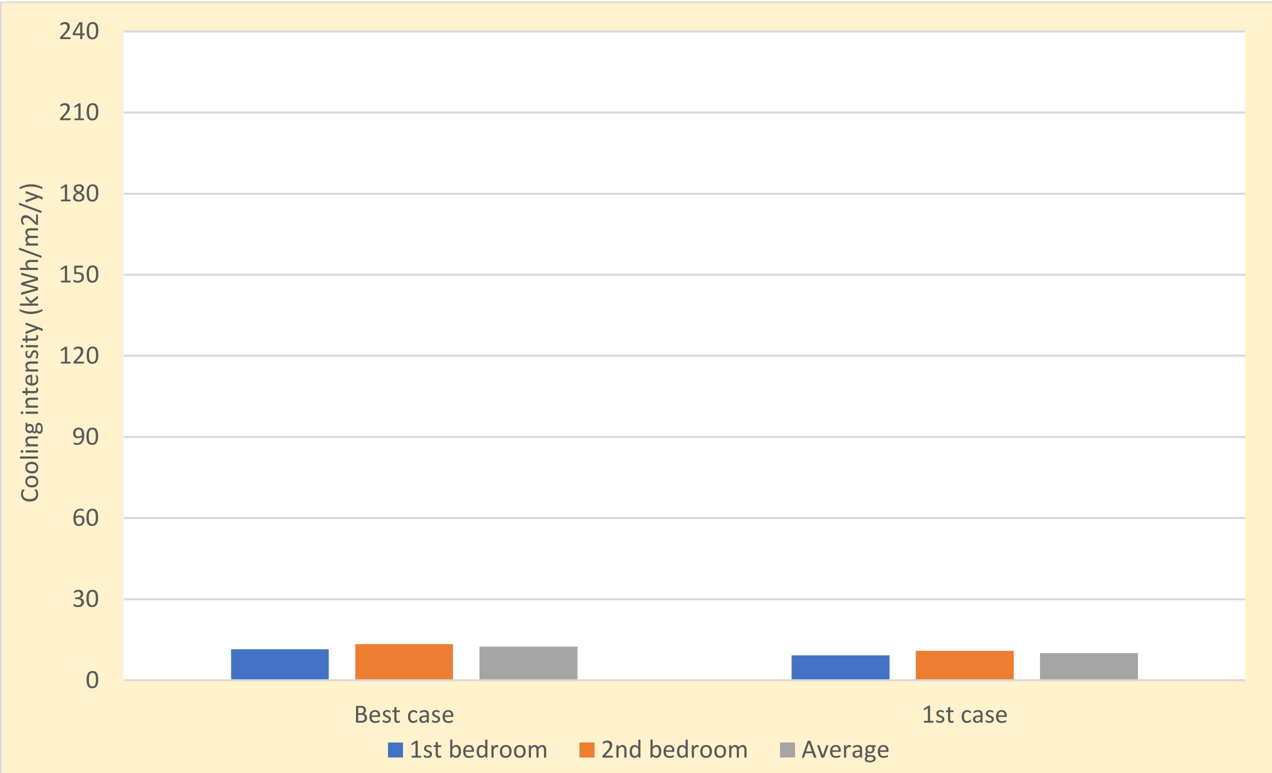

Figure 8.5.5.1: Annual cooling load for best case and the proposed ventilation strategy (kWh/m2/y)

- **The effect of set thermostat point of the A/C**

The potential saving of the cooling load by raising the A/C thermostat setting was proposed for use in the studied rooms. The annual cooling load was estimated when applying the different temperature settings, along with the implementation of the recommended best case fabric combinations with the thermostat set at 25°C. The potential reduction in the percentage of cooling load comparing the conditions in the best case with the different temperature degrees can be seen at table 8.5.5.2. The results revealed that by raising the A/C thermostat setting from 23.9 °C to 25°C achieves a potential reduction in cooling load of 48.2 %, while even bigger reductions of 56.5% and 77.5% are achieved when raising the temperature to 26°C compared to the best and 1st cases respectively (see figure 8.5.5.2).

Table 8.5.5.2: Description of the best case and the proposed set thermostat points of the A/C

Combined cases	Combination type	Average annual cooling ($kWh/m^2/y$)	Reduction of cooling load (%)
Base case	TC5 (23.9˚C)	24.0	-
Best case	TC3 (25˚C)	12.4	48.2
1st case	TC6 (26˚C)	5.4	77.5

