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Energy Efficient Strategies for the Building Envelope of Residential Tall Buildings in Saudi Arabia

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ABSTRACT

The energy demand in the Gulf countries in general and in Saudi Arabia in particular has been increasing sharply in the last decades as a result of the diversification plans that aim to reduce reliance on oil-based income. Tall building construction, associated with many environmental and ecological challenges, played an essential role in these plans, as a mean to attract new economies based on global placemaking and international tourism. The significant use of air conditioning to cool indoor spaces, particularly in residential buildings, accounts for more than half of all energy consumption in the country, and despite governmental efforts, the scattered conservation efforts have been largely ineffective due to factors such as lack of awareness and information, in addition to the limitation of the local energy efficiency building regulations.

This research aimed to find and prioritise building envelope design solutions that can reduce high energy consumption and cooling loads while maintaining indoor environment for residential tall buildings in Saudi Arabia. In order to achieve that, a hypothesis of integrating engineering and design parameters of the building envelope as a design strategy for tall buildings envelope were proposed, and to test it, a mixed method approach was followed including literature review, data collection, dynamic building simulations and parametric analysis.

The main findings emphasised how combining both engineering and design parameters of the building envelope can be an effective way to achieve energy efficiency in residential tall buildings in the hot climate of Jeddah. Especially in relation to solar heat gains, the highest contributor to cooling loads in this building type. The findings highlighted that while the thermal properties of the wall type can reduce up to 10% of the cooling loads, applying external shading devices can achieve a reduction of up to 30% in solar gains. Moreover, effective consideration of building orientation can significantly reduce cooling loads by 25% and solar gains by 60% for the perimeter zones. Based on this, a set of guidelines that incorporate a comparative tool were introduced to help designers to determine the thermal performance and energy use of a typical residential tall building in the early stages of the building's design. Which also aim to enhance the effectiveness of the local building codes and energy efficiency regulations in relation to this building type.

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

To all those people who I greatly doubt will ever read my PhD - except my supervisors and proof-readers- nevertheless, as Rowan Moore (2012) said, they have “provided in different ways the inspiration, information, education, help, love and/or DNA without which this book would have been impossible”:

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And finally, I dedicate this work to the best gift I have never dreamt of, Dana, my daughter, who glued it all together.

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CAIT: Climate Analysis Indicators Tool

CCPI: Climate Change Performance Index

DWTC: Dubai World Trade Centre

ECRA: Electricity & Co-generation Regulatory Authority

GBC: Green Building Code

GCC: Gulf Cooperation Council

GSAS: Global Sustainability Assessment System

KACST: King Abdulaziz City of Science and Technology

MWE: Ministry of Water and Electricity

NEEP: National Energy Efficiency Program

REDF: Real Estate Development Fund

SEC: Saudi Electricity Company

SEEC: Saudi Energy Efficiency Centre

UAE: United Arab Emirates

WTO: World Trade Organization

CFD: Computational fluid dynamics

CRFS: Climate interactive façade systems

CSFS: Classical single façade system

DL: Daylighting

HPI: High performance insulation

HAS: Horizontal shadow angle

HVAC: Heating, ventilation and air-conditioning

IEC: Israel Energy Code

IGU: Insulated glazing units

ILD: Internal-load dominated

LSR: Light-to-Solar Ratio

LT: Lighting and Thermal

MRT: Mean radiant temperature

PMF: Permasteelisa Moving Forward

PMV: Predicted Mean Vote

PPD: Predicted Percentage of Dissatisfied

PV: Photovoltaic

RHG: Relative heat gain

RIBA: Royal Institute of British Architects

SC: Shading Coefficient

SHGC: Solar Heat Gain Coefficient

SHGF: Solar Heat Gain Factor

SLD: Skin-load dominated

TEC: Thin Environmental Cladding

TET: Total energy transmittance

U-value: Thermal transmittance

VLT: Visible light transmittance

VSA: Vertical shadow angle

WWR: Window-to-wall area ratio

CTBUH: Council on Tall Buildings and Urban Habitat

EWS: External wall systems

IECC: International Energy Conservation Code

LEED: Leadership in Energy and Environmental Design

PVB: Polyvinyl butyral

SSG: Shadow Box Spandrel Glass

TBW: Thermal Blocks Wall

UCW: Unventilated Cavity Wall

CMU: Concrete Masonry Unit

PF: Projection Factor

INTRODUCTION

This introductory section presents the topic of this study and establishes the basis for its development. It defines the research rationale and main aims and objectives, in addition to introducing the research methodology and thesis structure which underpins this work.

INTRODUCTION

> *"The eye is engaged but not the body. Mostly, you are not invited to move through these works, unless by lift or escalator. Climate is an awkwardness, to be banished by air-conditioning. Similarly smell: this can be repurchased as perfume. As you enter from the heat and dust outside, you are lightly gripped by mechanical clamminess, in a transition we now treat as normal. It tells us that the air and temperature have been paid for, and that we agree to the terms and conditions of the people who have paid for them. As the architect Rem Koolhas says, conditioned space is conditional space."*
>
> Rowan Moore, architecture critic of the Observer, in his book, 'Why We Build', p.22-23, 2012
>
> *"Ultimately, although current global architectural standards used in the tall buildings in the Middle East are not fully appropriate to the local climatic context, architectural values can change as economic values change, and while the Middle East is founded upon the energy model of the past, it also has energy resources for a 'greener' future of cities, having the biggest potential to harvest solar power in the world, at the building and urban scale."*
>
> Joana Carla Soares Gonçalves in her book, 'The Environmental Performance of Tall Buildings', 2010, p.136-137

For the last few years, the rapid development in the Gulf Region has been driven by the desire to move away from oil and build a future economy that is based on financial services, global placemaking and international tourism (Hammoud, 2016). In the middle of this, tall buildings have played a crucial role in creating iconic structures that generate value and recognition, becoming a source of identity and transforming emerging cities in the region into global destinations (Moore, 2012). However, this rapid urbanisation combined with the availability of cheap energy for heating and cooling has also created many ill-conceived buildings, based on short-sighted economic arguments, which neither accord with local cultural aspects nor comply with fundamental energy efficiency rules or the specific environmental considerations for the region (Kaufmann in Hausladen et al., 2008).

The vast majority of tall buildings in the Gulf Region are entirely dependent on mechanical air conditioning, creating a difference in temperature between indoor and outdoor spaces of up to 20°C, enough to cause a thermal shock when moving between them (Yannas, n.d). Besides that, the excessive use of completely sealed and fully glazed façades has been widely criticised for its high consumption of energy resources, and several studies have argued that fully glazed building skins, even those with 'intelligent features', lead to overheating in the internal spaces due to excessive solar gain, which has to be compensated for by mechanical air conditioning leading to high building energy consumption (Al-Hosany, 2002; Elkadi, 2006; Shuttleworth, 2008).

In Saudi Arabia, air conditioning to cool indoor spaces accounts for over 70% of electricity consumption, and about 40% of the total annual electricity consumption in the Kingdom (El Khoury, 2012, cited in Myrsalieva and Barghouth, 2015). As power-generating plants in the country are dependent on hydrocarbons, using natural gas, heavy fuel oil, crude oil and diesel oil, the building sector, especially the residential sector, has been identified as a major contributor to carbon dioxide emissions arising from the combustion of fossil based fuels (Obaid and Mufti, 2008; Reiche, 2010).

The paradox lies in the fact that these energy-intensive buildings are a result of the huge diversification plans and massive construction projects that aimed to pull the economy away from oil-dependency. The resulting industrial expansion and rapid urbanisation, in addition to the urban population growth and young demographic profile, have created huge pressure on housing demand in the region, especially in Saudi Arabia. As result, the country is witnessing an unprecedented boom in real estate development in order to address the major housing shortage, which will require the construction of at least 2.32 million residential units by 2020 (Opoku and Abdul-Muhmin, 2010; Alrashed and Asif, 2015).

Major cities such as Jeddah, located on the west coast of the country, are experiencing population growth at an annual rate of 2.2% with Jeddah expected to reach 5.6 million people by 2029. As the city is currently challenged by poorly controlled expansion and inadequate infrastructure (Abdulaal, 2012), the Municipality of Jeddah has developed a city-wide strategic growth plan which includes regeneration projects and comprehensive urban mega projects that involve the construction of many high-rise residential towers in prime locations overlooking the Red Sea. These include the 5.3 million square metre Jeddah City Development, anchored by the mixed-use 1,000-plus-metre tall Jeddah Tower. Given the important role tall buildings, specifically residential tall buildings, play in the city's development plans, they are considered a key area for improvement in energy efficiency in order to boost the local economy, as reducing domestic fossil fuel use will mean more oil and natural gas for export, helping the Kingdom prepare for the post oil age and bringing clear environmental benefits (Reiche, 2010).

Despite the fact that the majority of tall buildings in the region are residential, very few studies have been conducted regarding the environmental performance of this building type. Therefore, the increased prevalence of residential tall buildings and the high domestic energy and air-conditioning requirements in the challenging climate of the Gulf Region, has led to a major question: How can we increase energy efficiency and reduce energy consumption in residential tall buildings in the region?

Starting from the macro scale, decision-makers and developers in the Gulf Region are now setting clean energy targets and implementing strategies that emphasise sustainable energy transition and reflect growing governmental concerns about domestic energy consumption. These plans have included establishing a common standard for energy efficiency regulations, which takes into account the existing standards through close cooperation between the authorities in each country. However, although adapting the built environment and building codes according to the local climatic and environmental requirements has been shown to lead to significant savings and reductions in energy demands (Lahn et al., 2013), many of these conservation efforts have been largely ineffective due to factors such as bureaucracy and governance challenges; lack of awareness, information, and enforcement; and lack of market incentives and political support (Obaid and Mufti, 2008; Reiche, 2010).

Focusing on the energy efficiency in residential tall buildings, it is well established that the main factors determining the energy use in a building are: climate, functional program, the building's form and envelope and the building systems (Brown and DeKay, 2001). Of these, the building envelope is responsible for a significant portion of the total energy consumption in the built environment (Al-Hosany 2002; Haase and Amato, 2006). Reflecting on the current energy codes and building regulations, especially those in Saudi Arabia, the typical approach usually deals with the minimum requirements of the building envelope, specifically the thermal transmittance values for the opaque and transparent elements of the building envelope, with little consideration for architectural design parameters which can have a significant impact on energy performance (Meir et al., 2012).

Such factors have driven this work which aims to analyse the energy performance of the current approach to building envelope design in the residential tall building sector in the Gulf Region in general and Saudi Arabia in particular in order to:

a) Identify limitations within the local building codes and energy efficiency regulations,

b) Find and then prioritise building envelope design solutions which can reduce energy consumption and cooling loads while maintaining a comfortable indoor environment for this building type, and

c) Investigate the possibilities of improving the parameters and benchmarks set in the local building codes and regulations in order to achieve this aim.

This thesis considers the hypothesis that current façade design approaches and building regulations that focus on the manipulation of 'engineering parameters' – glazing percentage, thermal properties of wall and glazing types – are not sufficient to achieve the necessary energy efficiency in residential tall buildings in the hot climate of the Gulf Region. The thesis questions the limitations of this focus on 'engineering parameters' and hypothesises that other architectural design parameters which are less common in their application in the region, such as shading devices and altering a building's orientation, could significantly improve both energy efficiency and the indoor environment.

To investigate this hypothesis, a mixed approach was followed including literature review, data collection, dynamic building simulations and parametric analysis. The literature review covers the energy context and climatic analysis in the Gulf Region, the main functions and environmental impact of the building envelope, and provides a comparative review of the building codes, energy efficiency regulations and environmental ranking systems in the region. Following that, a series of case study buildings in Dubai, Abu Dhabi and Jeddah were chosen and evaluated in order to identify the current building envelope characteristics of residential tall buildings in the region. Furthermore, the thesis makes use of two case studies, a representative hypothetical case study and an existing case study (Corniche Dreams Tower); these were used to conduct parametric studies through dynamic thermal simulations with the aim of investigating the impact of both the engineering and design parameters of the building envelope on cooling loads and energy efficiency in residential tall buildings in the Gulf Region, and comparing the results with common practice and current building codes.

The novelty of this work lies in exploring the impact of both the engineering parameters, which dominate current studies and guidelines, and the design parameters, which affect the architecture of the building as well as its energy performance. The work is up to date with regulations, strategies and assessments of the residential tall buildings used as case studies, especially those in Jeddah. Ultimately, this work aims to contribute to the effectiveness and potential enhancement of the local building codes and regulations for tall buildings in the Gulf Region, especially in terms of building envelope energy efficiency measures and design benchmarks, in order to reduce energy consumption while maintaining indoor comfort.

The structure of this thesis is divided into three sections: a lead-in original literature review that establishes the scene for the development of the research; the data collection of the characteristics of residential tall buildings in the Gulf Region used to develop the dynamic building simulations to study the thermal performance for each case study; and the sensitivity analysis of the parametric studies that led to the environmental strategies for the building envelope parameters.

The chapters – shown in Table 1 – are organised as follows:

Introduction: This introductory section includes the research rationale, aims and objectives, methodology and research structure.

Chapter 1 – **Energy and Residential Tall Buildings in the Gulf Region:** This chapter contains lead-in background information that sets the research context and outlines the economic, energy and climatic context in the Gulf Region with special focus on housing and residential tall buildings.

Chapter 2 – **Tall Buildings Envelope Design, Functions and Performance:** This chapter includes a lead-in focused literature review and explains the physics, functions and the methods used to evaluate the environmental performance related to the building envelope, including thermal and visual performance.

Chapter 3 – A Comparative Analysis of Tall Building Codes and Practices in the Gulf Region: This chapter contains a lead-in original literature review about the tall buildings codes and green building regulations and ranking systems in the Gulf Region. It also comparatively analyses these codes and regulations, thereby contributing to current knowledge and informing the Characteristics Table and parametric analysis in the following chapters.

Chapter 4 – An Evaluation and Analysis of the Characteristics of Residential Tall Buildings: This chapter includes original core research materials that add to the knowledge and consists of two main sections. The first section explains the Characteristics Table which was compiled from the architectural and thermal façade characteristics of 11 residential tall buildings in the region to qualitatively and quantitatively evaluate their energy performance. The second section analyses the results of the Characteristics Table and establishes a) the main parameters for the parametric study, and b) the façade configuration for the hypothetical base case for sensitivity analysis.

Chapter 5 – Thermal Simulations of Envelope Parameters: This chapter presents the basis and the method of the parametric study that forms the second stage of the original core research. The dynamic building simulation using Tas explores and compares the results of two sets of simulations: the first concerned with envelope engineering parameters (glazing percentage, glazing properties, wall construction type) and the second with envelope design parameters (shading devices). The selection of the engineering parameters and the development of the hypothetical base case were based on the results of the Characteristics Table and the main standards in the local building codes and rating systems. The selection of the design parameters responded to Jeddah's local context and climate and were based on the review of precedents and the design process and approach to practice. The outcome of this chapter aims to a) identify to what extent the building envelope can improve the environmental performance of this building type, and b) define the most promising solution in relation to cooling loads and energy efficiency in order to test it on the existing case study, as described in the following chapter.

Chapter 6 – Thermal Simulations of Case Study: The Cornish Dreams Tower: This chapter includes core original research that adds to the knowledge. It analyses the outcomes of the simulations detailed in Chapter 5 and explains how they were implemented in a real-life case study. An existing residential tall building in Jeddah, Cornish Dreams Tower, was selected as the case study. The chapter describes the architectural drawings, building materials and specifications of the building, and the empirical data collected over one year, including air temperature and humidity, which was used to evaluate the current performance of the building envelope. The results of the parametric study and sensitivity analysis are examined in order to identify the best building envelope solution in relation to cooling loads and energy efficiency, without compromising design and thermal and visual comfort. The main findings of the parametric studies informed the final stage of the research which aimed to determine the most promising environmental envelope design strategies for this building type.

Chapter 7 – Environmental Strategies for Building Envelope Design: This chapter forms the lead-out concluding material that summarises the results of the analyses from the previous chapters. It links the literature-based discussion with the original research argument to deliver a series of energy efficient environmental envelope design strategies for residential tall buildings in the hot Gulf climate and concludes by providing guidelines to directly inform the work of designers and architects in the region.

Conclusions and Further Work: The last section of this study presents the final conclusions and makes recommendations for future work.

Table 0-1 the structural plan for the thesis chapters

The Impact of the Building Envelope on the Energy Efficiency of Residential Tall Buildings in Saudi Arabia

Methodology	Proposed Chapter	Proposed Sub-Chapter
Introduction	Research rationale and structure, methodology, aims and objectives	
Lead-in + Focused Original Literature Reviews *Establishes the scene for the development of the research study*	**1.** Housing and energy in the Gulf Region	Economic, energy and climatic context
	2. Tall buildings envelope design	Physics and functions of building fabric Environmental performance and evaluation
Lead-in + Literature Reviews + Core *Data collection for current residential tall buildings in the Gulf Region*	**3.** A comparative analysis of tall buildings codes in the Gulf Region	Building codes, regulations and sustainability rating systems
	4. An analysis of the characteristics of residential tall buildings	Characteristics Table: - Method, results and discussion. - Main parameters for parametric study - Configuration of hypothetical case study
Core + Addition to knowledge *Investigating the Thermal Performance of Tall buildings through Dynamic Building Simulation using Tas*	**5.** Sensitivity analysis of envelope parameters <u>Engineering parameters</u> *Wall Construction* *Glazing percentage* *Glazing properties*	Scope and method Parameters and Matrix Hypothetical Model Description Assumptions Results
	<u>Design Parameters</u> *Shading* *Building orientation*	Scope and method Assumptions Results
Core + Addition to knowledge *Empirical data, data collection and dynamic building simulation through a parametric study exploration*	**6.** The Corniche Dreams Tower case study	The Tower Design and Description Empirical data The base case simulation model
	Parametric study *using the results from Chapter 5*	Scope and method Assumptions Results
Core + Lead out *Summary discussion of finding*	**7.** Environmental envelope design strategies	
Lead out + Conclusions	Conclusions and further work	

CHAPTER 1: Energy and Residential Tall Buildings in the Gulf Region

This chapter establishes the basis of this research in terms of the energy and climatic context, housing, and residential tall buildings in the Gulf Region in general and in Saudi Arabia in particular. The economic setting and energy situation are explored to enable an understanding of household energy use in the region. In addition, climatic conditions are analysed in order to understand their impact on the energy performance of buildings. The observational analysis of tall buildings in the Gulf Region reveals that the building envelope and façade design seems to be the most dynamic element in relation to climate and cultural factors, reflecting the importance of this building element in the development of tall buildings.

Chapter 1 ENERGY AND RESIDENTIAL TALL BUILDINGS IN THE GULF REGION

> *"Gulf countries are at a juncture of history where decisions are being made which will be crucial not only for the gratification of present 'needs' but for future generations that may not have seemingly infinite oil revenues".*
>
> Kaizer Talib in his book 'Shelter in Saudi Arabia', 1984, p.7
>
> *"What might energy sustainability mean for the Gulf? The Bruntland Commission's definition of sustainable development should have particular resonance for domestic energy management in the Gulf countries. There is, after all, a direct relationship between the energy that they consume at home and their future potential to export the commodity on which they depend."*
>
> The Chatham House Report about 'Saving Oil and Gas in the Gulf', 2013, p.2

While holding approximately 30% of the world's proven oil and 23% of proven gas reserves (BP, 2013), energy demand in the six Gulf Cooperation Council countries (GCC), Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (UAE), has increased sharply in recent decades as a result of their rapidly growing populations and the expansion of industrialisation and development projects. Ironically, the huge diversification plans, including developments in infrastructure, industrial expansion and massive construction projects, that aimed to diversify the economy and pull it away from oil-dependency, has resulted in more energy-intensive developments, such as new economic cities and financial districts, which in turn require more fossil fuels. As most power generation plants in Gulf countries are conventional fossil fuel thermal plants, using natural gas, heavy fuel oil, crude oil and diesel oil, without carbon dioxide abatement, (Obaid and Mufti, 2008; Lahn et al., 2013), this dependence on hydrocarbons has made the GCC countries some of the top contributors to pollution in the world (Reiche, 2010). Consequently, there is an urgent need for ecological modernisation and environmental improvements in the Gulf Region.

The rapid development in the Gulf Region is strongly associated with tall building construction, leading to an apparently endless race to construct the world's tallest building. These ever-taller buildings have played a crucial role in emphasising the role of global place making and international tourism within the region's growing cities (Hammoud, 2016).

In this chapter, the foundations of this research are established through an exploration of the economic, energy and climatic contexts in the Gulf Region in general and in Saudi Arabia in particular. The historical background is also discussed, and the housing and tall building typologies are defined.

1.1 Gulf Region: The Context

Since the discovery of oil in the 1930s in the Gulf Region, the countries of the Gulf Cooperation Council (GCC) have relied on oil for global and energy security. The exploitation of the vast oil reservoirs in the area in the second half of the 20th century has led to unprecedented modernisation and industrialisation on both urban and rural levels. This urbanised development can be explained chronologically through three main stages.

The first stage started in the late 1940s and early 1950s as the first oil boom funded the development of basic infrastructure such as roads, electricity and communication, dramatically changing the life-style, the social context of the outdoor environment and, consequently, the pattern of the urban fabric (Akbar, n.d.; Talib 1984).

The second stage was during the late seventies when a sharp increase in world oil prices produced a significant rise in national incomes, especially in Saudi Arabia (Akbar, n.d.). This rapid development led to a sudden growth in population due to the importation of foreign labour in addition to the drift of locals to the main cities, which created a greater demand for housing. As a result, decisions regarding the urban and built environment were made under increasing pressures (Talib, 1984), with no time for an evolutionary process for planning or design concepts (Adas, 2001). At the same time, this new architecture was heavily influenced by technological changes, especially air conditioning, and economical mass production, which replaced the more climatically and culturally appropriate vernacular architecture. Moreover, as Adas (2001, p.12) states, "*the increase in people's income opened the door to various ways of life with new requirements different from what they (were) use(d) to. There followed environmental changes in the living and working conditions of both urban and rural dwellers*". Overall, these urban developments were based on economic and demographic surveys and traffic studies irrespective of peoples' cultural and social lives, while the built environment was influenced by Western images and technological advances without any link to the natural environmental or to socio-cultural factors (Adas, 2001).

The third stage started in the late 1990s and early 2000s with the rapid economic growth that led to mega-scale projects and tower architecture in line with diversification plans that aimed to reduce reliance on oil-based income (Bahaj et al., 2008). This active construction, most evident in Dubai and Abu Dhabi in the UAE and Doha in Qatar, occurred at a very fast pace with no time to consider the environmental implications. Thus the issue of sustainability was neglected (Al-Sallal, 2004), resulting in the GCC countries featuring among the top 25 countries with the highest rates of carbon dioxide emissions per capita according to the United Nations Statistics Division (2007) and the Climate Analysis Indicators Tool (CAIT) (cited in Reiche, 2010).

In 2011, the GCC countries consumed almost as much oil and gas as Indonesia and Japan combined, a quantity greater than the entire primary energy consumption of Africa, yet they have just one-twentieth of that continent's population (Lahn et al., 2013). This demand is growing frighteningly fast - at an average of 6% over the last 10 years - and if the region's fuel demand continues rising as it has over the last decade, it will double by 2024, a deeply undesirable prospect for both the national security of each state and the global environment (Lahn et al., 2013) (Figure 1-1). The Climate Change Performance Index (CCPI) 2009 (Germanwatch, 2009 cited in Reiche, 2010) ranked Saudi Arabia bottom of the list in terms of climate protection performance, emphasising the need for ecological modernisation and environmental improvements in the Gulf Region.

The sections that follow discuss the energy context in the Gulf Region in general and in Saudi Arabia in particular, focusing on current energy usage, the challenges and the efforts being made to achieve the efficient use of natural resources.

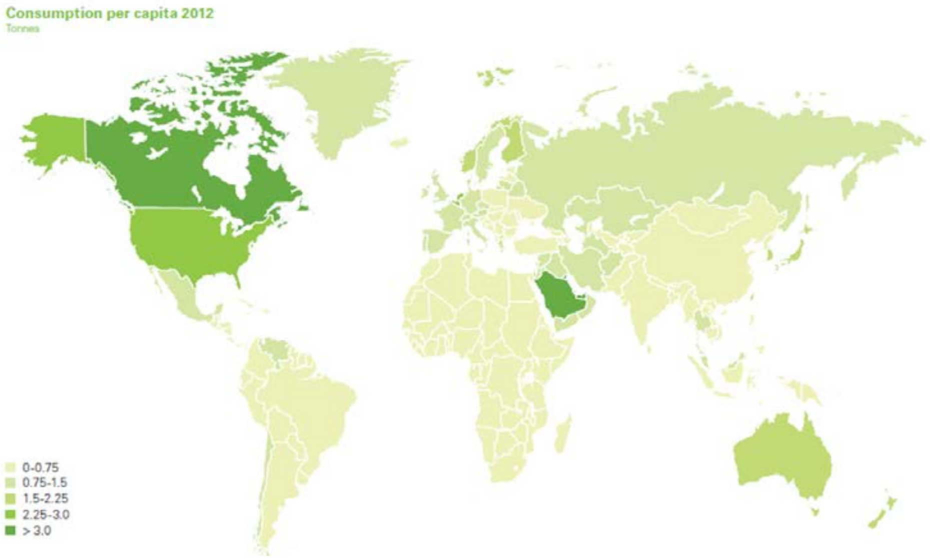

Figure 1-1 Oil consumption in the world; note the high oil consumption in the GCC countries, especially in Saudi Arabia, the UAE, Qatar and Kuwait. (Source: BP Statistical Review of World Energy, 2013)

1.1.1 The Economic and Energy Context

Energy consumption in the GCC has been rising over the last four decades (Figure 1-2) notably in Saudi Arabia, given the country's much larger population and land size. According to Al Ghabban (2013) and Lahn et al. (2013), the growth in fossil fuel consumption in Saudi Arabia has risen by more than 27% in the last four years, and based on the current pace of the national projections, population growth, urban development and industrial plans in the GCC countries, energy demand is expected to nearly triple by 2030. This requires serious energy efficiency policy interventions. In order to inform the appropriate design of these interventions, it is important to first examine the energy use in each country. Figure 1-3 shows a simplified sectorial breakdown of energy consumption in each GCC country representing the four main segments: electricity and cogeneration, industry, transport and non-energy use. The breakdown illustrates how electricity generation losses, mainly through air-conditioning and water production, represent a high portion of energy consumption (Alnaser and Alnaser, 2011; Lahn et al., 2013).

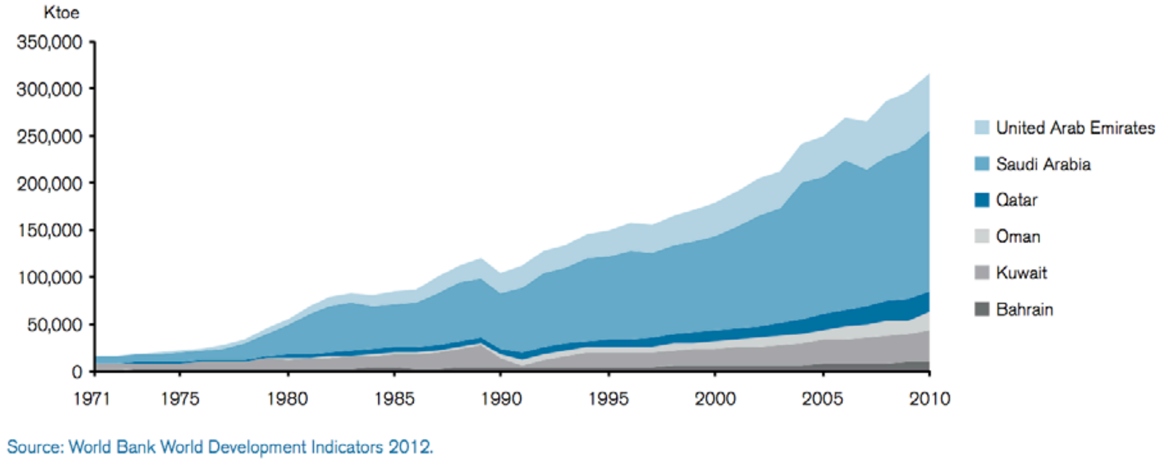

Figure 1-2 The GCC countries energy consumption between 1971-2010 (ktoe). (Source: Lahn et al., 2013, p.4)

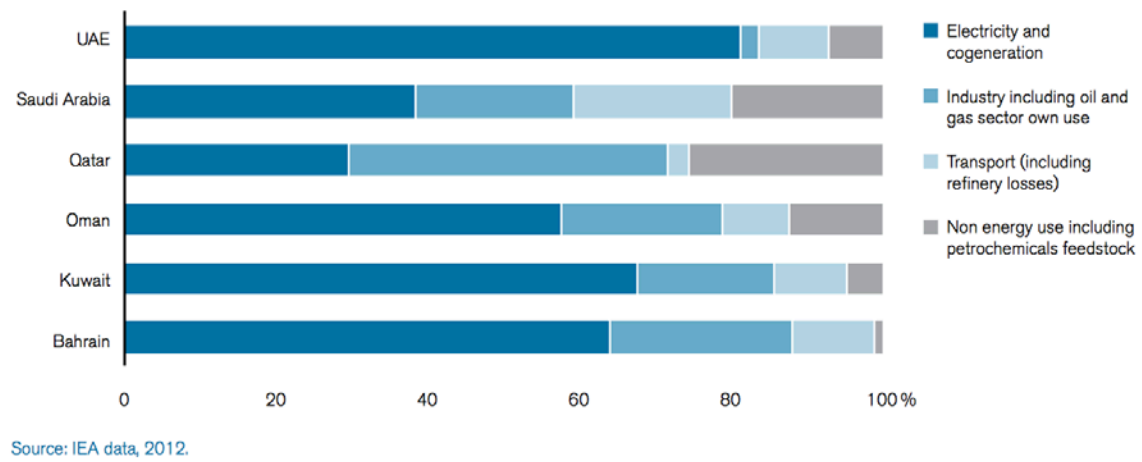

Figure 1-3 Basic sectorial breakdown of energy consumption in the GCC countries. (Source: Lahn et al., 2013, p.7)

Figure 1-4 shows that 37% of the total energy consumption in Saudi Arabia goes on electricity and cogeneration, with 51% of this delivered energy consumed within the residential sector. This indicates that housing and residential buildings are responsible for more than half of secondary energy consumption across the country. Figure 1-5 reveals that the significant use of air conditioning to cool indoor spaces accounts for much of this energy consumption, since cooling makes up over 70% of electricity consumption in the residential sector in Saudi Arabia and about 40% of the total annual electricity consumption in the kingdom (El Khoury, 2012, cited in Myrsalieva and Barghouth, 2015).

Lahn and Stevens (2011, p.9) also highlight that in Saudi Arabia, "*electricity generation capacity has doubled in the last decade to around 50,000MW but still struggles to keep up* *with demand in summer, which rises by as much as 50%. Air-conditioning is the crucial factor in this peak, accounting for around 52% of the country's total consumption during these periods*", and identify buildings, especially residences, as a key area for improvements in energy efficiency. Despite this, and regardless of the projected peak demand growth of at least 7% per year in the next decade in the GCC countries, no state has yet developed a domestic energy policy (Lahn et al., 2013).

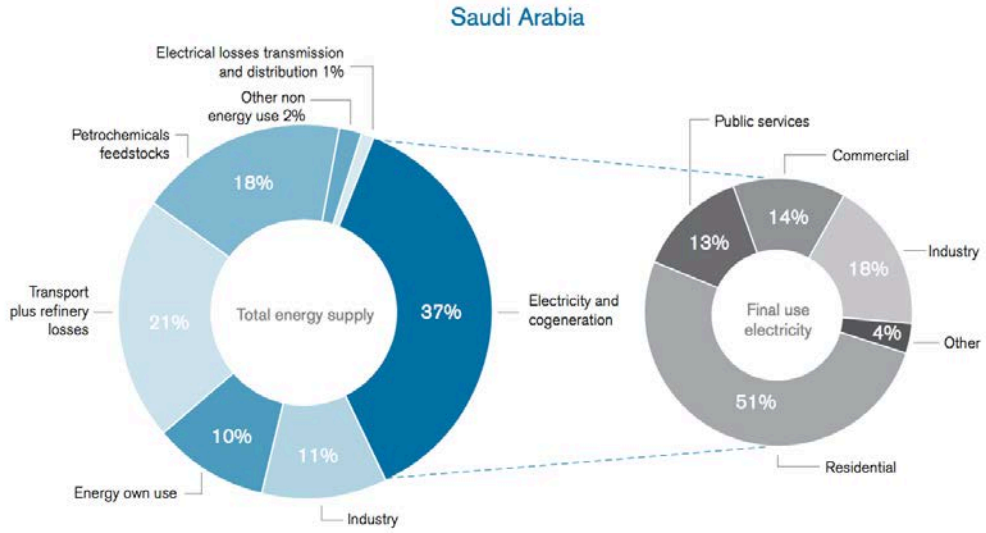

Figure 1-4 Total Energy Supply Breakdown for Saudi Arabia. (Source: Lahn et al., 2013, p.35)

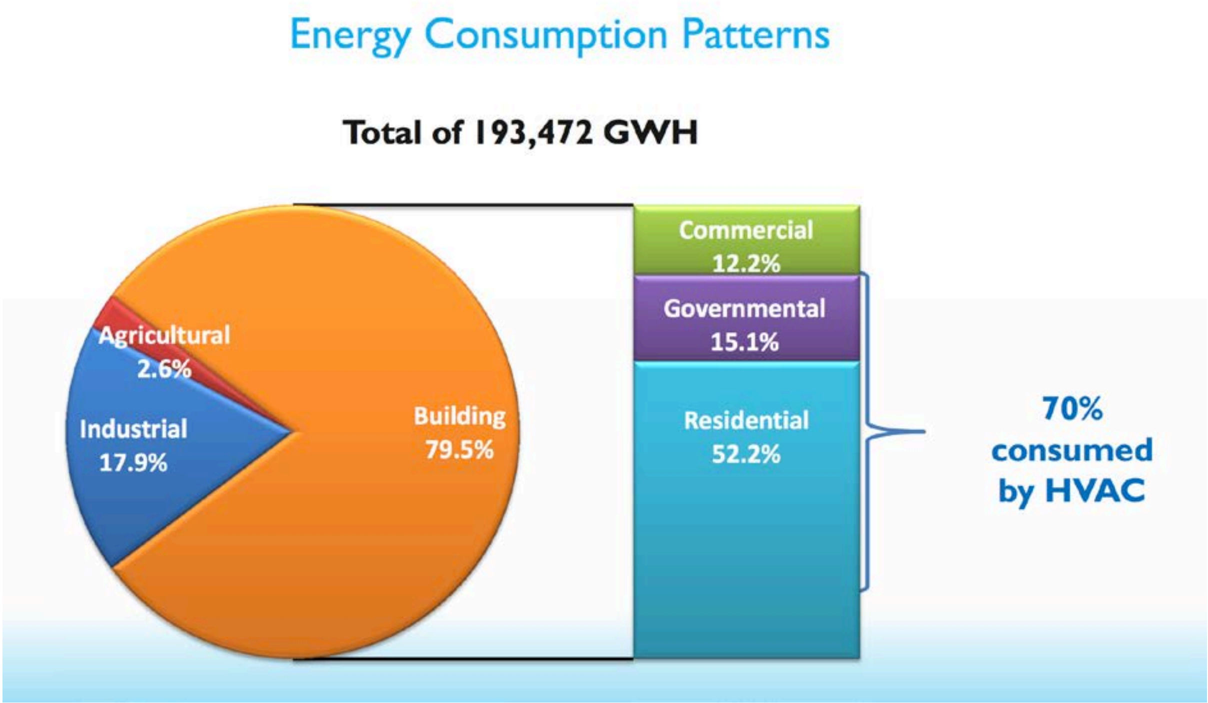

Figure 1-5 Energy consumption patterns in Saudi Arabia as supplied by The Saudi Electricity Company (SEC) in 2009. (Source: Al Ghabban, 2013, p. 17)

Talking about climate change policy and energy conservation in the oil-rich GCC countries might seem absurd, but meeting the sustainable energy goals of a more efficient use of fossil fuel and an increased share of renewable energies in the GCC will have global impact, as Lahn et al. (2013, p.vii) note: "*In the Gulf, where air-conditioning equipment frequently uses twice as much energy as the best available technology, standards and innovation to cool down using less energy will have global relevance*." Beside the effect on the local economies and the obvious environmental benefits, reducing the domestic use of fossil fuels will mean more oil and natural gas for export, which prepares the countries for the post-oil age (Reiche, 2010).

The rising global awareness regarding sustainability in all its disciplines has started to set a trend amongst decision makers and developers in the GCC countries, notably since 2009. Remarkable progress regarding clean energy targets and efficiency strategies that emphasise sustainable energy transition is now evident (Lahn et al., 2013). Table 1-1 summarises recent climate protection policies, including ratification of the Kyoto Protocol, administrative capacities to deal with climate change issues, governments targets, implemented policies, availability of oil, and the status of sustainability and green building standards in the GCC countries (Reiche, 2010, p.2401; Lahn et al., 2013; Myrsalieva and Barghouth, 2015). The table shows that all GCC countries now have long-term strategic clean energy plans or targets, with several significant steps towards conservation. Some countries, such as Saudi Arabia and the UAE, have introduced an independent electricity regulator in an attempt at energy policy coordination, which is instrumental in promoting an energy conservation agenda which takes the demand side into account. However, these targets addressing energy consumption are concerned only with the power sector and none have CO_2 emission reduction targets save Abu Dhabi in the UAE, the only city in the region to follow a strategic approach by making a pledge to reduce CO_2 emissions by 7% by 2020 (Reiche, 2010; Meir et al., 2012). The table also underlines that the most progressive building standards in the region are in Abu Dhabi and Dubai in the UAE, and Qatar. Abu Dhabi's Estidama Pearl Rating System, which began to be applied in 2010, was the first of its kind in the region to draw on international best practice but with adaptations to suit local climatic conditions and social needs. Furthermore, the Green Building Code (GBC) in Dubai is the only established green code in the region, while Qatar has pioneered the Global Sustainability Assessment System

(GSAS) in which energy and water efficiency are benchmarked and attached to a six-star rating system (Construct Arabia, 2012; Lahn at al., 2013).

Focusing on the efforts in Saudi Arabia, the Saudi Energy Efficiency Centre (SEEC) established in 2010 under the umbrella of the King Abdulaziz City of Science and Technology (KACST), formerly launched in 2002 as the National Energy Efficiency Programme (NEEP), engages all relevant ministries and industry partners and may be the most ambitious attempt at strategic coordination to date. SEEC has initiated energy efficiency training and awareness programmes, conducted energy audits and developed energy efficiency codes for buildings. It has also issued energy efficiency standards for selected household appliances and developed a labelling programme for these appliances (Lahn and Stevens, 2011). The Ministry of Water and Electricity (MWE) has also taken several steps to implement energy conservation and reduce peak load demands, including the formation of an Energy Conservation and Awareness Department to impose limits on the maximum power that can be delivered to electricity consumers, establishing demand-side management actions, and rationalising the use of electricity (Al-Ajlan et al., 2006).

The MWE in collaboration with the Saudi Electricity Company (SEC) has also published and distributed the first edition of the *Energy Conservation and Load Management Consumers' Guide*, in addition to promoting public and governmental sector awareness of energy conservation through organized workshops, meetings and site visits. Moreover, Saudi Arabia's Electricity & Co-generation Regulatory Authority (ECRA) has submitted detailed plans to achieve overall conservation and peak demand reduction targets to the Saudi government for approval. These plans aim that by 2032 renewable energy with nuclear baseload will relegate fossil fuel generation to meeting peak demand during the summer months only (Lahn et al., 2013).

Saudi Arabia has shown further commitment to renewable energy by adopting ambitious targets and establishing the King Abdullah City for Atomic & Renewable Energy (KA-Care), a dedicated institution for the development of renewable energy projects. And lately, as part of the "Saudi Arabia Vision 2030" policy paper, KA-Care has issued a tender for technical, financial, and legal consultants attracting private developers to participate in renewable energy power generation projects targeted for 2020.

Table 1-1 Driving forces for climate protection policies, and energy conservation and green building standards in the Gulf Cooperation Council countries. (Source: compiled from Reiche, 2010; Lahn et al., 2013; Myrsalieva and Barghouth, 2015)

Country	Ratification of the Kyoto Protocol	Administrative institution dealing with energy policy	Long-term Strategic Orientation	Technical Programmes	Targets	Measures	Status of Implementation	Availability of oil (proven reserves according to BP if production continues at the rate of the year 2007)	Buildings Sustainability Standards or Energy Efficiency Regulations	Regulation Coverage and Implementation Status
Bahrain	In 2006	Public Commission for the Protection of Marine Resources, Environment and Wildlife	The Economic Vision 2030 for Bahrain	The National Energy Efficiency Action Plan (NEEAP)	No information	No information	First draft prepared	< 20 years	Thermal insulation implementation for buildings (1999)	Mandatory for commercial buildings since 1999 and for all buildings since 2013
Kuwait	In 2005	Environment Public Authority	Kuwait Vision 2035	KISR Energy Efficiency Technology Program	- Improve EE of power stations by 5% - Reduce energy consumption in existing buildings by 10% - Reduce energy consumption in new buildings by 30%	No information	Adopted	> 100 years	Mandatory Energy Conservation Code of Practice for Buildings No R-6, (2014)	Adopted in 1983 by the Ministry of Electricity and Water, revised in 2014, includes voluntary provisions
Qatar	In 2005	National Climate Change Committee, Qatar (2007)	Qatar National Development Strategy 2011-2016 towards Qatar National Vision 2030 by the Qatar General Secretariat for Development Planning	Tarsheed campaign (KAHRAMAA, Qatar General Electricity & Water Authority)	- Reduce per capita electricity consumption by 20% and per capita water consumption by 35% over 2011 levels by 2017	*Existing buildings* Chiller maintenance Monitoring control and analysis of consumption Thermostat settings Isolation and decommissioning of chillers Balancing and recommissioning of A/C systems	Adopted in 2013, under implementation Awareness campaigns ongoing Drafted detailed plan for projects and strategies to meet targets	62.8 years	Qatar's Global Sustainability Assessment System (GSAS)	GSAS incorporated into the Qatar Construction Standards in 2012. 3 stars to be achieved by all new civic buildings from 2012, new commercial buildings from 2016 and new residential buildings from 2020.
Saudi Arabia	In 2005	Saudi Energy Efficiency Center (est. 2010) building on the former National Energy Efficiency Programme (2002)	National Energy Efficiency Program (NEEP) 2005-2030	Electricity load management and demand side management (ECRA)	- Reduce peak by 14% by 2021 - Reduce energy consumption (over projected increase) by 8% by 2021	*Existing buildings:* Replacement of old air-conditioning units; building and roof insulation; lighting replacement (CFLs) *New buildings:* Efficiency measures (high-efficiency A/C units and insulation). Public sector: Improved motor efficiency; street-lighting replacement *Load management and demand reduction programmes:* Time-of-use tariff, Direct load control, Interruptible tariffs, Curtailable load management	Adopted Piloting completed on LM/DR measures. Proposal for full package of measures submitted to Council of Ministers for approval	69.5 years	Saudi Energy Efficiency Building Code (2007)	No information
UAE/ Dubai	In 2005	Dubai Supreme Council of Energy (est. 2009)	Dubai Integrated Energy Strategy 2030	No information	No information	No information	No information	< 10 years	Dubai Green Building Regulations and Specifications	No information
UAE/ Abu Dhabi	In 2005	Abu Dhabi Demand Side Management Working Group (2008) – now the Cooling Taskforce (2012)	Abu Dhabi Economic Vision 2030	Comprehensive Cooling Plan (Cooling Taskforce, Executive Affairs Committee)	- Reduce electricity demand by 15% of 2010 demand by 2020 (4,500 GWh/yr out of a total demand [excluding ADNOC])	*Existing buildings* Chiller maintenanceMonitoring control and analysis of consumption Thermostat settingsIsolation and decommissioning of chillers Balancing and recommissioning of A/C systems	Approved and at stage of refinement with further surveys planned to map user behaviour, buildings' current energy use and pilots to test savings	91.9 years	Abu Dhabi's Pearl Rating System, part of Estidama programme	All government buildings must comply with '2 Pearl' standard. Since 2010, all new buildings must comply.

Nevertheless, even though GCC countries have adopted a more pro-active approach toward environmental issues reflecting their governments growing concern about domestic energy consumption, these scattered conservation efforts have been largely ineffective due to factors such as bureaucracy and governance challenges, lack of awareness and information, lack of market incentives and unpredictable political support (Obaid and Mufti, 2008; Reiche, 2010). Moreover, "*a central challenge is that authority over the energy sector in all GCC member states is fragmented. The responsibility and the capacity to act effectively within the sector are scattered between different ministries and regional authorities*" (Lahn et al., 2013, p.vi). In addition to the political challenge of curtailing subsidised energy prices this also hinders investment in renewable energy since solar and wind power plants would not be commercially viable under the current low pricing system (Lahn and Stevens, 2011). Another major problem is enforcement of regulations such as appliance and building standards. For example, the Saudi building code has mandated thermal insulation against heat for all new buildings since 2010 as this has been proven to reduce energy demand in villas by 30–40%. However, new buildings continue to be erected without proper insulation (Lahn et al., 2013).