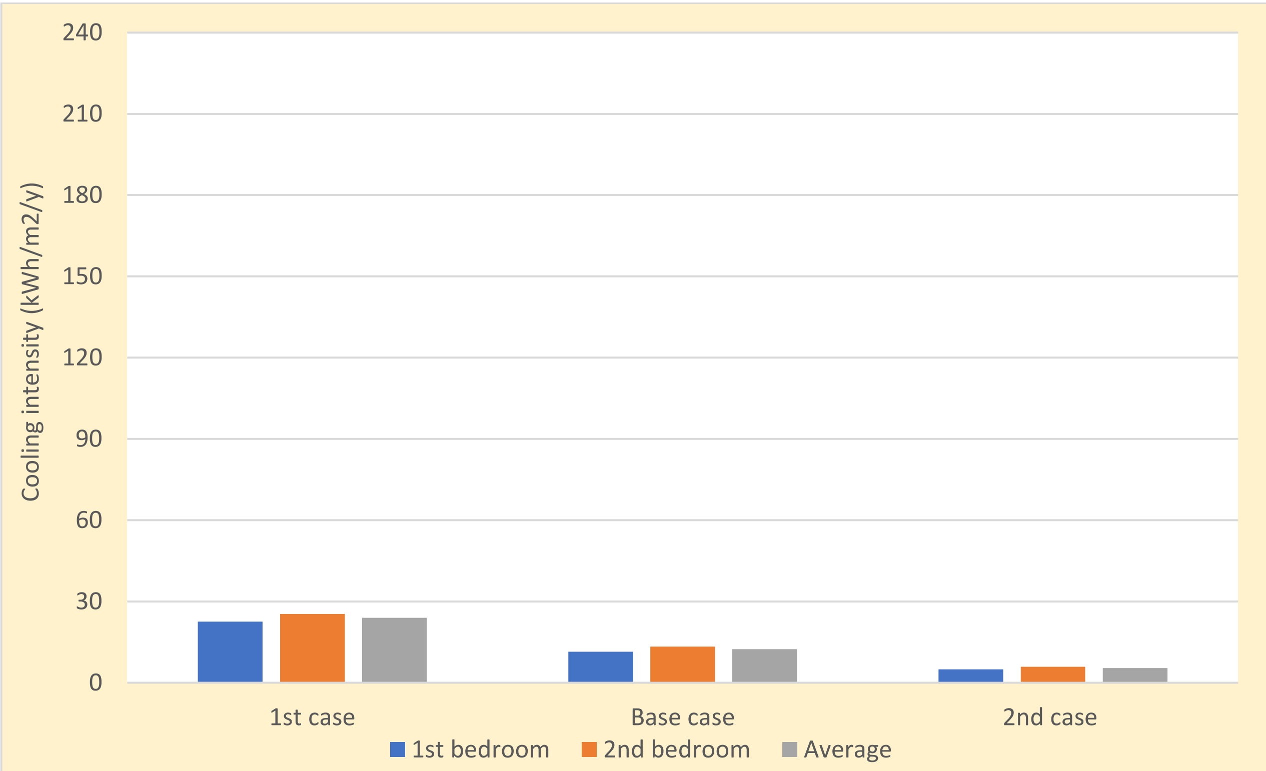

Figure 8.5.5.2: Annual cooling load for best case and the proposed set thermostat points of the A/C (kWh/m2/y).

8.6. Summary

Potential improvements to the indoor thermal environment were assessed using thermal simulation for various proposed house components including walls, roofs, floors and windows. The proposed fabrics are applied to all the four chosen houses separately.

The annual cooling load and the percentage of cooling load reduction were estimated by applying each element separately, and by applying combinations of the proposed components. In view of the thermal analysis of the four houses, six walls, four types of roofs, two ground floors, and three types of window and shading were proposed and simulated. According to the annual cooling load of the proposed fabrics, eleven combinations of all the four houses were selected and simulated to ascertain indoor thermal performance and to identify the improvements which could be achieved in terms of the annual cooling load. The annual cooling load of the proposed fabric combinations were simulated and then measured. In the light of the potential cooling savings for the various proposed combinations of fabrics, a number of combinations are recommended for each house.

By implementing the recommended combinations of fabrics, the maximum annual potential reduction of the cooling load is 56.4%%, 47.3%, 58.2 and 79.5% of the houses in Makkah, Jeddah, Riyadh and Taif respectively. As a result, the proposed annual cooling use intensity become 79.7 kwh/m2/y, 66.8 kwh/m2/y, 83 kwh/m2/y and 12.4 kwh/m2/y of the houses in Makkah, Jeddah, Riyadh and Taif respectively.

Therefore, other strategies to enhance the indoor thermal environment and reduce cooling load in these houses such as night time ventilation, adjusting the A/C thermostat setting, along with improving the houses' fabrics, are recommended. The night ventilation strategy to enhance the indoor thermal environment was proposed and examined. The results show that by applying the night ventilation, potential decrease in the percentage of annual cooling load of 6.5%, 8.8%, 4.5% and 19.3 % could be achieved in the houses in Makkah, Jeddah, Riyadh and Taif respectively. Finally, the set thermostat point of the A/C was proposed and examined. The results showed that raising the thermostat setting by 1k, achieved a potential reduction the annual cooling load of 13.2%, 16.9%, 12.5% and 56.5 % in the houses in Makkah, Jeddah, Riyadh and Taif respectively.

Chapter 9

Conclusion and recommendations

9. Conclusion and recommendations

9.1. Introduction

The key aim of this work is to assess the current indoor thermal performance of low-rise residential housing in Saudi Arabia and to identify alternative materials that could be used to improve energy efficiency. A wide range of factors impact energy efficiency in residential houses these include the use of poor-quality construction materials, lack of strict building regulations, economic issues and cheap electricity costs.

In the research, existing low-rise residential houses located in four different climatic zones have been used to assess the influence of outdoor conditions and enable comparisons to be made between them. Moreover, by researching the houses, it was possible to identify the current situation regarding thermal efficiency in the country and the thermal indoor conditions that require further improvements. Once the houses were analysed, different materials were suggested for use in the construction of houses that could improve indoor thermal environment.

To follow the research objectives, two fundamental research methods were combined in the study, namely physical measurements and computer-modelling. Other methods including observations and a review of the literature were also used to meet the six objectives of the research.

The study used physical measurements as its main tool for examining and monitoring the conditions of the indoor thermal environment, with a focus on the relation of building fabrics to the energy used for cooling. Through computer-modelling, the thermal performance of the houses could be explored in more depth and areas for improvement could be identified.

In summary, four residential buildings were monitored throughout the summer and winter months of 2018, with collected data being analysed using Microsoft Excel software. Thermal Analysis Software (TAS) was then employed to simulate, analyse, model and modify the four houses. Several conclusions and recommendations were made according to the research results. The main conclusions and recommendations are outlined in the following sections.

9.2. Research conclusion

The first point to make is that the researcher has successfully met the main aim proposed for the study. The main aim of the present study is to assess the indoor thermal performance of homes in Saudi Arabia and make recommendations for improvements. The primary focus is on lowering the dependence on mechanical cooling systems. The design strategies and building materials used in the construction of houses is reviewed to identify those most suitable for the different climate zones in the country. The remainder of this section discusses the conclusions in reference to each of the research objectives.

First objective

Analyse factors leading to the high energy use in residential buildings and the chosen case studies including details about buildings age, location, architectural drawings, envelopes materials used and their characteristics, as well as the forms they take and the surrounding conditions.

Chapter 2 assesses the current thermal status of houses in Saudi Arabia in details. Moreover, the houses' key physical features and the overall energy situation in Saudi Arabia were investigated in terms of available energy sources, consumption and prices. Finally, the designs and types of houses, as well as the building materials used to construct them, were considered.

Second objective

Investigate the climatic parameters of Saudi Arabia and how they impact the design of houses. This can be achieved with a thorough knowledge and understanding of the outdoor environmental conditions. Successful environmental design is inextricably linked to an understanding of the external climate and its influence on human requirements. This understanding plays a large part in determining which thermal properties are essential in the external building envelope.

Chapter 3 discusses the different climatic conditions chosen in depth. The country's hot zone will serve as the focal point. The key factors impacting thermal comfort in these hot climate areas were highlighted to identify the available options for improvement. The thermal comfort conditions that residents of hot climates prefer will also be outlined.

Third objective

Review a variety of energy efficient building strategies and suggest suitable ones for reducing the high energy consumption in residential buildings. Moreover, employ appropriate instruments and simulation software tool to evaluate, validate and improve the residential buildings thermal performance in a hot climate.

Chapters 4 investigates architectural design strategies for hot regions and factors causing heat loss/gain in residential buildings were investigated. Chapter 5 shows the selection of instruments and a thermal-modelling computer program which were selected based on specific criteria.

Forth objective

Evaluate the internal environmental conditions of the chosen case studies. This can be achieved by monitoring selected thermal environmental variables using instruments and computer model during winter and summer.

Chapter 6 discusses monitoring the internal environmental conditions during two major fieldworks. The case studies are evaluated for the first time through the use of specific tools. The data was collected during the winter and summer months of 2018. Subsequently, the thermal efficiency of each house was evaluated, and comparisons made. The most significant factors impacting indoor thermal efficiency were also discussed. The second stage of evaluating the houses was taken place in chapter7. At this stage, thermal-modelling software (TAS V9.4.2) was used. The thermal efficiency of each house was evaluated, after which comparisons were made.

Fifth objective

Validate the findings between the physical measurements and computer-modelling results.

Chapter 7 illustrates for the simulated energy model to be acceptable, calculation of the root mean square error (RMSE) and normalised mean bias error (NMBE) should be in the range of 30% and 10% respectively for a model that deals with hourly figures based on ASHRAE guidelines (ASHRAE, 2014). This study recorded hourly dry bulb temperature which is a measure of air temperature and it is usually the most important thermal environmental variable. While calculating both the RMSE and the NMBE, two methods were used: the first method consists of dividing the recorded data into winter and summer, while the second consists of calculating the values of the entire monitored temperatures during the total monitored hours.

Sixth objective

Identify ways to modify building materials to retrofit energy efficient homes. By using the most suitable building materials, energy efficient houses can be retrofitted.

Chapter 8 discusses the strategies for improving the thermal efficiency of the houses in depth. Results of the thermal simulation of proposed houses' components (such as walls, roofs, floors and windows) were presented and recommendations were made for potential means of enhancing the thermal environment by applying each element separately and in combinations.

9.3. Contribution to Knowledge

The research has made the following contributions to the body of knowledge:

1. Evaluating and valdiating thermal perfomance for residential buildings in four climatic zones in Saudi Arabia.

In the case of Saudi Arabia's residential buildings, there is limited data published when it comes to thermal performance evaluation which involves internal temperature measurements. To increase knowledge in this area, and to examine the thermal performance of these residential structures, this research gathered temperature data together with additional environmental variables for two rooms in all of the four houses, during the winter and summer seasons. In addition, related weather data was also collected. Overall, the intention was to establish a deeper comprehension of the thermal performance of current building design strategies.

2. Retrofitting design strategies for existing residnetial buildings in Saudi Arabia to decrease cooling load use.

The proposed annual cooling use intensity become 79.7 kwh/m2/y, 66.8 kwh/m2/y, 83 kwh/m2/y and 12.4 kwh/m2/y of the houses in Makkah, Jeddah, Riyadh and Taif respectively. As a result of implementing the recommended combinations of fabrics, the maximum annual potential reduction of the cooling load is 56.4%%, 47.3%, 58.2 and 79.5% of the houses in Makkah, Jeddah, Riyadh and Taif respectively.

3. Offerring adaptive strategies to allign with the design strategies to enhance the indoor thermal condition of residenial buildings.

The results show that by applying the night ventilation, potential decrease in the percentage of annual cooling load of 6.5%, 8.8%, 4.5% and 19.3 % could be achieved in the houses in Makkah, Jeddah, Riyadh and Taif respectively. On the other hand, raising the thermostat setting by 1k, achieved a potential reduction the annual cooling load of 13.2%, 16.9%, 12.5% and 56.5 % in the houses in Makkah, Jeddah, Riyadh and Taif respectively.

9.4. Conclusion from field monitoring and thermal analysis

9.4.1. Microclimate of the house in Makkah

On the whole, the IAT difference was relatively limited and constant. This is primarily due to severe climate conditions. Moreover, the internal temperatures of the house in both winter and summer months surpasses the upper-temperature limit for thermal comfort mandated by the SBC.

All environmental variables linked to the bedroom (BR) are slightly less than the guest room (GR) because the rooms near the bedroom are air-conditioned, whereas the rooms nearest to the guest room are free running. In both rooms, the FIST and RIST increase in the late afternoon, irrespective of the indoor and outdoor temperatures. This is because an extensive amount of heat is transferred through the rooms' two external walls throughout the day, as well as through the bedroom's roof.

The surface temperature of the inside wall in the guest room (GR) increases by approximately 1.5°C in winter between 9:00 and 15:00. The increase in temperature is likely due to the rise in the outdoor air temperature throughout the day. The high intensity of solar radiation means that the OAT will be hotter than the internal walls. Both walls, however, have similar performance generating average temperatures of 27.5 °C, 27.5 °C and 29.5 °C at 9:00, 12:00 and 15:00 respectively. The temperature of the south-facing inside wall of the bedroom (BR) rises by over 2 °C between 9:00 and 15:00, whilst the west-facing wall rises by approximately 1 °C during the same period. Both walls, however, have similar performance. The south-facing wall generates average temperatures of 26 °C, 26 °C and 28 °C at 9:00, 12:00 and 15:00 respectively and the west-facing wall has an average temperature of 26.5 °C, 26.5 °C and 28.5 °C at the same time intervals, respectively.

During the summer, both walls perform similarly at 9:00. The ISTEW for both walls is very similar at 15:00. However, there is a temperature drop of 2°C at 12:00. Compared to the other environmental variables outlined above, the inner surface temperature of external walls (ISTEW) is always higher because the external walls are constantly exposed to high levels of solar radiation.

9.4.2. Microclimate of the house in Jeddah

In general, the IAT was constant between the guest room (GR1) and THE bedroom (BR1). The indoor temperature of the bedroom was 1°C lower in the winter and 2 °C lower in the summer than the guest room, which may be due to the difference in the room area. The bedroom is less than half the size of the guest room and also is less exposed to the outdoor temperature through the external walls because the guest room has two walls. It could also be because the corridor and other rooms near the bedroom were air-conditioned during the monitoring period. Lastly, the upper-temperature limit of the thermal comfort level mandated by the SBC was exceeded in both the summer and winter months.