Despite the challenges facing the formulation of energy policy plans in the GCC countries, there is rich potential for collaboration over the best ways to introduce new sources of energy and technology into the region, especially given the common aspirations and shared climate, energy and market conditions, employment challenges and the rapid urban and industrial development expected in all countries over the next decade. According to Lahn et al. (2013), improving building efficiency is the one area where GCC countries have agreed to introduce a cooperative plan and are making progress on establishing common building standards which recognises the region's climate and socio-cultural factors. Pilot studies and practice have shown that adapting the built environment and building codes to work with rather than against the Gulf Region's harsh climate provide some of the largest proven savings to date, with up to 60% reductions in energy demand as a result of changes to existing buildings and 70% in new buildings, against the existing average. If these common building standards were incorporated into the national legislation in each country, "*this would create a substantial market for energy-efficient building materials, bringing down the cost of imports and potentially encouraging some local manufacture over time. Bulk buying would become possible. It could also open the door to tighter collaboration on training and* *effective regulation practices, as well as presenting opportunities for economies of scale in research and development*" (Lahn et al., 2013, p.25). However, for this to be possible it is essential to have collaboration between ministries, municipal governments and electricity authorities in order to strengthen the potential for enforcement of such building standards.

Al-Ajlan et al. (2006) have identified three high priority demand-side programmes for energy conservation; (1) load management, (2) air conditioning and (3) energy efficient buildings. Load management is concerned with the time-of-use tariff, monitoring and evaluation, system planning integration and enforcement. Air conditioning focuses on systems efficiency, operation and maintenance, training and programme acceleration. Finally, the energy and building efficiency programme includes characterisation, simulation and thermal insulation, design and building codes and standards. It is the latter with which this research is most concerned .

Based on the above arguments, the focus of this research is Saudi Arabia, given that it is the largest country in the Gulf Region in terms of land mass, population (26 out of the 39 million people in the GCC live in Saudi Arabia) and energy reserves (it sits atop 19% of the world's proven oil reserves) (Alnaser and Alnaser, 2011; Hvidt, 2013,). Also, the current construction boom, either in the proposed economic cities or as part of the new legislation towards developing affordable housing schemes across the country, poses huge global ecological and environmental challenges (Construct Arabia, 2012).

The city of Jeddah in particular is witnessing an active construction movement, especially with the emergence of the first kilometre-plus-high structure in the world, Jeddah Tower. Jeddah plays an important role in the Saudi economy as the second largest city in the Kingdom with around 80% of imports entering the country through the city. Jeddah also functions as the gateway to the two holy cities, Makkah and Medina, with visitors arriving by both sea and air (Al-Otaibi, 2004). Therefore, Jeddah was chosen as the main location for the work undertaken here, for ease of access and availability of information, in addition to the growing interest in tall building design reflected in recent regulations at the municipal level, notably *The Guidelines for Tall Buildings Specifications and Technical Requirements for Jeddah* which will be discussed in Chapter 3. The city of Dubai in the UAE was also investigated for comparative purposes in terms of building codes and regulations since it is the only city in the Gulf Region with established Green Building Regulations, in addition to having the largest number of tall buildings in the Gulf Region including the current tallest tower in the world, Burj Khalifa. Thus, it will be possible to draw lessons from existing buildings analysis or perhaps 'borrow' regulations and buildings codes (where applicable) for building design in Jeddah.

Finally, exploring the economic and energy context of the GCC countries has established that the built environment, especially residential buildings, is the largest contributor to the high levels of energy consumption and CO_2 emissions in the Gulf Region. In addition, the current building regulations are still immature in terms of energy efficiency and environmental consideration. Therefore, it is vital to improve the energy and environmental performance of buildings in order to promote sustainable development in the Gulf Region, and the investigation of the climatic conditions is important for any effort to achieve this, both in terms of energy consumption and the potential for renewable energy (Alrasheda and Asifa, 2015). Therefore, the following section explores the climatic conditions in the Gulf Region.

1.1.2 The Climatic Conditions in the Gulf Region

According to the Koeppen-Geiger Climate Classification (Wikipedia, 2017), the countries of the Gulf Region are classified as a single climatic zone known as 'arid desert hot climate' (BWh) (Figure 1-6). Geographically, they are located in the hyper-arid climate within the world desert belt with an aridity index (average annual precipitation/potential evapotranspiration [P/PET]) of less than 0.3 (Meir et al., 2012). The main cities in the region are located in the hot dry zones between 15° and 30° north of the equator, including Abu Dhabi (24° 28´N, 54° 22´E), Doha (25° 18´N, 51° 31´E), and Jeddah (21° 29´N, 39° 12´E). The main characteristic of the hot dry zones is strong, direct solar radiation with an absence of cloud cover and clear skies. The abundant sunshine and intense solar radiation causes strong surface heating, leading to air temperatures of up to 50°C. The average relative humidity ranges between 30% and 40% but maritime areas experience higher relative humidity levels of up to 90%. The vegetation cover is sparse and the ground is dry and barren resulting in high winds at low levels (Koch-Nielsen, 2007). As for Saudi Arabia, Said et al. (2003, cited in Alrasheda and Asifa, 2015), have classified the country into six climatic zones; given the fact that the Empty Quarter is an uninhabited region, the other regions are represented by five main cities: Dhahran, Guriat, Riyadh, Jeddah and Khamis Mushait. These climatic zones and their representative cities are shown in Figure 1-7.

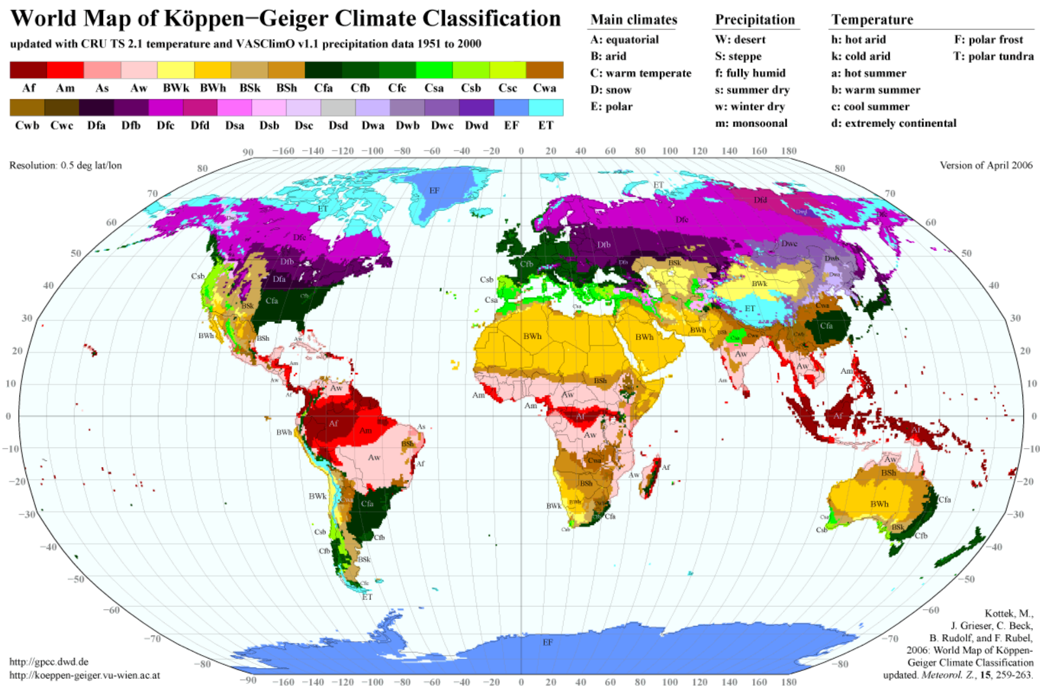

Figure 1-6 World Map of Koppen-Geiger Climate Classification. Note the location of the Arabian Peninsula and the Gulf Region within the yellow classification of BWh (arid desert hot climate). (Source: Institute for Veterinary Public Health, 2017)

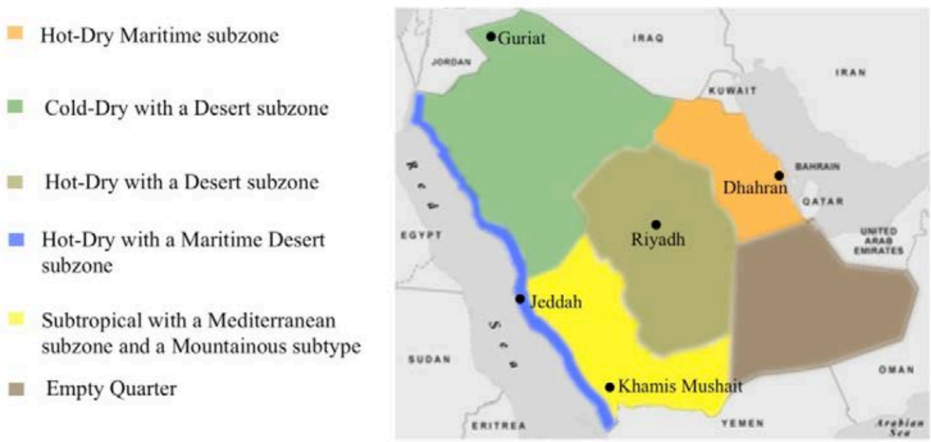

Figure 1-7 The climatic zones in Saudi Arabia based on the method devised by Said et al. (2003, cited in Alrasheda and Asifa, 2015, p. 1429)

In this section, a cross comparison was conducted between the climates of the main coastal cities in the Gulf Region, Dubai and Abu Dhabi in the UAE, Doha in Qatar and Kuwait City in Kuwait; these were then compared with the climate in Jeddah, which is located on the coast of the Red Sea in the west of Saudi Arabia. Interpreting the hourly data weather files from Energy Plus, the monthly average dry bulb temperature, relative humidity and wind speed were compared. This comparison was done in order to explore the possible varieties and similarities in the various climatic conditions that impact buildings and occupant comfort throughout the Gulf Region.

Since the climate in the Gulf Region is predominantly hot due to its geographical location, the main climate elements that affect the heat discomfort[1] were compared: air temperature (Figure 1-8) and relative humidity (%) (Figure 1-9). Looking at Jeddah and Dubai, the average monthly air temperature is similar in both cities, with a maximum difference of only 3℃ in the winter with Dubai having a milder winter than Jeddah. The seasonally diurnal temperature in Jeddah is narrower than in the other cities, while Kuwait is characterised by a dry desert climate with cold winters and hot summers and an annual relative humidity below 40%. On the other hand, the annual relative humidity in the other cities ranges between 55-61%. The relative humidity is generally higher at the end of the summer (late August to early October) when the sea temperature reaches its maximum and the relative humidity can reach up to 90% (Najib, 1987 cited in Al-Lyaly, 1990). In conclusion, it is clear that the coastal cities of the Gulf region, apart from Kuwait City, share similar climate characteristics (high air temperature and high relative humidity) which makes the cities of Jeddah and Dubai comparable in terms of design strategies based on the climatic conditions (see 1-10). Thus, the following climatic analysis will cover these two cities (Figure 1-10), including a review of the main climatic characteristics that affect the design parameters in the building codes and regulations in the region.

The analysis of Jeddah's climate was undertaken in a previous study by the author (Ghabra, 2012) using the monthly and daily climate data for the period between 1970 and 2011 (excluding 1980 and 1984 where some data was missing) obtained from the Jeddah Regional Climate Centre in the Presidency of Meteorology and Environment, in addition to the hourly data for one year (2005) from EnergyPlus. Additionally, the table of Climatic Design Conditions from Chapter 14 in the *2013 ASHRAE Handbook - Fundamentals* was used. As for

[1] According to Givoni (1998), 'Heat Discomfort' involves sensible heat and sensible perspiration, which are affected differently by the temperature, humidity, and air speed.

the climatic analysis of Dubai, it was conducted through literature review (Al Zahed, 2007; Bilow, 2012), in addition to analysis of the hourly data for one year (2005) from EnergyPlus.

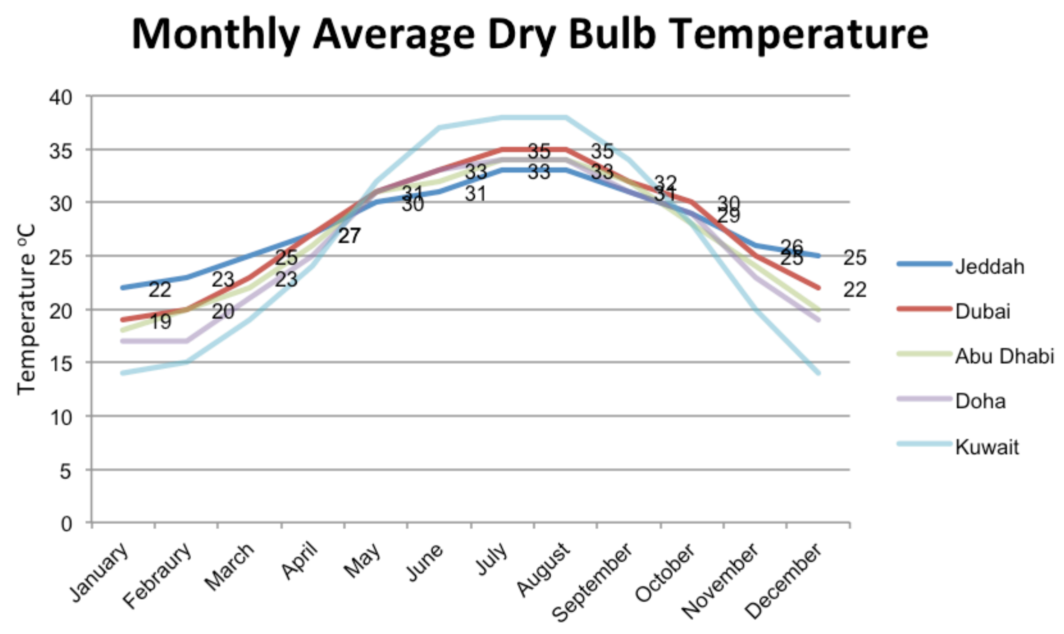

Figure 1-8 Monthly Average Dry Bulb Temperature in the main cities in the Gulf Region. Note the similarities between Dubai, Abu Dhabi, Doha and Jeddah

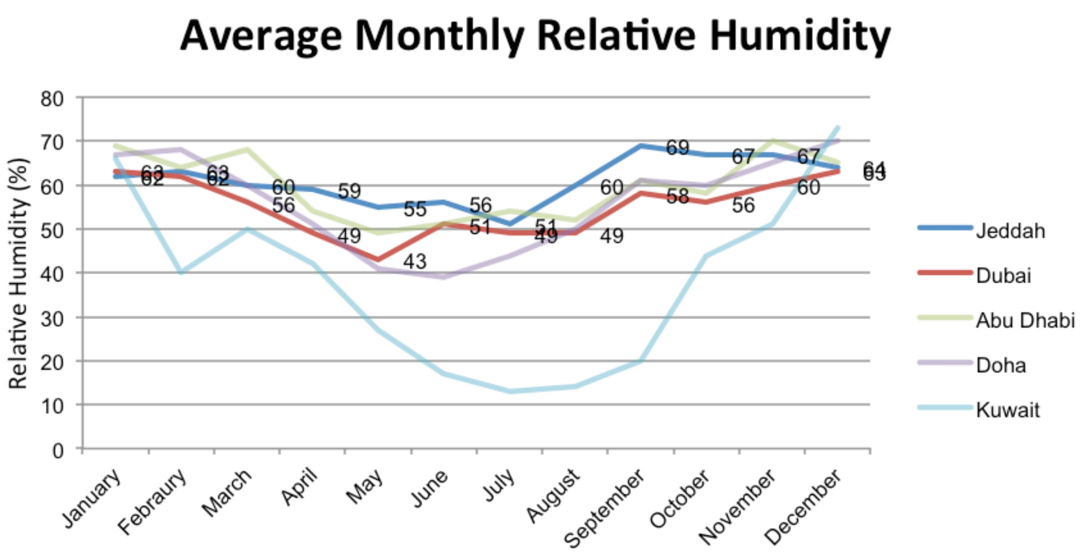

Figure 1-9 Average Monthly Relative Humidity in the main cities in the Gulf Region

Figure 1-10 The location of Jeddah in Saudi Arabia and Dubai in the UAE (indicated by red arrows)

a. Temperature and Humidity

Jeddah is located on the western coast of Saudi Arabia at 21°29' north and 39°12' east. It is situated on the narrow Tihama coastal plain bounded to the east by mountains and foothills (Talib, 1984; Al-Lyaly, 1990). Geographically, the area is relatively flat with no significant topographic relief and very sparse vegetation.

In relation to air temperature, Figure 1-11 shows the monthly diurnal average in Jeddah, where the mean maximum dry bulb temperature in the summer months of July and August reaches 38°C and the mean minimum temperature is between 24℃ and 27℃, with a narrow diurnal difference of up to 14°C. The winter is mild and January is the coldest month, with a mean minimum temperature of 18℃. Generally, the annual average temperature is 28℃ which shows that the climate is predominantly hot. Hence minimising heat gains and maximising heat loss is a prime consideration especially in the warmer seasons.

Jeddah suffers from high relative humidity most days of the year with an annual average relative humidity of 61%. The lowest it gets is in the early summer months of June and July when the mean minimum relative humidity falls below 40%, but as shown in Figure 1-9, the relative humidity increases between August and October and, coupled with the high air temperature, it can become very uncomfortable. According to Figure 1-12, which illustrates the diurnal difference in the daily average relative humidity by comparison with the dry bulb temperature, relative humidity is lowest in the afternoon and early evening (between 14:00 and 16:00) during all months. Nevertheless, sea breezes bring in moist air at noontime which increases humidity levels, as will be discussed below. The chart in Table 1-2 shows the interdependencies of dry bulb temperature and dew point temperature, the relatively narrow difference decreases toward the end of the summer, indicated higher humidity in the air as previously stated.

As for Dubai, it is located at 25° 15’ north 55° 18’ east on the northeast of the United Arab Emirates where Dubai Creek meets the Gulf. According to Al Zahed (2007), the winter months (December to February) are cool to warm with an average maximum of 22℃, although the temperature can reach up to 30℃. The summer months (June to September) are warm and humid with an average maximum of around 42℃. As in Jeddah, the annual average temperature is around 28℃ while the humidity varies seasonally from about 40% in winter to approximately 70% in summer. Bilow (2012) comments that due to the high temperature, the climate of cities like Dubai and Abu Dhabi is classified as a desert climate; however, the values for air humidity are significantly higher than those of Singapore which is classified as a tropical climate. The annual average relative humidity in Dubai is 55%, and as Figure 1-8 suggests, Jeddah experiences slightly higher relative humidity levels than Dubai. This is also supported by the larger difference between the dry bulb temperature and dew point temperature shown in the chart in Table 1-2.

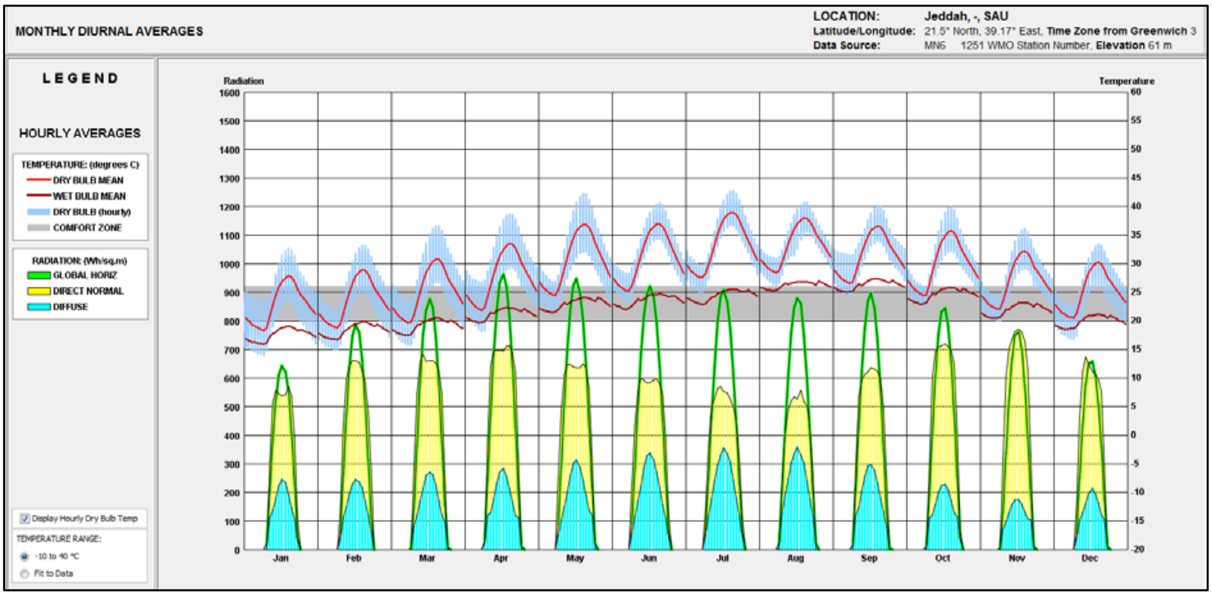

Figure 1-11 Monthly diurnal average in Jeddah, Saudi Arabia (Plotted using Climate Consultant 5.4)

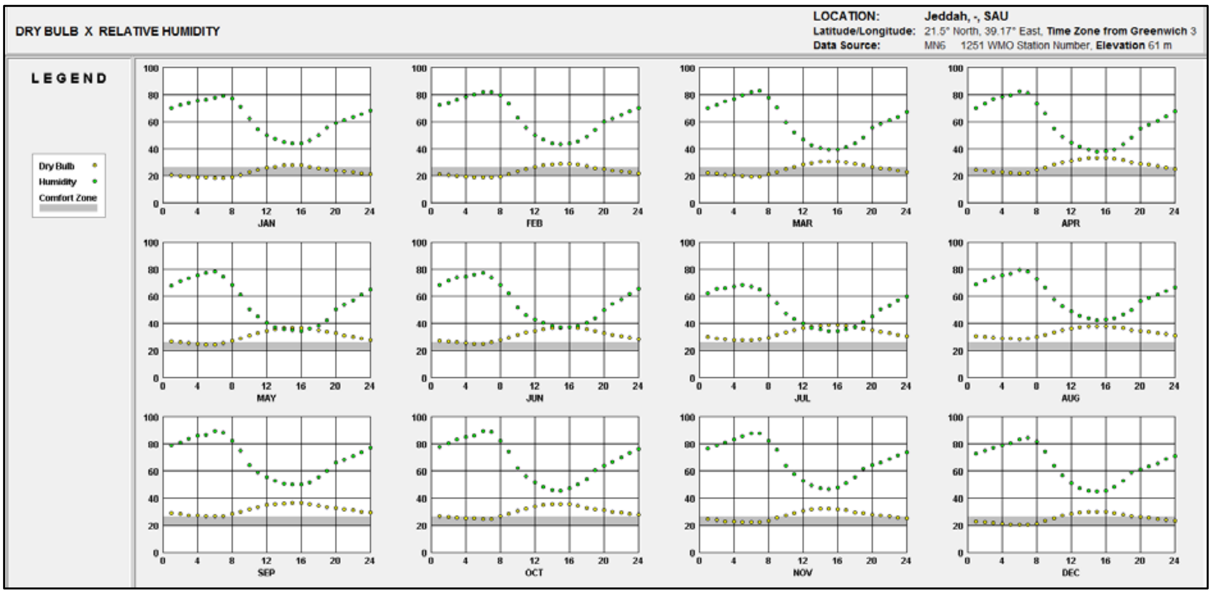

Figure 1-12 Graph to compare average diurnal dry bulb temperature and relative humidity (Plotted using Climate Consultant 5.4)

b. Prevailing Wind and Sea Breeze

As illustrated in the wind rose diagram in Table 1-2, the prevailing winds in Jeddah blow from the north-northwest (330°- 360°) and are mostly light to moderate throughout the year. Additionally, "*Southerly winds which sometimes occur at any time of the year are usually accompanied by rises in temperature and humidity. Sometimes they blow up suddenly causing sand and dust storms; and they are occasionally accompanied by thunderstorms and* *rainfall. Eastern winds which blow during June are accompanied by the "samum" which develops into sand and dust storms. The visibility on some days is less than one kilometre, but these unusual conditions do not exceed seven days a year*" (Najib, 1987, cited in Al-Lyaly, 1990, p.12). However, more recent weather data for Jeddah from the National Metrology and Environment Centre states that blowing sand occurred for only 40 days in the last 41 years (from 1970 to 2011), which is an average of less than a day in a year. This indicates that dust storms are relatively unusual in Jeddah.

Clearly, the prevailing north and north-west winds are considered most desirable for passive natural ventilation and cooling effect in the hot humid climate of Jeddah. The wind speed in Jeddah is above 2 m/sec for more than 57% of the year (5010 hrs). However, the maximum value of over 6.0 m/sec occurs in March, and then the range decreases slowly until October and November when the mean wind velocity falls below 2 m/sec (Al-Lyaly, 1990). Thus, the wind speed in Jeddah is generally sufficient to supply air flow, especially for night time ventilation, but not in the warmer seasons when it is most needed.

Moreover, as a coastal city, Jeddah experiences diurnal wind changes referred to as land and sea breezes which influence the magnitude of the diurnal range of air temperature and the humidity conditions: "*At night, breezes from landward tend to be dry, but lower temperature raises the relative humidity. By day, higher temperatures lower the relative humidity but sea breezes bring in moist air and have the opposite effect*" (Edwards, 1987, cited in Al-Lyaly, 1990, p.86). This may increase the discomfort levels due to higher levels of relative humidity.

As for Dubai, the wind rose in Table 1-2 shows that the prevailing winds with a frequency of occurrence of up to 700 hours are those from the northwest of up to 3 m/s (Bilow, 2012). Other winds come from the south, from the mainland, northeast and easterly direction, which blows over the water and is cooler (below 25℃) but significantly less frequent (400 hours), affecting the efficiency of the wind to provide sufficient air movement for passive cooling.

c. Solar Path and Radiation

Due to Jeddah’s latitude, the sun-path diagram (Table 1-2) illustrates that for almost half of the year (April to September), the sun could appear in the northern part of the sky dome (shown in orange). Furthermore, since the annual average sky cover in Jeddah is around 2 oktas[2] indicating a clear and cloudless sky throughout the year, in addition to the high solar altitude all year around, abundant solar radiation causes surface heating and raises the air temperature. Therefore, it is necessary to quantify the amount of global solar radiation received.

As can be seen from the second column in Table 1-2, the maximum global radiation values are recorded during the months from March to October and can peak at 655 Wh/m^2. The lowest global solar radiation falling on a horizontal plane is that occurring in December and January, and the yearly average value is 588 Wh/m^2. The chart also illustrates the relationship between the global solar radiation and air temperature in Jeddah. The comparison with the temperature curve suggests hazy summer seasons because the radiation lies below the temperature (Bilow, 2012).

Al-Lyaly (1990, p.92) explains the diurnal variation for the total solar radiation for Jeddah: "*intensity increases generally rapidly in the morning after sunrise under the clear morning skies and declines more gradually during the afternoon. Maximum solar radiation is experienced between 11:00 a.m. and 12:00 p.m. in all months. The maximum air temperature occurs some two to three hours after the time of maximum radiation*", due to the increased surfaces temperature as mentioned above.

The next section analyses the climate in Dubai and compares it to Jeddah's in order to draw meaningful conclusions to inform the environmental design strategies in this climate.

As in Jeddah, the sun-path diagram of Dubai in Table 1-2 shows that for part of the year, especially in the summer months from May to August, the sun appears in the north. As for the solar radiation, the chart in Table 1-2 displays the average annual global solar radiation in Dubai with the highest values between April and August when it can reach up to 617 Wh/m^2. The early average value of global radiation is 525 Wh/m^2, slightly less than in Jeddah. Again, the comparison with temperature curves indicates hazy summer and autumn seasons (Bilow, 2012), which is worse than in Jeddah.

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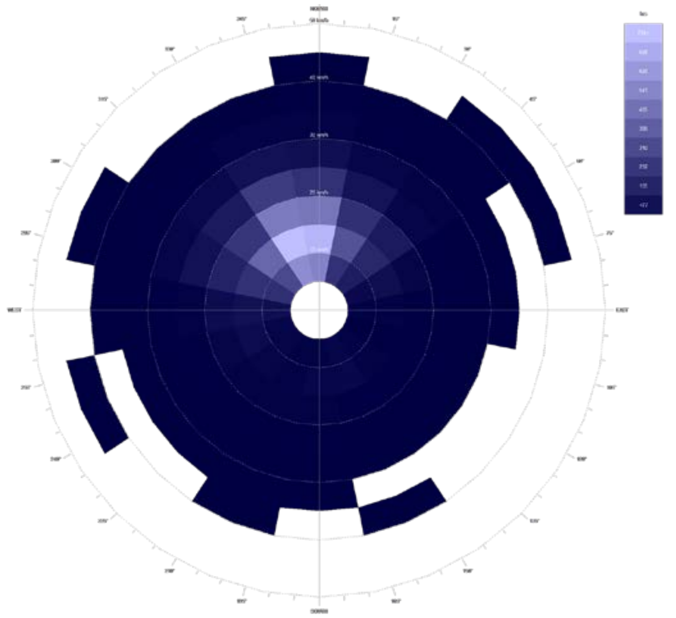
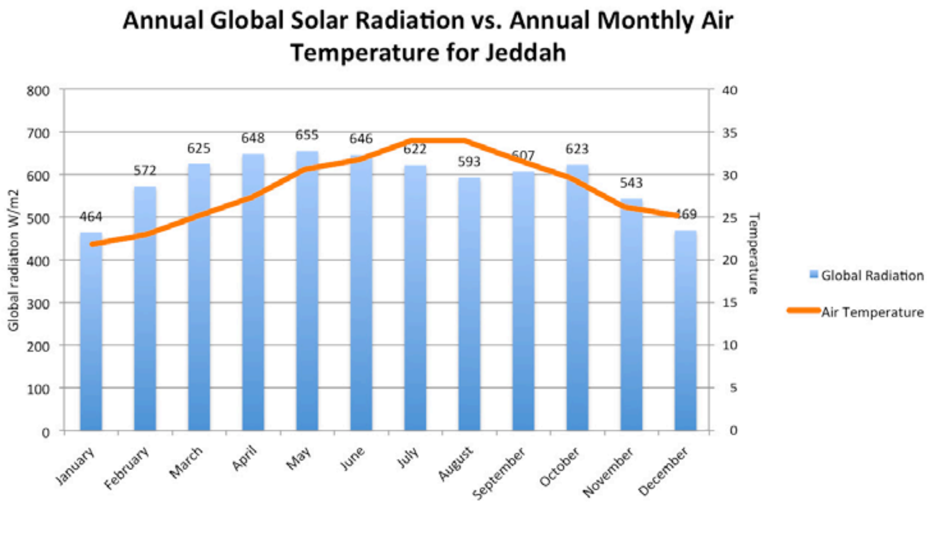
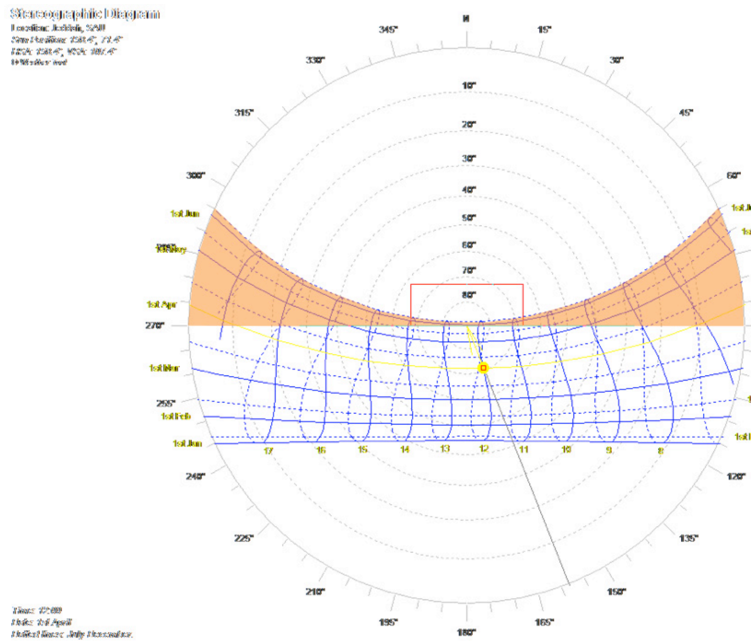
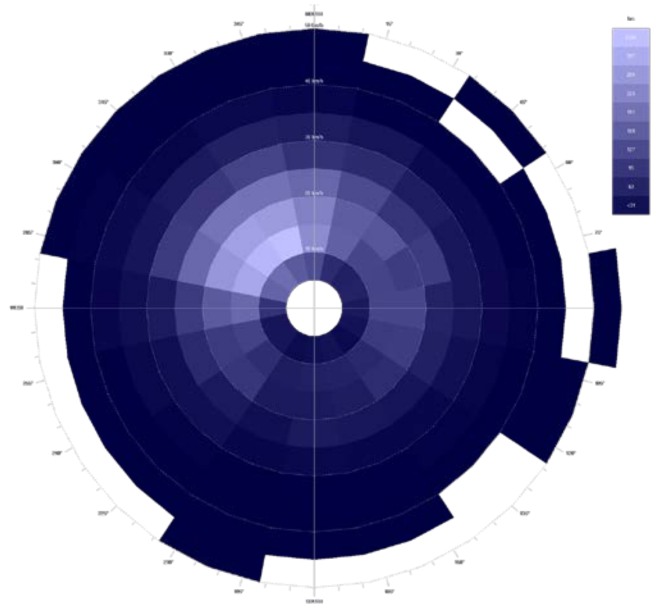
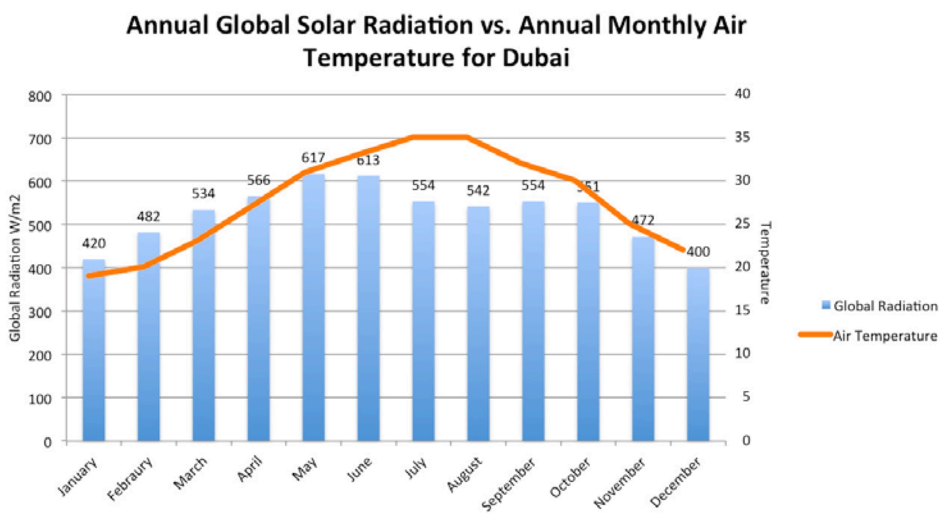
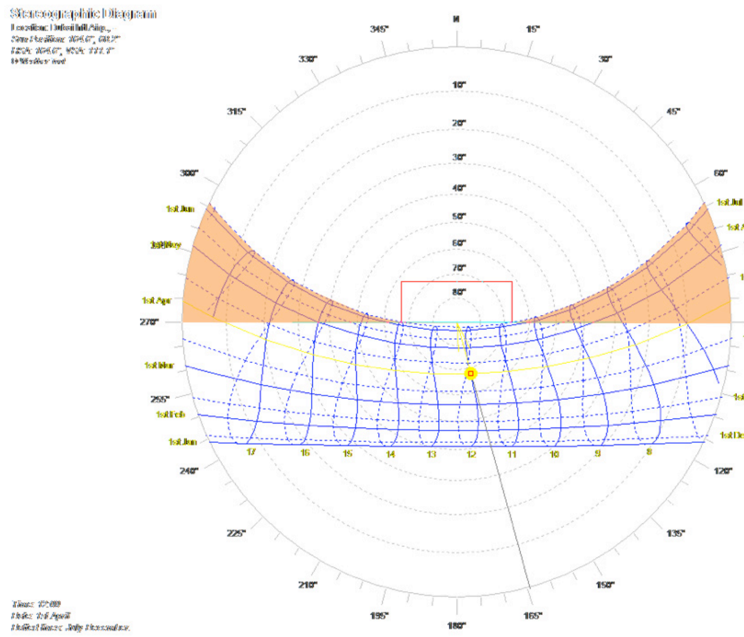
[2] Okta is a unit of measurement used to describe the amount of cloud cover at any given location such as a weather station.

According to Al-Hosany (2002), the long periods of intense solar radiation in the UAE result in high mean radiant temperatures that contribute indirectly to heating both the air and the constructed mass of buildings, even if the air temperature is not particularly high. As this leads to much worse indoor environmental conditions, decreasing the intrusion of solar radiation should be a priority in building design.

Table 1-2 Climate Data for Jeddah in Saudi Arabia and Dubai in the UAE. (Source: plotted by Weather Tool 2011)

<table>
<tr><th>City Location</th><th>Prevailing wind frequency</th><th>Annual Global Solar Radiation and Air Temperature</th><th>Sun Path Diagram</th></tr>
<tr><td>Jeddah
21°29′ N
39°12′ E</td><td></td><td>
</td><td></td></tr>
<tr><td>Dubai
25° 15′ N
55° 18′E</td><td></td><td>
</td><td></td></tr>
</table>

d. Psychrometric Chart

Previous analysis of the hourly weather data by the author (Ghabra, 2012) reveals that the dry bulb temperature in Jeddah falls within the comfort range of 18-27℃ for more than 46% of the year (4043 hrs), especially in the winter and early spring. This is also supported by Al-Lyaly's (1990) analysis of the comfort zone in Jeddah based on Evans' observations about comfort temperature ranges (1980, cited in Al-Lyaly, 1990, p.94) which are as follows: "*it is interesting to note that in Jeddah approximately 34% of the year falls within the comfort zone and 20% is in the modified comfort zone*". However, according to the *ASHRAE Handbook of Fundamentals Comfort Model* (2005), the ambient air temperature in Jeddah falls within the comfort range (20-26.1°C)[3] for only 16.1% of the year (1409hrs), as shown in the psychrometric chart in Figure 1-13. Nevertheless, passive cooling using natural ventilation can bring the comfortable hours up to 34%. The case in Dubai is somewhat better as 21.7% of the year (1905hrs) falls within the ASHRAE comfort model due to the lower winter and autumn temperatures (Figure 1-14). Obviously, the use of mechanical ventilation and cooling through air conditioning systems increases the comfortable hours up to the maximum 100%.

There are some concerns regarding the application of ASHRAE comfort standards regarding humidity and air speed limits in hot-humid locations such as Dubai and Jeddah. Givoni (1998, p.35) argues that "*the narrow temperature range specified in the ASHRAE Handbook suggests the need for cooling in situations where natural ventilation may provide acceptable indoor conditions*", which "*can cause a waste of energy by heating or cooling buildings to temperatures and humidity levels not justified by the actual comfort needs of the local population*".

Following these lines, Al-Hosany (2002) questions the influence of the occupants' background cultures on the comfort zone based on Humphreys' (1996, cited in Al-Hosany, 2002, p.26) studies of adaptive approaches to thermal comfort that show how different cultures shift the comfort zones in relation to the outdoor temperature. She argues that

[3] For people dressed in normal winter clothes, the Effective Temperatures are (20-23.3°C) measured at 50% relative humidity. If people are dressed in lightweight summer clothes, this comfort zone shifts to become 2.8°C warmer.

though a slight shift in the comfort environment can have major energy implications in the working environment in the UAE, it is still very difficult to formulate an absolute definition of thermal comfort, especially in the affluent societies of the Gulf Region.

Givoni (1998, p.36) supports this idea by stating "*it is basically impossible to have 'universal' comfort indices and standards. Countries, or even regions with different climates within a given country, may have to develop comfort indices and standards taking into account specifically the acclimatization of the population, as well as its standard of living and experience*".

In conclusion, the above analysis of the climatic conditions in both Jeddah and in Dubai shows comparable similarities and highlights the extent of environmental stress in the 'hot-dry maritime desert climate' they are classified as. This is considered one of the must unfavourable climates on earth (Koenigsberger et al., 1974, cited in Al-Hosany, 2002).

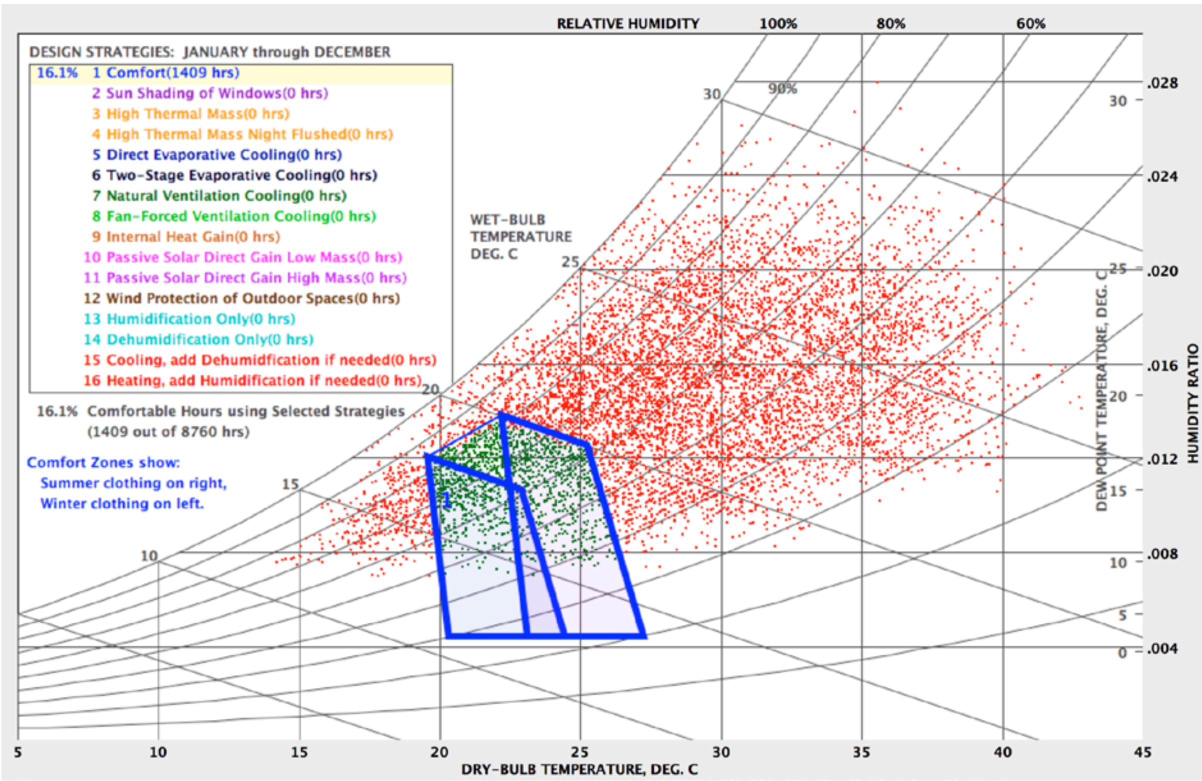


Figure 1-13 Psychrometric Chart for Jeddah. According to the ASHRAE 2005 Comfort Model, only 16.1% of the year falls within the comfort zone (Plotted using Climatic Consultant 5.4)

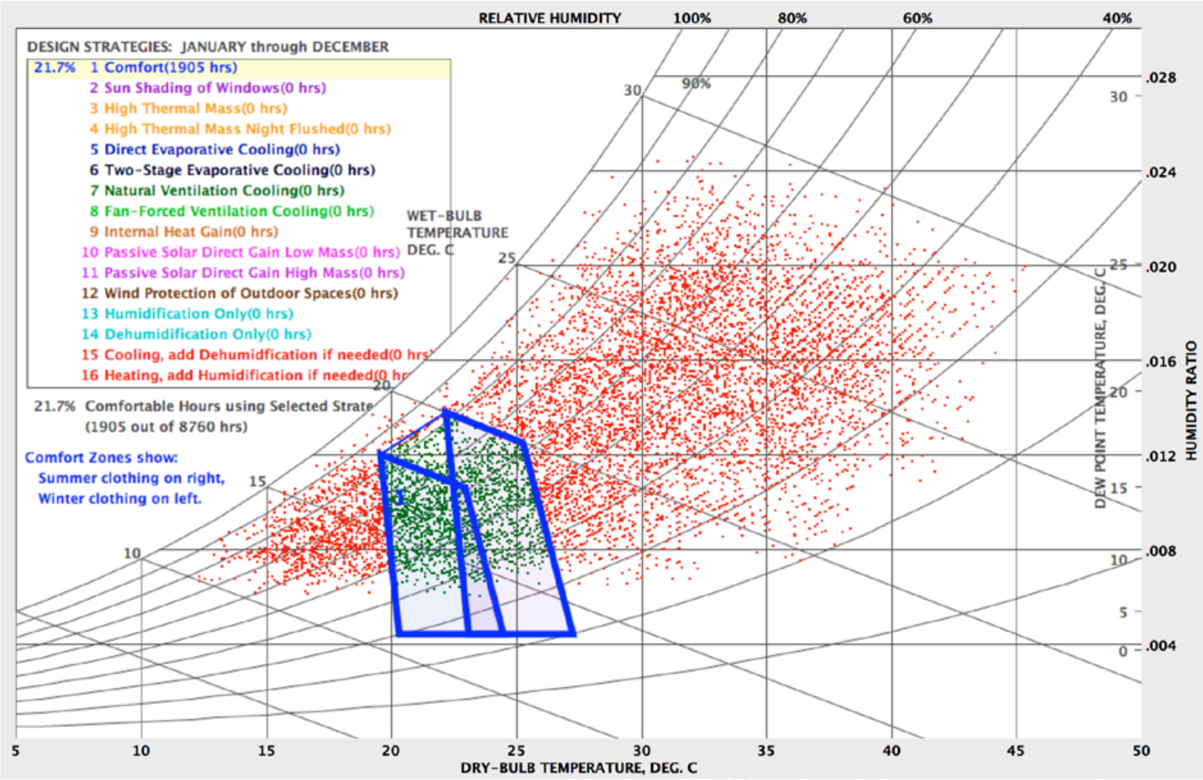


Figure 1-14 Psychrometric Chart for Dubai. According to ASHRAE 2005 Comfort Model, 21.7% of the year falls within the comfort zone (Plotted using Climatic Consultant 5.4)

1.2 Housing and Tall Buildings in the Gulf Region

As discussed in Section 1.1, although the vast oil and fossil fuel reserves in the GCC countries resulted in rapid economic growth, it is the desire to move away from oil that has driven the recent unprecedented boom in real estate development (Hammoud, 2016). Moreover, urban population growth and the concentration of economic, industrial and administrative activities have increasingly attracted large domestic and foreign populations (Al-Shihri, 2016). As a result, the construction sector in the GCC countries has been booming, with up to five million residential units under construction, making it among the biggest and fastest growing construction markets in the world (Abdelsalam and Gad, 2009). In 2011, around 30% of the completed tall buildings above 200 metres in height were in the Gulf Region, with four ‘Supertall’ buildings (300+ meters) out of ten in the same region, particularly in the UAE, Qatar and Saudi Arabia (CTBUH, 2012).