All environmental variables of the bedroom are slightly less than the guest room because the rooms near the bedroom are air-conditioned, whereas the rooms nearest to the guest room are free running. The surface temperatures of both the inside walls were constant during the winter. Both walls performed similarly with average temperatures of 28 °C, 29 °C and 28 °C at 9:00, 12:00 and 15:00 respectively.

All walls performed similarly in the summer at the 9:00 and 12:00 intervals. However, there was an ISTEW increase of 2°C at 15:00. This increase in the surface temperature of the inside walls is most likely due to the external air temperature, which increased significantly throughout the day as a result of high-intensity solar radiation hitting the walls. The inside wall surface temperature in both rooms is in line with the IAT. However, the walls of the guest room are around 3 °C warmer than that of the bedroom's west wall.

9.4.3. Microclimate of the house in Riyadh

It was found that the IAT difference for the 1st guest room (GR2) and the 2nd guest room (GR3) was constant and was the same for the two rooms when no A/C was used. This is due to a lack of natural ventilation, which also contributes to the prevention of a lower IAT at night time, even if the OAT is well below that of the indoors in winter. Moreover, people prefer to use mechanical climate control measures even in the winter rather than opening windows. This is evident from the use A/C for four periods for GR3 and one period for GR2. Aldossary et al's., (2015) findings are also in line with these results. The latter researchers found that residents do not always want to use natural ventilation or fans. Most participants in the research reported dissatisfaction with these cooling methods. Lastly, in winter, the internal temperatures fall within the upper-temperature limits for thermal comfort mandated by the SBC. However, it exceeds the upper-temperature limit in summer.

During the summer season, the FIST and RIST in both rooms increases in the late afternoon, irrespective of the internal and external temperatures. This is primarily due to the extensive heat transferred throughout the walls during the day.

The surface temperature of the inside wall in the first guest room (GR2) was constant during winter with an average temperature of 24 °C at 9:00, 12:00 and 15:00. For the second guest room (GR3), the inside wall temperature increased co from 21°C (9:00) to 22°C (12:00) and finally to 23.5 °C in the late afternoon. The increase in temperature is inevitable given the increase in outdoor air temperature, which rises significantly throughout the day due to the intense solar radiation. However, the exception to this is the reading taking at 9:00, where the OAT temperature is the same as that of the average internal surface temperature of the external wall. In terms of the ISTEW in the first guest room, the pattern is the same as that for the other environmental variables mentioned above. However, the inner surface temperature of the external walls ISTEW in the second guest room was always found to be lower than that of the aforementioned variables.

Although both walls perform similarly in the summer at both 9:00 and 12:00, there is a 3 °C rise in the temperature of the wall in the first guest room at 15:00. For the first guest room, the ISTEW is always higher than the other variables. This is primarily because the walls are hit by very intense solar radiation during the day. For both rooms, the ISTEW has the same pattern as the RIST.

9.4.4. Microclimate of the house in Taif

The IAT difference was limited for both rooms, although it was slightly less for BR2, perhaps because the bedroom has just one external wall. The IAT change was 3°C in winter and 4°C in summer. This may be attributed to the poor building of the roof. Moreover, there is a lack of natural ventilation and this most likely plays a significant role in the inability to achieve a lower IAT during the night when the OAT is much less than indoors. Lastly, in winter, internal temperatures fall within the upper-temperature limits mandated by the SBC. However, in summer it exceeds the upper-temperature limit.

During winter, there is a constant increase in outdoor air temperature from 24 °C to 27 °C. This is the result of high-intensity solar radiation. At all times, the indoor air temperature has a constant average of 24 °C in the first bedroom (BR2). However, although the globe temperature is the same at 12:00 and 15:00 with the IAT, it decreases to approximately 2 °C less than the temperatures of the IAT at 9:00 am. Moreover, the floor and roof surfaces temperature are noticeably different from the other temperatures. The floor inner surface temperature (FIST) and the roof inner surface temperature (RIST) can vary by as much as 5 °C. Secondly, at 15:00, the RIST and the OAT are the same. The RIST may even be higher at 12:00. Thirdly, at 9:00 am, the FIST is 4 °C less than the IAT and the RIST 2 °C lower. This is due to the high thermal conductivity of the roof material. The indoor air temperature of the second bedroom (BR3) shows a constant average of 22.5 °C at 9:00 am and 12:00 pm. However, the 15:00 reading shows an increase to 24 °C. The trends for globe temperature, FIST and RIST are the same as those in the other room. At 12:00 in the summer months, the outdoor air temperature increases by over 5°C from the initial measurement, which then increases again to 39 °C at 15:00. For the two rooms, the globe temperature is always the same as the IAT. The internal surface temperatures of both the floor and the roof follow the same pattern for both rooms, meaning there is an increase between 9:00 and 15:00. However, there can be a difference of up to 4°C between them. The RIST is in line with the OAT pattern and is 3°C higher than the other variables.

Moreover, the two rooms face an easterly direction. All walls perform similarly and follow a pattern of a 4°C temperature increase from 9:00 am-12:00 pm and a further 1°C increase at 15:00 in winter. All walls in both rooms perform similarly in the summer, with their surface temperatures increasing steadily throughout the day until late afternoon. Additionally, the patterns of the ISTEW, GT and IAT are the same at every time interval.

9.5. Conclusion based on thermal modelling of proposed fabrics

To identify areas for potential improvement, a thermal simulation was carried out for all of the components of the houses under investigation. This includes the roofs, floors, windows and walls. The alternative materials were applied separately to all four residential properties. To estimate the annual cooling load and the achievable cooling load reduction (in %), each element was applied individually, and then in combination with other proposed components. For the four houses, thermal analysis was carried out and a total of six walls, four roof types, two ground floors, and window and shading types were simulated. Based on the outcomes of the annual cooling load for the proposed materials, eleven combinations were selected for the four houses and subsequently simulated to reveal the indoor thermal performance of the properties and the total potential reduction to the annual cooling load. After this, the annual cooling load of the proposed materials was measured. Several appropriate combinations were recommended for each house based on the potential reduction in energy required for cooling.