In Saudi Arabia, the number of people in urban areas has been growing at the rate of about 6% annually, compared with the average national population growth rate of 2.6%. In order to cater for the growing population of 30.77 million people (citizens and foreign residents), large-scale housing and residential projects are being planned and implemented in major cities such as Jeddah (Al-Shihri, 2016). The residential sector is expected to experience a significant growth in future with estimates suggesting that in order to meet the needs of the growing population, the country has to build 2.32 million new homes by 2020 (Alrashed and Asif, 2015). In the following sections, housing in Saudi Arabia in general and Jeddah in particular is considered along with the tall buildings trend in the Gulf Region.

1.2.1 Housing in Saudi Arabia

Amongst the GCC countries, Saudi Arabia has the largest real estate market with a very young demographic profile (around 45% of the population is below age 20 years) and a rapid urbanisation rate which creates huge pressure on housing demand. The residential sector is characterised by a major housing shortage that will require enormous investment to add at least 1 million units in the coming years (Opoku and Abdul-Muhmin, 2010).

The increase in crude oil revenues in the 1970s created a boom in the national economy which brought a sharp rise in national and household income (Bahammam, 1998). Since that time, the provision of decent and safe housing to Saudi citizens has been a national objective included in all Five-Year National Development Plans with housing programmes grouped into two: the Public Housing Sector and the Private Housing Sector. During the earlier plans, there were remarkable achievements in housing allocation. For example, a specialised financial institution called The Real Estate Development Fund (REDF) was set up to extend interest-free credit to individuals (Al-Otaibi, 2004), giving thousands of families the opportunity to own their own houses for the first time (Bahammam, 1998), and a total of 889,000 housing units were constructed during the last four plan periods, against the target of 880,000 (Al-Otaibi, 2004). By the end of the 1980s this housing surplus constituted a basic housing stock that could accommodate as much as 47% of the national population and 64% of the total urban population (Al-Hathloul and Edadan, 1992, cited in Al-Otaibi, 2004).

However, in the mid-1980s, governmental funding for the REDF fell from more than 600 million to 200 million Saudi Riyal, due to a drop in oil prices. A second drop at the beginning of the 1990s due to the Gulf War resulting in a further shortage of funding affected the housing construction industry leading to a significant reduction in the housing supply in

Saudi Arabia. As a result, in the 1990s the country created a strategy of housing stock management through rationalising public and private sector participation in the housing market (Al-Hatloul and Edadan, 1992, cited in Al-Otaibi, 2004). Since the government joined the World Trade Organization (WTO) in 2006, many economic reform measures, laws and regulations have restructured the national economy, including the approval of a number of mega development projects. These positive developments acted as an incentive for investment, especially in the housing sector (Al-Sayari, 2007). However, although the Saudi housing market has witnessed strong growth during the past years, housing costs are rising in most cities, and doing so significantly faster than incomes, which are not as healthy as they were during the oil boom years of the 1970s or the years immediately thereafter (Salama & Alshuwaikhat, 2006, cited in (Opoku and Abdul-Muhmin, 2010).

Moreover, the rapid growth in the size of the Saudi population occurred mostly in urban areas such as Jeddah, which plays an important role in the Saudi Arabian economy as the second largest city in the country. The urban population in Jeddah grew rapidly from 1970 to 2002 to an estimated population of 2,560,000 with average annual growth rates of 12.43% in 1970 and 11.05% in 2000. New employment opportunities encouraged migration from rural area resulting in a rapid expansion of the city, and it was during this period that the national and regional role of Jeddah was established and decisions and ideas implemented that governed and shaped the urban growth of the modern city (Al-Otaibi, 2004). However, Jeddah, like other cities has experienced a shortage of housing and continued increases in housing prices. The difference between the expected growth in population and the supply of housing stock over the next few years (Figure 1-15) indicates a growing gap between demand and supply with an estimation that up to 78,000 extra housing units will be needed within the next few years (Al-Otaibi, 2004).

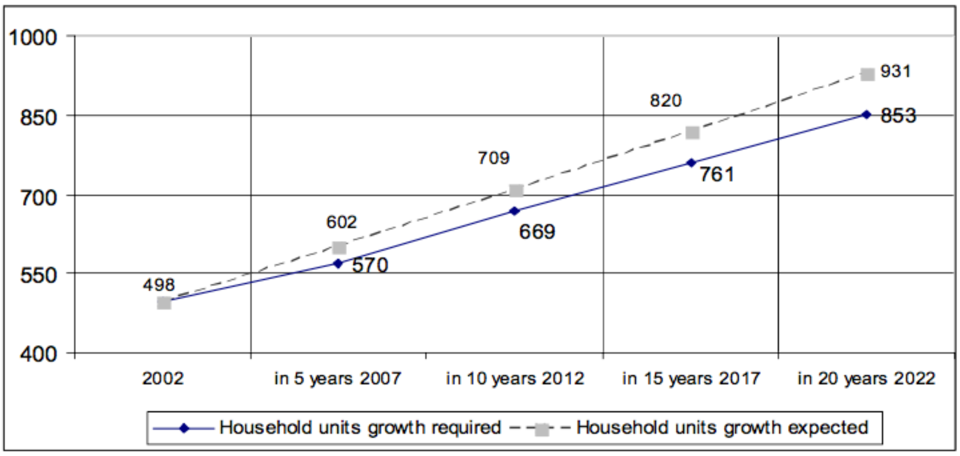


Figure 1-15 Expected household units growth (reflecting population growth) and household growth required (reflecting the number of homes expected to be built) forecast from 2002-2022 (Source: Alneeah Consultancy, Municipality of Jeddah, 2002, cited in Al-Otaibi, 2004, p.6)

1.2.2 Housing Types in Jeddah

Housing preferences are driven by demographic factors, such as movement through the life cycle, in addition to location, neighbourhood characteristics, and most importantly, earning capacity and incomes. Households are also constrained in their housing choices by the supply of housing available in the market (Al-Otaibi, 2004).

The housing industry in Saudi Arabia and in Jeddah in particular has experienced major changes since the mid-1950s with the introduction of the gridiron street pattern and the flats or apartments and detached villa-type dwellings (Bahammam, 1998). This drastic change in the physical environment was influenced by modern urbanization in the USA and in Europe (Eben Saleh, 2002). Changes in housing design and the employment of foreign architects have also lead to the introduction of new types of housing units, as have the municipal building regulations and the conditions imposed by the Real Estate Development Fund (REDF) which provides long-term interest-free loans to Saudi citizens who build their own homes (Bahammam, 1998, Al-Otaibi, 2004). According to Al-Hathloul (1981, cited in Bahammam, 1998), whereas the traditional dwelling was built incrementally according to the immediate needs of the family, the contemporary villa-type dwelling is built as the final product of a new design concept governed by municipal rules and regulations which seldom considers cultural and climatic requirements (Eben Saleh, 2002), and brings with it new styles of furniture and major changes in construction techniques and building materials.

The housing market in Jeddah is characterized by different types of housing: detached villas, semi-detached villas and flats, which represent the majority of housing in the city. The villa-type dwelling has emerged as a result of the imposition of set-back planning regulations creating an island building design which meets concerns for access, ventilation and fire spread. It became the main form of new housing occupied by the average Saudi family, individually designed and constructed as a two-storey detached dwelling, walled and set in the middle of an individual lot with yards on the four sides within a subdivision laid out on a variation of gridiron plans (Bahammam, 1998, Eben Saleh, 2002). The contemporary villa-type dwelling usually consists of separate men’s and women’s reception and dining rooms, one or two living rooms, three or more bedrooms and bathrooms, one or two kitchens, and several storage areas. Some villas also have first floor balconies and dressing rooms (Bahammam, 1998).

Another type is the compound, which was first introduced by oil companies in the Eastern province of Saudi Arabia. These compounds vary from a small cluster of dwellings to the size of a small town containing all the amenities required for everyday life. Although compounds are mainly occupied by government employees or expatriate workers, new compounds are now being constructed for Saudi occupation (Eben Saleh, 2002).

The changes in the types of houses in Jeddah since the 1970s reflect differences in household type and family size. Al-Otaibi (2004) has compared surveys conducted at different points in time from 1970 (Robert Matthew) and 1977 (Sert Jackson) to the study by Bee’ah Consultancy in 2002. According to his study, the number of villas has grown from 3,250 to 57,647 units, an increase from 4% to 12% in the market share of villas. Meanwhile the number of flats has grown from 21,300 to 335,670 units, an increase from 28% to 68% of all housing stock (Table 1-3).

Table 1-3 Housing type changes from 1970 -2001. (Source: Albeeah Consultancy, Municipality of Jeddah, 2002, cited in Al-Otaibi, 2004)

	Villas		**Flats**		**Traditional Houses**		**Others**	
	No.	**%.**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Robert Matthew 1970	3,200	4.32	21,300	28.29	38,900	51.66	11,580	15.74
Sert Jackson 1977	14,229	8.20	99,726	57.48	43,474	25.06	16,060	9.26
Bee’ah Consultancy 2002	57,647	11.63	335,670	67.72	100,275	20.23	2,082	0.42

Al-Otaibi's study reveals that the number of houses in Jeddah has increased dramatically due to the economic boom, the fast pace of the modernization process over the last three decades and the rapid urban population growth. However, as the city expands beyond its historic boundaries, extending for more than fifty kilometres along the Red Sea coast, with a population approaching four million, opportunities arise for as much as 20 million square feet (1.85 million square meters) of new residential and commercial developments (Hammoud, 2016). This increased sprawl to cater for the increased population has many implications for the sustainability of the built environment. Much recent research has recommended high residential densities to prevent urban sprawl and promote sustainable urban extension, arguing that communities operate more efficiently when residents live in denser urban surroundings (Al-Shihri, 2016). Tall buildings and skyscraper construction can play a crucial role as a high-density sprawl-reduction method to reduce energy and efficiency losses while improving sustainability. Moreover, building tall and iconic structures are a mechanism for generating value and identity, boosting recognition, and creating global 'destinations' for emerging municipalities such as the city of Jeddah (Hammoud, 2016).

This dual mentality of placemaking and sprawl-reduction has greatly influenced the design and implementation of Jeddah Tower, the 1,000-plus-metre tall building which will anchor the planned 5.3 million square metre Jeddah City development located north of Jeddah. The government is also investing heavily in the infrastructure of the area as part of the new 'economic' cities plan that aims to diversify the Saudi economy away from the oil industry, whilst the private sector is constructing new villa developments stretching northwards along the Red Sea coast (Moser et al., 2015, Hammoud, 2016). However, as mentioned earlier, this type of rapid economic growth and development has intensified energy demand in Saudi Arabia, generating an urgent need for policy makers in the country to turn their attention to designing a comprehensive energy conservation policy to minimize the effects of such massive energy consumption on environmental quality and energy export-driven revenue (Mahalik et al., 2017).

In the following section the tall buildings typology in the Gulf Region is explored further in order to establish the foundations of the work presented in the subsequent chapters.

1.2.3 Tall buildings in the Gulf Region: Historical Background

The topic of tall buildings in the Gulf Region is huge in terms of both quantity and height. Looking at the history of tall buildings in the Gulf Region, an observational analysis reveals three or four historical phases when changes to the design of the building façades were most evident. These stages are also related to periods of economic boom in the region. The earliest examples of tall buildings were constructed between the early seventies and early nineties, notably during the second oil boom which was associated with the sharp increase in prices in the 1970s. In 1979 the Dubai World Trade Centre (DWTC) was built at 184 metres high and is considered the first tall building in the region (CTBUH, 2017). However, very few other towers were built during these twenty years.

Figure 1-16 shows the towers built in the first historical phase in the Gulf Region. In this first generation of buildings, it is clear that a solid, punched window façade design was dominant, which can be considered an advantage in the hot climate of the Gulf Region. Al-Sallal (2004) has assessed (DWTC) according to the sustainable design guidelines for tall buildings derived from Ken Yeang (1999, cited in Al-Sallal, 2004), concluding that the DWTC has an appropriate façade design regarding sun shading and permeability to natural air. As shown in Figure 1-16, The National Commercial Bank in Jeddah was designed considering the inward orientation typical of Islamic traditional design. Each of the V-shaped floors is shielded from direct sun and wind, while massive openings allow light into the interior across three landscaped courtyards. "*A central wall that extends from the skylight of the first floor up through the roof allows accumulated heat to rise out of the building*" (SOM, 2017). The Islamic Development Bank was designed with minimal numbers of slits installed on the external walls in order to block the strong sunlight. "*Detailed studies and processes have been done to harmonize the building with the local climate and to achieve the integration of the Islamic design and the modern architectural techniques*" (Nikken, 2013). This indicates that the earliest tall building designs were more considerate of the climate and culture of the Gulf Region.

The second phase of tall buildings was in the second half of the 1990s and the early 2000s when the implementation of various diversification plans in the GCC countries led to mega-scale projects, especially in the UAE. The tall building construction during this period was rapid and façade designs ranged from semi-transparent or partially glazed façades to fully glazed façades, as in the Deira Twin Towers built in Dubai in 1998 and the Kingdom Centre in Riyadh in 2002 (Figure 1-18). As the major cities in the Gulf Region tried to reinvent themselves as major international destinations with modern, corporate-style management, it appears that "*in an attempt to create contemporary cities, glass facades seem[ed] to provide the ultimate solution*" (Elkadi, 2006, p.87). These fully glazed structures relied exclusively on extensive mechanical air conditioning, dependant on low cost, fossil fuel derived electricity, and, as a result, were widely criticised.

The third phase of tall buildings reflects the increased global awareness of sustainability and energy efficiency within the field of architecture. New buildings that claimed to be 'green', 'environmentally-friendly' and 'climatically-responsive' emerged, notably Al Hamra Tower in Kuwait (2011) Al Bahar Tower in Abu Dhabi (2012) and Doha Tower (2012) (Figure 1-19). The façade design seems to be the main feature used in the environmental strategies in these buildings, either through advanced shading systems, orientation responsive transparency and opacity in the glazed façades, or double skin façade technologies.

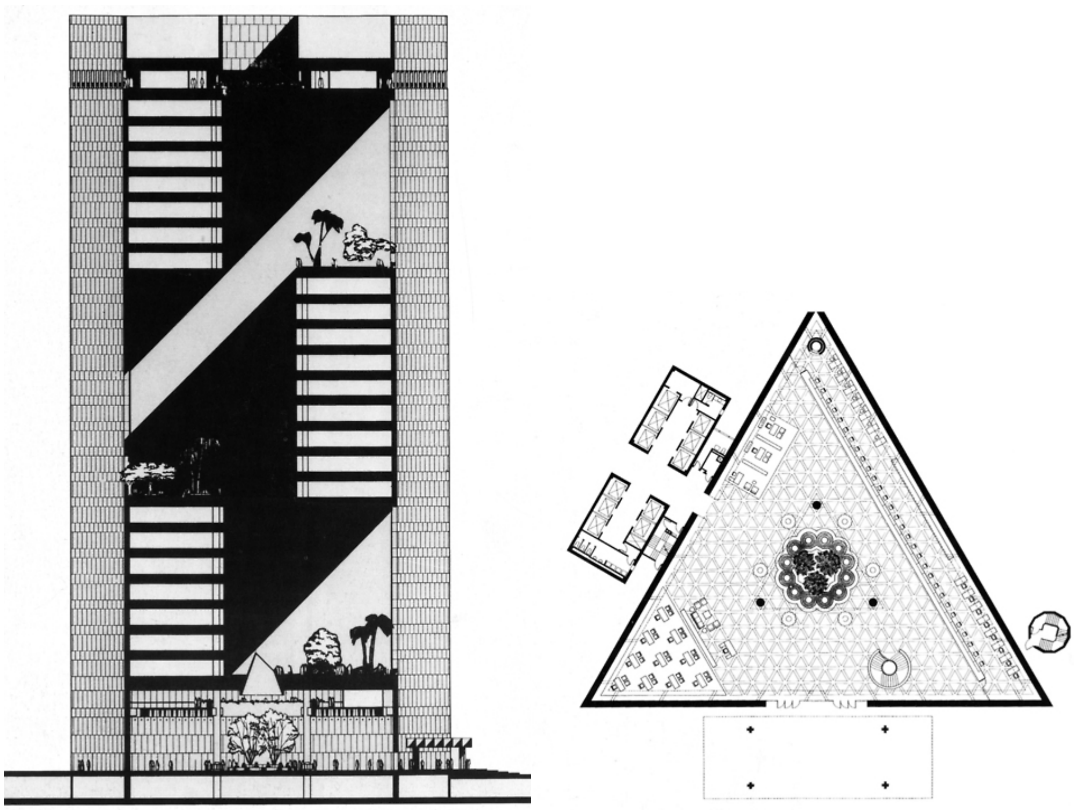


Figure 1-16 Section and Ground floor plan of National Commerce Bank, Jeddah, Saudi Arabia, designed by SOM in 1983. The inward orientation responds to both cultural and climatic considerations. (Source: Archive of Affinities, 2012)

The geometry of Al Hamra Tower in Kuwait City was carefully designed in response to the specific environmental and urban conditions of the site. As Figure 1-20 shows, the "*expression of the flared wall and the exposure of the south wall of the central core allowed for extensive glass use on the north, west and east sides of the tower, while providing a measure of environmental protection from the desert sun by presenting a nearly solid stone façade to the south*" (Agarwal et al., 2007). The variation of the façade material treatment according to orientation is considered as the main environmental strategy in this tower. The concrete construction and stone cladding of the southern façade act as thermal mass walls, while the curved east, west and north façades are clad in vision glass, providing views across the city and Kuwait bay (CTBUH, 2013). However, it is interesting to note that due to the lack of an extensive domestic building code in Kuwait, Al Hamra Tower was designed to meet the requirements of the 2003 edition of the International Building Code and all standards referenced therein (Agarwal et al., 2007).

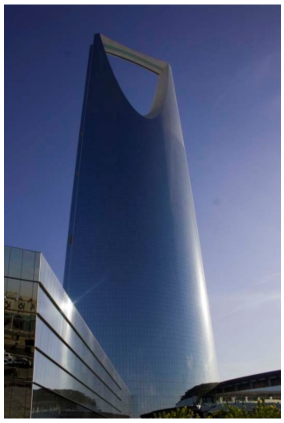
Dubai World Trade Centre (DWTC), 1979, Dubai ***Deira Tower, 1980, Dubai*** ***National Commerce Bank, 1983, Jeddah*** ***Islamic Development Bank, 1993, Jeddah***

Figure 1-17 The first generation of tall buildings built in the Gulf Region. (Source: Council on Tall Buildings and Urban Habitat, 2017; Nikken, 2013)

Dubai Creek Tower, 1995, Dubai

Deira Twin Tower, 1998, Dubai

Al Faisaliah Centre, 2000, Riyadh



Kingdom Centre, 2002, Riyadh

Figure 1-18 Examples of the second generation of tall buildings in the Gulf Region. (Source: Council on Tall Buildings and Urban Habitat, 2017)

O-14, Dubai, 2009

Al Hamra Tower, Kuwait, 2011

Al Bahar Tower, Abu Dhabi, 2012

Doha Tower, Doha, 2012

Figure 1-19 Examples of the new, more environmentally responsive towers in the Gulf Region. (Source: Council on Tall Buildings and Urban Habitat, 2017)

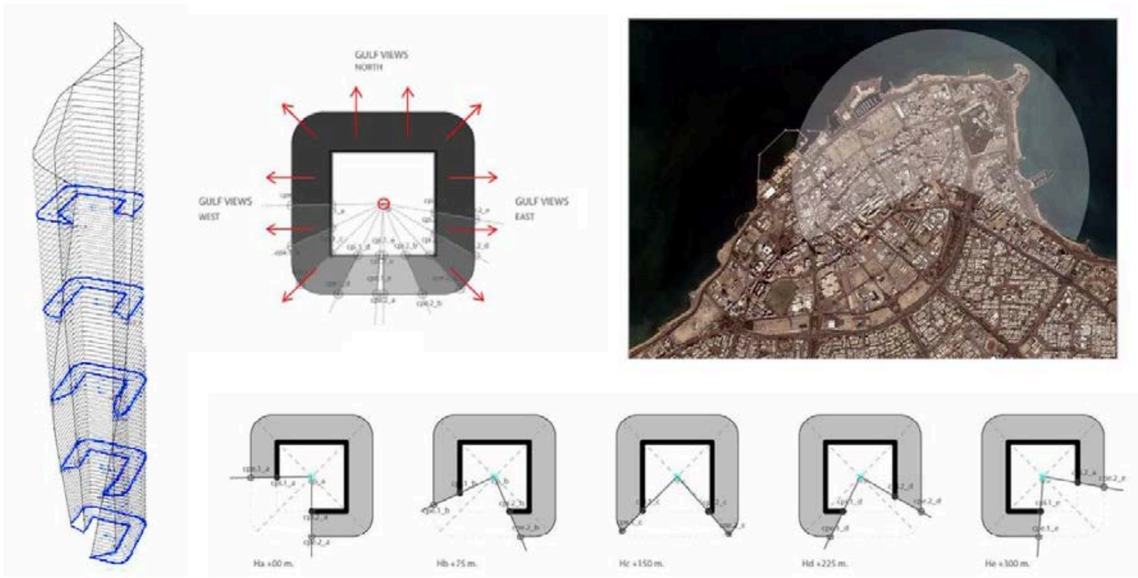


Figure 1-20 Al Hamra Tower geometry in response to the site's urban and environmental requirements, Kuwait City, SOM. (Agarwal et al., 2007)

Another good example of a sensitive response to culture, context and climate is the Doha Tower in Qatar (Figure 1-21). The tower façade consists of two layers, a layer of reflective glass curtain wall system completed by roller blinds on the inside, and an outer shading layer that clads the whole building in an intricately patterned stainless steel screen, a reference to the traditional Islamic '*mashrabiya*'. "*The design for the system involved using a single geometric motif at several scales, overlaid at different densities along the façade. The overlays occur in response to the solar conditions: 25% opacity was placed on the north elevation, 40% on the south, and 60% on the east and west. The overall façade system is estimated to reduce cooling loads by 20%*" (CTBUH, 2012, desMena, 2014). Again, the variation in façade treatments and shading elements according to orientation is the main environmental strategy used to exclude intense solar radiation and minimize solar gains while the indoor experience is enhanced through spectacular patterns of light and shadow falling in the interior.

Most available studies and articles describe these award winning tall buildings in relation to their architectural merit and the excellence of innovation in their design. However, it seems that less attention has been paid to the evaluation of the environmental performance of these tall buildings, either by quantitative measures or through post occupancy evaluations.

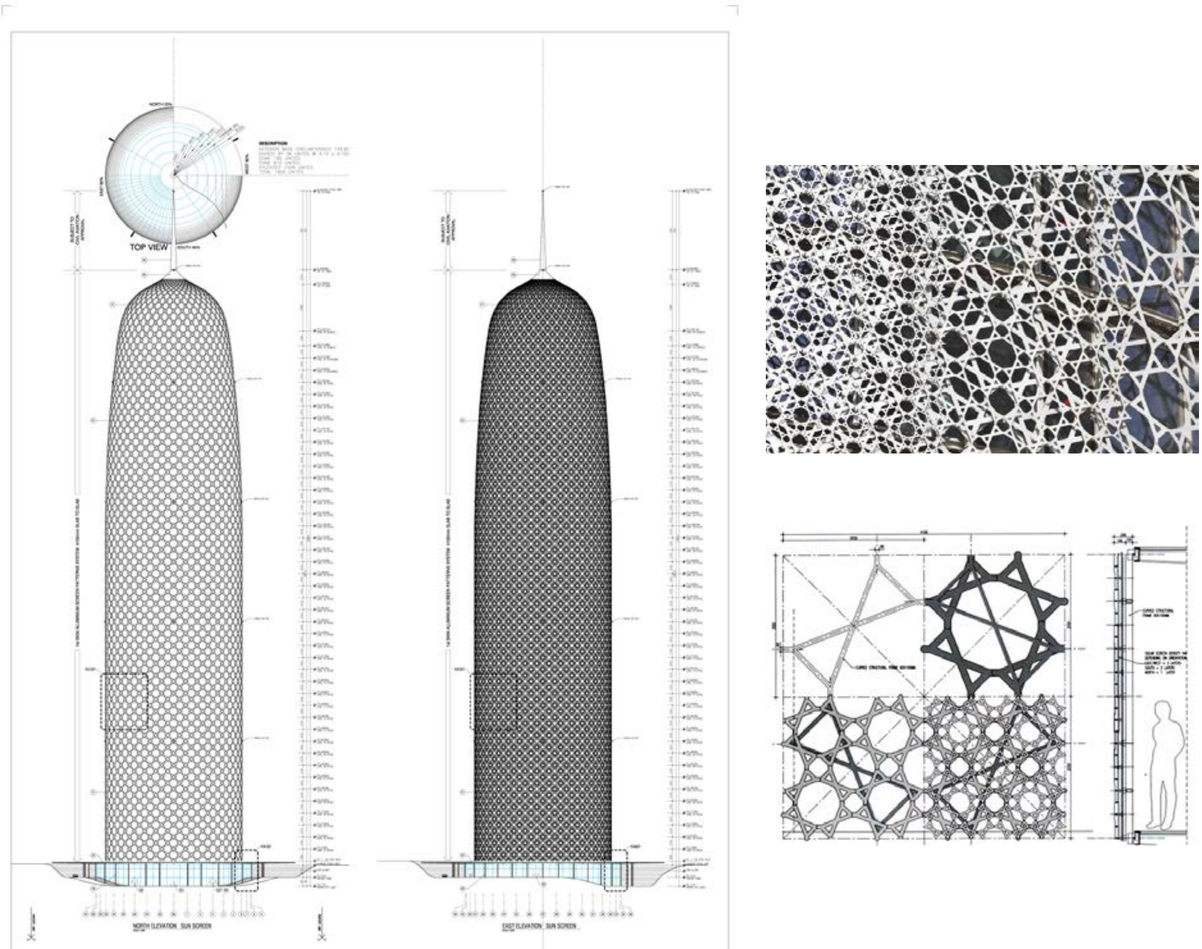


Figure 1-21 The elevations of the North façade (left) and the East façade (right), and details of the façade design of the Doha Tower designed by Atelier Jean Nouvel (desMena, 2014

1.2.4 Functions, Typology and the Culture of Glass

The above comparison looked at the different façade designs for tall buildings in the Gulf Region over the last twenty years; another aspect to consider is each building's function. The tall building type was introduced in many cities in the Gulf Region, particularly Dubai, as an attempt to identify itself as a major tourist destination. Therefore, "*whilst the majority of high-rise tower buildings in Europe, America and the Far East are constructed as office buildings in order to give a company statement, in the Middle East the high rise building market is dominated by hotels and residential towers*" (Bahaj et al., 2008, p.721). In Dubai, which contains most of the tall buildings in the Middle East, more than 50% of tall buildings are residential, and, given that 15% of mixed-use towers also include residential floors, 70% of the city's tall buildings have a residential type profile (Figure 1-22). As for Jeddah, 56% of the tall buildings are residential or include residential floors. Despite this, very few studies have been conducted regarding the environmental performance of this building type, which emphasises the importance of evaluating this building type in the Gulf Region.

Another aspect to explore is the cultural acceptance of glazed tall buildings as places to live. Elkadi points out that in Dubai "*while CCTV systems are sharply resented by the local population, transparency of their own glazed urban environment, including housing blocks, is welcomed*" (Elkadi, 2006, p.89), although this may be due to the high percentage (75%) of foreign residents. In Saudi Arabia for example, there is an increased demand for high-rise residential apartments, especially along Jeddah Corniche with its panoramic views of the city to the south and east, and the open expense of the Red Sea to the west (Harris, 2013; Hammoud, 2016). However, while many of these towers are fully glazed, others look more like the smaller scale apartment buildings common in the area (Figure 1-23). This can be seen as a reflection of the local desire for a more private and conservative tall building architecture, which ultimately influences the façade design.

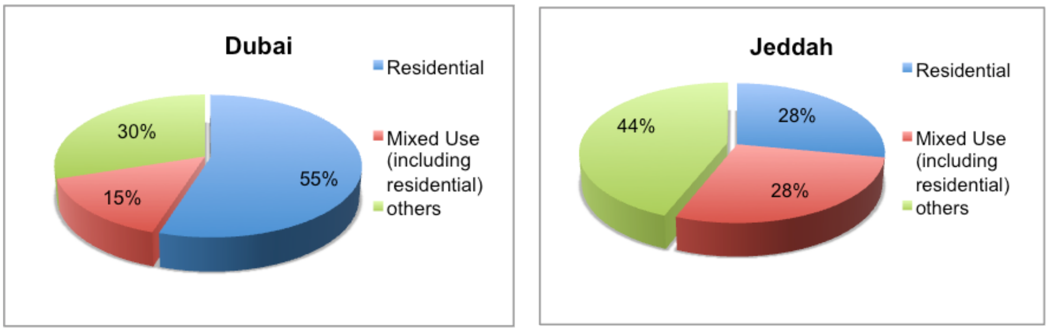


Figure 1-22 Percentage of residential tall buildings in Dubai and Jeddah. (Source: Author, based on data obtained from the CTBUH Skyscraper Centre)

Figure 1-23 On the left, a typical commercial and residential building in Jeddah, and on the right, the 30–storey Dyar Al Bahr residential tower. Note the similarities in the arches and window-like

1.3 Conclusion

Energy consumption in the GCC countries has risen rapidly over the last four decades, notably in Saudi Arabia which is the largest and most populous of the Gulf states. Energy demand is expected to nearly triple by 2030, a prospect which calls for serious energy efficiency policy interventions. In Saudi Arabia, residential buildings account for 51% of all primary energy consumption across the country, with the use of air conditioning to cool indoor spaces accounting for more than half of the energy consumed in buildings. In the city of Jeddah, on the western coast of Saudi Arabia, the emerging active construction of residential and mixed-use tall buildings threatens to increase energy consumption still further. Therefore, this study will focus on energy efficiency in residential tall buildings in Jeddah in Saudi Arabia.

The development or adaptation of building codes and standards are a high priority when it comes to reducing energy use and increasing energy and building efficiency. However, few studies have evaluated the effectiveness or the applicability of the energy conservation measures especially in tall buildings design. Therefore, another objective of this research is to contribute to the energy and efficiency standards for tall building in Saudi Arabia, and to make recommendations for designers and architects.

Climate analysis has revealed that the coastal cities of the Gulf region, apart from Kuwait City, share similar climate characteristics, notably high air temperature and high relative humidity, which makes the cities of Jeddah and Dubai comparable. This is a particular advantage as Dubai has the largest number of tall buildings among the GCC countries and the only established green building codes in the region.

Observational analysis of tall buildings in the Gulf Region has revealed that the building envelope and façade design seem to be the element which has changed most frequently as tall building design has evolved. It is also the main architectural feature used in the development of environmental strategies in these buildings, either through advanced shading systems, orientation responsive transparency and opacity in the glazed façades, or double skin façade technologies. In the next chapter, the building envelope is defined as a key aspect in designing energy efficient and climate responsive tall buildings.

CHAPTER2: Tall Building Envelope Design, Functions and Performance

This chapter describes the multiple functions of the building envelope in relation to heat transfer, solar gains, daylight, shading and ventilation, in order to understand the environmental and energy performance of this key building element. It explains how the energy balance of a building depends greatly on the properties of the envelope's materials, and introduces some of the design tools and techniques used to estimate and assess the implications of the façade design and building envelope on the energy use.

It also discusses recent studies concerned with reducing cooling loads and high-energy consumption through thermal optimisation of the building envelope, reflecting on the current and future challenges associated with increasing the energy efficiency of fully glazed tall buildings in the hot climates of the Gulf Region.

Chapter 2 TALL BUILDING ENVELOPE DESIGN, FUNCTIONS AND PERFORMANCE

"The improvement in glass technologies in the twentieth century has dramatically extended the power of architecture over nature and enabled architects to marginalize the role of environmental forces in determining the configuration of façades. The façade's role shifted from being a shield from, or interaction with, natural forces, to being a manipulator of those forces."

Professor Hisham Elkadi, Dean of the School of the Built Environment, University of Salford Manchester, in his book 'Cultures of Glass Architecture', 2006, p.21.

"This environmental diode, a polyvalent wall as the envelope of a building, will remove the distinction between solid and transparent, as it will be capable of replacing both conditions and will dynamically regulate energy flow in either direction depending upon external and internal conditions, monitor and control light levels and constant ratios as necessary at all points in the envelope."

Mike Davies of Chrysalis Architects and Richard Rogers and Partners in the RIBA Journal article, 'A Wall for All Seasons', 1981, p.56.

It is well noted that most tall buildings in the Gulf Region are designed with no regard to the local climate. Instead, they rely on active systems to overcome the impact of uncomfortable climatic conditions, making them major contributors to high-energy consumption and carbon dioxide emissions. Thus, much of the responsibility for reducing the environmental impact of buildings lies with architects, developers and engineers. Building designs should be responsive and adaptive to local climatic conditions and architects ought to produce intelligent building morphologies that reduce the energy need for cooling, heating and lighting to a figure close to zero (or even negative) as the building becomes an energy generator. The building envelope is regarded as the key aspect in designing climate responsive buildings, fulfilling the basic need of defining the exterior and the interior, separating yet allowing exchange and permeability, and determining the interrelation between the given external conditions and the required internal conditions, while acting as the 'calling card' of the building and its designer (Wigginton and Harris, 2002; Schittich, 2006; Hausladen et al., 2008; Koch-Nielson, 2007).

In this chapter, the multi-functionality of building envelopes and their impact on the building's environmental performance are considered, with a particular focus on tall buildings in the challenging climate of the Gulf Region.

2.1 The Functions of the Building Envelope

According to Brown and DeKay (2001), there are three main factors that determine a building's energy use: (1) climate, (2) programme (function and occupancy) and (3) form (envelope, building shape and construction). A building's form and envelope influence its heating and cooling requirements to maintain comfort. The energy balance of a building depends greatly on the properties of the envelope material, which is made up of three main groups of elements: opaque, transparent and translucent (European Commission, 1990, cited in Elkadi, 2006, p.57). Elkadi explains that "*The transparent components of the building envelope are usually the most interesting parts, due to their dynamic nature. They are more responsive to short-and long-term changes in the interior and exterior conditions. They have more complex functions, allowing views and communications with the outside, providing heating through the controlled use of solar gains, and cooling by shading and ventilation.*" (Elkadi, 2006, p.57). The following sections briefly describe the main functions of the building envelope in relation to heat transfer, solar gains, daylight, shading and ventilation.

2.1.1 Thermal and Light Transmittance

As defined by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (2013), 'heat transfer' is energy transferred from a higher-temperature region to a lower-temperature region by one or more of three modes: conduction, radiation, and convection. 'Thermal transmittance' (U-value) or 'skin heat flow' can be defined as the time rate of heat flow through the building skin for each degree of temperature difference between the inside and outside temperature. There are several factors that affect the rate of heat flow through the building envelope: the ratio of skin area to floor area, percentage of window area, quality of glazing of transparent elements, wall construction and insulation thickness for the opaque elements, in addition to function and occupancy which determine the difference between the inside and the outside temperature (Brown and DeKay, 2001; Hausladen, et al., 2008).

Thermal transmittance is a function of the types of materials in the building envelope and can be reduced by increasing the insulation thickness. Thermal transmittance is determined by factors such as the climatic conditions, building type, proportion of window area, glazing type, type of construction, and available space. In relation to building type, buildings with high internal loads using lower heat insulation or 'poor insulation' may be justified since high insulation can reduce the building's ability to lose heat (Brown and DeKay, 2001; Hausladen, et al., 2008).

As for thermal transmittance in the transparent elements of the building envelope, thermal transmittance through conduction can be affected by the thickness of the glass, while applying coatings can modify radiation, and modifying the construction can control convection (Compagno, 2002). Glazing composition is usually made of one pane of glass, two-pane or three-pane units (double or triple glazing). Four independent factors affect the U-value in glazing (identified by Givoni, 1998, cited in Elkadi, 2006, p.60): the existence and number of air spaces between glazing panels, the properties and/or treatments of the glazing material and surfaces, the gas which fills the air spaces, and the materials and detailing of the window frames.

These factors also influence the light transmittance. Daylight travels in different wavelengths which can be divided into three groups: visible light transmittance (VLT),[4] ultraviolet transmittance factor, and infrared transmittance (heat). When solar radiation strikes the glazing surface, it is either absorbed by the glass, reflected back to the outside or transmitted into the building (Elkadi, 2006). Compagno (2002) defines the three main physical parameters in the evaluation of incident light and thermal gain or loss for glass as: thermal transmittance coefficient, the U-value (as defined above), and light transmittance and total solar energy transmittance.

The relationship between thermal and light transmittance is one of the most challenging characteristics of glass; the more light transmittance the glass pane allows, the more thermal transfer it permits. This relationship, especially in glass façades, is greatly influenced by the continuous changes of climatic conditions and cloud cover. It impacts solar gains, visibility, provision of daylight and glare (Elkadi, 2006).

[4] The visible light transmittance factor is the amount of the visible portion of incident radiation that penetrates a window, expressed as a percentage (Button and Pye, 1993, cited in Elkadi, 2006, p.59).

2.1.2 Solar Gain

According to Brown and DeKay (2001), although 0-12% of the available solar heat reaches the interior spaces through opaque elements, depending on the colour of the exterior surface and its insulation quality, this percentage is small compared to the solar gain through glazing, which can be as high as 85% of the incident solar radiation. Heat gain from the sun is largely dependent on the area of transparent and translucent surfaces of the building envelope, their orientation and energy transmittance (which are based on the g-value[5] of the glazing and the reduction factor of the solar screening), and the climate, which determines the availability of the sun (Brown and DeKay, 2001; Hausladen, et al., 2008). Hausladen et al. (2008) argue that the amount of solar radiation entering the building and the thermal dynamic of the building increase in proportion to the window area, which may consequently raise the cooling demand. The proportion of window areas in façades is also closely interlocked with the façade orientation since it determines the azimuth and altitude angles of the sun in relation to the façade and the intensity of solar irradiance.

As for the glazing heat transmittance, several terms are used to define it, including 'Solar Heat Gain Coefficient' (SHGC), which is used to quantify how much solar heat the window blocks and what part of the incident radiation reaches the interior (Szokolay, 2008). It is different from the shading coefficient (SC) which is "the ratio of solar heat gain through fenestration, with or without integral shading devices, to that occurring through unshaded 1/8 inch (3mm) thick clear double strength glass" (ASHRAE, 1986, cited in Elkadi, 2006, p.61). SHGC is gradually replacing SC in glass window literature and should be included along with U-value to describe a fenestration's energy performance (Elkadi, 2006; ASHRAE, 2013). ASHRAE (1997) also defines the amount of radiation gained through single-pane clear glass under clear skies as the 'Solar Heat Gain Factor' (SHGF) (Brown and DeKay, 2001). SHGF is represented through calculated values for solar irradiance in W/m2,tabulated by latitude, month, time of day, and orientation (Szokolay, 2008), and this data can be used to predict the heat gain through windows for the worst-case cooling scenario. In hot climates with high

[5] In the USA, solar heat gain coefficients (SHGC) are used whilst in Europe, g-values (window solar factors, solar factors or total energy transmittance (TET) are preferred. In essence, these both represent the fraction of incident solar radiation transmitted by a window, expressed as a number between 1 and 0, where 1 indicates the maximum possible solar heat gain, and zero no solar heat gain.

solar radiation, low SHGC values are desirable, indicating lower transmitted solar heat gain. As for Shading Coefficient (SC), it correlates positively with visible transmittance; meaning when the amount of light transmitted through glazing decreases, the visible light transmittance decreases affecting daylight levels inside the building.

Given the central relationship between light and heat transmittance (see Section 2.1.1), Light-to-Solar Ratio (LSR) is a common measure of the performance of glazing units. Elkadi (2006, p.62) defines this as "*the ratio of visible light transmittance (VLT) divided by the solar heat gain coefficient (SHGC) for the glazing system*". In hot climates or buildings where maximum daylighting and minimal solar heat gain is desirable, high values of LSR are recommended. Elkadi (2006, p.63) has determined the highest possible ratio for LSR as approximately 2.0. "*Clear glazing units have a value close to 1.0, while a good spectrally selective glazing system would have a value greater than 1.7*". Further analysis of daylight follows below.

2.1.3 Daylight

The use of daylight in buildings is essential for indoor comfort and wellbeing, in addition to reducing lighting energy demand and cooling loads. As the connector to the external world, the building envelope has a significant influence on the availability of daylight within the building. The entry of daylight is highly dependent on the façade orientation, the opening sizes and position of windows and the natural light transmittance characteristics of the transparent elements of the building envelope.

Natural light has two main components: sunlight, or 'direct light', that arrives directly from the sun in a clear sky, and daylight, or 'diffused light', the non-directional light arriving from the sky hemisphere which is scattered due to moisture or particles in the atmosphere. Direct sunlight generally leads to large differences in luminance and direct glare, but can be deflected and aimed into the depth of the room. Diffused daylight is considerably lower in energy than direct light, thus is preferable in terms of thermal comfort, but can be directed over short distances only and cannot be directed. Climatic factors such as solar altitude and sky conditions influence the illuminance, colour, luminance and therefore the intensity of daylight and the atmosphere of the room (Hausladen, et al., 2008; Szokolay, 2008).

The design of the façade is affected by the conflicting requirements of more daylight (as an energy conservation measure), and avoiding the risk of glare arising from high luminance or luminance contrast if the windows are too large. Glare can be in the form of direct glare, contrast glare or reflection glare. Szokolay (2008) and Hausladen et al. (2008) suggest some measures to reduce such glare occurring, including the use of low-transmittance glass, internal blinds or curtains, or external adjustable glare protection devices. Another problem that might arise from direct sunlight is uneven room lighting, which enhances both direct and contrast glare. Therefore, solar screening louvers and light redirection systems might be required to facilitate the entry of natural light and direct it into the depth of the room to enhance visual comfort and even out room lighting. Further discussion of shading and solar screening follows in the next section.

In addition to the issue of glare and visual comfort control, the proportions of the window area and the glazing properties of the building envelope significantly affect daylight optimization. ASHRAE 2013 defines window area or the window-to-wall area ratio (WWR) as the ratio of the transparent glazing area to the outdoor floor-to-floor wall area. The recommended window area is 50% of the wall area with a maximum window area of 40% of the above-grade wall area (ASHRAE standards, 2004, IECC, 2006, cited in Ko et al., 2008).

Glazing affects visual comfort since solar control glass with low g-values reduces light transmittance to about 40%, which in turn affects natural light transmittance. This can reduce the adequacy of daylighting, leaving the depth of the room so dark that artificial lighting is necessary (Hausladen, et al., 2008). Therefore, it is important to consider fenestration size and position, and glazing type in façades in order to create sufficient daylight levels and maintain minimum indoor brightness levels for the building’s occupants.

2.1.4 Shading

The shading systems in the building envelope determine the total solar radiation transmitted into the building. It is important to determine whether shading is needed or not in the first place in order to determine the most appropriate design. For example, in predominantly overcast cool climates, sunlight will usually be welcome whenever it is available as long as glare or excessive contrast is avoided. However, in climates or buildings where sunlight must be controlled, it is essential to assess the duration of sunlight obstruction and exposure at a given point on the façade, to establish the critical times and the extent to which the sun is penetrating the building. According to Szokolay (2008, p.165), this is a purely geometrical task: "*the sun position in relation to the window is to be established first. The horizontal shadow angle (HAS) at the time of question is the azimuth difference between the sun's direction and the orientation. The solar altitude (ALT) must be projected onto a plane perpendicular to the window, to get the vertical shadow angle (VSA). Once these two angles are known the sun penetration, the sun-lit patch on the floor or on the work-plane, can be constructed*" (Figure 2-1).

As mentioned above, the design of the solar screening or shading system depends on the building's orientation. According to Hausladen et al. (2008), horizontal shading features such as cantilever projections, roof overhangs or balconies can be used to exclude direct sunlight on the south façade, while east and west façades can be screened with vertical louvers. The intensity of solar radiation and whether it is direct or diffused also affects the design of solar protection: overhangs designed to protect from direct radiation are not necessarily adequate to protect from diffuse radiation that comes from the whole sky. Moreover, the material used to construct the shading device has an effect on the shading factor: opaque and solid material have a solar protection factor of 100% while translucent or transparent materials such as fabric and vegetation have less. However, care should be taken to use materials with low heat storage capacity to avoid reflecting heat onto the building or trapping hot air which causes heat to be transferred inwards through the structure (Koch-Nielson, 2007).

Another important aspect to consider is the position of the shading device or solar screening, since the shading factor F_c depends on its placement inside or outside the building. As Hausladen et al. (2008, p.46) note: "*external screening can be between three and five times as efficient, although it has to be raised in windy conditions, internal systems are low maintenance, inexpensive and can be deployed irrespective of the weather. [Indeed,] by installing the solar screening in the façade cavity of double-skinned facades or in box windows, solar screening can be highly efficient and unaffected by the weather*". Also, solar screening impacts the achievable proportion of the window area and care should be taken to ensure it doesn't impose limitations on the building's outward views.

Finally, when considering shading and solar screening, it should be noted that managing the entry of light, room temperature and user expectation can be challenging, and the user control strategy adopted considerably influences both room climate and user satisfaction (Hausladen, et al., 2008; Szokolay, 2008).

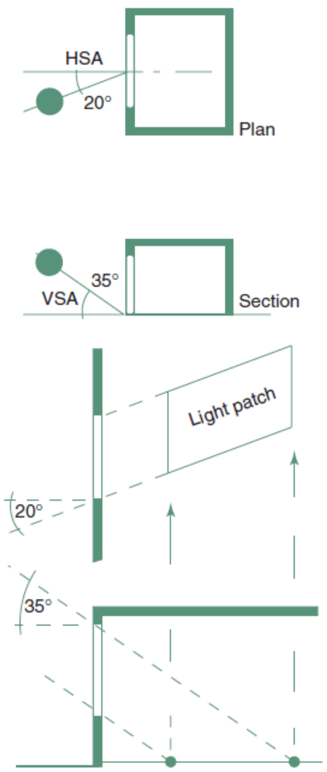


Figure 2-1 Construction of sun penetration through the horizontal (HAS) and vertical shadow angles (VSA) as illustrated by Szokolay (2008, p.165)

2.1.5 Ventilation

The design of the building envelope and façade concept should allow the option of natural ventilation when appropriate in order to achieve an overall feeling of well-being while reducing technical complexity and energy demand, especially in moderate and temperate climates (Hausladen et al., 2008). Generally, the suitability of natural ventilation is higher in domestic environments than in office buildings; nevertheless, its feasibility depends largely on its acceptability to the client and the building occupants, in addition to the urban context and technical practicalities (Etheridge and Ford, 2008).

ASHRAE (2013) defines ‘natural ventilation’ as the flow of air through open windows, doors, grilles, and other planned building envelope penetrations, driven by natural and/or artificially produced pressure differentials. In other words, this air movement can occur in two ways: (1) due to wind-generated pressure difference, and (2) due to temperature-generated pressure difference or buoyancy (Hausladen et al., 2008, Koch-Nielsen, 2007).

When designing the building envelope for natural ventilation, it is important to combine the functions of ventilation, daylight entry and outward views in one element, as Hausladen et al. (2008, p.54) make clear: “*For natural ventilation the opening light of a window must be finely adjustable in order to offer a certain degree of weather protection, ensure complete air exchange, contribute to limiting thermal discomfort and prevent the entry of noise*”.

Hausladen et al. (2008) go on to categorise ventilation elements by building location and type (Table 2-1), including window ventilation suitable for locations with little noise and low wind speeds, and ventilation through double skin façades, which is advantageous in noisy or windy locations but can cause overheating. Then there are ventilation flaps in the case of tall buildings that provide façade ventilation even in strong winds. Essentially, the main factors that determine the numbers of air changes in ventilation through the building envelope are the type, treatment, position and location of the façade openings and the driving forces of thermal buoyancy and wind, since the size of the openings on the windward and leeward sides of a building affect air flow internally, and the differences in height between leeward and windward openings create variations in internal air distribution (Koch-Nielsen, 2007).

Moreover, according to Etheridge and Ford (2008, p.6), “*it is not just the openings in the envelope that are important to natural ventilation. The fabric of the envelope can provide one or more of the following functions: adventitious leakage, thermal insulation, thermal storage (for night cooling), environmental conditioning (e.g. double skin façades)…. one particularly interesting idea is the use of porous envelopes through which the ventilation air is induced to enter basically purpose-designed adventitious leakage.”* Therefore, it is important to consider infiltration ventilation that can provide basic air exchange with little entry of noise.

Table 2-1 Advantages and disadvantages of ventilation elements for various locations and building types (Source: Hausladen et al., 2008, p.55)

Ventilation element	Advantage	Disadvantage	Location
Double-skinned façade	Wind-protected solar screening Comfortable introduction of supply air in winter Night ventilation	High cost No views out Risk of summer overheating	
Window ventilation and ventilation flap	Cost-effective Direct view out	Unprotected solar screening	High rise, exposed to wind
Window ventilation and box window	Direct view out Very flexible solution Night ventilation	Only partially protected solar screening	
Window ventilation and controlled ventilation elements	Direct view out Night ventilation User-dependent ventilation	Requires control system Higher cost Unprotected solar screening	
Box window	Night ventilation Comfortable introduction of supply air in winter	No direct view out Risk of summer overheating	
Window ventilation and box windows	Direct view out Very flexible solution Night ventilation		Noisy locations
Window ventilation and infiltration	Sound-insulation basic ventilation Direct view out Cost-effective	Limited sound insulation	
Window ventilation and sound-insulated ventilation elements	Sound insulation ventilation Direct view out	High complexity	
Window ventilation	Direct view out Cost-effective	No protected night ventilation	
Window ventilation and baffle panel	Night ventilation	Limited view out	Quiet location
Window ventilation and infiltration	Direct view out Basic air changes Basic night ventilation	Unnoticed air changes	
Window ventilation and controlled ventilation element	Direct view out User-dependent basic ventilation	Higher cost Requires control system	

2.2 The Environmental Design of Building Envelopes

After establishing the main functions and environmental physics related to the building envelope, it is essential to investigate the impact of the façade design on the indoor environment and energy consumption within the buildings themselves.

The building envelope can be responsible for as much as 30% of the total energy consumption in a building, especially for cooling loads (Elkadi, 2006). Hauser, in Hausladen et al. (2008, p.39), recognises the significance of the façade in this respect, noting that "*the external cooling load of a building is primarily determined by its façade, where there are often conflicting demands of architecture, natural light, visual relationships with the outside world, and cooling load*".

Globally, the excessive use of fully glazed façades has been widely criticised for contributing to over-consumption of the world's energy resources, especially after the 1973 energy crisis. "*The notion of 'totally' sealed façades failed aesthetically and functionally. Their energy consumption was huge, and their occupants were not happy*" (Elkadi, 2006, p.22). However, abandoning glass was not the answer; instead, the construction industry came up with more efficient solutions, especially for the glass material. Terms like 'intelligent' façades were widely implemented, and new research paradigms emerged. In the 1980s, energy efficiency rather than energy conservation became the main priority and more efficient systems and technologies were introduced into buildings. Following that, in the early 1990s, the concept of sustainable development started to surface in the built environment, introducing technical fixes to integrate sustainability and energy efficiency measures into building envelopes (Elkadi, 2006). Nevertheless, several studies have criticised the use of fully glazed façades, even those with 'intelligent features', notably Shuttleworth (2008) who argues that a fully glazed building skin leads to overheating in the internal spaces due to excessive solar gain which necessitates mechanical conditioning leading to high energy consumption, and that implementing shading devices to reduce solar gain results in complicated, expensive and high maintenance façades. This then brings up the central question: how can we design sustainable envelopes that minimise the building's environmental impact?

Several papers have examined the design process and approaches to the building envelope that seek to ensure satisfactory savings and users comfort. According to a study by Ochoa and Capeluto (2009), careful planning and decision-making during the different stages of the intelligent façade design process is the key to producing energy efficient buildings, a fact which is frequently overlooked. Haase and Amato (2006) debated whether the trias energica or the energy triangle approach related to the work of Lysen (1996) could be used to provide a sustainable façade design, incorporating energy conservation, energy efficiency and utilizing renewable energy. The energy conservation strategies should be tested against the climatic conditions in each location to deduce the best strategies for comfort improvements to be incorporated into the building design. Energy efficient technologies such as active building components, optimising daylight use, and the optimum orientation of façades offer the possibility of reducing energy consumption. Finally, in order to utilise renewable energy most effectively, it is important to first evaluate the amount of renewable energy available then identify the possibilities of implementing renewable energy such as Building Integrated Photovoltaic (BIPV) or wind power. However, the study confirmed the dependence of sustainable façade design on the building characteristics like length, depth and height.

In an earlier study, Oral et al. (2004) grouped the various parameters that influence the design of the building envelope in two sets: (1) parameters related to the outdoor environment, such as outdoor air temperature, solar radiation, outdoor humidity, wind velocity, illumination level and sound level, and (2) design parameters related to the built environment, which are considered according to four different criteria of scale, the external settlement unit scale, building scale, room scale and element scale (material characteristics for the opaque and transparent components of the building envelope). Like Haase and Amato, the study aimed to develop the sequential steps of an approach that allows the construction of a building envelope with optimal performance in respect of thermal, visual, and acoustical comfort. These steps in the design process of the building envelope are illustrated in Figure 2-2 below. The main idea of this study is the optimization of the performance of the building envelope in order to provide comfortable conditions and minimal energy consumption (Oral et al., 2004).

Design process of the building envelope with respect to heat, sound and light	1. Determination of the values related to the **outdoor environment**
	2. Determination of the values related to the built environment (**Room properties**)
	3. Determination of the required indoor conditions (**Thermal, Acoustic, Visual comfort conditions**)
	4. Determination of the building envelope alternatives (**transparent and opaque components' properties**)
	5. Calculation of the **indoor thermal, acoustic and visual conditions** in the room and evaluation of the alternatives
	6. **Appropriate envelope alternative determined**

Figure 2-2 Design process of the building envelope with respect to heat, sound and light (Source: Oral et al., 2004, p.283)

Another study by Ochoa and Capeluto (2009) presented design strategies for intelligent façades and proposed a design assistant tool to help select starting solutions from different façade and element combinations, based on the principles of an energy code for hot climates, in addition to providing practical guidelines to enact these strategies. According to the authors, it is important for the design team to decide on one of three options in the early stages: whether they will depend on (1) active element performance only for the façade design (active features only), such as fan ventilation and internal and external glare-activated blinds, or (2) active element performance combined with climatic building principles (passive design + active features), or (3) designing with climatic principles using adequately passive strategies, such as manual night ventilation (passive design only). To test how important decisions taken in the early stages of design are, a parametric study was conducted measuring the variations between the three alternatives: active features only, passive design only, or passive design and active features considering careful climatic planning, adequate passive strategies combined with suitable active elements, and the specific climate type in the framework of the Israel Energy Code (IEC). The base case was an office building located on the coast of Haifa, Israel, and the alternatives were tested for energy consumption and visual comfort. The results revealed that the integral planning of the 'active features and passive design' provides consistent energy savings and predictable visual control behaviour, indicating that considering adequate elements and strategies during the early design phases brings more flexibility and larger energy savings. Nevertheless, there are limitations to developing intelligent façades from the early design stages, mainly because the existing design and simulation tools require precise, detailed data (such as fan air speed, insulation layers, etc.) which may be unknown or irrelevant at the early design stages. As an alternative, the authors developed a solution-suggesting tool called 'NewFacades' which proposes intelligent façade combinations together with energy and glare evaluations for a given situation, allowing additional refining and development of one or more façade combinations. The alternatives are formed by using the IEC's optimised prescriptive section, which is based on economic energetic criteria. The results are given to the user as a list of alternatives including detailed active and passive elements in addition to the monthly/annual energy consumption and visual comfort expressed in graphical form. Furthermore, the authors set the following energy and comfort guidelines for intelligent façade design in hot climates: (1) climate strategies including heat rejection (adequate orientation, insulation, window size, shading), ventilation especially for hot-humid climates, and sunlight controls to provide visual comfort while reducing heat gains through overhangs, shades and light shelves; (2) design strategies through integral planning practice from the early design stages and considering the façade as an essential part of energy efficient design not as a separate product; and (3) functional recommendations as to the operational and behavioural aspects that must be considered in order to ensure the façade is acceptable to end users, both in daily use and in terms of maintenance. Essentially, the study concluded that energy performance depends on more than one component, and integration should begin with a design process that incorporates adequate climatic principles and considers elements to fulfil them. This idea is especially important for façades of high-rise buildings, for, as Linde et al. (2012, p.48) make clear: "*the 'design process' for complex bespoke architectural high rise facades is an abstract term that in reality is not a single process but… simultaneous cross-disciplinary design processes*".

Further to the environmental functions listed in Section 2.1, and besides considering comfort (acoustic, glare, natural daylight transmission and radiant surface effect) and energy (solar heat gains, thermal transmissions, leakage), building envelopes in tall buildings must be designed to cope dynamically with numerous building system requirements, including structural (building movements), weather tightness (durability, water exclusion), security (fire, impact), while maintaining the desired architectural aesthetic, which can be achieved using an advanced control system that includes blinds, HVAC (heating, ventilation and air-conditioning), occupancy sensors and lighting. A study by Linde et al. (2012) identified the constraints to achieving such a façade with whole-building environmental system integration due to different time schedules when the environmental systems are implemented and the façade designed. In order to solve this problem, the authors proposed an alternate design process that looks at holistic system performance or 'holistic design'. This encourages broad innovative multi-disciplinary thinking instead of the 'convergent design' approach which reviews design impacts sequentially and continuously relies on specialist knowledge limited to one narrow field. In one case study, the holistic design approach was adopted to solve the complex designs of the Thin Environmental Cladding (TEC) façade by Permasteelisa Group, Fiberline Composites and Arup. However, it was not made clear how things might have differed if the convergent approach had been adopted instead. The authors highlighted how the adequacy and reliability of a design requires the use of suitable and reliable engineering tools and software that analyses the overall system and the interaction of all façade components. They also criticised the current energy modelling software used to size environmental systems since they only utilize simplistic façade models, glazing properties and U-value without considering advanced multiple layered façade systems. Like Ochoa and Capeluto (2009), Linde et al. (2012, p.53) proposed two software packages developed by Permasteelisa, EPBD and Permasteelisa Moving Forward (PMF). EPBD software "*undertakes dynamic whole-building energy simulation that considers the dynamically variable façade properties as well as the impact of ventilation, shading response and daylighting*" while PMF is an effective design management system to improve the challenging and complex process of multiple entities of design, fabrication, sub-contracting, assembly and installation of a project from the early design stages to on-site status reporting. Although the study might seem biased since it is affiliated with the Permasteelisa Group and promotes their software without comparison with other competitor software, the proposed holistic design approach is worth investigating in regard to façade design.

Following the emphasis on integrated and interactive design processes for energy efficient buildings, Bolin and Gilchrist (2012) carried out an investigation using building energy modelling to consider how the climate and choice of exterior envelope system might interact with a building's HVAC system to optimise building efficiency and reduce energy consumption. The investigation focused on three primary efforts: (1) Window-to-Wall Ratio

(WWR) Adjustment, (2) Massing Alternatives, and (3) Glazing/HVAC Alternatives. Firstly, twelve diverse representations of cities were chosen based on the ASHRAE International Climate Zones. The process then started with a base case of an 80-storey office tower complying with the ASHRAE Standard 90.1-2007 Energy Standards for Buildings Except Low-rise Residential Buildings. The WWR was initially 40% but later increased to 65% (to be more consistent with current trends in tall building design that express a more transparent aesthetic), but the SHGC and Centre of Glass U-value were adjusted so the building loads were identical to the 40% WWR minimally compliant model. To show how glazing orientation has a distinct impact on orientation, the massing alternatives were square footprint, rectangular footprint with the long axis in the east-west orientation, and rectangular footprint with the long axis in the north-south orientation. As for the glazing performance and envelope cladding alternatives, they included four double-paned insulated glazing units (IGU), one triple-paned (IGU), one horizontal shading element, and one ventilated curtain wall. The numerous combinations of massing, climate zone, envelope cladding and system alternatives produced 750 possible options, of which the study evaluated 336. Although the large number of combinations made it difficult to draw any strong and fast conclusions from this study, the main conclusion was that the specific climatic conditions are more important in the selection of the most appropriate and energy efficient HVAC systems in tall buildings than the building envelope configuration. Another conclusion related to glazing properties for tall buildings in hot climates (Riyadh was selected as an example of a very hot and dry climate) states that SHGC is more important than U-value. The required SHGC for the adjusted baseline is 0.17 (0.20 SC); however, "*to improve upon this baseline performance using glass technology alone, an envelope would need to utilize heavily tinted, fritted glass and accept a VLT (visible light transmittance) below 20%*" (Bolin and Gilchrist, 2012, p.334). This would significantly affect daylighting levels and views, a major issue in tall buildings. Additionally, although the use of external shading improves the envelope energy performance, it needs careful planning in the context of tall building design.

In conclusion, the environmental design of the building envelope should evolve from a holistic and integrative practice that synthesises the different functions and systems of the façade, the comfort and satisfaction of the users, and the energy efficiency of the building

(Elkadi, 2000, p.97). This integration should start from the early stages of the design process, and although some software packages have been proposed to aid design team in choosing good starting solutions for the façade combinations (Linde et al., 2012; Ochoa and Capeluto, 2009), other studies suggest that simpler, manual design tools might be more helpful at this initial stage. The following section considers some of these design tools and their application for tall building design, especially in hot climates.

2.3 The Evaluation of the Environmental Design of Building Envelopes

As Elkadi (2000) notes, it is difficult to evaluate the performance of the skin separately from the performance of the building as a whole since the definition of the skin boundaries is not yet clear. Nevertheless, research efforts over decades have produced numerous design tools and techniques intended to aid the design and evaluation of the energy efficiency of a building by estimating and assessing the implications of the design of the façade and the building envelope on its energy use. These design tools range "*from those used to inform the design process by indicating trends in energy use associated with strategic design decisions, to tools to predict the energetic performance of detailed architectural and engineering proposals*" (UCD, 1995, p.2). Design tools can assist where specialist or expert knowledge of a topic is not available. They address many design related issues that are interrelated and affect both each other and the overall performance of a building or service system, such as building fabric, thermal and daylight performance, comfort, ventilation, infiltration, shading and energy consumption (THERMIE, 1995), all of which are related to the building envelope design in one way or another. Ultimately, as Baker and Steemers (1996) observe, these design tools can shift the emphasis from the number to the trend and from evaluation to comparison.

These design tools are often presented at a rule-of-thumb level, focusing on just one or two design issues to avoid complexity, especially in the early stages of the design process when things proceed rapidly and assumptions are made to reduce the information needed as input, sacrificing precision of information to increase speed of use (THERMIE, 1995; Baker and Steemers, 2000; Brown and Dekay, 2001). For example, the Lighting and Thermal method (LT) developed by Baker (1995) is a manual energy-design tool, requiring only a pencil and a calculator, that uses given assumed values to test the relative performance of a number of design options instead of a precision model producing accurate estimates of the building energy performance. Baker and Steemers (1996) divide the building factors that influence energy use into two sub-categories: building-design parameters and engineering parameters. Building-design parameters, like the plan depth, interact with other parameters and have an impact on the form and performance of the building, while engineering parameters, like the U-value, can take on values independently from other parameters. The LT method is concerned with the main issues designers consider early in the development of a building design: the form of the building (its plan, depth, section, orientation, etc.), the design of the façades (area and distribution of glazing), and the proportion of perimeter (or passive) zones (i.e. the area within six metres of the external walls). The method relies upon the concept of ‘passive zones’, defined by orientation, and ‘non-passive zones’, which are away from the envelope, taking into account the energy and heat flow affected by the fenestrations in the passive areas (Figure 2-3) (Szokolay, 2008).

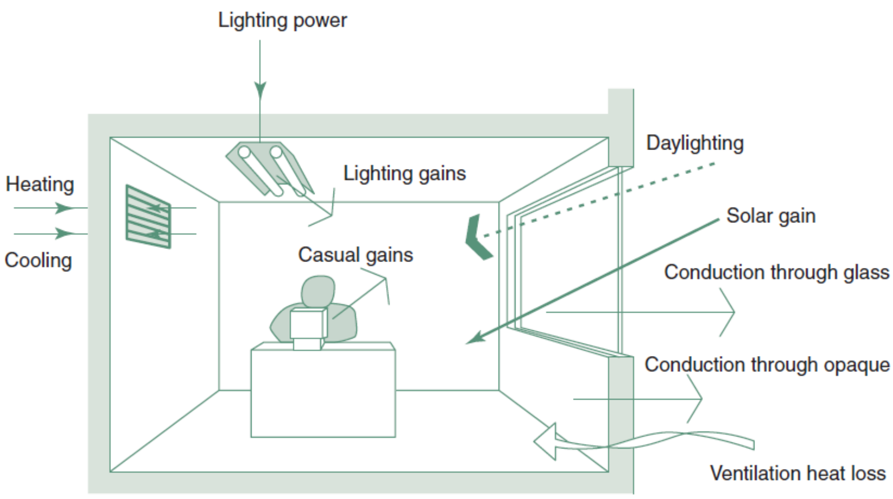


Figure 2-3 Energy flows considered in the LT method (Source: Baker et al., 1999, cited in Szokolay, 2008, p.182)

The basis of this design tool is a set of graphs known as the LT Curves that give annual primary energy consumption per square metre for north, east, west and south orientations of the façade, plus one for horizontal glazed apertures (roof light). Curves are presented for lighting, heating, ventilation and cooling, and total energy, in two climatic zones, northern UK and southern UK (Baker and Steemers, 2000, p.93). These curves are derived from a computer-based mathematical model, and since the LT method is primarily concerned with energy use for electric lighting, especially for non-domestic buildings in milder climates, it is important to understand the mathematical model that drives it in order to determine its applicability to other climate zones and building types, notably residential towers in the hot-humid climate of the Gulf Region.

Hyde and Pedrini (n.a.) have argued that a number of issues arise concerning the use of this method in hot climates for both the inputs of the basic parameters of the building form and the energy parameters inputs. Firstly, as regards the plan assessment and building form parameters, *"in warmer climates the buildings are in heat surplus rather than heat deficit and this places a differing thermal dynamic process. Secondly, the use of natural lighting and ventilation as environmental resources are significantly different in warm climates. Higher natural light levels and clear skies coupled with high humidity and solar gain are problematic*". Moreover, "*there is little consideration of shading effects and their impact on the energy consumption due to cooling loads and electric lighting loads. A simple method is available to interpret the existing data by assuming reductions of glazing ratios due to the blocking effects of shading devices. Whilst this approach may be satisfactory for cool or Mediterranean climates, the subtropics and tropics receive high levels of solar radiation which contributes significant heat loads*". Another issue is that the passive and non-passive zones or thermal zoning concept – which is the basis of the LT method – might be different in warmer climates due to higher levels of daylighting. In their study, Hyde and Pedrini emphasised the importance of establishing a more holistic energy analysis of the lighting and cooling energy consumption for shaded façades and proposed the LTV method (Lighting Thermal and Ventilation), which considers climate responsive design strategies for warm climates that can be used by architects to reduce energy consumption, covering façade planning and service strategies. They conducted two parametric studies to examine these primary design strategies and the results produced a set of guidelines for climate responsive design in warm climates; however, it did not define comparable graphs or curves like the LT method that integrate the effects of these strategies into a summative framework.

In essence, the LT method illustrates the two main issues which form the basis of this research: the importance of addressing climatic responsive design and energy use issues in the early design stages, and the integrated effect of façade design and thermal zoning on the energy consumption of the building.

Other methods or analysis techniques that inform the early design stages are the Skin Heat Flow and Window Solar Gain techniques proposed by Brown and DeKay (2001), which are discussed in further detail in Chapter 4. These emphasise the relationship between energy consumption and early design parameters and share some similarities with the LT method as they too are based on heat conduction through the external envelope or building skin, in addition to the integration of glazing ratio and building form. However, where the LT method relies on many fixed assumptions, especially for the thermal characteristics of the building envelope, the Skin Heat Flow and Window Solar Gain techniques allow for variations in these inputs. Moreover, while the LT method gives only broad indications of the primary annual energy consumption for lighting, heating and cooling and other techniques only estimate the heat flow through the skin and the solar gain through the windows and their contribution to building cooling and heating loads with no consideration for lighting, the Window Solar Gain technique requires certain values for the Solar Heat Gain Factor (SHGF), and shading coefficient for windows, both available in ASHRAE 1997, in addition to the glazing percentage. Note that the SHGF considers the window orientation, which means that several graphs will be produced depending on the window orientation.

Table 2-2 summarises the main comparisons between these methods, note that the two techniques proposed by Brown and DeKay (2001) can be used together to get the total heat gains through the building envelope.

Table 2-2 Comparisons between the design tools proposed by Baker and Steemers (1995) and Brown and DeKay (2001)

	The LT method (Baker and Steemers, 1995)	**The Skin Heat Flow (Brown and DeKay, 2001)**	**Window Solar Gain (Brown and DeKay, 2001)**
Climate	Specific to non-domestic buildings in UK.	Doesn't specify a certain climate or building type.	Doesn't specify a certain climate or building type, though the Solar Heat Gain Factor (SHGF) can be found in ASHRAE (1997) for 16°- 64° north lat.
Considerations	Based on mathematical model for heat conduction through external envelope Considers some outdoor weather and climate variables such as outdoor temperature, solar radiation and sky luminance. And they are fixed. Based on the concept of thermal zoning.	Based on the rate of heat flow through building skin Based on the thermal characteristics of the material. Does not consider outdoor weather or climatic variables.	Based on the amount of solar radiation transmitted through glazing and the thermal properties of glazing. Considers one climatic variable (clear-day radiation) to calculate SHGF.
Inputs	The main inputs are: zone area (m^2), façade glazing ratio (%), specific energy consumption per m^2 for light, heating, cooling, UHF. The envelope thermal characteristics are assumed and fixed, such as glazing type and U-value.	The main inputs are: U-value of opaque skin (W/Km^2), Overall skin U-value (W/Km^2), percentage of skin in double glazing (%), exposed skin area/floor area.	The main inputs are: Solar Heat Gain Factor (W/m^2), Percentage of skin in glazing (%), Shading coefficient (Glass X shade).
Outputs	The final output is annual primary energy consumption per square m (kWh/m^2).	The final output is skin heat flow (W/Km^2 of floor area), which determines cooling and heating loads.	The final output is the solar heat gain (W/m^2 of skin area), which determines cooling and heating loads.

In conclusion, based on the above argument and comparisons, it seems that using the analysis techniques and design tools proposed by Brown and DeKay (2001) might be more appropriate in the design or evaluation of buildings in the hot climates of the Gulf Region, for the following reasons:

- They are not specific to a certain building type or climate, unlike the LT method which is specific to non-domestic buildings in the UK climate. Therefore, it is possible to evaluate the impact of the façades of residential tall buildings using these techniques.

- They are more flexible in terms of variations in the inputs of the building envelope thermal characteristics. However, "*direct comparison of the LT-calculated energy performance with a real building is not likely to be relevant, unless it is known that the assumptions made by LT accurately describe conditions in the real building*" (Baker and Steemers, 2000, p.93). Meaning that the assumptions regarding the envelope characteristics for example should be similar, which is limiting.

- Unlike the LT method, they are not based on the thermal zoning concept, which, as Hyde and Perini (n.a.) argue, is different in hot climates, thus eliminating uncertainty of outcomes.

Although the LT method gives more information regarding energy consumption, Brown and DeKay techniques are simpler and provide the required initial understanding of the envelope performance. However, the author understands the limitations of these techniques and intends to use them only as the basis to start developing her own techniques for the assessment of building envelopes for tall buildings in the hot climate of Saudi Arabia.

Since the main focus of this study is the performance of the building envelope and façade design in residential tall building in the Gulf Region, the next section will review the current literature regarding the evaluation of the building envelope in the Gulf Region in order to establish the main gaps in current knowledge.

2.4 The Environmental Impact of Glazed Façades in the Gulf Region

The climate analysis for the cities of the Gulf Region conducted in Section 1.1.2 concluded that cooling, which is usually provided through mechanical ventilation and air-conditioning systems, is inevitable in this climate. However, the availability of cheap heating and cooling energy has created large numbers of buildings which neither accord with the criteria of the construction culture nor comply with fundamental energy efficiency rules (Kaufmann, in Hausladen et al., 2008, p.29). Meir et al. (2012, p.26) argue that "*over the last few decades, rapid urbanization in the UAE, as well as in other Gulf Cooperation Council (GCC) member states, has been characterized as showing significant influences of occidental architecture imported and implemented without adaptation considerations. This has had a great impact on the urban and architectural landscape not only in form (high-rise buildings with large glass facades), but also in subsequent energy demand for air conditioning, which has been on a steep rise.*" Nevertheless, as discussed in Chapter 1, the ecological building design approach adopted in other countries is now starting to affect policies in the Gulf Region too.

The Gulf Region has great potential for improving its sustainable development by taking an energy responsible approach to designing buildings that have a reduced impact on the environment. Reflecting on the literature review and studies conducted in the Gulf Region, most studies are concerned with reducing the cooling loads and air-conditioning demand through envelope thermal optimisation to increase the energy efficiency and operation of HVAC systems without compromising the desired level of thermal comfort (Fasiuddin and

Budaiwi, 2011; Iqbal and Al-Homoud, 2007). Interestingly, the primary focus of the literature is on the end product of one or more parameters, usually the thermal properties of the building envelope, rather than developing the design process or the integration of planning and design of the energy consumption elements, which, as discussed in Section 2.2, are the main contributors to energy efficient and climate responsive design.

There are many studies that evaluate the energy conservation measures in the built environment in the Gulf Region which ultimately inform the situation in Saudi Arabia. For example, Radhi (2009) conducted two studies focusing on the building envelope thermal insulation codes in Bahrain. In his first study, he investigated the ability of the current envelope thermal insulation codes in 'Article 32'[6] of Bahrain's new building energy codes to achieve the target of 40% reduction of building electricity consumption and CO_2 emissions in commercial buildings set by the country's Electricity and Water Authority. Cooling loads and electric energy were taken as criteria to assess the adequacy of these codes and two office buildings, a high-rise (12-storey) building and a low-rise (two-storey) building, were chosen as case studies. These were simulated in DOE in a parametric analysis, considering the thermal insulation code by multiplying the U-values of the walls and roofs, and the impact of window codes by altering the window area, construction of walls and glazing properties, respectively. The main findings of this study showed that in hot climates, tall buildings with large glazing area, regardless of their function, are skin-load dominated buildings and not internal load-dominated, as offices usually are. The thermal analysis revealed that reducing the thermal transmittance of the walls and roofs by reducing the U-value did reduce cooling loads but only in a relatively small pattern; in fact, it was shown that in such buildings in hot climates, reducing the thermal transmittance of the walls and roofs might increase the cooling loads because of the trapped internal heat gains.

As for the impact of the window code in relation to window area and glazing characteristics, the reduction of the WWR, and the reduction of the glazing U-value, shading coefficient and

[6] According to Radhi et al., (2009, p.2532), the Bahraini building energy regulation is an envelope components design standard that considers the heat flow through individual components of the building shell (e.g. external wall, roof and window). It considers the maximum U-value for two elements of the building envelope. For roofs and walls these are 0.6 and 0.75 W/m^2 °C, respectively. Article 32 permits the use of single glass in buildings with an area of glazing less than 20% of the façade. Where the area exceeds this percentage, the regulation requires the use of double-glazing.

visible light transmittance, clearly had a positive impact on cooling loads but it negatively affected the lighting loads since daylighting levels were reduced and artificial lighting was needed more often. However, the study concluded that the current prescriptive envelope components codes that aim to optimise the thermal performance of air-conditioned building envelopes alone are not sufficient to achieve the set reduction benchmark. Therefore, a more holistic approach must be applied.

In the second study, Radhi et al. (2009) investigated the influence of current envelope component regulations, including thermal insulation and window parameters, on the internal environment and thermal comfort in residential buildings in Bahrain. The drive behind the study was the lack of experience of the impact of the building standards on the internal environment, which may result in an energy efficient building that does not provide thermal comfort, due especially to the glazing impact. A parametric case study of a one-storey building was conducted through simulations using DesignBuilder software. The assessments of thermal sensation were based on simple measures of the indoor temperature, mean radiant temperature, relative humidity, air velocity and solar gains and represented by the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). The study suggested that an appropriate and careful treatment of building thermal mass could offer a better opportunity to control heat flow and provide a more comfortable internal environment than using a lower value of thermal insulation. Even though the Gulf Region is characterised by a hot-humid climate, these results can be justified since the Gulf Region suffers from higher air temperature and lower humidity in the summer months which may increase the diurnal variation and the effectiveness of the thermal mass strategy.

As for the window thermal and optical parameters, solar gain seemed to be the dominant factor with respect to the perception of comfort. Discomfort increased with higher SHGC, coupled with the secondary impact from the absorption of vertical solar radiation by the glazing systems. The window area also had an impact on thermal comfort by allowing more solar gains, which in turn affected the indoor air temperature. Thus, discomfort increased as the window area increased. Finally, the study concluded that although the thermal insulation regulations in Bahrain make little impact on thermal comfort, the use of a lower U-value and higher thermal mass can reduce the heat gain and, consequently, improve the internal conditions. On the other hand, the window regulations, particularly glazing, are more influential due to the high solar radiation. Therefore, it is important to improve the solar performance of glazing by considering the optical properties, including shading coefficient, light reflection and absorption, and most importantly, the window area, which can also be controlled through shading devices.

Along these lines, an earlier study by Al-Homoud (2003) emphasized the importance of using thermal insulation effectively to reduce the thermal loads of buildings in hot climates and cut the overall building energy needs, especially for air-conditioning and ventilation. He argued that although current regulations in the Gulf Region set minimum levels for thermal resistance values, "*most buildings in the region are not well insulated due to the absence of enforcements of such regulations and other standards from the regulating authorities' side as well as the lack of appreciation of the attained energy savings and economic gains from the user side. Consequently buildings use more energy than is necessary for their operation*" (Al-Homoud, 2004, p.236). However, he remained optimistic, highlighting the increased awareness and realisation of energy conservation benefits that led to the formulation of the thermal insulation regulations in buildings, and the tendency to expand the use of thermal insulation and other energy-conservation measures, in addition to the growth in relevant local industries to support future demand. An assessment was conducted to evaluate the impact of the building type (residential profile, office profile with light internal loads that represents skin-load dominated (SLD) buildings, and another office profile with heavy internal loads that represents internal-load dominated (ILD) buildings) on the performance of different types of envelope thermal insulation in two climatic conditions: the hot-arid climate in Riyadh and the hot-humid climate in Dammam. The study concluded that building type has a role in determining the effectiveness of envelope thermal insulation on the thermal performance of buildings, especially for SLD buildings with a residential profile. Of note also is the finding that the reduction in annual energy use and peak cooling loads was more significant in the hot-humid climate of Dammam, which might be the result of the difference in the severity of climatic conditions compared to Riyadh. Two earlier studies by the same author in 1997 concerning envelope optimum thermal design of air-conditioned residential and office buildings in hot and hot-humid climates in Saudi Arabia revealed that annual energy savings of as much as 37% and 38% respectively were achieved through the optimisation of a small two-storey residential building in Riyadh and in Jeddah (Al-Homoud, 2004, p.236).

As for the glazing elements of the building envelope, Aboulnaga (2006) looked at the influence of glass as a building element, whether a window or a fully glazed façade, assessing and evaluating its impact on the daylight environment inside buildings in Dubai, UAE. Fifteen buildings were investigated in terms of glass thickness, SC, LT, reflection and relative heat gain (RHG). The values of these glazing characteristics were compared with the upper benchmark enforced by the Dubai Municipality based on Thermal Insulation Resolution No. 66 (SC = 0.35) and the Bahraini Municipality upper limit (SC = 0.25). Based on these regulations they were classified into high performance, intermediate performance and low performance glazing types. The study concluded that glazed buildings with low SC (below 0.2), which fall well below the Dubai and Bahrain municipalities' maximum benchmarks, are the best performers in terms of LT and RHG. It also meant lower solar heat gain and glare. However, the evaluation of these towers didn't exceed the comparison in relation to these benchmarks, which is insufficient to produce enough evidence to draw a firm conclusion.

The above studies emphasise the importance of the building envelope characteristics, especially the effects of glazing on cooling loads and thermal comfort, and how the building regulations response to this may not necessarily be adequate. The following review highlights the literature specifically related to tall buildings in the Gulf Region as many studies have evaluated the so-called 'glass towers' in the region. These evaluations were carried out mostly through parametric analysis to study the impact of the glass material on the daylight environment, energy consumption and thermal comfort. The studies discuss the emergence of this building type as a result of rapid economic growth and the drive to introduce new symbols of power and prestige rather than fundamental environmental considerations.

Reflecting on the advantages and disadvantages of tall buildings in general, Givoni (1998) finds some advantages of tall buildings in hot climates as high-rise buildings tend to improve the air quality at street level by increasing the mixing of the cleaner air flowing above the urban canopy with air at ground level, thereby reducing the pollution concentration at ground level and positively impacting the health of the urban population. Moreover, because of the generally higher wind speeds above the average height of the urban canopy, and the further increase in the wind speed with height, the upper floors of tall buildings benefit from better ventilation conditions during periods of weak winds, but are exposed to more severe winds during storms. Lastly, the inhabitants of the upper floors of high-rise buildings often enjoy an expensive view of distant scenes from their windows.

On the other hand, the main disadvantage of these fully glazed structures in the hot climate of the Gulf Region is that they can only function through the extensive use of mechanical air-conditioning, which is reliant on fossil fuel derived electricity (Bahaj et al., 2008). Another disadvantage is highlighted by Etherige and Ford (2008, p.2): "*a particular problem with tall buildings is that they are often prestigious buildings that are air-conditioned to give close control of the internal environment under all conditions. These high expectations put more emphasis on achieving a natural system that gives as much control as possible, which is a major challenge*". However, as tall buildings are becoming predominant in the Gulf Region, "*more attention should be paid to designing them in an ecologically responsive way. This includes the importance of a careful façade design that ensures optimised energy conservation but also the utilization of solar radiation to meet the energy needs in the building.*" (Haase and Amato, 2006, p.2). This is particularly important as tall buildings are less likely to be shaded by nearby buildings, increasing the intensity of solar radiation impinging on them, either direct, diffused, and/or reflected off the roofs of lower buildings.

Along the same lines, Assem and Al-Mumin (2010) summarised the advantages and disadvantages of using large glazed areas in tall buildings. These included the suitability of the material for construction, as it is lightweight and fast to build, increasing the connectivity between the indoor and outdoor environment through transparency and views, and the provision of natural daylight. However, the most common disadvantages include the high cooling loads due to the significant irradiance levels, thermal discomfort due to the higher mean radiant temperature (MRT) caused by high surrounding surface temperatures, high infiltration rates resulting from unintentional outside air leakage due to poor workmanship, the need for continuous maintenance due to the hot and dusty conditions, and visual discomfort from the glare.

A study by Assem and Al-Mumin (2010) investigated the effect of glazing type and other energy conservation measures, such as building orientation, heat recovery system, lighting control, internal shading and overhangs, on the peak power demand of air-conditioning systems in tall and fully glazed office buildings in Kuwait. A computer model of an office building in Kuwait was established in EnergyPlus based on a survey of 10 individually-selected tall buildings with large glass façade areas in Kuwait, including Tijarya Tower and Al-Hamra Tower. The simulation compared two cases associated with the occupancy schedule: a government office building scheduled from 7am to 2pm, and a private office scheduled from 8am to 5pm, in addition to comparative analysis of different glazing types (clear double pane, tint low-e, clear low-e, reflective low-e), and the energy conservation measures mentioned above. The study concluded that glazing characteristics alone could not achieve the maximum peak load set by the Kuwaiti codes and other energy conservation measures had to be incorporated in the design. Thus, the results of the study can provide architects with recommendations as to the selection of glazing type and HVAC systems for fully glazed high-rise office buildings in hot climates.

Another study by Iqbal and Al-Homoud (2007) investigated the impact of alternative energy conservation measures on energy requirements in a six-storey office building in Dammam simulated in DOE-4 energy simulation program. The energy conservation measures were classified into three categories: no cost measures (set point temperature, night time setback, schedule of lighting and equipment), low cost measures (insulated wall and roof, more efficient glazing system, energy efficient lamps), and major investment measures (replacement of air-conditioning systems). The simulations showed that the glazing system plays an important role in the energy use pattern and in reducing the internal heat gains due to the large glazing area in the building. Indeed, the study found that the combined effect of all the energy conservation measures could result in annual energy savings of as much as 36%. It recommended using low-emittance double-glazing for energy efficiency, especially in large glazed buildings in hot climates, advice endorsed by Assem and Al-Mumin in 2010.

Regarding the emerging glazing technologies or new façade systems in buildings in the hot climate of the Gulf Region, a study by Bahaj et al. (2008, p.720) emphasised the importance of exploring the technical, economic, environmental and indoor comfort implications of the glazing technologies for façade application, since *"advanced glazing and solar control technologies are key to improving current performance levels and represent a first step towards higher sustainably of highly glazed tower buildings if these continue to be constructed*". The emerging glazing technologies had previously been viewed across the areas of high performance insulation (HPI), solar control (SC), daylighting (DL) and the potential of PV. Parametric simulations were run with models of rooms in the Burj Al Arab and the Jumaira Beach Hotel and seven glazing types technologies were assessed, addressing performance in terms of user comfort and building carbon foot print, operation and maintenance, availability, lifetime and risk. They were compared with existing low-e glazing and tinted glass with the aim of predicting the electrical air conditioning savings that could be achieved by the application of various façades technologies. As expected, the results indicated that minimizing solar heat gains would significantly reduce cooling loads in the Gulf Region, emphasizing the important role of glazing components in building façades.

Turning to other possible solutions, a study by Hamza (2008) investigated the performance of double skin façades in hot arid area by adopting an analytical approach using dynamic simulation software. A comparative analysis of cooling loads on a single skin base case was compared against three possible changes to the physical properties of the external layer of the double skin façade. The simulation results emphasized the influence of the façade orientation on cooling loads, especially in the direct solar radiation intensities in hot arid climates. For single skin façades, the solar coefficient of 0.27 can be considered as a benchmark for reducing cooling loads. The results also concluded that using a double skin façade with reflective glass on the outer leaf of the configuration led to the highest reduction in cooling loads compared with the benchmark single skin, which, according to the author, could replace the use of solid or heavy shading materials. This study opens many opportunities regarding the use of double skin façades in hot climates.

In a similar vein, a study by Radhi et al. (2013) investigated the impact of climate interactive façade systems (CRFS) on cooling energy in a multi-storey fully glazed building in the hot-arid climate of Al-Ain in the UAE. The assessment was carried out using building energy simulation and computational fluid dynamics (CFD) and compared the performance of CRFS with classical single façade system (CSFS), showing that CRFS façades can save up to 20% of cooling energy loads, which supported their previous study of the applicability of double skin façades for office buildings in hot climates. However, both studies were performed on multi-storey buildings but not on tall buildings. Other studies have suggested also considering the environmental variation with height or altitude for energy generation in building design, construction and operation, especially for 'super' tall buildings. A study by Leung and Weismantle (2008) based on an earlier study by Ellis and Torcellini (2005) looked at a hypothetical residential building similar to Burj Dubai (Burj Khalifa) located in the hot-humid climate of Dubai as a case study. This covered elements available at height and suggestions as to how to harvest and benefit from them, and indicated that the environmental factors that vary with altitude, such as temperature, air density and moisture, have a significant effect on the reduction in energy use and cooling loads. The study also offered advice on the design and operation of tall buildings based on calculations of the temperature and air density lapse rate.

2.5 Conclusion

Based on the above arguments, the building envelope can be defined as a key aspect in designing climate responsive buildings, determining a building's energy use and influencing its heating and cooling requirements. According to the publications discussed here, the building envelope could be responsible for as much as 30% of a building's cooling load. It also functions as an environmental filter, connecting the given external conditions and the required internal conditions. Careful planning and integration during the design process of the building façade is the key to producing energy efficient buildings, since decisions made at different stages of the building envelope's design can affect overall energy consumption and building performance. Nevertheless, most studies about the building envelope in the Gulf Region have focused on one or more of the engineering parameters - as described by Baker and Steemers (1996) - such as the thermal properties of the skin, rather than the integration of planning into the design process or the design of the energy consumption elements. This leaves a gap in the knowledge which has not yet been investigated.