When the proposed combination of materials is applied, the potential maximum annual decrease in cooling load is 56.4% in the Makkah house, 47.3% in Jeddah, 58.2% in Riyadh and 79.5% in Taif. Consequently, the intensity of the proposed annual cooling is 79.7 kwh/m2/y for Makkah, 66.8 kwh/m2/y for Jeddah, 83 kwh/m2/y for Riyadh and 12.4 kwh/m2/y for Taif.

It is thus advised that other techniques are used to improve the indoor thermal performance of houses including adjusting the A/C thermostat settings, night time ventilation, and upgrading the houses' building materials. In this research, the use of night ventilation to improve the indoor thermal performance was assessed, and findings indicated that it could generate reductions in the annual cooling load of 6.5% in Makkah, 8.8% in Jeddah, 4.5% in Riyadh and 19.3 % in Taif. Lastly, an assessment was carried out on the method of alternating the thermostat points of the A/C and findings indicated that increasing the set thermostat by 1k could generate potential reductions in the cooling load of 13.2%, 16.9%, 12.5% and 56.5 % in Makkah, Jeddah, Riyadh and Taif correspondingly.

9.6. Recommendations for further research

- Replacing single-glazed windows with double-glazed ones has a small impact on the cooling load.
- The cooling load can be significantly reduced, and the aesthetic appeal enhanced by fixing shutters or external shading to counteract the heat gain.
- For cooling, thermal insulation is essential. The most effective thickness of insulation varies according to different regions.
- Floor surfaces with direct exposure to the ground have a small effect on heat loss and gain. Nonetheless, the heat loss and gain through the roofs and external walls in various orientations has a more significant impact and thus requires more attention.
- This research study was limited by time and accessibility constraints and thus was restricted to four climatic zones. It is recommended that future research explores other regions throughout the country to determine the efficacy of various design permutations within these different climatic zones.
- A major limitation of the study is that only four buildings were included, and these all conform to the villa prototype design of residential buildings throughout the country. It is thus recommended that future studies investigate other residential prototypes.
- The research and scope of the present work were limited to just a few variables associated with indoor thermal performance in houses. Nonetheless, other factors including lighting and occupancy levels were not considered. These aspects should be covered in future research.
- The accuracy of the findings and conclusions can also be affirmed if future studies conduct the same research using different methods.
- Only a limited number of rooms in the houses were included in the research. Future research should increase the number of rooms under consideration.

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Appendix

Appendix A: Data logger specifications and user's manual

Appendix B: Infrared thermometer specifications and user's manual

Appendix C: Globe thermometer specifications

Appendix D: AVM 714 Anemometer specifications

Appendix E: MP-100: Pyranometer

Appendix A: Data logger specifications and user's manual

Elitech®

RC–5 USB Temperature Data Logger Operation Instruction

I. Product overview:

This data logger is mainly used for temperature recording during storage and transportation of foodstuff, medicine, chemicals and other products, especially widely used in all links of warehousing, logistics and cold chain, such as refrigerated containers, refrigerated trucks, refrigerated package, cold storage, laboratory, etc.

II.Specification:

Product size: 80mm (length) X 25mm (width) X 12 mm (height)

III.Technical parameters:

1. Temperature unit: ℃ or ℉ optional
2. Temperature measuring range: -30℃～+70℃; Resolution: 0.1℃;
3. Accuracy: ±0.5℃ (-20℃～+40℃) ;Others, +1℃;
4. Sensor: Internal NTC thermal resistor;
5. Record capacity: 32000points(MAX);
6. Record interval: 10s～24hour adjustable;
7. Communication interface: USB interface;
8. Power supply: inner wide temperature CR2032 battery or power supply via USB interface;
9. Battery life: in normal temperature, if the record interval sets as 15 minutes, it could be used half a year.
10. Safe level: IP67;

IV.Initial use:

1. Install RC-5 temperature data logger data management software. Connect RC-5 with computer via USB, and install USB driver according to the Installation Tips.
2. Open RC-5 temperature data logger data management software, the data logger will automatically upload data after connected with computer. After checking the information, exit from connection interface.
3. Click the "parameters setting icon" in the tool bar. After finish the parameters setting, click "save" button to save all the parameters and exit from parameter setting interface.
4. Hold and press left button for more than 4s, the symbol ▶ lights, then it starts recording. Click the icon of "upload data" to view the data.
5. Exit from RC-5 temperature data logger data management software.

V.Data access:

The recorded data information could be accessed from the temperature data logger. And this process will not clear the historical memory or stop record process if it is in the record status.

1. Connect the data logger with computer via USB interface, after successfully connection, the icon shown in the LCD of data logger will light.
2. Open RC-5 temperature data logger data management software, click the connection icon in the tool bar. After checking the connection information, exit from connection interface.
3. Click the data uploading icon in the tool bar, then it will upload the data to the computer.

Note: RC-5 parameters setting is operated through computer, for the details, please see the help file of RC-5 temperature data logger data management software.

VI.Function description:

The data logger has two button: left button and right button. Left button is to start recording and switch between menu items, and right button is to stop recording and return to the menu items.

The data logger display interfaces includes: status display, record capacity display, time display, date display, Max. temperature display, Min. temperature display, temperature upper limit display, temperature lower limit display.

If no operation within 15 minutes, the data logger will turn off the display automatically.

If the display has been turned off, short press the left button to enter the display interface. Each time short press the left button, it will shift among the display interfaces according to the sequence as described above.

Status display interface: See Figure 1

After short press the left button, it enters to the status display interface from the display turn-off status. The temperature displayed in the LCD screen is the current environmental temperature. In the status display interface:

If the symbol ▶ lights, indicate the data logger is in the status of recording.

If the symbol ▶ flashes, indicate the data logger is in the status of start time delay.

If the symbol ■ lights, indicate the data logger has stopped recording

If neither of the symbols ▶ and ■ lights, indicate the data logger has not started recording.

If the symbols of ⤒ or ⤓ light, indicate the measured temperature exceeds its temperature upper/lower limit.

The temperature shown in this status display interface is the current environmental temperature.

Record capacity display interface:

When the symbol "Log" lights, it indicates that it enters to capacity display interface. The number shown in the LCD is the recorded temperature group, the interface is shown as Figure 2:

(Figure 2)

Time display interface:

In time display interface, it displays the hour and minute of the data logger. The time format is 24 hours. The display interface is as shown in Figure 3:

(Figure 3)

Date display interface:

In date display interface, it displays the month and date of the data logger, display interface is shown as Figure 4:

(Figure 4)

Note: The data below the symbol “M” indicates month, and the data below the symbol “D” indicates date.

Max.temperature display: The maximum temperature valued measured since the beginning of recording, its display interface is shown as Figure 5:

(Figure 5)

Min.temperature display: The minimum temperature measured since the beginning of recording, display interface is shown as Figure 6:

(Figure 6)

Temperature upper limit display interface shown as Figure 7:

(Figure 7)

Temperature lower limit display interface shown as Figure 8:

(Figure 8)

VII.Operation instruction:

1. Start recording

After setting RC-5 parameters in data management software, the function of recording has not been started yet, at this time, press the left button for more than four seconds in the status display interface, the symbol ▶ lights, and then the recording is started. If the symbol ▶ flashes, indicate the data logger is in the status of start time delay.

**** After finishing parameters setting in RC-5 temperature data logger data management software, it will clear up the recorded historical data. Please read and save data before parameter setting!***

2. Stop recording:

① The data logger will automatically stop recording when the recording capacity is full. In the status display interface, the symbol " ■ "lights, it means recording stops.

② If "permit stopping by pressing button" is set, press the right button for more than four seconds, in the status display interface, the symbol " ■ "lights, it means recording stops.

③ It could stop recording though setting in data management software. In the status display interface, the symbol " ■ "lights, it means recording stops.

****After the data logger stops recording, it could not be started again by press the left button. It could only be started by setting the parameters in RC-5 data management software.***

3. Switch menu items:

By short pressing left button, display interface will switch in turn.

4. Return to the status display interface

By short pressing right button, it will return to the status display main interface from current display interface.

5. Alarm status Instruction

During recording, if the measured temperature is higher than temperature upper limit, in the status display interface, the symbol " ⤒ " lights, indicating upper limit alarm; if the measured temperature is lower than temperature upper limit, in the status display interface, the symbol " ⤓ "lights, indicating lower limit alarm.

6. Record interval

The record interval could be set in RC-5 data management software. After setting, it will save the data in the data logger according to the set record interval. In RC-5 data management software, when record interval is set, click the setting bar of record time length, then the software will automatically calculate the record time length.

7. Record time length

The "record time length "means the total record time when the memory reaches its full capacity.

8. Clear the recorded data

The recorded data could be cleared through setting the parameters in RC-5 data management software.

9. Inner clock and calendar

The clock could be adjusted by RC-5 data management software.

10. Sensor failure

When there is a sensor failure or over temperature range, it could query by two methods as below:

① When the temperature exceeds temperature range or there is a break circuit or short circuit, it will display "Err" in the position of temperature in the status display interface.

② There will appear an instruction of "Sensor error" in RC-5 data management software.

11. Battery level indication

The battery level could be displayed in RC-5 LCD screen.

Battery level indication	Level
	25%~100%
	10%~25%
	<10%

Note: If the battery is in a very low level (<10%), please replace the battery timely.

12. Other function:

A、Record time delay: Set "start delay time" in the item of "parameter setting" in RC-5 data management software, then press left button for more than 4s in the status display interface, then the symbol" ▶ "flashes which indicate in the status of record time delay, and after started, the symbol" ▶ "stops flashing.

B、Temperature unit ℃ or ℉ optional, the default setting is ℃

C、 Serial number and user information could be set by software.

13. RC-5 temperature data logger data management software

It has the data analysis function, and could show the data in the data label or in data graph. Historical data can be queried, save, print or exported in the format of Word, Excel, TXT, or PDF. And the data management software has two versions: Windows version and Mac version. For Windows data management software, it supports the system of Windows XP, Windows 7, and Windows 8; and for Mac data management software, it supports the system of OSX10.5.6 or above. For the details, please refer to Help file of RC-5 data management software.

14. RC-5 parameter setting items in temperature data logger data management software:

Note: It is the factory default setting in the brackets. The factory default state of data logger is without starting. record interval (15 min); start delay time (0); meter station (1); Button stop (Disabled); temperature unit (° C); upper temperature limit (60 ° C); lower temperature limit (-30 ° C); temperature calibration (0 ° C); clock set (current time); set the number (001); set user information (RC-5).

VIII.Battery replacement:

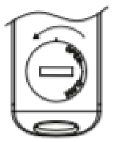


Figure 9

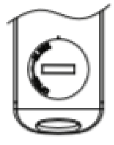


Figure 10

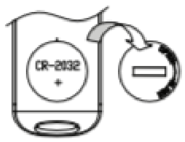


Figure 11

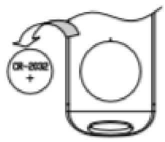


Figure 12

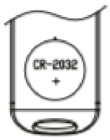


Figure 13

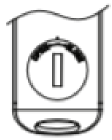


Figure 14

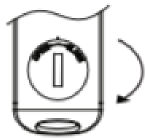


Figure 15


Figure 16

Replacement steps:

1.Rotate the battery cover counter clockwise to the position as shown in Figure 10.
2. Remove the battery cover.
3. Remove the old battery from the battery slot.
4. Put the new battery into the battery slot.
5. Place the battery cover in the position shown in Figure 14.
6. Rotate the battery cover clockwise from Position shown in Figure 15 to the position shown in Figure 16.

Note: The pole piece in the bottom of the battery slot is negative.

IX.Accessory list

Standard accessory list
One RC-5 temperature data logger
One operation instruction

Note: The software or user manual could also be downloaded in our website: www.e-elitech.com

Optional accessory list

One software installation CD

Jiangsu Jingchunag Electronics Co.,Ltd.

V1.0

Appendix B: Infrared thermometer specifications and user's manual

ANGGO

ANGGO infrared thermometer helps the users measure temperatures from a safe and hazard-free distance (above boiling points and below freezing points)

— Max and Average Temperature Function

It can get the highest and average temperature of the area and keeps the data on the bottom of the screen for future recording.

— EMS Adjustable Available

Each article has its own emissivity, so that the function of adjustable emissivity makes the test more accurate via adjusting suitable emissivity based on different article. (Emissivity of articles are referred to the user manual.)

— Instant Result Readout

Point the laser on any stuff and their surface temperature will show within less than a second by pressing the thermometer trigger. And one button to switch between Fahrenheit and Celsius without measuring again.