The design of the building envelope, especially for tall buildings, is not a single process but a holistic cross-disciplinary design process that depends firstly on the outdoor environment and climatic conditions for each location, secondly on the building design, such as form, orientation and material characteristics, and thirdly on the functional recommendations as well as the building HVAC system. The early stages of the design process require rule-of-thumb design tools to evaluate the performance of the building envelope in relation to heat transfer and solar gains. The techniques proposed by Brown and DeKay (2001) can be used to establish the total heat gains through the building envelope for tall buildings in the hot Gulf climates, as will be demonstrated in the methodology of the forthcoming chapters.

The energy balance of buildings depends greatly on the properties of the envelope material, especially the glazing, due to their dynamic nature and multi-layered functions in relation to heat transfer, solar gains, ventilation and daylight. In the hot climate of the Gulf Region where solar radiation is abundant, the solar gain through glazing can be as high as 85% of the incident radiation. Therefore, the window and glazing properties are more influential than the wall properties for both energy savings and thermal comfort. In relation to glazing physical parameters, results have shown that the SHGC is more influential that U-value in energy consumption and thermal comfort since it determines the solar radiation penetrating through windows. Another important factor is window size since heat gain from the sun increases in relation to the proportion of window area, which consequently raises the cooling demand. Finally, the orientation of the glazing components also affects the solar gain, the design of the solar screening or shading system, and the entry of daylight as the brightness from the sky depends mainly on the elevation angle. Defining the glazing elements as the most influential components of the building envelope in relation to energy use and thermal comfort has determined the focus of this research, which will go on to study the parameters of the glazing elements in residential tall buildings in the Gulf Region.

In the next chapter, the current building codes and regulations and building rating systems in the Gulf Region are evaluated and compared in order to extract standards, energy targets, and values for the building envelope parameters such as U-value or SHGC to use as references and benchmarks for the next stages of the research methodology.

CHAPTER 3: A Comparative Analysis of Tall Building Codes and Practices in the Gulf Region

This chapter presents the first stage of the core research. This involved an evaluation and comparison of current local energy efficiency related building regulations, rating systems and approaches to practice in the Gulf Region, with the goal of understanding the major challenges, opportunities and novel approaches being developed and deployed. The findings indicate that the main challenges in tall building façade design in the region are on two levels, climatic and regulatory. This suggests that a mandatory regulatory framework should be developed and applied in order to deliver energy efficient buildings. Moreover, if energy efficiency is to be achieved in residential tall buildings, an integrated holistic cross-disciplinary design approach should be adopted in local building energy efficiency practices in the Gulf Region in general and in Saudi Arabia in particular.

Chapter 3 A COMPARATIVE ANALYSIS OF TALL BUILDING CODES AND PRACTICES IN THE GULF REGION

> *"Different countries have developed their specific vision of how to incorporate sustainable development particularly to the built environment. Special focus should be put on the building envelope design since the local climate requires customized solutions…. The building envelope ought to be: affordable, durable, energy-positive, environmental, healthy and comfortable, and intelligent."-*
>
> Matthias Haase and Alex Amato in their paper about Sustainable Façade Design for Zero Energy Buildings in the Tropics, published in The 23rd Conference on Passive and Low Energy Architecture, 2006, p.1
>
> *"The most direct path to improving efficiency is likely through mandatory regulations and standards as opposed to behaviour changes which might take years or decades to make impact."*
>
> Nurzat Myrsalieva and Amer Barghouth in the Arab Future Energy Index (AFEX) for Energy Efficiency in 2015, p.13

In the previous chapters, the author has established that residential buildings in Saudi Arabia account for more than 50% of all delivered energy consumption across the country, with the use of air conditioning to cool indoor spaces accounting for more than half of the energy consumed in buildings. Other sources have claimed that buildings consume up to 70% of energy in the Gulf Region - compared to 40% worldwide - due to the predominance of glass skyscrapers and the hot climatic conditions (Al Arabiya News, 2012). Additionally, research has indicated that the building envelope could be responsible for as much as 30% of the cooling loads, therefore, the design of the building envelope has a significant impact on a building's energy use and its heating and cooling requirements. Furthermore, studies have shown that adapting the building codes and regulations to work *with* rather than *against* the harsh climate in Saudi Arabia and the GCC countries represents some of the largest proven savings, with up to 70% reductions in energy demand. However, a report from Ventures Middle East (Construct Arabia, 2012) noted that amongst the GCC countries, only the UAE and Qatar are pioneers in developing exclusive building codes to address the problems of sustainability and standardization to bring building construction up to international standards, and while Saudi Arabia has been quick to follow, Bahrain and Oman are yet to engage meaningfully with green building construction.

The overall aim of this research is to investigate the performance of residential tall building façades in the Gulf Region in order to assess and prioritise energy efficient building envelope solutions and design strategies for this building type. Therefore, one of the main objectives of this chapter is to investigate and evaluate current energy efficient codes and building regulations in the Gulf Region in relation to the energy performance of residential tall buildings in order to contribute to their effectiveness and potential enhancement. This chapter also contains interviews with key practitioners from three leading engineering design companies who are actively involved in the design of tall buildings in the Gulf Region. These interviews were conducted in order to better understand the industrial approach to the research findings discussed in Chapter 2, to collect further data and to identify the main challenges and opportunities involved in the design of this building type.

3.1 Energy Efficient Building Regulations in the Gulf Region

The most progressive energy efficient building regulations in the GCC countries are those in Abu Dhabi, Dubai and Qatar. The Estidama Pearl Rating System in Abu Dhabi, which began to be applied in 2010, was the first of its kind in the Gulf Region to draw on international best practice but with adaptations to suit local climatic conditions and social needs. Qatar has pioneered the Global Sustainability Assessment System (GSAS) in which energy and water efficiency are benchmarked and attached to a six-star rating system (Lahn et al., 2013). In addition, as mentioned earlier, the GCC countries have agreed to introduce a common standard for energy efficiency regulations which takes account of existing standards through close cooperation between the standards authorities in each country and is likely to draw heavily on GSAS and the Pearl Rating System (Lahn et al., 2013). Therefore, this study focuses on the three established energy efficient building regulations and sustainability rating systems in the Gulf Region: the Green Building Regulations and Specifications from Dubai Municipality (GBRS, 2010), the Pearl Building Rating System for Estidama (PBRS) from Abu Dhabi (Estidama, 2010b), and the Global Sustainability Assessment System (GSAS, 2013) from Qatar). These are reviewed and evaluated for two main reasons: firstly, to understand the current regulations determining the building characteristics and design approaches in the Gulf region, especially for tall buildings; secondly, to use them as a benchmark to assess the Saudi Building Code Energy Conservation Requirements (SBC 601, 2007), which is the standard used for new buildings in Jeddah in Saudi Arabia, the focus of this research. Moreover, the Guidelines for Tall Buildings Specifications and Technical Requirements for Jeddah (Municipality, 2013) are reviewed and compared as well.

Energy efficient building regulations are usually divided into three types: prescriptive based regulations, performance based regulations, and the mixed approach, a compromise between the prescriptive and performance based types. According to Myrsalieva and Barghouth (2015, p.51), *"performance based regulations are generally regarded better than prescriptive ones, as they look at the building as a whole system and allow achieving EE [energy efficiency] at the lower cost due to greater flexibility given to designers and architects. At the same time, performance based regulations can be more difficult to design as they require a higher level of expertise, which is often lacking in developing countries. They also require the policy makers to have more detailed data on the baseline energy consumption in order to develop realistic EE requirements"*. This categorization will be used in the following reviews.

3.1.1 The Green Building Regulations and Specifications in the Emirate of Dubai

The government of the UAE has identified the building sector as a major consumer of energy in the country, and realised the important role that efficiency codes can play in reducing energy consumption. Hence, the thermal insulation code was first applied in the country, and then green building codes were introduced (Radhi, 2010).

In Dubai, the Electricity and Water Authority issued the second phase of its Green Building Regulations and Specifications (GBRS) in April 2010 as part of Dubai's Strategic Plan 2015 to create a more sustainable urban environment and extend the ability of the emirate's infrastructure to meet the needs of future development (GBRS, 2010). These regulations also aim to reduce energy demand in new buildings by up to 40% (Meir at al., 2012). In order to achieve this, Dubai has chosen a regulatory framework rather than a rating system which reviews various aspects of the building process and awards 'credits' or 'points' for a certain level of achievement. The GBRS are an addition to the current codes and standards that set out mandatory minimum performance standards for buildings. They are applied voluntarily to public and private buildings, but mandatorily to all new governmental buildings.

The GBRS have been developed to be Dubai-specific, closely related to Dubai's particular climate and conditions. Their aim is to create a link between Dubai's building regulations and the wider picture of sustainability, and they are intended to improve the performance of buildings in Dubai by reducing the consumption of energy, water and materials, improving public health, safety and general welfare and by enhancing the planning, design, construction and operation of buildings. They comprise two documents: the Green Building Regulations and Specifications and the Practice Guide document. The Practice Guide provides guidance and further information on implementation and compliance, including a re-statement of each of the regulations, and offers some explanation of the reasons for the regulations and their intended benefits. However, it is not intended to provide detailed design information or to be a substitute for the experience and expertise of building designers and contractors.

As the GBRS explain, there are two compliance routes for energy performance in buildings: a) The standard method, referred to as the 'Elemental Method', which means buildings must comply with all of the regulations; b) The alternative method, referred to as the 'Performance Method', a calculation method that can be employed for a building which may not comply with all the elemental requirements (orientation of glazed façades, minimum envelope performance requirements, energy efficiency in HVAC equipment and systems, lighting power density for interiors). The Performance Method compares the annual energy consumption of the proposed building with that of a reference building that meets all the elemental requirements using a calculation tool such as dynamic thermal modelling. The reference building must be equal in shape, size and operational patterns to the proposed building. Compliance with the GBRS will be demonstrated if the annual energy consumption of the proposed building is equal to or lower than the annual energy consumption of the reference building.

The GBRS include sections about ecology and planning, building vitality, and resource effectiveness, including energy, water, material and waste. In the Ecology and Planning section there is a chapter about the orientation of glazed façades or external shading which allows the choice of either providing external shading by installing horizontal external shading devices with a minimum Vertical Shadow Angle (VSA) of 70° or orienting the glazing by calculating the total area of glazing on each façade and confirming that the north façade has at least 60% of the total area of glazing. It also highlights the benefits of implementing this regulation noting that reducing direct solar radiation in this way corresponds to a 7% reduction in a building's cooling demand. Another important section is Building Vitality as it includes a chapter about ventilation and air quality which specifies the ratio of openable window to floor area at 10% and discusses the benefits of introducing natural ventilation through openable windows by adapting the mixed mode ventilation method especially in residential buildings. Table 3-2 summarizes the main energy efficiency building regulations mentioned in the GBRS relating to the orientation and treatment of glazed facades which are applicable to tall buildings in the region.

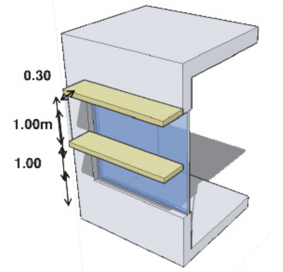
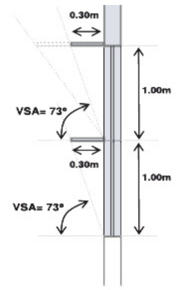
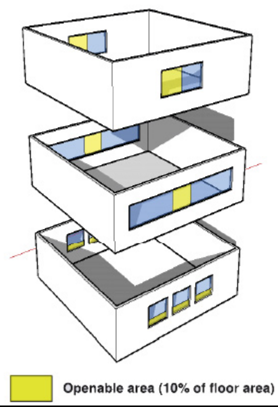
The GBRS mention the ASHRAE Standard 55-2004 (ANSI/ASHRAE 55-2004, 2008) as a useful reference for understanding some of the regulations related to thermal comfort, air quality and ventilation. However, the regulations have developed their own range of temperature and humidity for building users in Dubai as shown in Table 3-1. According to the GBRS, any heating, ventilation and air conditioning (HVAC) system must be capable of providing this range of conditions for 95% of the year to ensure occupants are both comfortable and productive.

Table 3-1 The acceptable range of conditions to achieve thermal comfort in Dubai (DGBRPG, 2011, p.120)

	Lower Limit	**Upper Limit**
Dry bulb temperature (°C)	22.5	25.5
Relative humidity (%)	30	60

Moreover, the GBRS Practice Guide explains that ventilation and air conditioning equipment in Dubai's buildings accounts for up to 60% of the total energy consumption, and that improving the performance of the building thermal envelope will result in lower air-conditioning requirements, reducing energy use, costs and maintenance. The thermal performance of the building envelope is dependent upon the heat transfer characteristics of each building envelope element, such as the U-Value and SC. The Resource Effectiveness section of the regulations specifies the minimum envelope performance requirements for the external building elements and glazed fenestration systems. The performance criteria are linked to the percentage of transparent glazed area by defining three glazing area ranges: up to 40% of the façade, up to 60% of the façade and greater than 60%, meaning that the higher the glazing area the lower the thermal transmittance values. These thermal requirements for building envelope components are discussed in more detail below and compared with the Saudi Building Code Energy Conservation Requirements (SBC 601) in Table 3-8.

Table 3-2 Energy efficient building regulations as specified and compiled from the Dubai Green Building Regulations; Practice Guide (2011)

Regulation	Guidelines	Impact	Illustrations
Orientation of Glazed Façades	At least (60%)[7] of the total glazed surface area of the building, (excluding glazed areas with back insulated panels), must have a predominantly north orientation. South and west glazed areas, excluding glazed areas with back-insulated panels, must be treated environmentally[8].	- In Dubai's near-equatorial latitude, the sun appears at higher angles with high incident solar radiation, resulting in direct solar heat gains, which increase the cooling loads of buildings. - Decrease the negative effect of solar gain, which increases the internal surface temperature of the windows. This increases the mean radiant temperature of the room, making occupants feel uncomfortable, even when the air temperature is within comfortable levels.	 [1] Horizontal shading devices protect from high-angle sun
Using external shading	Using external shading instead of tinted glass and internal blinds. A Vertical Shadow Angle (VSA) of 70° as a minimum requirement that can be achieved by various combinations of shading design.	Positioning horizontal shading fixtures with a VSA of 70° on a building with a glass surface area of 40% of that of the façade, the reduced direct solar radiation corresponds to a 7% reduction in building cooling demand.	 [2] Elevation view: VSA of a pair of horizontal fins
Openable Windows	For all new buildings, openable windows must be provided to allow mixed mode ventilation that combines mechanical and natural ventilation for at least parts of the year. The ratio of openable windows to floor area to be at least 10%.	Using natural ventilation reduces energy consumption and provides improved indoor environmental quality, control by occupants and psychological and health benefits.	

[7] The GBRS specify 50% while the Practice Guide states 60%

[8] The GBRS do not clearly explain how to environmentally treat these facades; however, they do mention the use of external shading which is considered an environmental response.

Finally, the Appendix includes Green Building Tips explaining some of the processes carried out as part of the development of the regulations, such as energy modelling conducted to show the impact of the percentage of glazing, orientation and shading on cooling loads. It also covers some voluntary aspects of building design and operation which can be incorporated in the Green Building programme, such as the glazing percentage, orientation and shading.

In conclusion, there are many advantages to the GBRS and its Practice Guide as follows:

1. They are accessible, available freely online and easy to read.
2. They propose both the Elemental Method, which is prescriptive, and the Performance Method, which is a simulation method and therefore more flexible.
3. The regulations are Dubai specific and relate to its specific climate and conditions, visible in building orientation considerations and shading elements specifications.
4. They provide clear communication to designers, architects, developers and contractors in terms of explaining the reasons and benefits for each regulation, its impact on sustainability, the environment, energy efficiency and user comfort.
5. They provide clear recommendations for the engineering parameters in building design and also include some advice on design parameters such as guidance on shading devices. Although they are not specific to tall building design in general, or to residential buildings in particular, they can be applied to most building types.
6. The regulations are explained clearly in a logical structure, each regulation starts with a statement followed by its goals and intentions, general background, the applicability in relation to building typology, the outcome and benefits regarding sustainability, energy and comfort impact, compliance and implementation guidance, in addition to common practices, solutions and references. This easy-to-follow structure can be used as a reference for other cities in the region, such as Jeddah in Saudi Arabia.

Dubai's Green Building Regulations and Specifications cover most aspects of sustainable building design, explaining in clear and direct language the intentions and benefits behind them and giving some technical data and specifications to guide the parties involved in the building industry. However, extremely tall buildings are exempt from these regulations.

3.1.2 The Pearl Building Rating System for Estidama in Abu Dhabi

The government of Abu Dhabi launched the Estidama Program as part of the Plan Abu Dhabi 2030 urban master plan that addresses sustainability as a core principle (Abu Dhabi Urban Planning Council, 2010). The Pearl Building Rating System (PBRS) is one of Estidama's key initiatives, similar to other LEED and BREEAM inspired assessment tools but very detailed and multi-faceted, and it is expected to be integrated into the building code (Meir et al., 2012).

The PBRS aims to address the sustainability of a given development throughout its lifecycle from design through construction to operation, providing design guidance and detailed requirements for rating a project's potential performance in relation to the four pillars of Estidama: environment, economics, culture and society. The rating system compromises two types of credits: 'Required' credits that must be met by every project submitted for a Pearl Rating with no credit points awarded for achieving them, and 'Optional' credits which are voluntary performance credits from which points may be accrued. Depending on the Pearl Rating level being sought by a design and development team, the number of credits and the level of achievement will vary from project to project. To achieve a 1 Pearl rating, all mandatory credit requirements must be met, as shown in Table 3-3.

Table 3-3 Pearl Building Rating Levels (Source: Pearl Building Rating System: Design and Construction, 2010, p.2)

Requirements	Pearl Rating Achieved
All mandatory credits	1 Pearl
All mandatory credits + 60 credit points	2 Pearl
All mandatory credits + 85 credit points	3 Pearl
All mandatory credits + 115 credit points	4 Pearl
All mandatory credits + 140 credit points	5 Pearl

According to Abu Dhabi Urban Planning Council, an Executive Council Order of May 2010 states that, as of September 2010, all new buildings must meet the 1 Pearl requirements whilst all new government funded buildings must achieve a minimum of 2 Pearls. Following this mandate, significant efforts have been made to align the PBRS with the Abu Dhabi Development and Building Codes (Estidama, 2010).

The Pearl Rating System recognises three rating stages: Design, Construction and Operational. It is organised into seven categories: integrated development process, natural systems, liveable buildings, precious water, resourceful energy, stewarding materials, and innovative practice. Each section includes both mandatory and optional credits and points are awarded for each optional credit achieved.

In relation to the minimum energy performance requirements, the rating system mandates using a decision-support tool to assist in making informed decisions regarding the options, implications and benefits of various aspects of the building design in order to achieve minimum levels of energy efficiency. It outlines the methodology to develop an energy model for the proposed building using appropriate dynamic simulation modelling software and to calculate the baseline building energy consumption according to the minimum mandatory requirements for building envelope, HVAC, service water heating, power, lighting and other equipment for the Building Performance Rating Method outlined in Appendix G of the ASHRAE Standard 90.1-2007. The rating system requires a minimum 12% performance improvement compared to the baseline building performance demonstrated by the energy simulation model as per the methodology outlined in the ASHRAE Standard. However, performance improvements within the PBRS are based on reduction in annual energy consumption (kWh) rather than cost, so all references to energy rates within Appendix G should be ignored.

The proposed building's performance improvement is defined in Equation 3-1 as:

$$\textbf{Percentage Improvement} = 100 \times \frac{\left(\text{baseline building performance (kWh/yr)-proposed building performance (kWh/yr)}\right)}{\text{baseline building performance (kWh/yr)}}$$

Equation 3-1: The equation used to calculate the improvement in the proposed building's performance within the Pearl Rating System, which is based on reductions in annual energy consumption (kWh) (Source: PBRS, 2010, p.141)

The proposed and baseline building performance must be calculated using the same dynamic simulation modelling software and the same weather data. Baseline HVAC systems and building envelope parameters must be set at those required in the ASHRAE Standards.

Additionally, proposed designs which demonstrate reductions of more than 12% beyond the baseline building consumption are awarded credit points in the PBRS. Additional award credit points can be also achieved if effective passive design measures and solutions are incorporated into the building design to reduce the external heat gain and cooling demand.

In addition, the PBRS offers an additional guidance document, the Energy Prescriptive Pathway, which includes a prescriptive methodology applicable to buildings with a gross internal floor area (GIFA) of 5000m^2 or less. The Prescriptive Approach outlines target performance for building envelopes, HVAC systems, service hot water, lighting (internal and external), and renewables. It is intended to set a higher standard of performance than the Performance Approach - or the Building Performance Rating Method mentioned above - in order to set suitably stringent targets for energy usage and to enable an appropriate level of improvement beyond the baseline requirements.

Moreover, PBRS has introduced the 'Estidama Energy Modelling Timeline' (Figure 3-1), which provides a summary of the major analytical steps typically undertaken throughout the design stages of any project: Concept, Scheme Design, Detailed Design, Working Drawings/Tender, Post WD/TD Issues, and finally, Estidama Design Submittal. A range of analysis techniques must be employed throughout these design stages including steady state calculations, dynamic thermal modelling, shadow/shading assessment, daylight modelling and computational fluid dynamics.

In conclusion, just like Dubai's GBRS, the documents associated with the PBRS are accessible, easy to read and freely available online. And even though they are a ranking system, they set minimum mandatory performance requirements for all buildings types in Abu Dhabi, including multi-residential developments, enforcing minimum standards and offering the flexibility of optional improvements. They also propose the prescriptive and performance methodology for building codes and regulations. However, unlike Dubai's GBRS, the energy requirements in PBRS are not specific to Abu Dhabi, since they follow the ASHRAE standards, and they do not set specific energy performance targets.

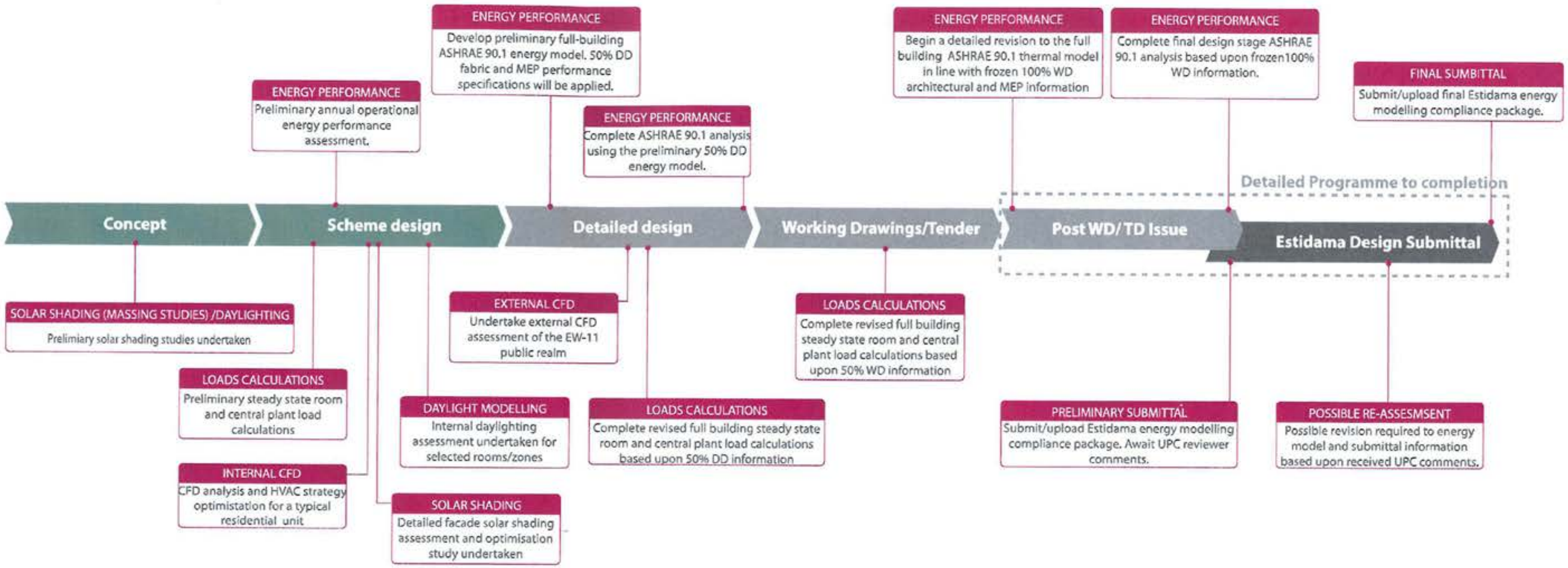


Figure 4-1 The Estidama Project Energy Modelling and Environmental Design Timeline (Buro Happold, 2013)

3.1.3 The Global Sustainability Assessment System in Qatar

In 2013, The Gulf Organisation for Research and Development (GORD) introduced the Global Sustainability Assessment System (GSAS) framework, formerly known as the Qatar Sustainability Assessment System (QSAS). The GSAS framework was initiated in 2007 and developed in collaboration with the TC Chan Centre at the University of Pennsylvania, the School of Architecture at the Georgia Institute of Technology, USA and other expert institutions (GSAS, 2017). The assessment system was developed by drawing together best practices from 40 different regional and international rating systems to create a sustainable built environment that minimises ecological impact while addressing specific regional needs, environment cultures and policies (GSAS, 2017). The measurements for the rating system are designed to be performance-based and quantifiable, the first such in the MENA region, and customised to the unique conditions and requirements of the State of Qatar (Meir et al., 2012). The GSAS includes schemes and typologies to evaluate commercial, core and shell buildings, residential (single family housing units and multi-unit dwellings), education buildings, mosques, hotels, light industry, and sports facilities, as well as projects on the scale of parks and districts. The complete resources for GSAS including the manuals of GSAS Building Typologies Design Assessment, the GSAS Building Typologies Design Guidelines, the GSAS Technical Guide, GSAS overview presentation, GSAS Supplementary Guide, GSAS certification flowcharts & processes, and application forms, are all available and accessible online.

The GSAS criteria are divided into eight categories: urban connectivity, site, energy, water, material, indoor environment, culture and economic value, management and operation. These are broken down into specific criteria that measure and define individual issues. All GSAS criteria and their associated measurements are quantifiable on the scale of 1 to 3. The assessment system consists of six certification levels to measure a project’s impact. The highest score a building can achieve is 3.0 and the highest certification level is 6 stars.

The resources for GSAS include the GSAS Building Typologies Design Guidelines, which provides recommendations and guidance on the effective implementation and the sustainable goals of each criterion within the design assessment system (Alhorr, 2015a). Meanwhile the GSAS Design Assessment evaluates the building during the design process, performing measurements related to normative standards and accepted practices, and considering what impacts the project can mitigate, in order for a project to receive its certification following the completion of the design verification process (Alhorr, 2015b). The GSAS Technical Guide also sets out to provide an overview of the assessment system for practitioners in the application of GSAS certification for design, construction, and operations of the built environment (Alhorr, 2017a). As for the GSAS Construction Management Guidelines as Assessment, it evaluates the sustainability impact of a building or infrastructure project over the course of the construction phase (Alhorr, 2017b).

In relation to the Energy category, the GSAS Design Guidelines 2015 provide a series of recommendations for designers to improve building energy performance through the components and parameters that affect the total building energy consumption. In order to establish these, GSAS has introduced an energy assessment methodology comprising performance-based normative calculations that calculate the building's energy demands and consumption and its CO_2, NO_x, and SO_x emissions due to energy use (Alhorr, 2017). This energy calculation is translated into the Energy Performance Coefficient (EPC), a measure that quantifies how well a building design performs in relation to a baseline design, which then determines the appropriate criterion scores.

The EPC is calculated at three levels of design (the building, its system, and its supply network) covering five assessment criteria:

1. Energy Demand Performance: represented by the EPC_{nd}[9] which is calculated based on building data, internal heat gain, occupancy, material, envelope input, fresh air ventilation and cooling energy needs;
2. Energy Delivery Performance: represented by EPC_{del}[10], calculated based on building systems, including ventilation, lighting, pumps, cooling, (de) humidifying, and domestic hot water preparation;

[9] 'nd' refers to 'demand' in Energy Demand Performance.
[10] 'del' refers to 'delivery' in Energy Delivery Performance.

3. Primary Energy Sources: represented by EPC_p. This criterion considers fossil fuel conservation. By utilising the characteristics of the overall energy supply network, losses and generation, a building's energy consumption is then translated into its depletion of primary energy sources;
4. CO_2 Emissions and Offset;
5. NO_x, SO_x, and Particular Matter (Alhorr, 2015b).

The GSAS Design Assessment obliges all projects to determine the Energy Demand Performance, which evaluates the thermal energy demand for different buildings types by calculating the monthly cooling needs to define a final EPC_{nd} value using Equation 3-2 below. Based on the inputs of the building's data, occupancy schedule, construction and envelope materials, this is used to determine the project's score for this criterion.

$$EPC_{nd} = Q_{design} / Q_{ref\_nd}$$

Equation 3-2: Calculated Energy Performances Coefficient to determine the building's energy demand performance in GSAS (Source: Alhorr, 2015b)

Where Q_{design} is calculated according to the GSAS Energy Application document, and Q_{ref_nd} is the baseline reference specified in the manuals. Table 3-4 below sets out the baseline references for each criterion of the building energy performance assessment levels for residential buildings specified in the GSAS Design Assessment (Alhorr, 2015). In terms of this research, the baseline of 121 kWh/m^2/yr for Energy Demand Performance (referred to as Q_{ref_nd}) is the most relevant one to be used as a benchmark (highlighted in Table 3-4).

Table 3-4 Baseline references for residential building energy performance assessments in GSAS (Source: GSAS Building Typologies Design Assessment (Alhorr, 2015b)

Energy Measure Criteria	Baseline Reference
Energy Demand Performance	121 kWh/m^2/yr
Energy Delivery Performance	98 kWh/m^2/yr
Fossil Fuel Conservation	179 kWh/m^2/yr
CO_2 Emissions	39,597 g/m^2/yr
NO_x, SO_x, and Particulate Matter	$NO_{x,ref}$ = 59 g/m^2/yr, $SO_{x,ref}$ = 111 g/m^2/yr

In conclusion, the GSAS framework, as a building energy performance assessment, uses holistic analysis for the predicted building energy consumption and to set targets for energy performance. In this respect it is unlike any other building code or ratings systems in the Gulf Region. Moreover, it provides clear design guidelines that are specific to Qatar and responsive to changes in building sites such as climate and orientation, including thermal specifications for the opaque and transparent elements of the building envelope and utilisation of passive solar design considerations, in addition to the building's internal loads.

However, although many large-scale projects in Qatar have adopted GSAS, the assessment system is not mandatory for all buildings in the country and this reduces its positive impact. Nevertheless, GSAS has been revamped and repositioned for adoption by the GCC countries as a regional green building code, as noted in Chapter 1 (Construct Arabia, 2012).

3.1.4 The Saudi Building Code Energy Conservation Requirements

The Saudi Building Code (SBC) is based on the International Code Council (ICC) and was published in 2007. It includes The Saudi Building Code Energy Conservation Requirements (SBC 601) which are based on the International Energy Conservation Code (IECC). The SBC 601 establishes minimum prescriptive and performance related regulations for the design of energy efficient buildings through the design of building envelopes and the selection and installation of energy efficient mechanical, service water heating, electrical distribution, illumination systems and equipment for the effective use of energy in buildings (SBCNC, 2007). They consider two buildings types: residential and commercial buildings. However, other than detached one and two family dwellings and townhouses, buildings with a height of four or more storeys are considered to be commercial regardless of the number of floors of residential occupancy.

The SBC 601 set a basis for two compliance assessment approaches for low rise residential buildings which can be followed in building design. The first approach is the performance or *simulation method* described by Lopes et al. (2011) which analyses and compares the annual energy consumption of the proposed building design with a reference building, called the 'Standard Design', that is equal in shape, size and operational patterns to the proposed building design, but whose enclosure elements (U-value for exterior walls, U-value and SHGC for fenestration systems, window area) and energy consuming systems are designed by climate accordance determined by degree-days calculated from the meteorological stations of Saudi Arabia and according to the requirements of the SBC 601. Two models must be built, the 'proposed design' model (in accordance with the proposed project) and the 'standard design' model (in accordance with the required efficiency level), and both configured and simulated using identical methods and techniques in order to prove that the 'proposed design' has equal or lower annual energy use than the 'standard design'.

The second option is the building envelope individual component performance approach. The SBC 601 set the minimum building envelope requirements for enclosed conditioned residential buildings, including moisture control, air leakage, fenestration SHGC, U-value for walls, roof/ceiling, floors and glazing. Compliance with the building code for this approach can be assessed by:

1. Total building envelope performance, where the total thermal transmission heat gain for the proposed building envelope does not exceed the total heat gain resulting from the proposed building conformance to the values specified in SBC 601, *or*
2. By acceptable practice on an individual component basis, where other assemblies are permitted, provided documentation, in accordance with accepted engineering practice, is submitted indicating the thermal transmittance value of the opaque elements,
   or
3. By prescriptive specification on an individual component basis, where the prescriptive building envelope requirements for glazing U-value, R-value for ceiling, floor and exterior wall are specified based on degree days and window area of gross exterior wall area.

Table 3-5 illustrates the prescriptive building envelope requirements for detached family dwellings in the locations of degree days (3890-4729) in the city of Jeddah.

Table 3-5 Prescriptive building envelope requirements for residential building types in Jeddah (DD3,900), (Source: SBC 601, 2007, p.4/13, Table 4.2.2.4)

Residential Type	Window area %	Glazing U-value (W/m^{2}°C)	Ceiling U-value (W/m^{2}°C)*	Wall U-value (W/m^{2}°C)	Floor U-value (W/m^{2}°C)
Detached one and two family dwellings	8	2.39	0.15	0.35	0.3
	12	2.27	0.11	0.27	0.3
	15	2.00	0.11	0.27	0.27
	18	1.88	0.11	0.22	0.18
	20	1.70	0.11	0.21	0.27
	25	1.42	0.11	0.30	0.18
Residential for more than two dwelling units	20	2.00	0.15	0.35	0.30
	25	2.00	0.15	0.35	0.30
	30	1.82	0.15	0.27	0.18

* U-values for ceiling, wall and floor were converted from R-value

In relation to tall buildings requirements, the SBC 601 (2007, p.1/2) state that buildings with four or more storeys above ground are considered commercial buildings for the purposes of the requirements, regardless of the number of floors that are classified as residential. Thus, all tall buildings, regardless of their function, are considered as commercial buildings, where the approach identified by 'acceptable practice' should be used for compliance assessment. The acceptable practice approach specifies the criteria for the building envelope components based on the percentage of the walls' glazing area. However, buildings with a glazing area in excess of 50% of the gross area of walls is required to meet the applicable provisions of ASHRAE/IESNA 90.1 (Energy Standard for Buildings Except Low-Rise Residential Buildings). The requirements for building envelope components are also dependant on climate, which is expressed through cooling degree-day. The maximum SHGC and U-value of windows and glass doors are specified based on the Window Projection Factor, which is determined in accordance with Equation 3-3:

$$PF = A/B$$

Equation 3-3: The equation to calculate Window Projection Factor based on the window's vertical and horizontal measures (Source: SBC 601, 2007)

Where: *PF* = Projection factor

A = Distance measured horizontally from the furthest continuous extremity of any overhang, eave, or shading device which is permanently attached to the vertical surface of the glazing.

B = Distance measured vertically from the bottom of the glazing to the underside of the overhang, eave, or permanent shading device.

Table 3-6 illustrates the building envelope requirements for the city of Jeddah, where the cooling degree-days were calculated based on the reference as 3,900.

Table 3-6 Building Envelope Requirements for 3889 ≤ Cdd (℃) < 4166, as extracted from the SBC601

Glazing percentage			**≤ 10%**	**10 – 25%**	**25 – 40 %**	**40 – 50 %**
Windows	*Solar Heat Gain Coefficient*	PF < 0.25	Any	0.5	0.5	0.4
		0.25 ≤ PF < 0.50	Any	0.6	0.6	0.5
		PF ≥ 0.50	Any	0.7	0.7	0.7
	U-value	PF < 0.25	3.975	2.839	2.271	2.271
		0.25 ≤ PF < 0.50	3.975	2.839	2.271	2.271
		PF ≥ 0.50	3.975	2.839	2.271	2.271
External walls (U-value)	*Framed R-value cavity*	No Framing	NA	NA	NA	NA
		Metal Framing	0.43	0.43	0.43	0.43
		Wood Framing	0.51	0.51	0.51	0.43
	Framed R-value continuous	No Framing	NA	NA	NA	NA
		Metal Framing	1.89	1.89	1.89	0.81
		Wood Framing	0	0	0	1.4
	Concrete masonry units (CMU) ≥ 200mm: U-value cavity	No Framing	NA	NA	NA	NA
		Metal Framing	0.51	0.51	0.51	0.43
		Wood Framing	0.51	0.51	0.51	0.51
	Concrete masonry units (CMU) ≥ 200mm: U-value continuous	No Framing	1.13	1.13	1.13	1.13
		Metal Framing	0	0	0	0
		Wood Framing	0	0	0	0
	Other masonry walls: U-value cavity	No Framing	NA	NA	NA	NA
		Metal Framing	0.51	0.51	0.43	0.43
		Wood Framing	0.51	0.51	0.51	0.51
	Other masonry walls: U-value continuous	No Framing	1.13	1.13	0.94	0.94
		Metal Framing	0	0	0	1.89
		Wood Framing	0	0	0	0

* U-values for walls were converted from R-value

Finally, building mechanical systems and equipment are mentioned in relation to heating and cooling load calculations. The design loads should be determined following the procedures described in the ASHRAE Fundamentals Handbook (ASHRAE, 2013). As for the design conditions, the SBC 601 set the outdoor design conditions based on the outdoor design temperature in the ASHRAE Fundamentals Handbook and the degree days calculated from the Metrology and Environmental Protection Administration in Saudi Arabia.

In conclusion, there are some critical points to reflect on:

1. Like most of the GCC standards, these energy efficiency regulations were developed with the support of external professionals and academic organisations, and they deal mainly with the building envelope (Meir et al., 2012).
2. As these energy efficient buildings regulations are based on international standards, they are not specific to the requirements of the built environment in Saudi Arabia.
3. Residential tall buildings of four or more storeys are classed as commercial buildings regardless of the number of residential floors. However, the functional and environmental requirements for these two building types are different in terms of

user schedules and internal gains in addition to the thermal and visual comfort requirements. Hence, applying the same building envelope requirements to different building types is questionable.

4. The regulations do not clarify or outline exactly how the designer could address energy efficiency in a building, a large part of which falls within façade design strategies. Moreover, some of the tables addressing the building envelope requirements are somewhat confusing in relation to window area and U-value.
5. The regulations direct the designer to follow ANSI/ASHRAE/IES Standard 90.1 for commercial buildings (and residential tall buildings) if the glazing area is greater than 50% of the gross area of exterior walls. However, ANSI/ASHRAE/IES Standard 90.1 (2010) provides minimum envelope requirements for facades with up to 40% glazing ratio only, and specifies that the glazing area should not exceed 40% of the gross exterior wall area. In other words, while the SBC 601 claim that the ASHRAE standards states the minimum building envelope requirements for building with glazing ratio over 50%, this is not true since the ASHRAE standards only provide this information for buildings with glazing ratio up to 40%.
6. The regulations determine the minimum requirements for the 'engineering parameters' of the building envelope, such as the U-value and SHGC, but fail to consider the envelope design parameters or their impact on energy performance, especially for residential tall buildings.

3.1.5 The Guidelines for Tall Buildings Specifications and Technical Requirements for Jeddah

The Municipality of Jeddah has been exploring the idea of setting guidelines for the design of tall buildings, especially after the announcement of their intention to construct the next world's tallest building, Jeddah Tower - formerly known as The Kingdom Tower. They produced the first 'Jeddah 1450 Tall Buildings Guide' in 2007, setting out *'specific guidance for the location and design of tall buildings within the territory of the Municipality of Jeddah. It is the first in a series of special planning guidance documents prepared by the Municipality of Jeddah to guide developers and inform planning decision making on issues of city wide importance*' (Jeddah Municipality, 2007). The guidelines were further developed in 2009 and

2010, and the final 'Guidelines for Tall Buildings Specifications and Technical Requirements' from the Jeddah Municipality were proposed in 2013; however, they are still in a draft form in Arabic. The main objectives of the guidelines are to emphasise the identity of the city of Jeddah as a global economic city and as the main gateway to the holy cities of Mecca and Medina. They also aim to develop an integrated and well connected urban fabric while creating a distinctive skyline for Jeddah, to ensure that an attractive environment is created through the effective use of public open spaces and pedestrian zones, and to reduce the influence of tall buildings on surrounding spaces in terms of services, traffic movement and environmental impact.

The guidelines document contain ten chapters starting with a general introduction to tall building requirements followed by the specific requirements for urban design, planning, architecture and structure, safety and security, electrical and mechanical requirements, and the environmental and sustainability requirements for tall buildings. It also outlines the procedures and licence approval process for tall building construction.

The guidelines include recommendations about Jeddah's skyline and urban planning, including height restrictions, architectural language and character, public realm and infrastructure, privacy and distance between buildings, environmental considerations such building orientation and its relation to wind, sun and shading, and building base and podium design. Figure 3-2 illustrates some elements of the architectural language and character of Jeddah which the guidelines propose for use in the design of tall buildings in the city.

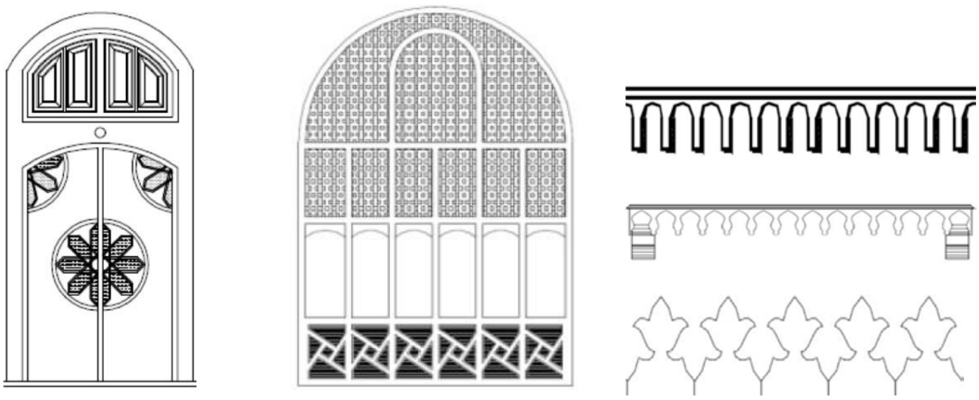


Figure 3-2: Elements from the local architectural language as proposed by the Guidelines for Tall Buildings Specifications and Technical Requirements from Jeddah Municipality (2013)

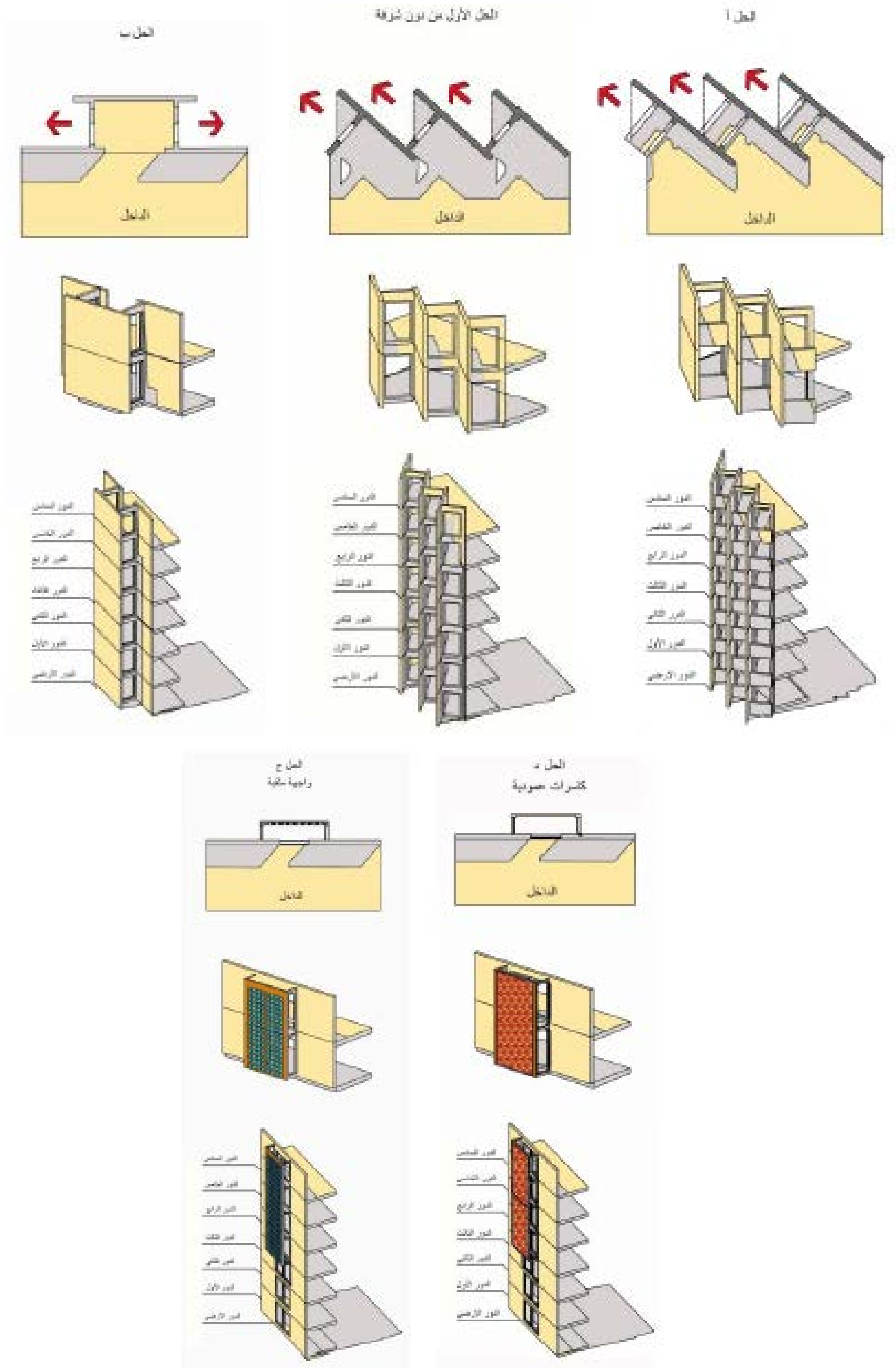


Figure 3-2 Design solutions for privacy considerations as illustrated in the Guidelines for Tall Buildings Specifications and Technical Requirements from Jeddah Municipality (2013).