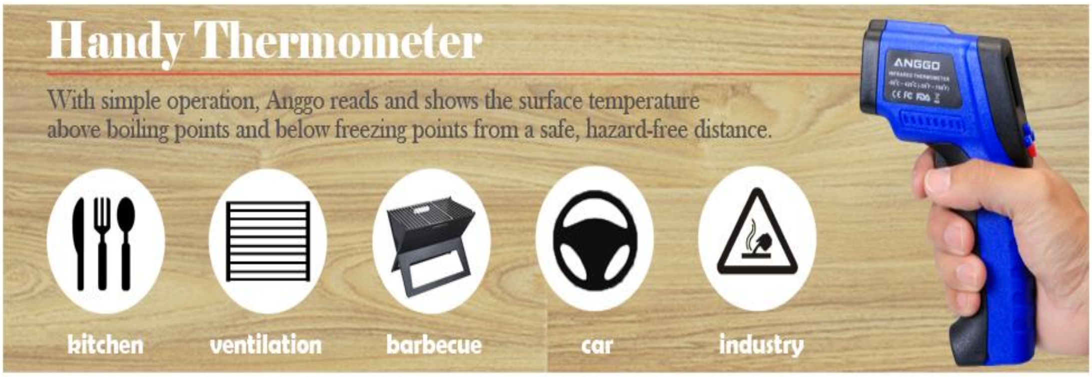
— Power Save: Bright LCD Screen and Backlight Display Selection.

1).Dates on LCD screen can been read under sunlight althought the backlight is off.

2).In dark place or somewhere the data is not seen clear on the screen, just turn on the led backlight.

— Professional blue color and anti-slip design.

Anti-slip design enables the infrared thermometer to be held firmly and not easy to get dirty. It helps the user get cozy touch feeling during testing temperature of any stuff.



Product Features

- Measures in Celsius or Fahrenheit mode with temperature range: -50°C to 420°C /-58 °F to 788°F with ± 1.5°C instrumental error.
- EMS adjustable emissivity function enables to get more accurate temperature by adjusting emissivity based on different articles.
- Built-in red laser for precisely aiming. Distance Spot Ratio: 12:1, and Response Time with 500ms for instant Result Readout.
- Portable and anti-slip design make it comfortable to be held and easily operated to get the temperature of any stuff outdoor and indoor.

Kindly tips:

*D : S= 12 : 1, means the Distance to the Spot Size of the unit is 12 : 1. As the Distance(D) from the target surface increases, the spot size of the area measured(S) by the unit becomes larger. So in order to get more accurate temperature, please pay attention to the Distance to Spot Size, or it will get some error if you neglect this.

*Anggo thermometer collects the infrared radiation energy from surface of the stuff that is focused by red laser, and transfer this information into electric signal via photodetector, then analyze and calculate its temperature. So please keep in mind that what you get is the surface temperature not inside temperature.

Hand-free Measure

It masks you know the temperature of any stuff around with no contact and protects you from getting hurt in many occasion.

Laser-shape Accuracy

temperature range: -50℃- 420℃(-58℉-788℉)

EMS Setting

Measure and get more accurate temperature via emissivity setting based on different articles.

Aluminum: 0.30
Ice: 0.98
Hot food: 0.93
...(More EMS collect in the Manual)

Specifications for Anggo no contact infrared thermometer

Item Dimensions: 6.4*3.6*1.7 inch

Net weight: 167g

Package Weight: 220g

Data show method: 3 o'clock LCD display with white LED

Power Required: 2 x AAA battery (Included)

Accuracy: ± 1.5°C for Celsius and ±1.5% for Fahrenheit

Measurement Range: **-58℉~788℉/ -50℃~420℃**

Usage occasion: non-contact to test surface temperature of articles such as boiling water, wine and candy making, beefsteak, coffee, car engine, air conditioning, fish frying, boiler, cooker, oven, or other stuff that are not get touch easily.

Appendix C: Globe thermometer specifications

EXTECH INSTRUMENTS

Experience the Extech Advantage

PRODUCT DATASHEET

Heat Stress WBGT Meter

Wet Bulb Globe Temperature (WBGT)

Considers the effects of temperature, humidity and direct or radiant sunlight

Features:

- Heat Stress Index measures how hot it feels when humidity is combined with temperature, air movement, and radiant heat
- Black Globe Temperature (TG) monitors the effects of direct solar radiation on an exposed surface
- Air Temperature (TA) plus Relative Humidity (RH)
- Selectable units of °F and °C
- In/Out Function displays the WBGT value with or without direct sun exposure
- Auto Power Off with override
- Built-in RS-232 interface with optional Windows® compatible software
- Complete with two AAA batteries

Optional Windows® compatible PC software (407752) for further data analysis and to generate reports

Applications:
- Athletic training
- Monitor outdoor working conditions
- Manufacturing

Specifications	Range	Basic Accuracy
Wet Bulb Globe Temperature (WBGT)	32 to 122°F (0 to 50°C)	±4°F/2°C
Black Globe Temperature (TG)	32 to 176°F (0 to 80°C)	±4°F/2°C
Air Temperature (TA)	32 to 122°°F (0 to 50°C)	±1.8°F/1.0°C
Humidity	0 to 100%RH	±3%RH
Dimensions	Meter: 10 x 1.9 x 1.1" (254 x 48.7 x 29.4mm) Ball: 1.6" dia, 1.4" high (40mm diameter, 35mm high)	
Weight	4.8oz (136g)	

Ordering Information:

HT30 ....Heat Stress WBGT Meter
407752 ....PC software and cable

CE

www.extech.com

Specifications subject to change without notice.

1/6/15 - R1

For user's manual, please visit: http://www.extech.com/products/resources/HT30_UM-en.pdf

Appendix D: AVM 714 Anemometer specifications

TECPEL

HOT WIRE ANEMOMETER

Model : AVM 714

CE

FEATURES

* Thermal anemometer, available for very low air velocity measurement.
* Slim probe, ideal for grilles & diffusers.
* Combination of hot wire and standard thermistor, deliver rapid and precise measurements even at low air velocity value.
* Microprocessor circuit,
* m/s, km/h, ft/min, knots. mile/h.
* Heavy duty & compact housing case.
* Data hold, Memory (Max. & Min.)
* Auto shut off saves battery life.
* RS 232 PC serial interface.
* Thermistor sensor for Temperature measurement, fast response time.
* Applications : Environmental testing, Air conveyors, Flow hoods, Clean rooms, Air velocity, Air balancing, Fans/motors/blowers, Furnace velocity, Refrigerated case, Paint spray booths.

HOT WIRE ANEMOMETER, Model : AVM 714

FEATURES	
* Thermal anemometer, available for very low air velocity measurement.	* RS 232 PC serial interface.
* Slim probe, ideal for grilles & diffusers.	* The portable anemometer provides fast, accurate readings, with digital readability and the convenience of a remote probe separately.
* Combination of hot wire and standard thermistor, deliver rapid and precise measurements even at low air velocity value.	* Multi-functions for air flow measurement : m/s, km/h, ft/min, knots. mile/h.
* Microprocessor circuit assures maximum possible accuracy, provides special functions and features.	* Build in temperature ℃, ℉ measurement. * Thermistor sensor for Temp. measurement, fast response time.
* Super large LCD with dual function meter's display, read the air velocity & temp. at the same time.	* Used the durable, long-lasting components, including a strong, light weight ABS-plastic housing case.
* Heavy duty & compact housing case.	* Deluxe hard carrying case.
* Records Maximum and Minimum readings with recall. * Data hold. * Auto shut off saves battery life. * Operates from 6 PCs UM-4 batteries.	* Applications : Environmental testing, Air conveyors, Flow hoods, Clean rooms, Air velocity, Air balancing, Fans/motors/blowers, Furnace velocity, Refrigerated case, Paint spray booths.

GENERAL SPECIFICATIONS			
Circuit	Custom one-chip of micro-processor LSI circuit.	Data Output	RS 232 PC serial interface.
Display	* 13 mm(0.5") Super large LCD display. * Dual function meter's display.	Operating Temperature	0 ℃ to 50 ℃(32 ℉ to 122 ℉).
Measurement	m/s (meters per second) km/h (kilometers per hour) ft/min (feet/per minute) knots (nautical miles per hour) mile/h(miles per hour) Temp.- ℃, ℉. Data hold.	Operating Humidity	Less than 80% RH.
		Power Supply	1.5 V AAA (UM-4) battery x 6 PCs. (Alkaline or heavy duty type).
		Power Current	Approx. DC 30 mA.
		Weight	355 g/0.78 LB.
Sensor Structure	*Air velocity :* Tiny glass bead thermistor. *Temperature :* Precision thermistor.	Dimension	*Main instrument:* 180 x 72 x 32 mm (7.1 x 2.8 x1.3 inch). Telescope Probe : Round, 12 mm Dia x 280 mm (min. length). x 940 mm (max. length).
Memory	Maximum and Minimum with recall.	Accessories Included	Instruction manual........... 1 PC. Telescope Probe....................1 PC. Hard carrying case.................1 PC.
Sampling Time	Approx. 0.8 sec.		
Power off	Auto shut off saves battery life or manual off by push button.	Optional Accessories	Datalogger software : SW-U801-WIN RS232 cable : UPCB-02

ELECTRICAL SPECIFICATIONS (23 5℃)			
Measurement	Range	Resolution	Accuracy
m/s	0.2 - 20.0 m/s	0.1 m/s	± (5 % + 1 d) reading or ± (1 % + 1 d) full scale ** Depend on which is larger.*
km/h	0.7 - 72.0 km/h	0.1 km/h	
ft/min	40 - 3940 ft/min	1 ft/min	
mile/h	0.5 - 44.7 mile/h	0.1 mile/h	
knots	0.4 - 38.8 knots	0.1 knots	
Temperature (℃)	0 ℃ to 50 ℃	0.1 ℃	± 0.8 ℃
Temperature (℉)	32 ℉ to 122 ℉	0.1 ℉	± 1.5 ℉

Note:
m/s - meters per second *km/h - kilometers per hour*
ft/min - feet/per minute *knots - nautical miles per hour*
mile/h - miles per hour (international knot)

* Appearance and specifications listed in this brochure are subject to change without notice. 0403-AM4204

Appendix E: MP-100: Pyranometer

SILICON-CELL PYRANOMETER METERS | MP-100 & MP-200

Features

Output Options
- Attached hand-held meter
- Separate sensor attached via cable

Stable Measurements
Long-term non-stability determined from multiple replicate pyranometers in accelerated aging tests and field conditions is less than 2 % per year.

Unique Design
A patented dome-shaped sensor head keeps the sensor clean and minimizes errors by shedding water. Sensors are housed in a rugged anodized aluminum body and electronics are fully-potted.

Typical Measurement Applications
- Solar panel arrays
- Agricultural, ecological, and hydrological weather networks

Calibration Traceability
Apogee SP sensors are calibrated through side-by-side comparison to the mean of (4) Apogee SP-110 transfer standard sensors under high intensity discharge metal halide lamps. The transfer standard sensors are calibrated through side-by-side comparison to the mean of at least (2) ISO-classified reference pyranometers under sunlight in Logan, UT. Each of (4) ISO-classified reference sensors are recalibrated on an alternating year schedule at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. NREL reference standards are calibrated to the World Radiometric Reference (WRR) in Davos, Switzerland.

Accurate and stable global shortwave radiation measurement

Product Specifications

	MP-100	MP-200
Calibration Uncertainty	± 5 %	
Measurement Repeatability	Less than 1 %	
Long-term Drift	Less than 2 % per year	
Non-linearity	Less than 1 % up to 1750 W m^{-2}	
Response Time	Less than 1 ms	
Field of View	180°	
Spectral Range	360 to 1120 nm	
Directional (Cosine) Response	± 5 % at 75° zenith angle	
Temperature Response	-0.04 ± 0.04 % per C	
Operating Environment	0 to 50 C; less than 90 % non-condensing relative humidity up to 30 C; less than 70 % non-condensing relative humidity from 30 to 50 C; separate sensors can be submerged in water up to depths of 30 m	
Sensor Dimensions	Integrated with Meter	24 mm diameter, 33 mm height
Meter Dimensions	126 cm length, 70 mm width, 24 mm height	
Mass	150 g	180 g
Cable	2 m of shielded, twisted-pair wire; additional cable available; TPR jacket (high water resistance, high UV stability, flexibility in cold conditions)	
Warranty	4 years against defects in materials and workmanship	

For user's manual, please visit: https://www.apogeeinstruments.com/content/MP-100-MP-200-manual.pdf