In relation to the architectural design requirements, the guidelines mention the design considerations for tall buildings such as entrances, vertical transportation, core design, the dimensional requirements for floor heights, parking, and mechanical floors, and minimum dimensional requirements for rooms, interior spaces and corridors. They include sections about natural and mechanical ventilation and lighting requirements but refer to the ASHRAE Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) for detailed recommendations. They also provide brief design solutions for the building façade which take account of privacy considerations as shown in Figure 3-3.

The chapter about the environmental and sustainability requirements for tall buildings briefly explains the international green buildings ranking systems such as LEED and BREEAM. It outlines the benefits of using design tools and building energy performance simulations to determine the energy loads for buildings, and recommends complying with building energy codes and regulations such as the IECC and ASHRAE Standard 90.1[11] to achieve energy efficiency in buildings. The chapter also comments on the use of renewable energy and waste water recycling and sewage treatment.

In conclusion, the Guidelines for Tall Buildings Specifications and Technical Requirements provide design recommendations for tall buildings in the urban context of the city of Jeddah, and include architectural design considerations in relation to the internal zoning and spaces of tall buildings; however, there is no differentiation between the requirements for different typologies such as commercial or residential tall buildings. As for the energy efficiency requirements for tall buildings, the guidelines focus on the engineering parameters of the building envelope and refer to the ASHRAE Standards for specifications, which is also used as a reference for internal thermal and visual comfort recommendations. Regarding the sustainability issues in tall buildings, again they refer to international rating systems such as LEED and BREEAM, thus failing to address local need and conditions. Moreover, as the title suggests, these guidelines act more as a set of design considerations than a compulsory building code. Nevertheless, they take the first step towards introducing sustainability and environmental design for tall buildings in the Gulf Region.

[11] ANSI/ASHRAE/IES Standard 90.1-2013 Energy Standard for Buildings Except Low-Rise Residential Buildings

3.1.6 Main Findings

As mentioned at the beginning of this section, current energy efficiency building regulations in the Gulf Region were reviewed for the purposes of evaluation and comparison and to extract benchmarks and energy targets. Table 3-7 compares these regulations in relation to their compliance approach, implementation status, engineering and design parameters, and energy performance targets. Comparing the Saudi SBC 601 and Dubai's GBRS shows that both regulations outline the prescriptive and the performance approach to compliance, while Estidama PBRS specifies the performance approach and GSAS introduces a new approach by setting minimum targets for energy performance. The SBC 601 set mandatory minimum requirements for residential and commercial building types, the GBRS set them for governmental buildings only while Estidama PBRS mandates minimum requirements for all buildings, with additional credit requirements for governmental buildings. As for GSAS, there is no specific implementation policy for the system yet. Where both the SBC 601 and Dubai's GBRS provide minimum requirements for the engineering parameters of the building envelope (U-value, SC or SHGC), the PBRS refers to the engineering parameters of the building envelope set out in the ASHRAE Standards 90.1-2007 for use when comparing performance in the Building Performance Rating Method, also outlined in the ASHRAE Standards. GSAS uses the engineering parameters of the building envelope as inputs in the Energy Performance Calculator which is used to obtain the Energy Performance Coefficient and finally the Energy Demand Performance of the proposed building. As for the design parameters, Dubai's GBRS include design recommendations for external shading devices while the PBRS provides design guidelines to obtain additional credit points in the rating system, but they are not a mandatory requirement. As for GSAS, the Design Guidelines manual should include design recommendations, but these are currently not reviewed due to lack of availability.

In relation to building envelope requirements, the SBC601 and Dubai's GBRS set minimum prescriptive requirements for the opaque and transparent building elements. Table 3-8 compares these values and shows that the SBC601 provides values only for building with glazing percentages of up to 40%, referring to the ASHRAE Standards 90.1 for buildings with more than 40% glazing, despite the fact that guidelines for such buildings are not actually available within ASHRAE Standards 90.1). Meanwhile Dubai's GBRS specify values for buildings with glazing percentages below 40%, between 40-60%, and above 60%. Comparing the two sets of regulations, the SBC 601 requires lower values for the opaque elements' U-value, but the GBRS specify more detailed and better performance for glazing elements. For example, the VLT is not required in SBC 601 while it is specified in GBRS.

Table 3-7 Comparison Table for the local energy efficient building regulations in the Gulf Region

Document	Compliance approach	Implementation	Engineering Parameters	Design Parameters	Energy Performance Targets	Notes
SBC 601	Prescriptive and Performance	Mandatory	SHGC and U-value for windows U-value for opaque elements based on glazing ratio and CDD	None	None	Reference to the ASHRAE Standards 90.1-2007 for the engineering parameters
GBRS	Prescriptive and Performance	Mandatory to governmental buildings, voluntary public and private buildings	SC, VLT and U-value for windows U-value for opaque elements based on glazing ratio	Considerations for external shading devices	None	Specific to Dubai's climatic conditions and needs
PBRS	Performance	Minimum requirements are mandatory for all buildings, additional requirements for governmental buildings.	Considered in the Building Performance Rating Method outlined in Appendix G in the ASHRAE Standards 90.1-2007	Considered as an additional credit points (not mandatory). Design measures mentioned include orientation, glazing ratio, external shading	A minimum 12% performance improvement compared to the baseline building performance as per the ASHRAE Standards 90.1	Provides a prescriptive approach but not relevant for tall buildings
GSAS	Performance	Not mandatory	Inputs for the Energy Performance Calculators	Not known	Baseline reference for Energy Demand Performance for residential buildings = 121 kWh/m2/yr	Specific to Qatar's climatic conditions and needs

Table 3-8 Comparison of the prescriptive minimum envelope requirements in SBC 601 and GBRS

Glazing Percentage	Building codes and regulations	Roof U-value (W/m^2K)	External wall U-value (W/m^2K)	Glazing Elements		
				Shading Coefficient	U-value (W/m^2K)	Visible light transmittance
10	SBC 601	0.18 – 0.2	0.4 – 1.8	Any	3.9	Not specified
	GBRS	0.3	0.57	0.4 (max)	2.1	0.25 (min)
20	SBC 601	0.18 – 0.2	0.4 – 1.8	0.57 – 0.8	2.8	Not specified
	GBRS	0.3	0.57	0.4 (max)	2.1	0.25 (min)
30	SBC 601	0.18 – 0.2	0.4 – 1.8	0.57 – 0.8	2.2	Not specified
	GBRS	0.3	0.57	0.4 (max)	2.1	0.25 (min)
40	SBC 601	0.18 – 0.2	0.3 - 1.4	0.4 – 0.8	2.2	Not specified
	GBRS	0.3	0.57	0.32 (max)	1.9	0.1 (min)
50	SBC 601	0.18 – 0.2	0.3 - 1.4	0.4 – 0.8	2.2	Not specified
	GBRS	0.3	0.57	0.32(max)	1.9	0.1 (min)
60	SBC 601	Not specified				
	GBRS	0.3	0.57	0.25 (max)	1.9	0.1 (min)
70	SBC 601	Not specified				
	GBRS	0.3	0.57	0.25 (max)	1.9	0.1 (min)
80	SBC 601	Not specified				
	GBRS	0.3	0.57	0.25 (max)	1.9	0.1 (min)
90	SBC 601	Not specified				
	GBRS	0.3	0.57	0.25 (max)	1.9	0.1 (min)
100	SBC 601	Not specified				
	GBRS	0.3	0.57	0.25 (max)	1.9	0.1 (min)

In conclusion, mandatory energy efficiency regulations for buildings, if enforced properly, can constitute a strong driving force for the construction industry (including architects, real estate developers, and construction companies) to start integrating sustainable and energy efficient solutions into buildings. However, at present, national or emirate-wide standards apply only to new buildings and are often voluntary or poorly enforced so a mandatory regulatory framework is required to ensure that all buildings implement sustainable practice (Lahn et al., 2013, Myrsalieva and Barghouth, 2015). However, current responsibility for enforcement usually lies with municipalities, which often lack financial and human capacity. Designing, constructing and renovating buildings according to energy efficient specifications will require an upgrading of the skills, knowledge and expertise of professionals in the construction sector – including architects, designers, contractors, installers and others – to properly inspect and review site plans, building designs and construction sites, capabilities which are still lacking in most of the Gulf Region (Myrsalieva and Barghouth, 2015). Moreover, the absence of enforcement of these regulations from the policy side, in addition to the lack of energy policies or strategic plans that determine benchmarks for energy reductions, may hinder the efficiency of such requirements. For example, the Saudi Building Code has mandated thermal insulation against heat for all new buildings since 2010 as this has been proven to reduce energy demand for villas by 30–40%. However, new buildings continue to be erected without proper insulation (Lahn et al., 2013). Also, in October 2012, the Green Building Chapter was established as part of the Saudi Council of Engineers to promote green building design by raising awareness through educational conferences and events (GBChapter, 2013); however, the activities of the Chapter are still very limited and have no impact on energy policies or building regulations. Some efforts have been made in the direction of energy efficient buildings through demonstrations and pilot projects that are LEED[12] certified or buildings designed according to green standards (Table 3-9), but again, these activities are not sufficient and more efforts need to be made to develop compliance tools and strengthen implementation capacities (Myrsalieva and Barghouth, 2015).

Table 3-9 Status of enforcement of energy efficient buildings in the GCC countries in 2014(Source: Myrsalieva and Barghouth, 2015, p.74)

Country	Number of Energy Efficient Buildings	Number of Demonstration/Pilot Projects
Qatar	173 (green buildings)	Information not available
Saudi Arabia	Nearly none	145 (green buildings)
UAE	802 (green buildings)	Information not available

Many cities in the Gulf Region are investing in residential tall buildings, notably Dubai and Abu Dhabi in the UAE, Doha in Qatar, Kuwait City in Kuwait, Manama in Bahrain, and Mecca, Jeddah, and Riyadh in Saudi Arabia. However, this new trend constitutes an architectural paradigm shift that focuses on sustainable design, reflecting rising global awareness of sustainability and energy efficiency in architecture, as discussed in Section 1.2.3. There are, as yet, few tall buildings that claim to be 'green', 'environmentally-friendly' and climatically responsive, but notable examples include the O-14 Building in Dubai, Al Hamra Tower in Kuwait, Al Bahar Tower in Abu Dhabi, and Doha Tower in Doha. These towers represent a new generation of tall buildings, offering high-performance systems, high-quality materials, and better interiors for occupants (Al-Kodmany, 2016). However, the challenge is to apply these energy efficient and green building practices to more than a handful of high profile projects in the Gulf Region through mandatory energy efficient building regulations and greater incentives for developers to build or retrofit more sustainably (Al Arabiya News, 2012).

[12] Green or "Leadership in Energy and Environmental Design (LEED)" certified buildings are buildings that are built in accordance with the US Green Building Council requirements on the design, construction and maintenance of green buildings. LEED certified buildings go beyond EE, and take into account all other environmental aspects of a building such as waste, materials used, water consumption, health impacts and others (Myrsalieva and Barghouth, 2015).

The following section identifies some of the key opportunities, challenges, and novel approaches in tall building design, through visits and interviews conducted by the author with key professionals undertaking the design of tall buildings in the Gulf Region.

3.2 Practice

The residential tall building stock in the Gulf Region includes a wide variety of buildings in terms of size, location, and the design of the building envelope. In the course of this research, the author conducted several visits and semi structured interviews with key professionals undertaking the design of tall buildings in the Gulf Region in order to collect data and identify some of the key opportunities, challenges, and novel approaches available in the design of this building type. These visits, conducted during April and May 2014, formed the early stage of this research methodology for data collection and included three companies in London associated with environmental design and building envelope engineering: Buro Happold Engineering, Arup, and Chapman BDSP. The following sections outline the interviewees, the data gathered and the main findings from these visits.

3.2.1 Buro Happold Engineering

Buro Happold Engineering have completed many projects in the Middle East, especially in the UAE and Saudi Arabia. The author was able to meet and interview the façade engineers for two of these projects, Aneel Kilaire façade engineer for The Landmark Tower, a 64-storey mixed-use tower completed in 2013 in Abu Dhabi (Figure 3-4), and Roberto Fabbri, façade engineer for the East-Walk Maryah Tower, a 32-storey residential tower, also in Abu Dhabi, due to be completed in 2018 (Figure 3-5).

Figure 3-3 The Landmark Tower in Abu Dhabi, completed in 2013 and designed by Pelli Clarke Pelli (Source: The Skyscraper Center, 2014)

Figure 3-4 Renderings of the East Walk residential project on Al Maryah Island (Source: Pascall and Watson. 2017)

The data obtained about the Landmark Tower included a Progress Report for the Conceptual Design stage, which contained structural issues, building services, a design and construction schedule and architectural drawings, the Performance Specification Report for Curtain Walling and Associated Cladding, which specified the building envelope performance recommendations (U-value and SC), and a study for the façade load analysis conducted by Kilaire (2015). In the interview, Kilaire emphasised that in the Gulf Region the most effective parameter in controlling solar gains is the glass g-value, followed by shading, either through material (glass frit), or architectural geometry and orientation. He added that dust poses a particular challenge in the region, limiting the use of some types of shading devices such as metal mesh that can trap dust. Also, the use of natural ventilation is very limited and often unfeasible. Along the same lines, in a later interview, Fabbri, who worked on the East-Walk Maryah Tower, noted that another significant challenge in the Gulf Region is the lack of local regulations specific to residential tall buildings that provide performance criteria and specifications for the façade components such as glass type, frames, opening sizes, or façade design requirements, whether sealed or open for example. Another challenge specific to his project was to provide good thermal transmittance (U-value), air and water tightness for the façade system, which used sliding doors and thus involved a lot of framing, especially given the lack of requirements and specifications.

On the other hand, Kilaire stressed that sustainability in façade design mainly looks at the use of local materials and energy performance, and that façade design is an integrated optimisation process which aims to achieve the architectural vision of a building by providing engineering solutions that are both feasible and buildable, as discussed in Section 2.2. This optimisation process includes testing all the different parameters that could be adjusted, such as architectural elements, location or materials. According to Fabbri, Buro Happold teams use a bubble diagram (Figure 3-6) to act as a checklist of all the performance requirements they have to set and to coordinate with the rest of the design team in an integrated process that sets the performance criteria and then the design principals for the systems. As part of this process, the design team produce two types of documents: the first consisting of the performance criteria regarding air tightness, U-value, g-value, etc, the second containing the details and products responding to the performance criteria, which should be coordinated with the architect to reach the final solution.

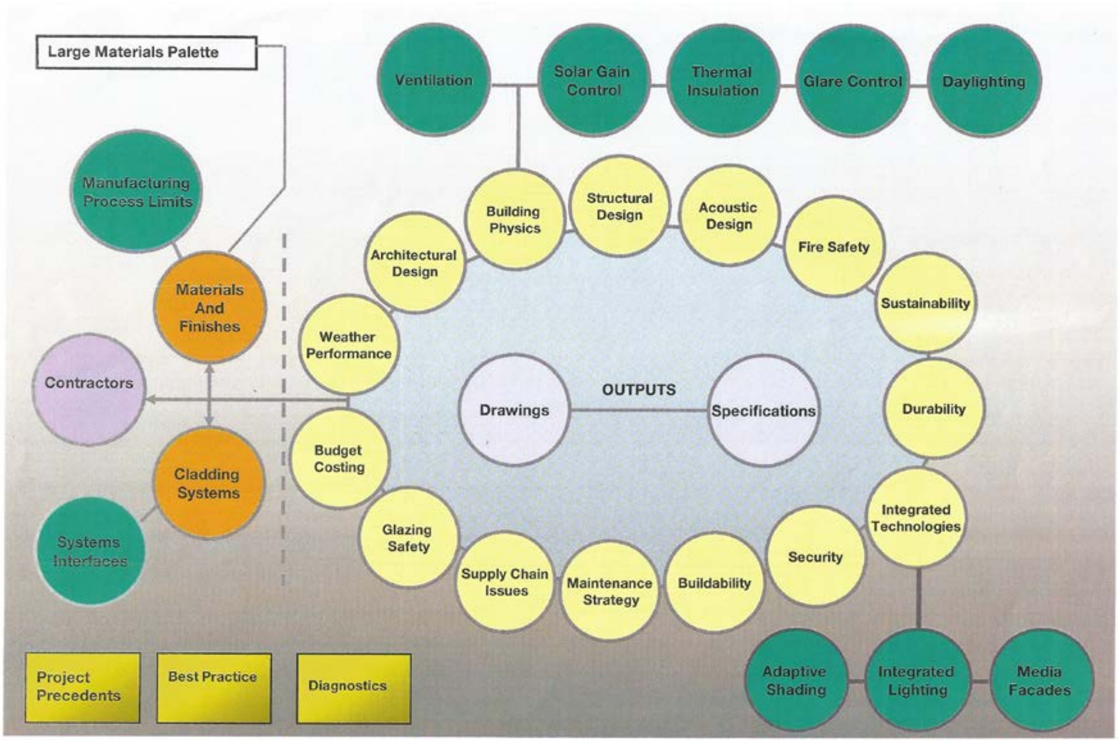


Figure 3-5 The Bubble Diagram followed in Buro Happold in the integrated process of the façade design

In the case of the East-Walk Maryah Tower, the proposed design approach to energy efficiency aimed to meet and then exceed mandatory Estidama Single Pearl requirements through the prioritisation of climate sensitive and passive design measures before the adoption of high efficiency active systems and renewable energy technologies. The key performance target for the tower is that the proposed annual energy performance (kWh/m2/yr) improves upon the ASHRAE 90.1 baseline by a minimum of 12%. In addition, there is a more stringent local master planning requirement that a 20% reduction be achieved. In order to achieve this, the design team have followed the Estidama Energy Modelling Timeline approach (Figure 3-1) with computational analysis of key design features and identification of key improvement measures undertaken to ensure the delivery of an energy efficient, comfortable and Estidama compliant buildings design.

The energy performance analysis following an 'all building' approach was performed for a typical residential floor, taking into consideration all building related energy requirements and energy efficiency measures, including building fabric, hot water, space cooling and heating, ventilation, lighting, vertical transportations, catering and appliances, and occupant behaviour. The buildings fabric solar performance optimisation study started with an assessment of the sun path in relation to the buildings massing to inform a high level of understanding of the local climate, followed by an overall assessment of all typical apartment level façades, assuming the specifications of solar control glass and the application of external shading devices. Findings and recommendations for each façade were outlined explaining the areas of primary concerns, the level of concern, and possible solutions e.g. reducing glazing area, reducing overall SHGC of the glass, or using external screens and shadings. The optimisation process included using dynamic thermal modelling to evaluate the building façades' and external shading devices' ability to limit unwanted solar gains, improve occupant comfort and reduce associated space cooling loads to improve the ability to meet Estidama energy performance targets.

As for internal comfort, due to the clear, sunny climate in Abu Dhabi, there is considerable scope to harness useful daylight ingress whilst mitigating the risk of over exposure and glare. Therefore, in order to ensure comfortable internal visual conditions, it was essential to optimise the façade design and associated solar control measures. Daylight modelling of a number of key spaces was undertaken for a clear sunny sky at 1200hrs on 21st September using Radiance software, and since the climate of Abu Dhabi requires mechanical cooling for the occupied zones throughout the year, a detailed computational fluid analysis (CFD) was used to assess the proposed mechanical cooling strategy's ability to maintain comfortable internal conditions within a representative combined living room/kitchen space.

Ultimately, the visit to Buro Happold confirmed that the main challenges in tall building façade design in the Gulf Region are on two levels, climatic and regulatory. According to the practice in Buro Happold, the climatic challenges can be overcome by the careful selection of material properties, especially glazing SHGC. As for the regulatory system, there is a lack of local regulations specific to residential buildings which provide performance criteria and specifications for the glass, frames and façade design elements. Moreover, Buro Happold's practice demonstrates that in order to achieve energy efficiency in residential tall building design, a hierarchical design approach consisting of a series of computational analyses of key design features throughout the design phases should be followed through the prioritisation of climate sensitive and passive design measures before the adoption of high-energy efficiency active systems and renewable energy technologies. This approach could be incorporated into the building energy efficiency regulations in the Gulf Region in general and in Saudi Arabia in particular to achieve energy efficiency in residential tall building design.

3.2.2 Arup

Arup has been working in the Gulf Region since the early 1970s, starting with the construction of their first major structural design projects in Saudi Arabia: the Riyadh Intercontinental Hotel and King Faisal Conference Centre, and the Mecca Hotel and Conference Centre (Pearson, 1980). Since then, Arup has built a strong presence in the Gulf Region (with offices in Abu Dhabi and Dubai), where their expertise range from structural engineering and vertical transportation to building design work, delivering ground-breaking projects including Doha's Aspire Tower in Qatar, the Aldar HQ and Yas Marina Hotel in Abu Dhabi, and, most recently, Al Bahr Towers (Figure 3-7), the new headquarters of the Abu Dhabi Investment Council (ADIC), whose innovative design features have resulted in a 40% saving in carbon emissions (Arup, 2017).

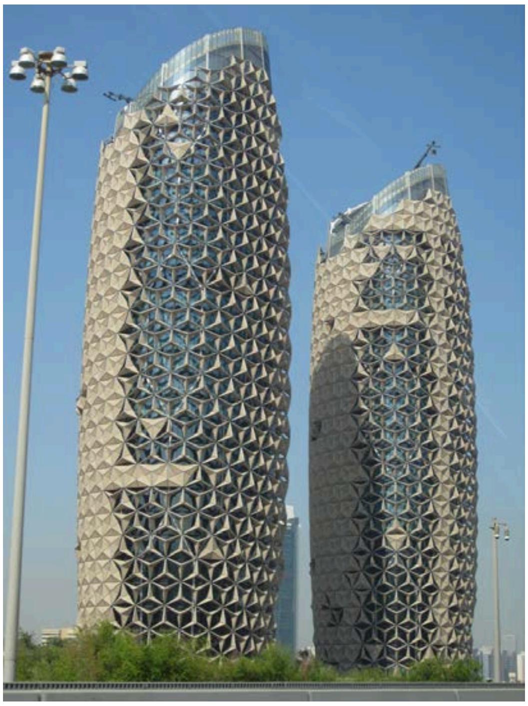


Figure 3-6 Al Bahr Towers in Abu Dhabi, designed by Aedas and supported by Arup as multidisciplinary engineering designers (Source: Composites and Architecture, 2017)

The visit to Arup aimed to explore the current and future building envelope technologies and façade design approaches based on the company’s vast experience, both worldwide and in the Gulf Region. The author had the chance to meet Mr Giorgio Buffoni, a member of Arup's façade engineering leadership team and part of the design team for the 26-storey, 145m tall Al Bahr Towers in Abu Dhabi, who provided architectural drawings and some published documents regarding the design process and innovations of the towers. According to these documents, the main issue the design team faced was the subtropical desert climate, characterised by high air temperature and very high solar radiation levels all year round. This made reducing the energy use associated with providing internal comfort a particular challenge which required an innovative solution. The answer was the 'Mashrabiya' shading devices which wrap around the towers and became a key architectural theme in their design (Armstrong et al., 2013). However, although this solved the primary issue of controlling solar radiation, the heavily shaded building made conductive gains due to temperature difference more of an issue, meaning that enhancing the thermal performance of the conductive component became more important (Buffoni, 2014). In the interview, Buffoni stated that the best approach to controlling heat gains in buildings in the Gulf Region is through parallel consideration of building form and orientation, shading system and glazing properties. In the case of Al Bahr Towers, in addition to the unique active shading system, argon filled double glazing was specified to minimise conductive heat gains, while lower g-value and additional fritting were used to reduce solar gains. This level of integration between different building elements to develop a building envelope that was both efficient and iconic would not have been possible without close coordination between the 300+ architects and engineers across 14 disciplines who worked together throughout the design process to deliver a truly integrated design (Armstrong et al., 2013; Buffoni, 2014).

This integrated design process consisted of different stages using simulation tools to inform decisions throughout the process, starting with a detailed weather data analysis of the climatic conditions which revealed the significant effect of diffused radiation and convective components. This step informed the choice of innovative materials to achieve an appropriate overall U-value for a typical panel configuration. In the following step, the mechanical, electrical and plumping (MEP) team set a maximum heat gain target for both solar gains and conductive gains. The conductive gains were assessed according to temperature variations and overall U-value, while the maximum solar gains were derived as a difference from the total MEP target. Next, heat gain optimisation was conducted using simulation tools and 3D thermal models without the Mashrabiya shadings to derive the solar exposure levels in W/m^2 for each orientation. This step identified the portions of the facades where additional external shading was required due to solar gains exceeding the total MEP heat gains target. Following that, the design of the Mashrabiya shading system went through an optimisation process, including testing nine scenarios to optimise the final shading extension according to building geometry and honeycomb pattern; this optimisation also included the panel position (open, intermediate, close) to avoid direct solar radiation while maintaining the maximum heat gains below the MEP target (Buffoni, 2013).

For Buffoni, the optimisation process is the next cutting-edge technology in building envelope and façade design. He agreed with Zemella and Faraguna (2014) that optimisation techniques offer immense potential for the improvement of performance-driven design, since they facilitate the adoption of an holistic approach providing optimal design solutions that can be properly identified only if all criteria are considered at the same time, rather than separately (as is the case in regular simulations of building performance). Generally, building simulation tools investigate the effects of different design parameters on a building's performance to determine the sensitivity of building performance to various parameters, thereby developing a reference for actual building design activities (Huang and Niu, 2016). However, the number of parameters that can affect a building's performance is huge, and in many cases different parameters exert conflicting influences. Moreover, the design of building envelopes involves a much larger number of parameters, and the relationships between different design parameters and their effects on the performance of the building envelope are more complicated, such as the different directions of heat flow which determine the heating load and cooling load, or the daylight and its relation to heat gain and lighting energy consumption. Since this comprehensive design of building envelopes requires the assessment of energy performance, thermal comfort performance and visual comfort performance using building performance simulation tools to achieve an optimal design solution (which often involves running a large number of simulation cases), this can be both expensive and time-consuming. Therefore, conducting a systematic and effective optimisation process for building design solutions can provide the right solution. This has resulted in the development of mathematical and algorithmic methodologies that raise the possibility of solving optimal building envelope problems more quickly and accurately (Huang and Niu, 2016).

The optimisation process is defined as the procedure to find the minimum or maximum value of a function by choosing a number of variables subject to a number of constraints. The optimisation function is called 'cost' or 'fitness' or 'objective function' and is usually calculated using simulation tools (Machairas et al., 2014). A building envelope design optimisation analysis has at least 4 steps:

1. Identification of the design variables and their relevant constraints.
2. Selection of a building performance simulation tool and creation of a building model.
3. Selection of an appropriate objective function, such as energy performance, life cycle and cost, or thermal and visual comfort.
4. Selection of an appropriate optimisation algorithm, such as generic algorithms (GA) and their modifications. These are the most popular optimisation algorithms used in building envelope optimisation studies due to their wide applicability, high accuracy and speed of operation (Machairas et al., 2014; Huang and Niu, 2016).

Ultimately, according to Huang and Niu (2016), to achieve the goal of sustainability in buildings, it is essential to conduct multi-objective building envelope optimisations that involve all three indices:energy performance, thermal comfort performance and visual comfort performance. However, Machairas et al. (2014) have argued that the transfer of a real-world design problem into the mathematical domain has limitations and that the most commonly used optimisation algorithms applied to building design problems cannot ensure that the optimal solution will be found. Buffoni also cited Faraguna and Zemella (2014) regarding the barriers obstructing optimisation from being applied to building design, namely a technological barrier, since applying the algorithms is not easy and can be time-consuming, and a cultural barrier as both architects and engineers are required to change their perspectives and approach the design process in a new way. Nevertheless, better building performance may be obtained by comparison with common practice where no optimisation is used. Therefore, an informed understanding of an optimization method's strengths and weaknesses is essential if it is to be used effectively (Machairas et al., 2014).

3.2.3 Chapman BDSP

Chapman BDSP is an independent design consultancy specialising in building, engineering, and environmental design services, headquartered in London but with offices in Abu Dhabi and Dubai. Their approach combines creative design and practical engineering to overcome technical constraints and deliver solutions supported by cutting-edge design, modelling and simulation techniques. They have experience of working on both low and high-rise projects in the Gulf Region, notably the twin 45- and 51-storey residential BLVD Heights towers in Dubai, and The World Trade Center development in Abu Dhabi. Formerly known as Central Market, this consists of two super tall buildings, an 88-storey residential tower, named Burj Mohammed Bin Rashid Tower, and a 58-storey office tower, both standing above a traditional souk, with up to seven levels of retail in the podium, a green roof above the souk, and a bridge system linking these areas together (Chapman BDSP, n.d., CTBUH, 2017) (Figure 3-8).

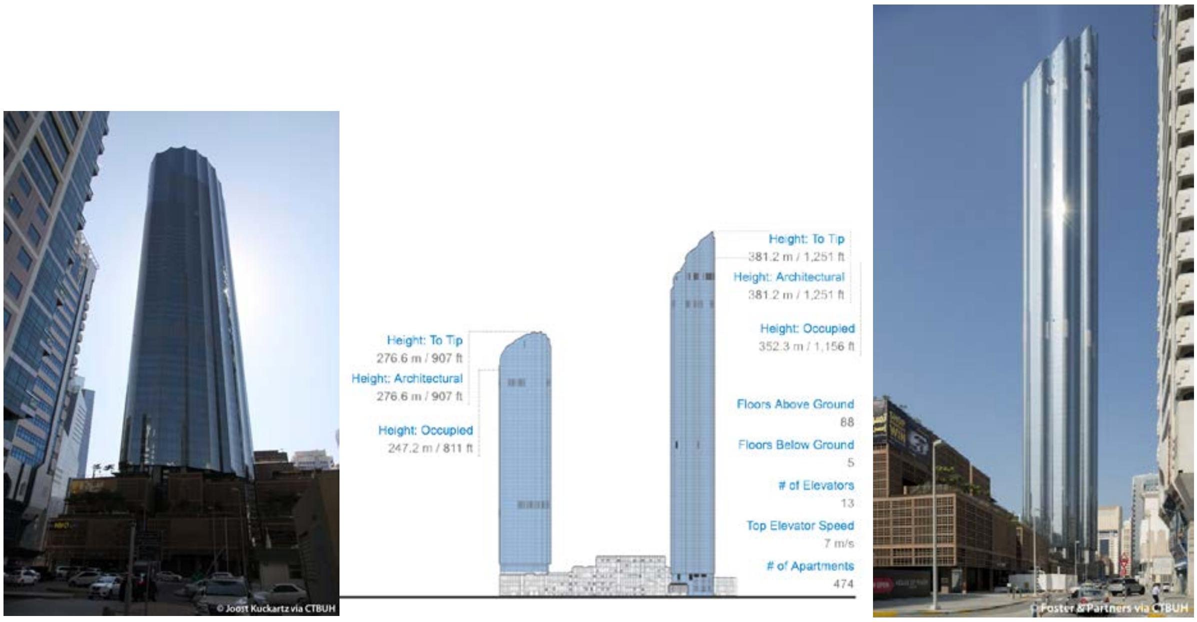


Figure 3-7 World Trade Centre development in Abu Dhabi, completed in 2014. On the left is the 276.6m high office tower, and on the right is the Burj Mohammed Bin Rashid residential tower standing at 381.2m high. (Source: Council on Tall Buildings and Urban Habitat 2017)

During the author’s visit to Chapman BDSP, she met Ian Duncombe, a Board Director at the consultancy, and Ivan Jovanovic, a sustainability consultant and, at that time, an associate at BDSP. They provided architectural drawings and other documents regarding the World Trade Center development in Abu Dhabi (then Central Market), including thermal performance and solar analysis, glass performance data and specifications, cladding concepts, and an environmental report that identifies and illustrates the principal environmental measures proposed by Foster and Partners, the design architects, and BDSP Partnership, the MEP engineers (Appendix A).

The discussion with Duncombe was structured around the main challenges the World Trade Center design team faced from the early conceptual design stages and the analysis of the form and orientation to the development and testing of the façade design and performance. According to Duncombe, at the start of the project in 2006, the brief was to achieve a good standard in terms of one of the international rating systems for the office tower only with no criteria applied to the other aspects of the project. However, as the project developed the client introduced the desire for the whole development to comply with a sustainable standard, and as there were no local standards at the time, LEED became the standard. As a result, the design team produced a report describing the main categories found in the LEED for New Construction Green Building Rating System. The report covered the various themes that should be considered for a sustainable approach to the design, construction and operation of the project, with a brief statement about what the scheme was achieving in relation to these criteria (Foster and Partners and BDSP Partnership, 2006). Later in the project the possibility of using the newly-introduced Estidama programme as a test project was discussed, but this was not taken forward.

The approach to the overall energy performance of the development was to achieve efficiency through holistic design; thus a number of design elements were integrated into the building in order to increase its energy efficiency. These included looking at aspects of building form and systems including solar collectors and the bespoke 'Abluft' ventilated three-skin façade that reduces solar heat gains by 50% (Chapman BDSP, n.d., CTBUH, 2017). Nevertheless, the design team faced numerous obstacles throughout the project. For Duncombe, one of the biggest challenges was the elimination of many sustainability driven concepts in order to reduce costs during the financial crisis in 2009. For example, the building envelope for the office tower was designed as an Abluft Façade, which is an established curtain wall technology characterised by a double-glazed outer skin and a single-glazed inner skin, with an actively ventilated cavity between them. This was supposed to provide the office tower with added value by improving thermal comfort and enhancing the general working environment while reducing cooling load demand (Foster and Partners, Arup and BDSP, 2009). As for the residential tower, the initial conceptual design for the building envelope envisaged a double skin with a buffer zone instead of a ventilated cavity between the two skins which could be used as a living space or as a winter garden; in this case, the cladding on the outside would wrap in and out to create spaces of varying depths in relation to the apartments, and every apartment would have its own winter garden. However, the idea of a double skin façade for the residential tower was eliminated and the building envelope was designed as a single skin in order to provide space for additional apartments. Duncombe said that even the double skin façade in the office tower was about to be downgraded to a standard double-glazing solution until the design team demonstrated very clearly the ability of the ventilated double skin Abluft façade to deliver higher levels of comfort and greater potential energy savings. Moreover, in the conceptual development of the project the roofs of the towers were deliberately orientated with a south facing pitch to maximise the amount of power that could be generated by Photovoltaic with PV installations at the top of each tower to generate electrical energy for the development, enhance its architectural quality, and provide valuable shading from the sun (Foster and Partners and BDSP Partnership, 2006). However, all this was eliminated as part of the value engineering. Likewise, integrated thermal solar tubes were planned and developed as part of the residential tower façade, but the whole system was cancelled due to feasibility and operational issues. Nevertheless, the challenge of having an all glazed façade in such a climate was always justified by the developer’s desire to maximise the panoramic views of the Gulf toward the Corniche. The smooth and sleek façade was designed with no edges or ‘dust collectors’ such as balconies or terraces or external shading, thus requiring minimal maintenance in such a dusty environment. Moreover, the rippling shape of the façade design created self-shading on the façade and reduced the total solar radiation per square metre falling on the inside (BDSP, 2006).

The interview with Duncombe also provided insight into the dominant factors in determining the environmental performance of the façade design, which he prioritised according to orientation, the amount of glazing, and shading devices. He emphasised the role of optimising the façade performance using computer simulations and physical mock up models but noted that, while you can optimise façade performance through testing and refinements using building simulation, when you are manufacturing thousands of panels to cover the façade of a tall building, the effort involved in conducting physical tests to validate the computer data and instil confidence that the performance is optimised properly is worthwhile, especially as many physical statics and dynamics cannot be fully judged by computer simulations alone. The interview concluded with Duncombe's personal opinion that energy strategies in general are often politically controlled and short term, thus produce only short term benefits, and that integrating renewables such as wind turbines or PV panels into new buildings is often regarded as a suboptimal solution and should be replaced by centralised renewable energy infrastructures that can deal with existing buildings as well as new building stock.

3.3 Conclusion

The evaluation and comparison of current energy efficient codes and building regulations in the Gulf Region in relation to the energy performance of residential tall buildings conducted here has highlighted three main issues:

1. Mandatory energy efficiency regulations for buildings can constitute a strong driving force to encourage the construction industry to start integrating sustainable and energy efficient solutions into buildings; however, at present, these standards apply only to new buildings and are often voluntary or poorly enforced. This means a mandatory regulatory framework focusing on all buildings should be applied and more effort put into developing compliance tools and strengthening implementation capacities.
2. All the local energy efficient building regulations, Saudi Arabia's SBC 601, Dubai's GBRS, Abu Dhabi's Estidama PBRS and Qatar's GSAS, either provide minimum requirements for the engineering parameters of the building envelope (U-value, SC or SHGC) or refer to the engineering parameters in the ASHRAE Standards, with little or no mention of the design parameters, except in Dubai's GBRS which provides design recommendations for external shading devices.
3. Although a handful of new tall buildings in the Gulf Region offer high-performance systems, high-quality materials, and better interiors for occupants, the challenge is to

apply these energy efficient and green building practices to more than a few high profile projects through mandatory, compulsory energy efficiency regulations that provide greater incentives for developers to build or retrofit more sustainably.

These issues constitute a gap in knowledge which this research aims to address by delivering guidelines and recommendations for the envelope design of residential tall buildings in the Gulf Region.

Moreover, the interviews conducted at the three major design and engineering practices in London emphasised the following points in relation to the challenges, opportunities and novel approaches regarding the design of tall building envelopes in the Gulf Region:

1. The main problem in the Gulf Region is the subtropical desert climate, characterised by high air temperatures, very high solar radiation levels year-round and significant dust issues. This makes reducing the energy use associated with providing internal comfort the biggest challenge faced by any tall building design team. The engineers agreed that the most effective parameters in controlling solar gains and determining the environmental performance of the façade design are the glazing amount and thermal properties, especially glass g-value, then shading, either through material (glass frit) or architectural geometry and orientation. Kilaire (Buro Happold) advocated limiting the use of some types of shading devices such as metal mesh that could trap dust, an idea supported by Duncombe (Chapman BDSP).
2. Another challenge in the Gulf Region identified by Fabbri (Buro Happold) is the lack of local regulatory requirements specific to residential tall buildings that provide performance criteria and specifications for the façade components such as glass type, frames, opening sizes, or facade design requirements. Duncombe also pointed out that this lack of regulation can contribute to the elimination of sustainability driven concepts under the pressure of value engineering or cost reduction.
3. Façade design is an integrated optimisation process to achieve the architectural vision of a building through close coordination to provide engineering solutions that are feasible and buildable. This process includes testing all the different parameters that could be adjusted such as architectural elements, location or materials. Buffoni (Arup) believes that the optimisation process is the next cutting-edge technology for

building envelope and façade design as it offers immense potential for the improvement of performance-driven design by facilitating the adoption of an holistic approach which provides optimal design solutions that can be properly identified only if all criteria are considered at the same time, rather than separately as in regular simulations of building performance. Duncombe also emphasised the importance of optimising the façade through physical mock up models to further validate the final results from the computer simulations.

In conclusion, the findings from the research in this chapter show that the main challenges in tall building façade design in the Gulf Region are on two levels, climatic and regulatory. The climatic issues can be overcome by the careful selection of the engineering parameters, especially the properties of the glazing material and, most importantly, through the careful planning and integration of a hierarchical design approach that involves a series of computational analysis and optimisations of key design features throughout the design phases. This holistic cross-disciplinary design approach, discussed in both the research and by practitioners, could be adopted in the building energy efficiency regulations in the Gulf Region in general and in Saudi Arabia in particular to achieve energy efficiency in residential tall building design, which could ultimately be connected to centralised renewable energy infrastructures serving the region's long term sustainability targets.

The next chapter will discuss the impact of the local energy efficiency building regulations on the current façade characteristics of residential tall buildings in the Gulf Region. The architectural data and information for selected residential tall buildings in the region were collected during the visits to the London-based consultancies and in local field studies; the main characteristics of these residential towers were then compiled into one table and compared and analysed in order to evaluate the energy performance of this building type.

CHAPTER 4: An Evaluation and Analysis of the Characteristics of Residential Tall Buildings

This chapter presents the results of the Residential Tall Buildings Characteristics Table as the first stage in the research methodology. It consists of two main sections: the first section explains the Characteristics Table which was compiled from the architectural and thermal façade characteristics of 11 residential tall buildings in the Gulf Region, and the second section evaluates their envelope performance in relation to heat transfer and solar gains.

The analysis of the Characteristics Table sets the basis for the parametric study simulation in the coming chapters by defining the architectural characteristics of the 'base case' design and determining the construction and glazing types that set the parameters for the parametric study simulations.

Chapter 4 AN ANALYSIS OF THE CHARACTERISTICS OF RESIDENTIAL TALL BUILDINGS

> *"My preoccupation with the connections between architectural form and energy is not because I think that all energy issues should profoundly affect architectural form but because architectural form can profoundly affect energy use."*
>
> G. Z. Brown and Mark DeKay in their book 'Sun, Wind & Light: Architectural Design Strategies',2001, p. xiv

As discussed in the previous chapters, the building envelope and façade design are considered to be the most significant architectural features determining energy use and heating and cooling requirements in tall buildings. A holistic cross-disciplinary design process for the building envelope is the key to producing energy efficient buildings, integrating factors such as the outdoor environment and climatic conditions, the building design and form, material characteristics and functional recommendations. This energy balance depends greatly on the properties of the envelope material, and in the hot climate of the Gulf Region where solar radiation is abundant, the window size, orientation, and glazing properties are more influential than the wall properties for both energy savings and thermal comfort. In order to evaluate the performance of the building envelope, it is important to use rules-of-thumb and design tools in the early stages of the design process, since decisions made at different stage of the building envelope's design can affect overall energy consumption and building performance.

This chapter introduces the first stage in the research methodology by evaluating the performance of selected tall building envelopes in the Gulf Region. The key aims here were to identify and quantify the parameters that may affect overall building energy performance and to use these as the basis for the parametric study presented in the next chapter.

In order to do this, data on residential tall buildings numbers and architectural characteristics was collected over a period of one year, and a series of case studies in Dubai, Abu Dhabi and Jeddah was compiled into a 'Residential Tall Buildings Characteristics Table'. Sources of information used included a literature review of previously published research, local energy efficiency building codes and regulations, the Skyscraper Center database managed by the Council on Tall Buildings and Urban Habitat (CTBUH, 2017), the Municipality for the city of Jeddah, and the author's interviews and informal discussions with building architects, engineers and developers (as detailed in Section 3.2). The information presented here, including the architectural specifications, the thermal properties of building envelopes and the glazing percentages were compared to local energy efficient regulations in order to investigate the impact of these regulations on the energy performance of residential tall buildings. Moreover, the compiled data was analysed using the two manual calculation techniques proposed by Brown and DeKay (2001) (as set out in Section 2.3), to evaluate the performance of the building envelope and obtain the total heat gains.

The main findings established an initial understanding of the issues and trends in relation to the current envelope characteristics of residential tall buildings in the Gulf Region. These were then used to determine the architectural characteristics for the 'base case' and to generate hypotheses about the parameters that impact the thermal performance of the building envelope, both of which informed the next stage of the methodology. The following sections explain the data-gathering process used to compile the Residential Tall Buildings Characteristics Table, its contents, the analysis undertaken and the main conclusions drawn from the results.

4.1 The Residential Tall Buildings Characteristics Table

The Residential Tall Buildings Characteristics Table was used as a research method to provide quantitative evidence of residential tall building envelope make-up and performance through a survey of existing residential buildings in Jeddah, Dubai and Abu Dhabi. The main objectives in compiling the table were directed towards exploring and gaining knowledge of the residential building stock for three purposes:

1. To understand the common architectural characteristics of residential tall buildings in the Gulf Region in order to inform the design and formation of the base case for the parametric study in the next chapter.
2. To evaluate the performance of current building envelopes in relation to the heat transfer and solar gains that may affect the overall building energy performance.

3. To identify the main parameters that influence energy use in order to explore these further in the parametric study.

The data compiled in the Characteristics Table includes basic building information, architectural characteristics, thermal properties for the building envelope, and the skin heat flow analysis. The table was created as an Excel sheet consisting of 172 rows and 56 columns and is too large to be included in the body of this thesis, but it can be found in its entirety in Appendix B. The following sections explain the basis of the table and how the above-mentioned objectives were met.

4.1.1 The Selection of the Locations

As mentioned in Section 1.1.2, the three cities selected are located in the Arabian Peninsula; Jeddah in Saudi Arabia on the coast of the Red Sea and Dubai and Abu Dhabi in the United Arab Emirates on the coast of the Gulf. The climate of these cities is considered as a hot dry maritime desert climate. An overview of the climatic conditions reveals comparable similarities, especially for monthly average air temperature, relative humidity and global solar radiation. These climatic similarities lead to similarities in design strategies and in the applicability of the energy efficiency building codes and regulations. This is most opportune as Dubai and Abu Dhabi have the largest number of tall buildings in the GCC countries, and both have established energy efficiency regulations and rankings, the GBRS in Dubai and Estidama's PBRS in Abu Dhabi. All these factors determined the selection of residential tall buildings located in these cities.

4.1.2 The Selection of the Buildings

The research focuses on residential tall buildings since they represent the majority of high-rise towers in the Middle East (Bahaj et al., 2008), and the selection of the buildings was primarily based on their function. Another important factor was the availability and accuracy of information. Initially, more than 36 residential and mixed-use buildings were reviewed, but much of the detailed information required for the analysis was unobtainable. Thus, the final table includes 11 residential tall buildings: five in Dubai (The Tower, Silverene Tower A, 23 Marina, Al Yaqoub Tower, Cayan Tower), four in Abu Dhabi (East-Walk Al Maryah Plaza, Landmark Tower, Gate District Tower, World Trade Centre – Burj Mohammed Bin Rashid), and two in Jeddah (Lamar Towers, Corniche Dreams Towers). Each tower is described briefly below in relation to the available information and sources:

4.1.2.1 Dubai

The Tower

The Tower is a 243m high tall building located in Dubai adjacent to the Emirates Towers Metro Station and is easily accessible from Sheikh Zayed Road and DIFC commercial district (Figure 4-1). The building, completed in 2002, has 54 storeys comprising 3 shop units, 192 one-bedroom and 180 three-bedroom apartments (Wikipedia, 2017, Colliers International, 2017). The architectural drawings of the tower were obtained from Khatib and Alami, the design architects, through personal connections.

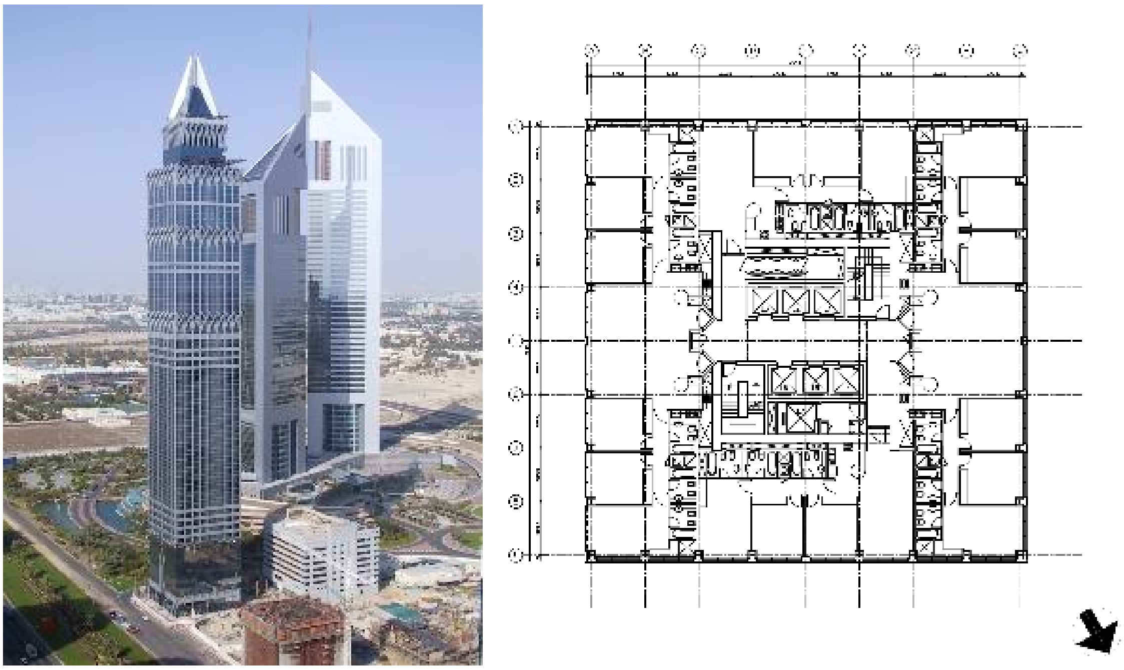


Figure 4-1 The Tower, completed in 2002 and located in Dubai (Source: Khatib and Alami)

Silverene Tower A

The Silverene residential towers, rising over 150m and 120m respectively, are part of the mixed-use development of the Dubai Marina area with panoramic views of the Marina (Figure 4-2). The 34 and 26-storey towers rise above two levels of common retail/parking and three below ground levels, in addition to an infinity pool and a health club for the tenants of the 552-unit development. The layout of the twin towers is highly efficient and the floor plates were optimized to include a variety of residential units with an average floor efficiency of over 84%. In addition, the towers employed several other methods to reduce construction time and cost while improving performance and overall experience (CTBUH, 2017; Ted Jacob Engineering Group, n.d.). The architectural drawings for the Silverene Tower A were obtained from the official website of the real estate developers, Palma Holdings. The design was considered as good practice and the thermal properties of the building envelope, such as U-value for walls and glazing, and glazing SC and VLT, was based on the minimum envelope performance requirements specified in Dubai's GBRS (2011, p.161), even though the tower was proposed and constructed before the introduction of the GBRS in 2011. The floor to floor height was assumed based on the average 3.6m height as in other residential tall buildings in Dubai.

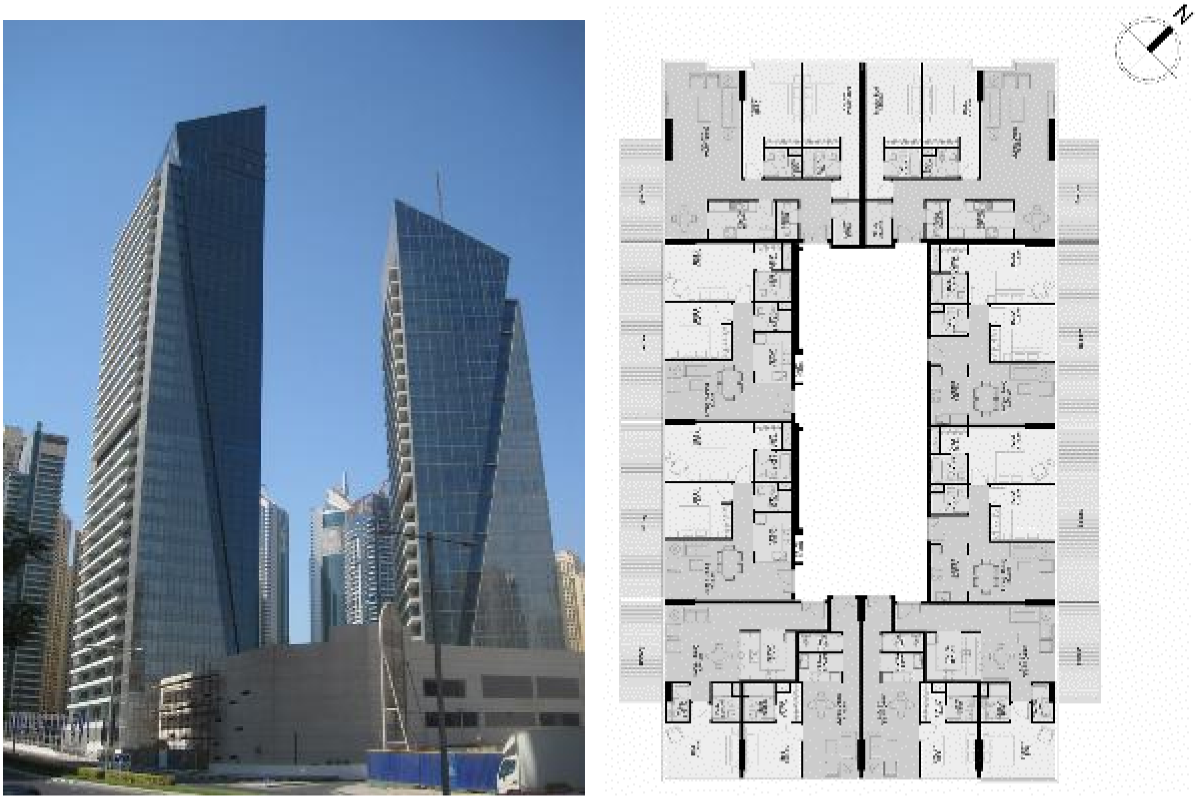


Figure 4-2 Silverene Towers in Dubai, the floor plan has an average typical floor efficiency of over 84% (Source: Ted Jacob Engineering and Palma Holdings)

23 Marina Tower

This supertall[13] 392.2m high residential tower, completed in 2012, stood as the world's tallest all-residential building until the completion of the nearby Princess Tower (Figure 4-3). It is located in Dubai next to a metro station and the Emirates Golf Club, offering panoramic views of the Marina, the Dubai International Marine Club, Sheik Zayed Road and Dubai Media City. The 90-storey tower is constructed in an octagonal shape, which maximizes the views from the apartments. The tower employs a curtain wall system of exposed white concrete and tinted blue glass, and includes 289 two- and three-bedroom apartments and four-bedroom 'duplex' apartments (CTBUH, 2017). The architectural drawings for the 23 Marina were obtained from a data website for real estate investors. As in the Silverene Tower, the thermal properties of the building envelope were based on Dubai's GBRS (2011, p.161).

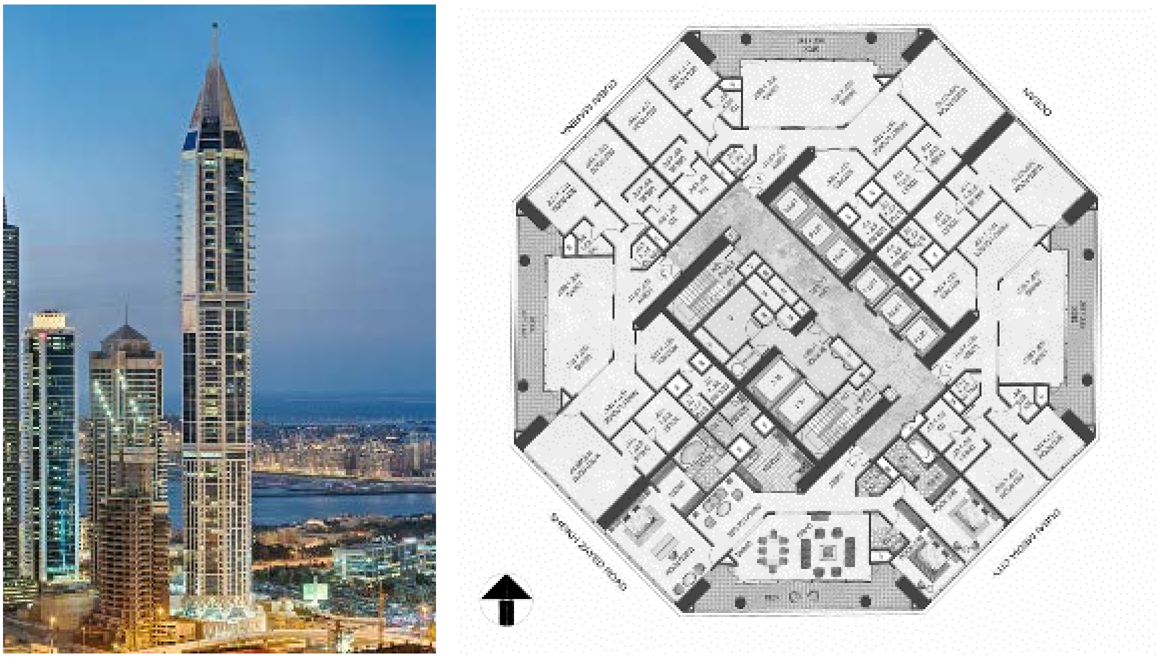


Figure 4-3 the 23 Marina Tower in Dubai, completed in 2012 (Source: Dubai Marina Properties)

Al Yaqoub Tower

[13] The CTBUH defines "supertall" as a building over 300 meters (984 feet) in height.

The supertall Al Yaqoub Tower stands 328m high on Sheikh Zayed Road in Dubai (Figure 4-4). After construction began in 2006, a programming switch from residential to commercial use was made, stalling construction until the revised plans were finalized, and the building was not completed until 2013 (CTBUH, 2017). However, the author was able to obtain the original residential plans for the tower through personal contacts with the Eng. Adnan Saffarini Office in Dubai, the design architects for Al Yaqoub Tower. The AutoCAD drawings stated that the curtain walls were made of reflective glazing, and the values for the VLT and SC for 6mm silver reflective glass were based on the table listing light and thermal transmission values for a variety of tinted glass in Elkadi (2006, p.67). Meanwhile the U-value for the opaque walls and glazing were based on the minimum envelope performance requirements specified in Dubai's GBRS (2011, p.161).

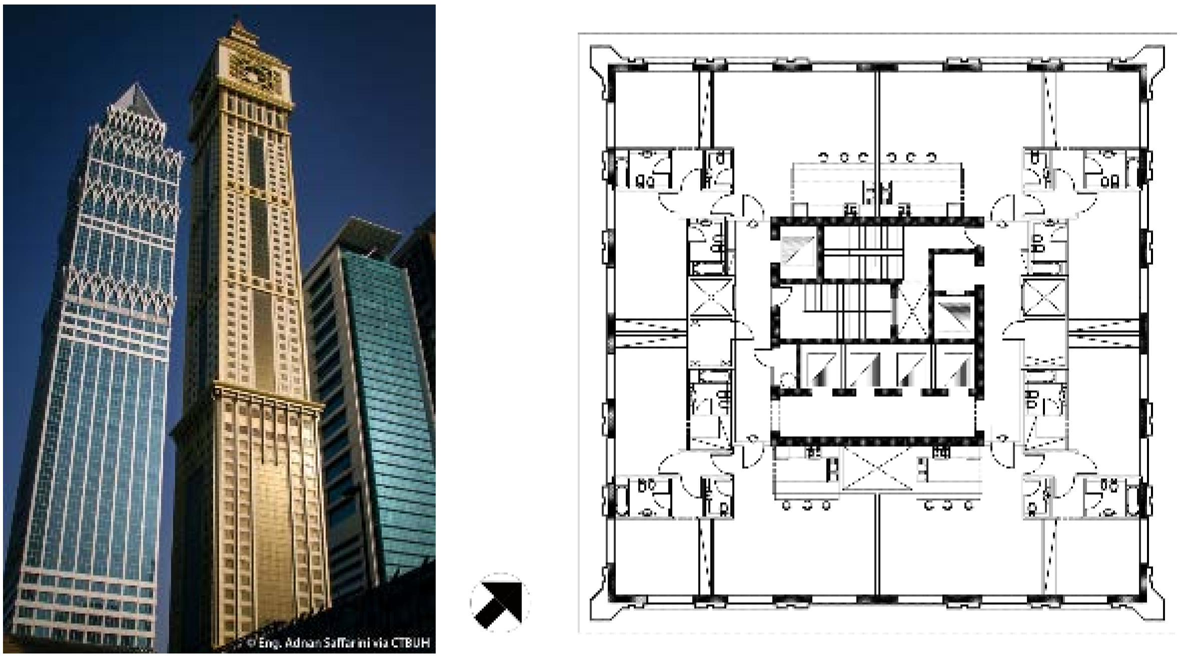


Figure 4-4 Al Yaqoub Tower, completed in 2013 in Dubai (Source: CTBUH and Eng. Adnan Saffarini Office)

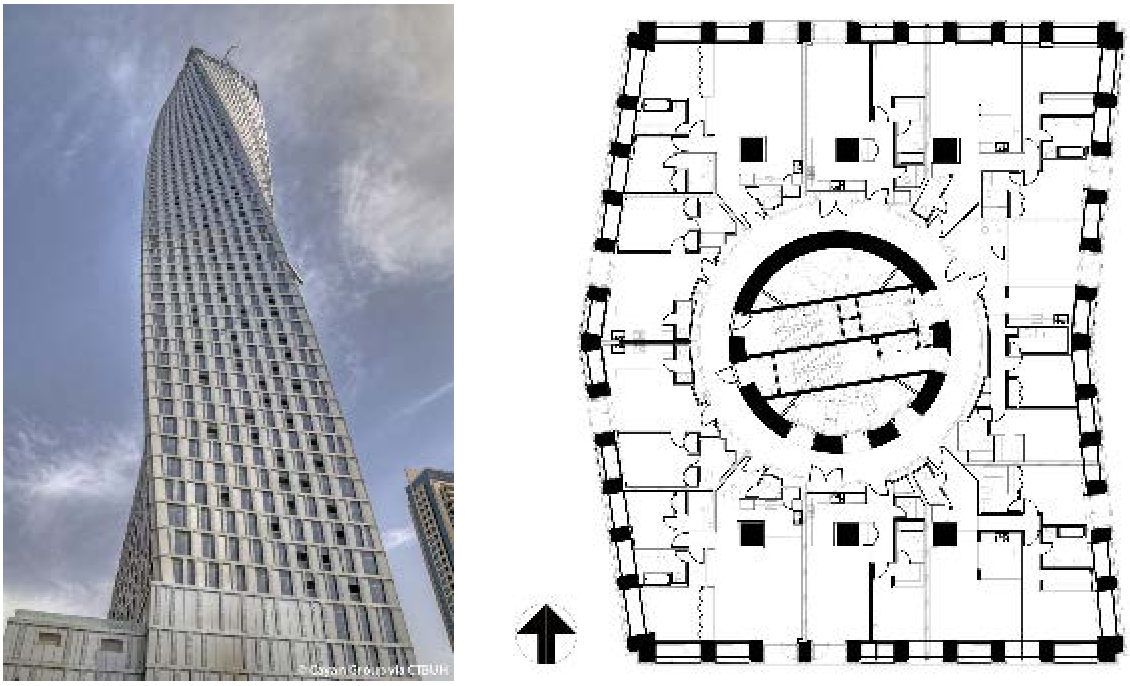


Figure 4-5 Cayan Tower, completed in 2013 in Dubai (Source: CTBUH and Khatib and Alami)

Cayan Tower

The Cayan Tower is a 306.4m high luxury apartment building designed by SOM and located in Dubai with a striking twisted shape, turning 90 degrees over the course of its height (Figure 4-5). Each floor is identical in plan, but is set 1.2 degrees clockwise from the floor below, giving the tower a distinctive form that provides a greater number of units with desirable views of the Gulf and Dubai Marina, while also preserving the views for residents living in neighbouring buildings. The tower took seven years to build and was completed in 2013. The structural system was determined through tests and analyses including the use of wind-tunnel testing and three-dimensional computer modelling. The 73-storey tower offers various residential units including studios, three-bedroom apartments and six levels of both half- and full-floor penthouses. According to the CTBUH, who named the tower 'Best Tall Building in the Middle East & Africa' in 2014, the tower's unusual shape is designed to reduce cooling demand and enhance indoor thermal and visual comfort. The building's twist generates self-shading, while the exterior terraces and the façade's metal cladding panels, high-performance glass, and deep sills around the recessed glass line further protect the building from direct solar radiation and glare, providing diffuse daylight to interior spaces while optimizing views of the surrounding marine environment. This enhanced design for solar control aimed to reduce the building's demand for cooling and provide a thermally comfortable environment. Moreover, while the tower's helical form acts as a shield from the northerly diurnal sandy and dusty winds, the HVAC system has also been specially designed to deal with desert conditions through the use of a dedicated external air system equipped with sand filters and heat pipes which distributes fresh air across the tower. This satisfies the cooling load while providing additional local filtering to reduce the level of fine particles entering through the façade. When outdoor conditions allow, windows can be opened so that natural ventilation can provide fresh air and passive cooling in interior spaces (CTBUH, 2017).

The architectural drawings and thermal specifications of the glazing for the building envelope were obtained from Khatib and Alami, the local architect of record, who cordially supplied the section about glazing from the main works contract. The U-value for the opaque wall was again based on the minimum envelope performance requirements specified in the GBRS (2011, p.161).

4.1.2.2 Abu Dhabi

East-Walk Al Maryah Plaza

The East-Walk Al Maryah Plaza is a residential project due to be completed in 2018, located on Al Maryah Island, an area at the very centre of the Abu Dhabi Economic Vision 2030 which is being promoted as the future financial hub of the Middle East (Figure 3-6). The design for the 153,000m² scheme consists of four glass and steel towers housing 30,000 residents, a luxury hotel and serviced apartments, together with office space and car parking facilities. The towers' design of sloping planes was inspired by sails, with balconies and terraces that reference elements of a ship's deck (Figure 4-6), while the diamond-shaped buildings maximise the flow of natural light and optimise views over the Gulf (Farglory, 2015; Pascall and Watson, 2017).

As mentioned in Section 3.2.1, the author obtained drawings and information for a typical 32-storey 165m-high residential tower of The East-Walk Al Maryah Plaza from Buro Happold Engineering. These included architectural drawings of a typical floor plan and façade sections and details, and relevant chapters and sections of the Progress Report for the Scheme

Design stage (Rogers Stirk Harbour Partners and Buro Happold, 2013), which contained external wall systems, façade performance criteria, building physics design criteria, and glazing specifications, in addition to the Solar Control Commentary and Recommendations report (Buro Happold, 2013).

The Progress Report contains a chapter on the external wall systems (EWS), which identifies the distinct types of external wall system constituting the largest part of the building façade (Figure 4-7). It illustrates the distinguishing characteristics, glass types and glazing specifications, intended performance and proposed composition of each system type. The description of the EWS includes a solar gain analysis for the glazing in the west lifts core comparing three different coverages of fritting for glass (15%, 30%, 45%) with the ASHRAE baseline, since the key performance target for the proposed design approach to annual energy performance (kWh/m^2/yr) was to exceed the Estidama requirement to improve on the ASHRAE 90.1 baseline by a minimum of 12%, and instead meet the more stringent local master planning requirement that a 20% reduction be achieved. However, the results of the solar gain analysis indicated solar control glass with at least 45% of frit coverage should be used, even though it would not outperform the ASHRAE baseline. Other analysis showed that increasing the percentage to between 50% and 60% outperformed the ASHRAE baseline but reduced the light transmittance to the core circulation area.

The Progress Report also included a section about the façade performance criteria which illustrated the criteria for architectural design, structural design, and building physics. These set the insulation and building envelope thermal performance, and involved sensitivity analysis, energy calculations and a brief parametric study for solar gain to find the optimal glazing g-value to control solar radiation and prevent excessive heat gain within the residences. This determined the glazing composition, treatments and type of glazing solar control coating, in addition to glare control solutions through external shading systems and internal blinds. Finally, the glazing specifications section set the design criteria for the glass selection in relation to a unified external appearance regardless of the application.

The report’s executive summary itemises the key studies undertaken over the scheme design stage, namely building fabric solar performance optimisation, internal thermal and visual comfort, building energy performance, and external comfort and microclimate studies. The summary also explains the key drivers for the delivery of comfort and energy efficiency incorporated into the design approach to the Al Maryah project, using the analysis techniques in Estidama's Energy Modelling and Environmental Design Timeline (See also Chapter 3, Figure 3-3), and illustrating the analysis findings and design recommendations. An appendix to the summary contains the energy efficiency measures and design benchmarks for building fabric, hot water, space cooling and heating, ventilation, lighting, and vertical transportation, in relation to the ASHRAE Baseline, the proposed scheme design and pioneering standards such as Passivhaus.

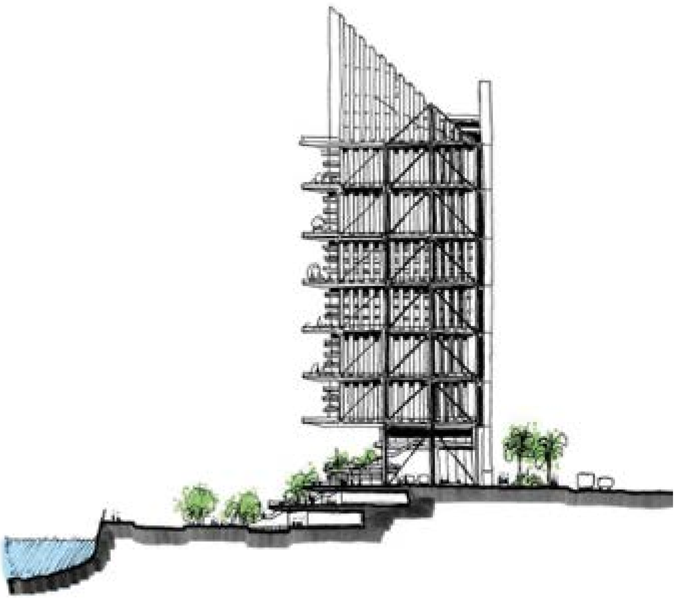


Figure 4-6 A residential tower of the East-Walk Al Maryah Plaza, a FarGlory Sowwah Development in Abu Dhabi (Source: Pascall and Watson, 2017)

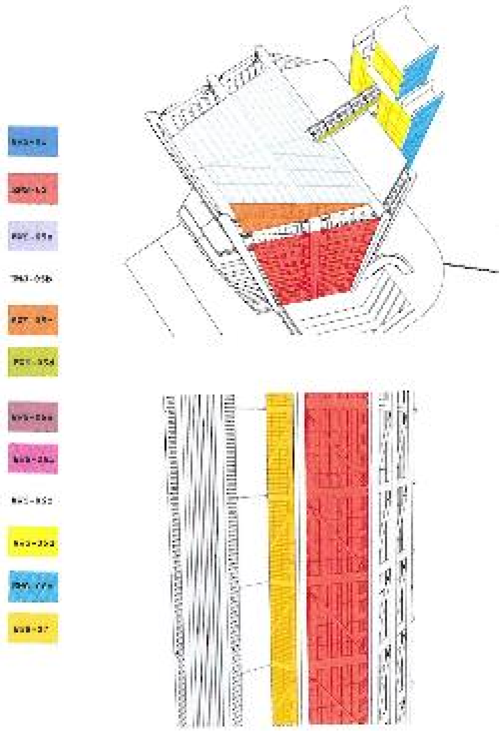


Figure 4-7 The external wall system constituting the building façade in the East-Walk Maryah Tower in Abu Dhabi (Source: Buro Happold, 2013)

<u>The Landmark Tower</u>

The Landmark Tower is a 64-storey, 330m-high tower completed in 2013 comprising 50 floors of residential accommodation, two floors of restaurants, one floor of health club facilities, four floors of office accommodation and two levels of retail. It also includes six levels of underground parking and a roof top sky garden (Figure 4-8) (BuroHappold, 2005). According to the CTBUH (2017), the Landmark Tower’s design used local precedents to address the challenging desert weather conditions in an environmentally sustainable and culturally sensitive manner. These include the layered shading screens extending from the building’s conditioned envelope and the plan geometry, which is based on the dodecagon, the 12-sided figure frequently used in Islamic art. Moreover, the tower top, which hosts a substantial sky garden, uses the temperature gradient and higher wind speed to reduce the need for cooling, a traditional practice in the Gulf Region (CTBUH, 2017).

The documentary information obtained about the tower included a 129 page Progress Report for the Conceptual Design stage (BuroHappold, 2005), which contains structural issues, building services, design and construction schedules and architectural drawings. The most relevant and useful data in this report is the architectural drawings, and the Outline Engineering Specifications section, which gives the site considerations in terms of location in Abu Dhabi, orientation and weather data. It also includes the general design data and parameters based on the ASHRAE standards relating to the design criteria and external and internal design conditions, and the building envelope performance recommendations (U-value and SC) based on Buro Happold's experience in the Middle East.[14] However, the building envelope performance parameters set out in the Progress Report were not used in the Characteristics Table as updated information was available in the Performance Specification Report for Curtain Walling and Associated Cladding (Buro Happold, 2006).

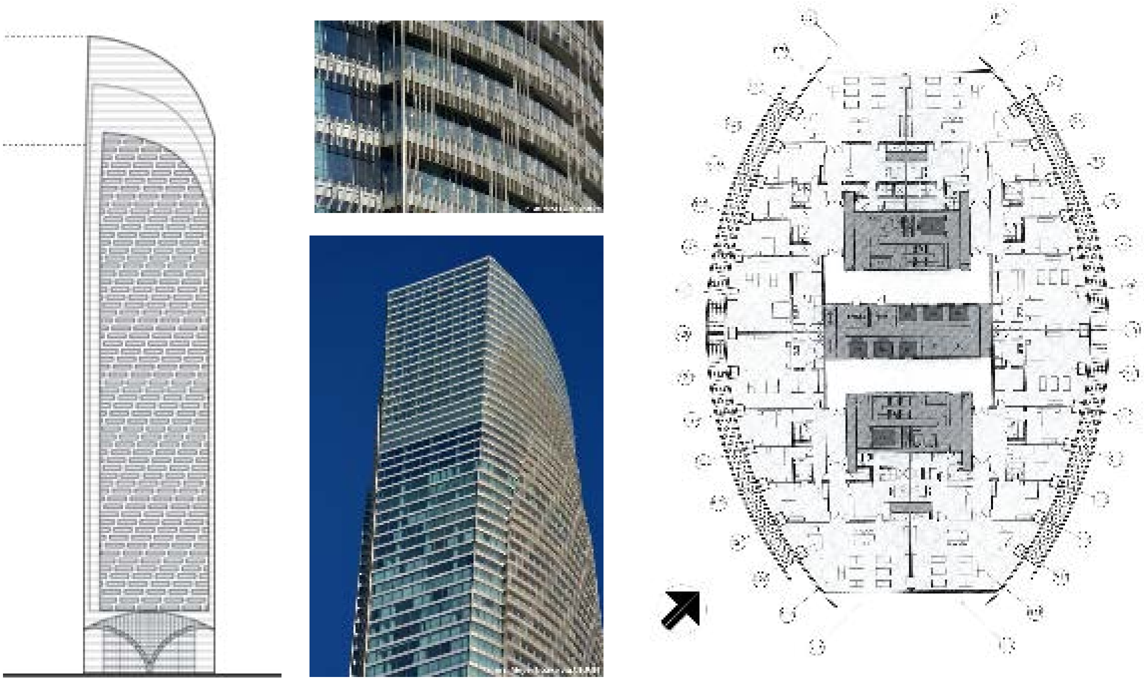


Figure 4-8 The Landmark Tower, completed in 2013 in Abu Dhabi (Source: CTBUH, and Buro Happold Engineering)

[14] In 2005, there were no best-practice codes for buildings in Abu Dhabi.

The Gate Residential Towers

The Gate Towers, completed in 2013, are located in the Shams Abu Dhabi district, a newly created land mass formed as an extension of the Central Business District of Abu Dhabi. This mixed-use residential project has a total of 3,533 luxury residential apartments in three 66 storey towers, connected at the top by a two-level sky-bridge structure that contains 21 luxury penthouses with indoor pools (Figure 4-9). According to the CTBUH (2017), both environmental and sustainability measures were considered in the design of the towers, notably the 14 hanging sky gardens, the selection and installation of mechanical and electrical equipment to improve indoor air quality and movement while controlling the temperature throughout the building, and the provision of a centralized cooling plant which serves the towers and the podium, thereby reducing energy consumption compared to conventional systems of individual chillers installed on each tower. Also, the facades are composed of glazed curtain walls with thermal specifications, such as U-value and SC, following the UAE authorities' requirements, while the insulation of building glazing using low-e coating has reduced the heat gain and cooling loads of the towers. Based on these social and environmental sustainability features, The Gate Towers were recognised as finalists in the 'Best Tall Building in the Middle East and Africa' category of the 2013 CTBUH Awards (Singh et al., 2013). Information about a typical residential tower, including the architectural drawings and façades external finishes, were again provided by Khatib and Alami, the design architects of record.

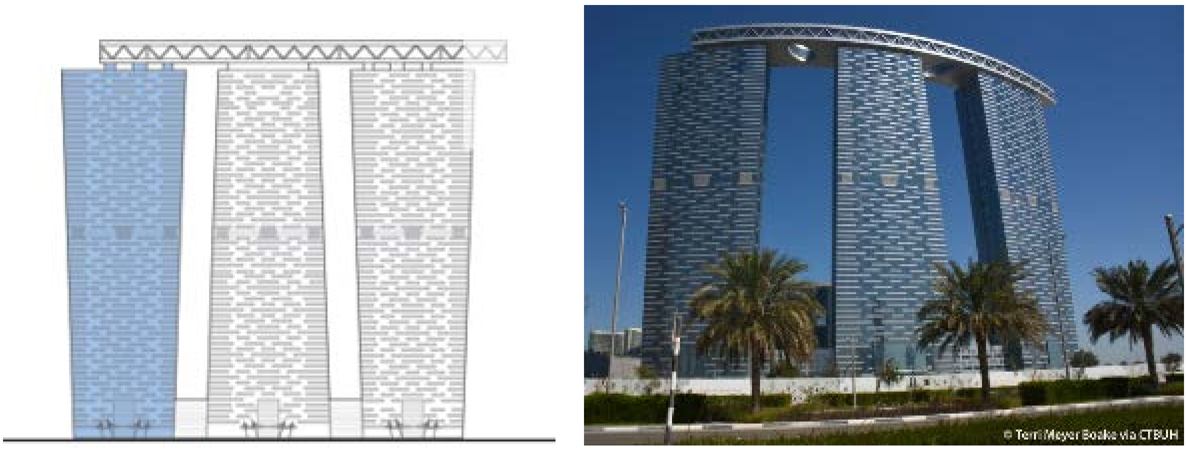


Figure 4-9 The three towers of the Gate completed in 2013, part of the largest development in Shams Abu Dhabi (Source: CTBUH, 2017

World Trade Centre – Burj Mohammed Bin Rashid

The Burj Mohammed Bin Rashid, designed by Fosters and Partners, was completed in 2014. It is located in the heart of Abu Dhabi as part of the larger World Trade Center complex at the site of the old Central Market, a traditional crossroads and meeting point in the city. The supertall 381.2m high residential tower is just one element of a 700,000-square-meter mixed-use development, which also includes an office building, a hotel, a traditional souk, up to seven levels of retail in the podium, a green roof above the souk, and a bridge system linking these areas together (Figure 4-10, 4-11). All the information about the towers, including architectural drawings, design developments reports and specifications, was obtained during the author's visit to Chapman BDSP, the project MEP design engineers.

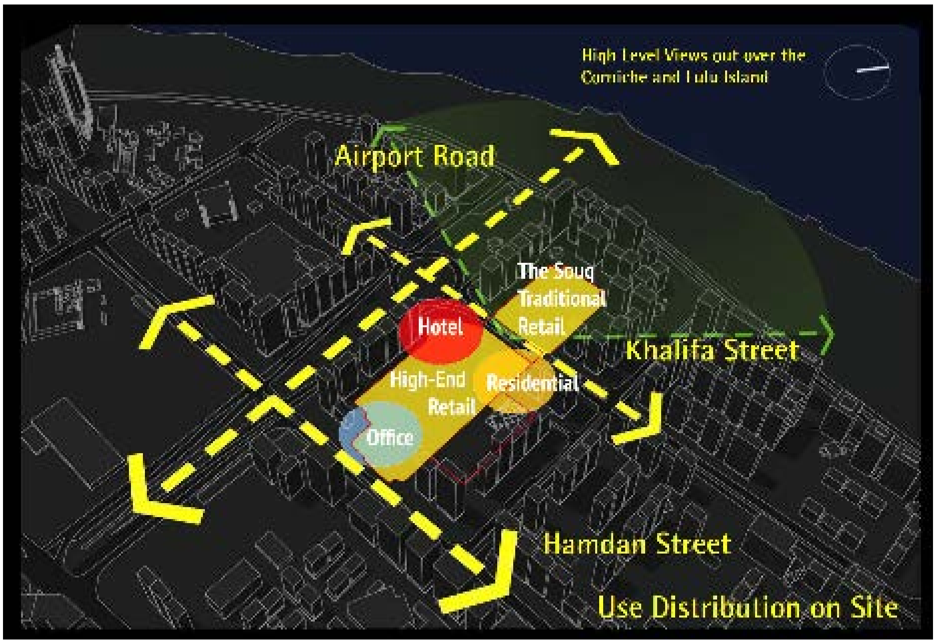


Figure 4-10 The distribution and connections of functions in the site of the World Trade Center complex in Abu Dhabi, UAE, designed by Foster and Partners (Source: Foster and Partners, 2006)

Figure 4-11 The World Trade Centre Complex in Abu Dhabi completed in 2014.The floor plan shows the residential tower, Burj Mohammed Bin Rashid (Source: CTBUH and Chapman BDSP)

At the beginning of the project in 2006, there was no established standard within the UAE for sustainable construction. However, the 'Masdar Initiative', Abu Dhabi's multi-faceted approach to alternative energy was launched later that year, and the vision for the World Trade Center development was adapted to reflect and express this shift towards sustainable energy. Formal accreditation through an alternative international standard such as Leadership in Energy and Environmental Design (LEED) was considered and Chapman BDSP carried out 'pre-assessments' using LEED for New Construction Version 2.2. The resulting environmental report set out a sustainability framework for the project with sections on sustainable sites, water efficiency, energy, materials and resources, and indoor environmental qualities (Foster and Partners and BDSP Partnership, 2006). The elliptical plan form for the tower was generated based on the geometrical grid of the underlying retail centre/souk plans and the introduction of an outer skin as a climate modifier, creating a smooth, reflective and fluted façade that requires minimal maintenance in the dusty desert environment. As noted in Section 3.2.3, in the conceptual development of the project, each of the tower roofs were deliberately orientated with a south facing pitch to maximise the amount of electrical energy that could be generated via photovoltaic panels, providing valuable shading for the roofs from the daytime sun while enhancing the architectural quality of the towers. Moreover, the initial design of the residential towers integrated a number of measures to increase their energy efficiency, such as solar thermal tube collectors for domestic water integrated into external wall systems, and a double skin façade with a buffer zone between the two skins to create living spaces and gardens for the apartments (as shown in Figure 4-12) (Foster and Partners and BDSP Partnership, 2006; CTBUH, 2017). However, most of these ideas were eliminated due to value engineering and financial issues (Duncombe, 2014).

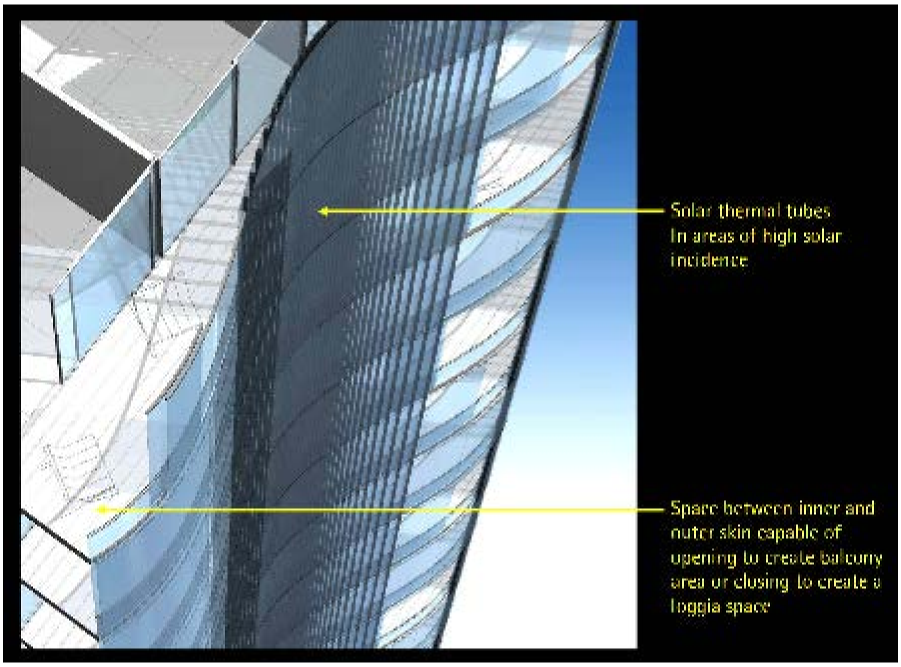


Figure 4-12 An illustration of the proposed solar thermal façade and double skin façade for the residential towers in World Trade Center in Abu Dhabi (Source: Source: Foster and Partners, 2006

4.1.2.3 Jeddah

<u>Lamar Towers</u>

This exclusive mixed-use development, estimated to be complete by mid 2018, is located along the North Corniche area in Jeddah, Saudi Arabia, on the Red Sea coast (Wikipedia, 2017). The development, designed by Saudi Diyar Consultants and RMJM, incorporates a podium of three levels of retail and ten levels of office space that connect two residential towers at the lower levels (Figure 4-13). These towers rise to 70 storeys (322m high) and 62 storeys (293m high) respectively and include large penthouses, duplexes, and studios as well as one, two, and three-bedroom condominiums. The towers are planned around a triangular shaped floor plate that allows all residential units to enjoy sea views (Diyar, 2011). The architectural drawings for the towers, which were obtained from Saudi Diyar Consultants through personal connections, include façade glazing load resistance calculation reports that specify the glass construction information but not the thermal specifications. Therefore, the U-value of the opaque walls was estimated based on the architectural drawings that state the outer skin is formed of 200mm insulated blocks.[15] The U-value for glazing was calculated[16] and compared against the optical and thermal performance values of glazing units using low-emittance coating given in Elkadi (2006, p.70) and Pilkington's table of indicative U-value for windows with wood or PVC-U frames, while the SC was estimated based on the SC values of windows and glazing in Brown and DeKay (2001, p.48)[17] and the VLT was estimated for 6mm grey glass type based on the light and thermal transmission values for a variety of tinted glass given in Elkadi (2006, p.67).

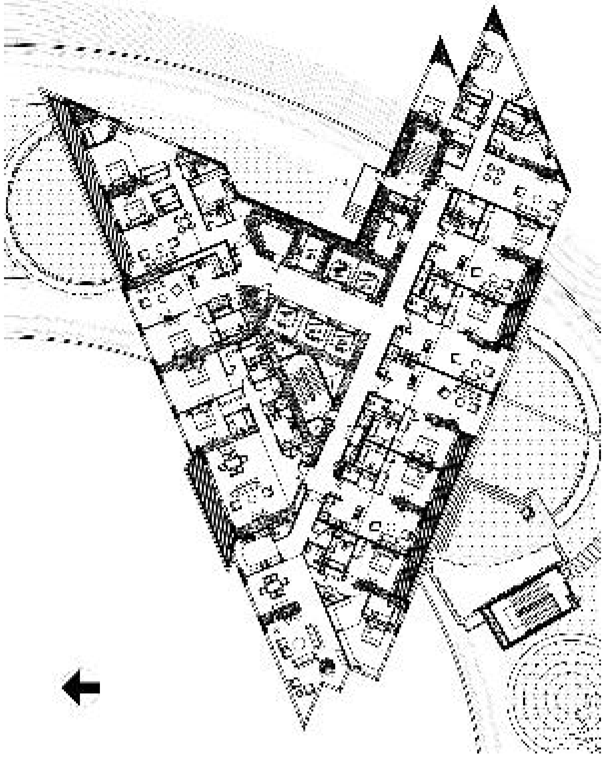


Figure 4-13 Lamar Towers in Jeddah, due to be completed in 2018 (Source: Skyscrapercity, 2007)

Corniche Dreams Tower

The Corniche Dreams Tower are four interconnected residential towers, locally designed and completed in 2011 (Figure 4-14). The floor plan for the 27-storey towers consists of four joined towers each with a separate core serving a single apartment per floor. The main elevation is oriented toward the west to take advantage of the views across the Red Sea. Mr.

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[15] The Product data sheet from Hussain Mohd. Abbas Block Factory (2017) states that the U-value for 200mm insulated blocks is 0.52 W/m^2K, so this was used in the Characteristics Table.
[16] The U-value for glazing was calculated online at http://www.thermalcalconline.com/u-value-calculator/u-value-glass/u-value-glass.html.
[17] The SC for double glazing clear grey glazing was (0.51) and for glazing with overhang balconies, the SC was (0.5x0.2 = 0.1).

Syed Zubair Jaffery, the maintenance manager, provided the main information for the tower including the wall type. Jaffery stated that the external walls are aluminium cladding (4mm) unventilated cavity wall composed of 600x600x100mm gypsum blocks with a 100mm air cavity and no insulation. The U-value of the opaque walls was estimated through manual calculation based on specifications from Viltabond Aluminium Composite Panels (R-value 0.0103 m2K/W) and Gyproc WallBoard from British Gypsum (R-value 0.52 m2K/W), while the air cavity was calculated based on Anderson (2006, p.11) who specifies that unventilated airspaces cavities in wall constructions have a resistance of 0.18 m2K/W. As for glazing specifications, Mr. Mohammed Kaki, the owner of the towers, provided the values for the VLT and SC for the glazing.

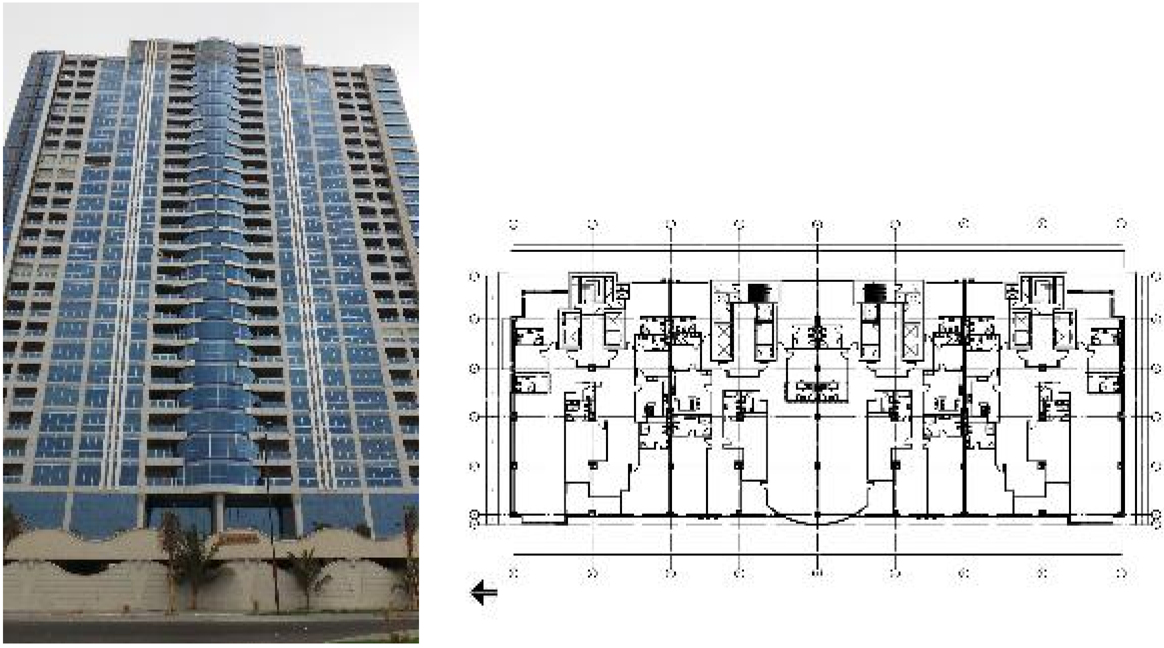


Figure 4-14 Corniche Dreams in Jeddah, completed in 2011

4.1.3 The Table Contents

Since the aim of the Residential Tall Buildings Characteristics Table was to establish the basis of the parametric study in the next stage of the methodology by meeting the three main objectives set out at the beginning of this section, the table contents, collected from architectural drawings and databases, was grouped into three main components:

1. Basic building information, used to gain a greater understanding of the common architectural characteristics of residential tall buildings and inform the design and formation of the base case for the parametric study in the next chapter;

2. Architectural data, used to evaluate the performance of current building envelopes in relation to heat transfer and solar gains; and

3. The thermal properties for the building envelope, used to identify the main parameters that influence energy use in order to explore them in the parametric study.

Following that, an evaluation of envelope performance in relation to heat transfer and solar gains was conducted using the two analysis techniques proposed by Brown and DeKay (2001): the Skin Heat Flow technique (Figure 4-15) and Window Solar Gain technique (Figure 4-17). Consequently, the thermal properties in the table were set to include the main parameters required for these two techniques, in order to understand which parameters have the greatest impact on the thermal performance of the building envelope.

As mentioned in Section 2.3, these analysis techniques were selected because they are most appropriate and applicable to the evaluation of building performance in the hot climates of the Gulf Region, and they are more flexible in terms of varieties for the inputs of the thermal characteristics of the building envelope, thus quickly providing the initial understanding of the envelope performance required at this early stage of the research. The Skin Heat Flow technique establishes how fast the heat will flow through the building's skin for each degree of temperature difference between inside and outside temperatures. It is based on the magnitude of the temperature difference, the thermal resistance or transmittance of the skin materials, and the area of the skin. According to Brown and DeKay (2001), this technique allows the designer to understand how the ratio of skin area to floor area, the percentage of window area, and the wall construction affect the rate of heat flow. As indicated in Figure 4-16, in the Skin Heat Flow technique, the heat flow through the skin is estimated by first knowing the U-value of the opaque skin (W/m^2K), then the percentage of glazing or glazing ratio (%), following the lines to the ratio of exposed skin to floor area.

As for the Window Solar Gain technique, the amount of solar radiation transmitted through the building skin is dependent on the available radiation in the climate, the building's form and orientation, the heat transmittance characteristics of the exposed skin, and the amount of glazing, which demonstrates to the designer the degree of importance of these design variables to the building heat gain rate. As shown in Figure 4-18, to estimate the solar heat gain through windows per unit of skin area,[18] first the solar heat gain factor (SHGF) should be calculated using the ASHRAE 1997 Fundamentals Handbook (ASHRAE, 1997, pp.29.29-29.35) for the appropriate orientation, hour, latitude and month. Then the percentage of glazing defined, and the SC for the glazing and shading device (if applicable). According to Brown and DeKay (2001), these techniques can be used together to determine the total heat gains through the building envelope. This helps to define and understand the context of the design problems and how are they affected by changes in the building's form and envelope construction, thereby informing decisions about the most important strategies to be further compared and investigated.

With these parameters in mind, Table 4-1 explains the three main components of the Characteristics Table and their definitions and main sources. The basic building information was mostly obtained from the Skyscraper Center database (CTBUH, 2017), while the architectural data was calculated using the available architectural drawings. As for the thermal properties of the building envelope, they were either provided by the design teams, obtained from the market based on construction type and specifications, or estimated according to the minimum requirements of the local energy efficiency building regulations for Dubai, Abu Dhabi or Jeddah, depending on the building's location.

The Characteristics Table in Appendix B illustrates each tower with an image and a simplified floor plan and gives the building architectural information and thermal properties, which were used for the manual performance evaluation regarding heat flow through the building skin. However, due to its size, it was not possible to include it within the text of this chapter.

[18] To determine the solar heat gain for the entire surface, multiply the heat gain in W/m^1 of skin by the area of skin. Complete this procedure for each surface for the same time and date. Then add these solar heat gains and divide the sum by the number of m^2 in the building to determine the solar heat gain per unit of floor area for that particular month and time of day (Brown and Dekay, 2001, p.50).

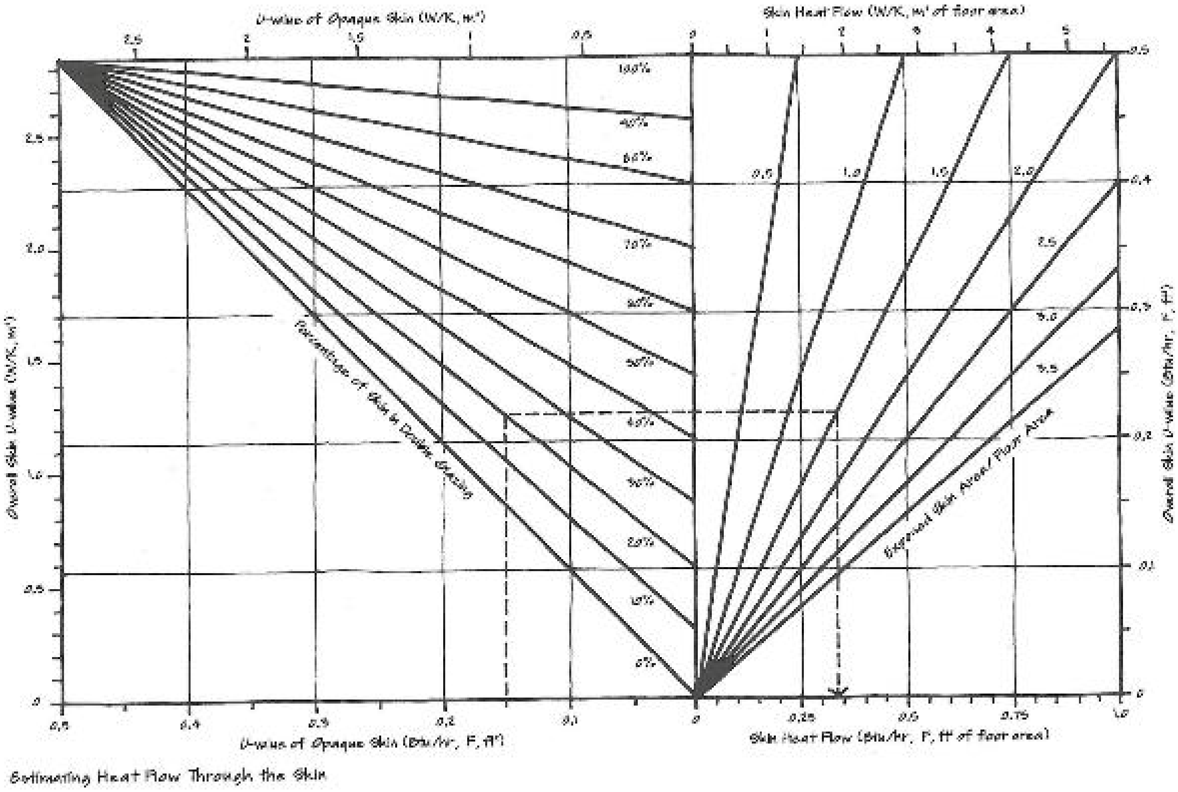


Figure 4-15 The Skin Heat Flow technique proposed by Brown and DeKay (2001, p.47)

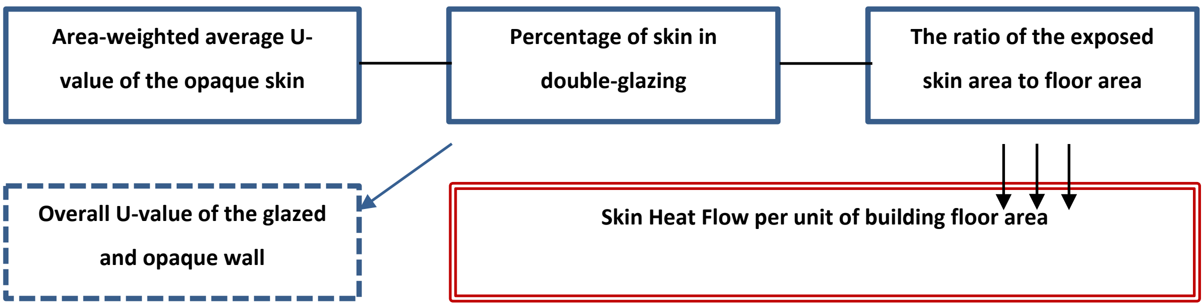


Figure 4-16 Flowchart of the main parameters required for the first technique to estimate the heat flow through building skin per unit of the building floor area

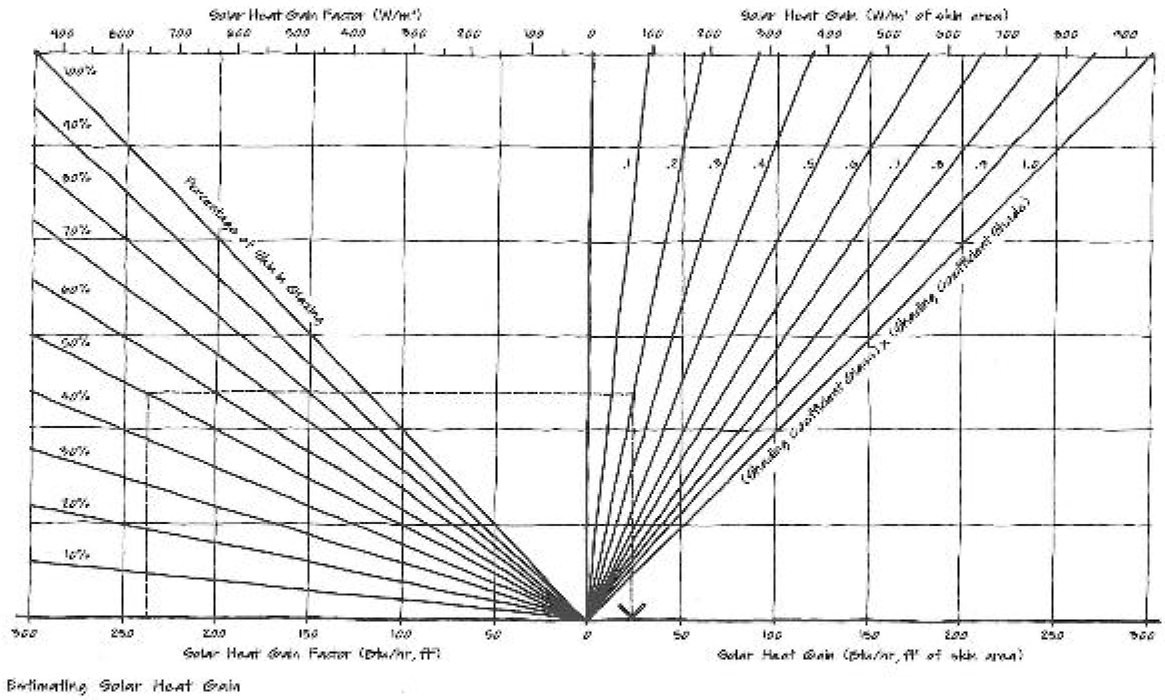


Figure 4-17 The Window Solar Gain technique proposed by Brown and DeKay (2001, p.50)

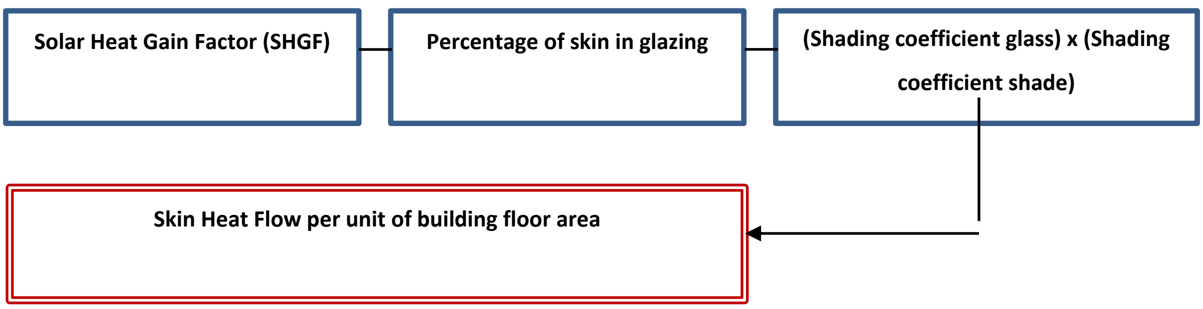


Figure 4-18 Flowchart of the main parameters required for the second technique to estimate the solar heat gain through the windows per unit of skin area

Table 4-1 The components of the Characteristics Table and their sources.

Component	Sources and definitions
Basic Building Information	
Building name and designer Image – City – Year – Function Height (m) Number of floors Building GFA (m^2)	Obtained from the Skyscraper Center database of the Council on Tall Buildings and Urban Habitat (CTBUH, 2017) For some buildings, the design team or developers provided the information.
Architectural Data	
Typical floor plan	Simplified floor diagrams illustrating building orientation, the shape of the floor plan, and main dimensions. Based on the architectural drawings available from the design team, developers or online.
Net internal area (m^2)*	Internal floor area calculated from architectural drawing for the residential zones for one typical floor plan, calculating the useable floor area of the building measured to the inside edge of the external wall. This excludes the service core area, mechanical floors and the ground floor lobby (Oldfield, 2012).
Gross external area (m^2)	Calculated from architectural plans based on Oldfield's (2012) definition of the total floor area of the building measured to the inside edge of the external wall
Core area (m^2)	Calculated from architectural plans for the area of the core system and vertical circulation
Typical floor plate efficiency (%)	Calculated from architectural plans based on Oldfield's (2012) definition of a building's floor-plate efficiency as the floor plate net-to-gross ratio
Typical floor plate width and length (m)	Calculated from architectural plans
Lease span (m)	Calculated from architectural plans based on Oldfield's (2012) definition of a building's lease span as the dimension between its core, or an internal corridor, and the external façade.
Core location	Based on architectural plans
Number of units	Based on architectural plans
Floor to floor height (m)	Calculated from architectural section
Floor to ceiling height (m)	Calculated from architectural section
Exposed skin area (m^2)	Calculated from architectural drawings: (Exposed walls of residential zone x floor to floor height) for one typical floor
Exposed skin area/ floor area	Calculated from architectural drawings
Glazing ratio of total exposed skin area (%)	One of the requirements for Brown and DeKay techniques. Calculated from architectural drawings based on Baker and Steemers' (2000) definition, which is the ratio of the glazed area of the total area of the façade for one typical floor = glass area/total façade area
Thermal Properties	
U-value of opaque skin (W/m^2K)	- Provided by the design team or, - Calculated based on construction type and specifications of Thermal Blocks in Hussain Mohd.Abbas Block Factory (2017) or, - Estimated from the minimum requirements for Dubai's GBRS (2011) for buildings in Dubai or, - Estimated from the minimum requirements for the SBC 601 (2007)[19] for buildings in Jeddah.
U-value for glazing (W/m^2K)	- Provided by the design team or, - Calculated based on construction type or, - Estimated from the minimum requirements for Dubai's GBRS (2011) for buildings in Dubai or, - Estimated from the minimum requirements for the SBC 601 (2007) for buildings in Jeddah.
Visible light transmittance VLT (%)	- Provided by the design team or, - Estimated from the minimum requirements for Dubai's GBRS (2011) for buildings in Dubai or, - Estimated from the minimum requirements for the SBC 601 (2007) for buildings in Jeddah. - Estimated based on Table 5.1 and 5.2 of thermal transmittance of a variety of tinted and coated glazing types in Elkadi (2006, p.67-68).
Shading coefficient (SC)	- Provided by the design team or, - Estimated based on given values from Elkadi (2006, p.67) or Brown and DeKay (2001, p.48) - Estimated from the minimum requirements for Dubai's GBRS (2011) for buildings in Dubai or, - Estimated from the minimum requirements for the SBC 601 (2007) for buildings in Jeddah. The SC for shading devices was estimated based on charts from Brown and

[19] The Saudi Building Code Energy Conservation Requirements (SBC 601) was based on the International Energy Conservation Code (IECC).

	DeKay (2001, p.49)
Solar heat gain coefficient (SHGC)	Calculated from the SC based on Elkadi (2006), SHGC = SC x 0.87
Glazing composition	Thickness of glass, air space, glass colour (when available from the design team or developer).
Glazing ratio for each orientation (%)	The ratio of the glazed area of the total area of one façade orientation (e.g. north facing façade) for one typical floor = glass area/total façade area
Solar Heat Gain Factor (SHGF)	The SHGF was calculated using Table 16 from the 1997 ASHRAE Fundamentals Handbook (p. 29.30) for 24° N. The values were chosen for summer solstice (21 June) for three different times: 8 a.m., 12 p.m., and 4 p.m.
Performance	
Estimated heat flow through skin (W/m^2K) of floor area	Based on the nomograph for the first technique (Figure 4-16) and using the following requirements from the table: U-value of opaque skin, glazing ratio of total exposed skin area, exposed skin/floor area.
Estimated solar heat gain (W/m^2) of skin area	Based on the nomograph for the second technique (Figure 4-18). The total solar heat gain for all the façade orientations at three different times of the day was calculated individually.

* For one typical floor

4.2 The Table Analysis

To establish the basis of the parametric study in the next chapter, the components of the Characteristics Table were analysed and sorted into three categories: firstly, the architectural and design characteristics that were used to establish the base case for the simulation, then the construction and glazing types which determined the tested parameters, and finally the results from the analysis for the Skin Heat Flow and Window Solar Gain techniques which set initial hypotheses regarding heat gain through the building envelope. The following sections explain the main findings in each category.

4.2.1 Architectural and Design Characteristics

The analysis of the architectural characteristics of the 11 tall buildings case studies was conducted in relation to the main design considerations that influence the design of tall buildings such as floor counts, floor-to-floor height, plan geometry, core location, and façade glazing ratio. Consideration was also given to other factors that are integral to tall building design such as the lease span and floor plan efficiency, which determine the usable space for a developer to rent out, thus increasing the income from the building.

The main findings show that the floor counts for the buildings range from 90 storeys for 23 Marina in Dubai, the third tallest residential building in the world, to 27 storeys for Corniche Dreams in Jeddah, considered a tall building in its surrounding context. The average number of floors is 62, which is common for many residential tall buildings in the region. Analysis also suggests that tall buildings in Dubai tend to be simpler in geometry and square in plan, either 30x30 or 40x40, while buildings in Abu Dhabi and Jeddah have a more complex geometry, including oval and triangular plan shapes. This might affect the floor plate efficiency which ranges from 84.6% in the Silverene Tower (Dubai) to 60.15% in the East-Walk Maryah Tower (Abu Dhabi) with an average floor plate efficiency of 65.4% amongst the buildings studied. Regarding the core location, the central core is the dominant system appearing in seven buildings while external cores appear in the other four. The lease span for the residential floors ranges from 8 metres (Al-Yaqoub Tower) to 16 metres (Landmark Tower). The average lease span for the 11 buildings is 10.4 metres. As for the floor-to-floor height, it ranges from 3.3 metres in the Gate District Tower to 3.6 metres in most of the other buildings. Finally, the glazing ratio of the total exposed skin area ranges from 72% (East-Walk Marayah Tower) to 20% (Cayan Tower). The average glazing ration for the buildings in the table is 48.6%, which is slightly higher than the recommended 40% in the ASHRAE standards. These architectural characteristics provided the main design considerations for the base case used in the parametric study. A detailed explanation of the base case formation will follow in Chapter 5, Section 5-2.

4.2.2 Construction and Glazing Types

The thermal properties of the building façade explained in Table 4-1 included the thermal transmittance (U-Value) of the opaque and transparent elements, the glazing composition, and the thermal and visual properties of glazing such as the VLT, SC and SHGF. The findings showed that the most common glazing systems used in residential tall buildings in the Gulf Region are double-glazed units with air-filled space and solar control coating. The building envelope parameters for the towers were compared with the local energy efficient building regulations for each city. For example, the building façade parameters of the towers located in Dubai were compared against the minimum envelope performance requirements specified in Dubai's GBRS, and the building façade parameters in Jeddah were compared against the building envelope requirements specified in SBC 601. As for the towers in Abu Dhabi, they were compared against the minimum energy performance requirements in Estidama's PBRS. Table 4-2 details the main types of glazing and their compliance with the local building codes and regulations. It shows that while the newly built towers in Dubai and Abu Dhabi comply with local building codes and regulations, the towers in Jeddah do not fully comply, despite the fact that the Saudi building code has mandated thermal insulation against heat for all new buildings since 2010.

The thermal properties of the opaque and transparent elements of the building envelope were used to set the matrix for the parametric study in the next stage, as will be explained in Chapter 5.

Table 4-2 Main types of glazing for the buildings in the Characteristics Table and their compliance with local building codes

Location	Wall U-value (W/m^2K)	Glazing composition	Glazing U-value (W/m^2K)	Visible Light Transmittance (%)	Shading Coefficient	Compliance with local building codes
Al-Yaqoub Tower Dubai (2013)	0.57	Not available	1.9	9	0.26	Yes, even though the glazing percentage is 23%, the values comply with the more stringent requirements of 60% glazing
Cayan Tower Dubai (2013)	0.57	Not available	1.75	43	0.35	Yes, the glazing percentage is 20% but they comply with the more stringent 40-60 % requirements.
East Walk Maryah Abu Dhabi (2017)	0.35	Double glazed insulated unit with aluminium frame: Monolithic heat strengthened 16 mm air space Laminated heat strengthened Clear glass with solar control coating (TBC)[20]	1.8	-	0.34	According to the design team, the energy performance of the building complies with the requirements of Estidama's PBRS.
Landmark Tower Abu Dhabi (2013)	0.35	Double glazing insulated unit: Heat strengthened glass with solar/thermal protective coating 16mm air space Laminated glass with PVB interlayer	1.4	50	0.3	Information not available
Gate District Tower Abu Dhabi (2013)	0.34	24mm hermetically sealed 4 side structural silicone double-glazed unit: 6 mm heat strengthened of Pilkington Shanghai 12 mm air filling 6 mm clear float annealed	1.7	24	0.28	Information not available
World Trade Centre Abu Dhabi - The Residences (Central Market) Abu Dhabi (2017)	0.35	Double glazing unit: 6mm heat strengthened glass 1.52 mm PVB 6mm heat strengthened glass 16mm Air space 6mm heat strengthened glass 1.52 mm PVB 6mm heat strengthened glass	1.4	24	0.24	Information not available
Lamar Towers Jeddah (2016)	-	Double glazing insulating unit: 8 mm Fully tempered 12.7 mm air space 6 mm Fully tempered Light and Dark Grey colours	2.8	39	0.51	The glazing U-value is slightly higher than the required value for the glazing percentage of 50%; however, the SC is lower than the required values which is better performance.
Corniche Dreams Jeddah (2011)	-	32mm Double Insulating Glass: 6 mm K-LITE -14 ON tempered 20 mm air space 6.00 mm EFG tempered Clear colour	2.7	13	0.23	

[20] Thermal barrier coating.

4.2.3 The Analysis of the Heat Gain through Building Skin

In order to identify the main envelope parameters that can affect overall building energy performance, the data compiled in the Characteristics Table was analysed using the Skin Heat Flow (Figure 4-16) and the Window Solar Gain (Figure 4-18) techniques. These were used together to evaluate the performance of the building envelope in relation to heat transfer and solar gains and to obtain the total heat gains through the building envelope.

Firstly, the Skin Heat Flow technique was used to estimate the heat flow through skin. This involved ascertaining the U-value for the walls, the glazing percentage, and the ratio for the exposed skin area to floor area (as shown in Figure 4-16). However, the results of this analysis were questionable since doubt has been cast on the process of relating envelope thermal transmittance to floor area rather than exposed skin area. For this reason, the final results were discarded. Nevertheless, the overall findings emphasised the significant impact the glazing ratio has on heat flow through the building envelope, since glass has a much lower resistance to heat flow than other building materials and allows higher thermal transmittance than opaque skin.

In the Window Solar Gain technique, the solar heat gain was calculated individually for each façade orientation by defining the glazing ratio, SC, and SHGF. The SHGF was calculated for each façade orientation for June at three different times of the day: 8 a.m., 12 p.m. and 4 p.m. (Figure 4-19). Then the total solar heat gain for a typical floor plan for each building was calculated from all the façade orientations and all the times in order to determine the most significant factors affecting solar gain. The results for the Window Solar Gain technique are illustrated in Figure 4-20.

The findings from the results showed that both Al-Yaqoub Tower and East-Walk Maryah Tower have the lowest solar heat gain, but for different reasons: Al-Yaqoub tower has a small glazing ratio (23%) on all façade orientations, while East-Walk Maryah has a very low SC due to the use of overhangs and balconies which provide more shading and significantly minimise solar ingress. This suggests that SC can overcome the problems associated with large glazing areas. On the other hand, the exposed façade area in Corniche Dreams Towers reduces the glazing ratio and consequently the solar heat gains.

Comparing the three towers in Abu Dhabi, the Gate District, Landmark Tower and World Trade Centre Abu Dhabi, it is clear that the glazing ratio is the dominating factor, since façades orientations and SC are fairly similar, but the slightly lower glazing ratio in the Gate District (45%) reduces the solar heat gain. It is also the dominant factor in Silverene Tower which has a very high glazing ratio (90%) in addition to the orientation of the façades.

The building geometry also plays a major role in terms of solar exposure: circular or octagon shapes are worst because solar gain is available throughout the day from every orientation. This is clear in the results for 23 Marina where the octagon plan received solar ingress and increased solar gain in addition to the large glazing area.

Ultimately, the main findings from the analysis show that the glazing ratio has a significant impact on both solar heat gain and heat flow through the building envelope, and that the building geometry affects the area of exposed skin. However, the SC can overcome the impact of a large glazing ratio if carefully implemented either as an engineering parameter solution (glass coatings) or a design parameter solution (shading elements).

29.30 1997 ASHRAE Fundamentals Handbook (SI)

Table 16 Solar Irradiance (E_{DN}) and Solar Heat Gain Factors (SHGF) for 24° North Latitude

Date	Solar Time	Direct Normal W/m²	Solar Heat Gain Factors, W/m²																	Solar Time
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Hor.	
Jun	6	307	112	222	294	318	298	229	122	26	22	22	22	22	22	22	22	26	54	6
	7	633	175	401	557	628	605	490	297	82	57	57	57	57	57	57	57	62	244	5
	8	764	157	397	580	674	668	563	370	135	85	82	82	82	82	82	82	86	456	4
	9	829	136	322	500	597	607	529	367	168	106	101	101	101	101	101	101	104	635	3
	10	864	129	227	357	442	462	412	301	172	122	114	114	114	114	114	114	118	773	2
	11	881	132	157	204	244	259	242	200	154	132	128	126	122	122	122	126	129	855	1
	12	886	135	135	135	135	135	135	135	135	136	135	135	135	135	135	135	135	880	12
HALF DAY TOTALS			897	1771	2530	2941	2938	2512	1717	803	590	572	567	565	565	565	567	589	3455	

Figure 4-19 The Solar Heat Gain Factor for 24°North Latitude as per the 1997 ASHRAE Fundamentals Handbook, the chosen times are highlighted

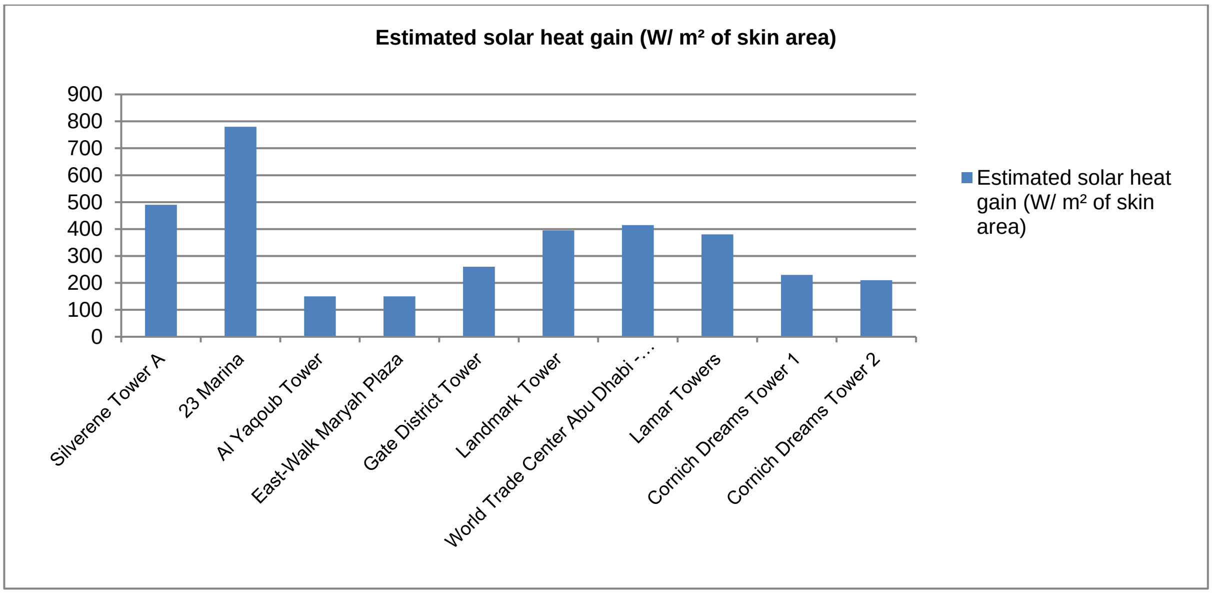


Figure 4-20 The results of the Window Solar Gain technique analysis from the Characteristics Table

4.3 Conclusion

This chapter has described the process whereby the architectural characteristics and building envelope properties of 11 residential tall buildings in the Gulf Region were compared by means of the Residential Tall Buildings Characteristics Table. In order to facilitate this comparison, the total heat gain through the building envelope for each case study was manually calculated using simple analysis techniques that consider the main parameters in the building envelope such as glazing percentage and the thermal properties of the opaque and transparent elements. The architectural characteristics, such as building storey count, floor-to-floor height, core location, building plan geometry and lease span, were used to define the common design considerations for a representative hypothetical residential tall building located in Jeddah to be used as a base case in the forthcoming parametric study. Meanwhile the thermal properties of the building envelope (glazing percentage, U-value of glazing and wall elements and SC of glazing) were used to develop the parameters for the simulation matrix, which compared different building envelope build ups and configurations, as will be explained in the next chapter. Finally, analysis techniques were used to examine case studies with a variety of different characteristics in relation to engineering and design parameters in the building envelope. However, it was a challenge to identify any correlation in this stage, since the analysis techniques looked at several parameters at the same time. Nevertheless, the results provide an insight into how shading coefficient can have a significant impact on the energy performance of the building envelope if carefully implemented either as an engineering parameter solution (glass coatings) or a design parameter solution (shading elements).

Based on this, the parametric study in Chapter 5 further examines the thermal performance of the building envelope using advanced dynamic simulation techniques in order to define the best and worst combinations of engineering and design parameters in relation to thermal transmittance and solar gains.

CHAPTER 5: Thermal Simulations of Envelope Parameters

This chapter investigates and compares the impact of different envelope parameters on the thermal performance of tall buildings in the hot humid climate of Saudi Arabia. In order to do this, the architectural characteristics of selected residential tall buildings in the Gulf Region – based on the Characteristics Table – were identified to establish a representative hypothetical base case in the city of Jeddah, then two parametric studies using dynamic thermal simulations were conducted. The first study examined the impact of the 'engineering parameters' of the building envelope and the best and worst combinations of glazing ratio, wall and glazing type were determined in order to understand the most influential parameter in relation to cooling loads and solar gains. As the results of the first study indicated that solar gains were the highest contributors to cooling loads, the second parametric study assessed the extent to which the 'design parameters' of the building envelope, such as shading elements, can improve the energy performance of residential tall buildings.

Chapter 5 SENSITIVITY ANALYSIS OF ENVELOPE PARAMETERS

> *"Environmentally, the glass tower of globalization has had a major impact on operational costs and building performance, being completely inappropriate for the hot humid and hot dry climates of Asia. Energy consumption for artificial cooling per square meter is significantly higher when compared to similar buildings located in the cities of temperate and cold climates in the US and Europe."*
>
> Joana Carla Soares Gonçalves in her book, 'The Environmental Performance of Tall Buildings', 2010, p.135

> *"The relationship between architectural form and energy are one example of a larger idea: the relationship of form and process…. My interest in the energy-form relationship is to explore how architectural form is in part a manifestation of the energy flows that are always present in a building. The designer can, with some experience, create form that guides and shapes those energy flows of sun, wind, and light."*
>
> G. Z. Brown and Mark DeKay in their book, 'Sun, Wind & Light: Architectural Design Strategies', 2001, p. xiv

Despite the Saudi government's growing concern about domestic energy consumption, conservation efforts have been largely ineffective due to the factors discussed in Chapter 3. The current local energy efficiency building regulations and environmental guidance mostly consider only the minimum thermal requirements for the building envelope parameters, such as adjusting glazing and wall thermal transmittance values, which are categorised as 'engineering' parameters (Baker and Steemers, 1996). Meanwhile, little consideration is given to architectural 'design' parameters such as shading devices, the balance between transparency and opacity, or diversity of building form and organization, all of which can have a significant impact on energy performance.

This main objective of this chapter is to identify the most influential building envelope parameter impacting the energy efficiency and cooling energy loads in tall buildings in the hot climate of the Gulf Region. In order to do this, two parametric studies were conducted to evaluate and compare the impact of both the engineering and design parameters of different envelope combinations. The first study focused on the engineering parameters, namely wall U-value, glazing shading coefficient, and glazing ratio, which were selected based on the parameters specified in the local building codes and practice. The results of this study then informed the second study which investigated the effects of shading devices as a design parameter.

The findings of the two studies were used to determine the best and worst combinations of engineering and design building envelope parameters in order to better understand the thermal performance of the building envelope.

Each parametric study was achieved through advanced dynamic simulation techniques using Tas modelling software. A sensitivity analysis method was applied in which one parameter was varied each time while the others remained fixed in order to identify the most sensitive parameter. Based on the findings from the Characteristics Table, a hypothetical base case was developed as a benchmark building representative of a residential tall building located in the city of Jeddah in Saudi Arabia. The results of the dynamic thermal simulation were evaluated in terms of annual cooling loads.

The following sections explain the scope, method, parameters selection and findings of the parametric study simulations.

5.1 The Simulation Scope and Method

The aim of the parametric studies was to examine the thermal performance of the building envelope in relation to decreasing thermal transmittance and solar gains. In the first set of simulations, the engineering parameters were selected and valued according to local energy efficiency buildings regulations and existing residential tall buildings in the Gulf Region (as detailed in the Characteristics Table). The results were evaluated based on cooling loads in relation to solar gains and conductive heat gain through the building envelope for both opaque and transparent elements. The best and worst performing engineering parameter combinations were identified for comparison with the design parameters in the second set of simulations, which focused on the shading elements of the building façade. Internal heat gains from occupants and equipment and internal heat transfer between the simulated zones were disregarded in the results analysis, since all internal zones were considered adiabatic. Moreover, since the construction methods were fixed, thermal bridging for all building elements and materials was not considered within the scope of this study.

The parametric studies were conducted through the use of dynamic thermal simulation software to study effective building energy performance given real climate considerations and the complex relationship between design characteristics, occupants, and mechanical and electrical systems in a building. As discussed in Section 3.2, dynamic thermal simulation is a reliable method to estimate the real-life performance of buildings in a cost-effective way, and provides a controlled environment where data can be adapted and altered. Moreover, the benefits of using simulation modelling to manage the feedback loops between the design decisions and their environmental impacts on the building, especially during the design process, are well established (Kirimtat et al., 2015). For familiarity and availability reasons, the author used Tas by EDSL as the thermal modelling software. Tas is a building modelling and simulation tool capable of performing dynamic thermal simulations for buildings. It allows for an accurate prediction of energy consumption, CO_2 emissions, operating costs and occupant comfort. The dynamic building simulations in Tas are conducted through an hourly analysis of the thermal state of the building throughout a typical year based on weather data selected by the user, which results in 8760 data outputs for each simulated variable (EDSL, 2012).

Sensitivity analysis through dynamic building simulation was used to evaluate the thermal performance of the building envelope and determine the energy demand for cooling for a hypothetical 'base case' representing a typical residential tall building in Jeddah. The simulations investigated two main aspects in relation to cooling load reduction: firstly, the reliance on engineering parameters in tall buildings façades following local codes and practices; secondly, a comparison of the engineering and design parameters for the building envelope.

The simulations aimed to address the following questions:

I. What is the impact of the 'engineering' parameters of the building envelope on the thermal performance of tall buildings in the hot humid climate of the Gulf Region?
II. What is the most significant engineering parameter in terms of its impact on the building's thermal performance?
III. To what extent can the 'design' parameters improve the thermal performance in comparison to the 'engineering' parameters?
IV. Which building envelope characteristics deliver the greatest energy efficiency when considering tall building typology?

The following sections detail the basis for each parametric study, describing the base case, explaining the parameters and then considering the results of the two sets of simulations.

5.2 Base Case Simulation Model

There are two methodologies underpinning the construction of a base case morphology: the existing base case and the conceptual base case (Hamza, 2004). In the context of this research, a conceptual generic base case model was constructed representing a hypothetical residential tall building in Jeddah, Saudi Arabia. The base case model was used as a unit of measurement to quantify changes in cooling loads in relation to the engineering parameters of the building façade.

To construct the base model, the architectural characteristics were compiled from extensive statistical data drawn from the findings of a qualitative and quantitative analysis of the 11 residential buildings in Jeddah, Dubai and Abu Dhabi in the Characteristics Table (Chapter 5). In creating the base model, consideration was given to aspects of building design such as building storey count and height, floor-to-floor height, core location, building plan geometry, and lease span.

In a 'real' scenario, the site upon which a tall building is constructed would heavily influence its height and dimensions. However, in a hypothetical conceptual base case, there is a level of abstraction to the representation of the architectural design, building service, and indoor spaces, where the relation between the building and its internal configuration and systems is simplified to decrease the number of model blocks, which might otherwise interfere with the result and lead to unnecessary software instabilities (Hamza, 2004).

The floor counts for the buildings in the Characteristics Table range from 27 to 90 storeys, with an average of 62 storeys and an average floor-to-floor height of 3.6m. Examination of a further 152 residential tall buildings in Dubai, Abu Dhabi and Jeddah showed that most were between 30 and 70 storeys high; therefore, it was decided that the base case building would comprise 62 storeys with a 3.6m floor-to-floor height, although the storey count decision did not impact the simulation at this stage. In consideration of the above, an initial overall building height of 223.2 meters was assumed.

The results from the Characteristics Table also revealed that tall buildings in Dubai tend to be simpler in geometry and square in plan, either 30x30 or 40x40, while those in Abu Dhabi and Jeddah have a more complex geometry including oval and triangular plan shapes. Additional analysis of 107 residential tall buildings in Dubai (91 towers), Abu Dhabi (11 towers) and Jeddah (five towers) showed that 34% had a square floor plan, while 47% had rectangular plans and 19% had a different shape (circular, triangular or composite). As a result, a square plan form (36x36 m) with a central core system was utilized for the base-case model to unify the façade area in each orientation. The plan dimensions responded to grid zoning in order to simulate spaces with the same floor area.

As for the interior organization, the building's lease span, defined as the dimension between the building core or an internal corridor and the external façade, was assumed to be the average of the 11 buildings in the Table, equating to 10 meters, regardless of the CTBUH-identified range of 6-9 meters as a typical lease span for hotel and residential floors in tall buildings (Ali & Armstrong, 2010).

5.2.1 Base Case Building Profile

The design considerations outlined in the previous section were utilized in the creation of a representative base case tall building. The overall architectural and engineering specifications assumed for the base case model are outlined in Table 5-1.

The typical floor plan of the simulation model consisted of five mid floors considered for data analysis (Figure 5-1). The results were plotted for eight perimeter zones (as shown in Figure 5-2). Each analysed zone was 6x6m with a different orientation: North, South, East, West, Northwest, Northeast, Southwest, and Southeast. As for the fenestration, a standard window size of 2.4x0.9m was used and repeated for each simulation zone to achieve the required glazing ratio. For example, as each zone is 6x6m ($36m^2$), for a zone that has one exposed wall (6x3.6m), two windows will achieve a 20% glazing ratio, hence, for a zone with two exposed walls, one window was placed in each exposed wall (Figure 5-3). The model and zone dimensions were fixed throughout the simulations, as it was not within the scope of this research to investigate the impact of different spatial configurations.

Table 5-1 Base case building specifications

Parameter	**Base Case Building Assumptions**
Total Building	
Location	Jeddah, Saudi Arabia
Height	223.2m
Storeys	62
Core location	Central
Building plan form	Square
Residential Floor Plan	
Typical floor GFA (m²)	1296
Typical floor NFA (m²)	1040
Floor Plate Efficiency	80.2%
Typical floor lease span (m)	10
Floor-to-floor height (m)	3.6
Envelope to floor ratio	0.5
Number of tested zones per floor	8

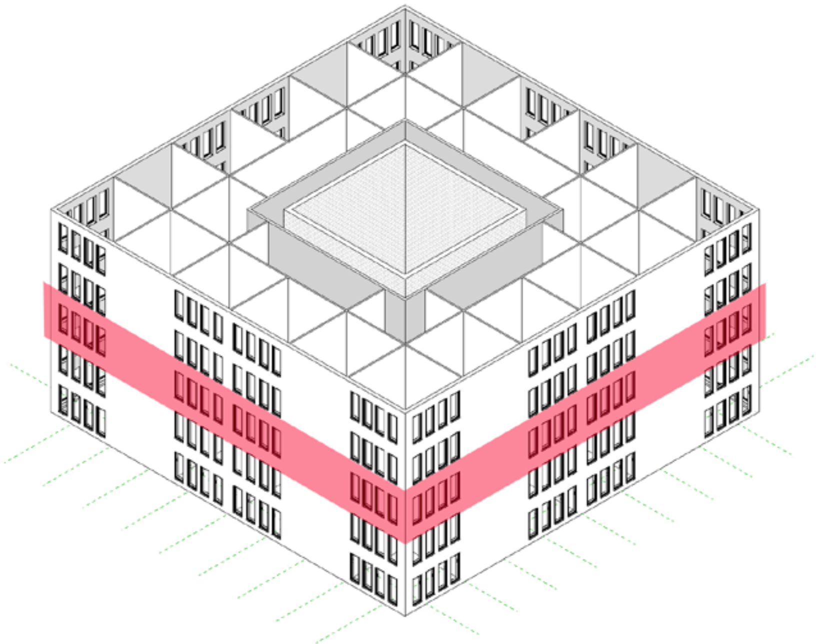


Figure 5-1 The base case model for 40% glazing ratio

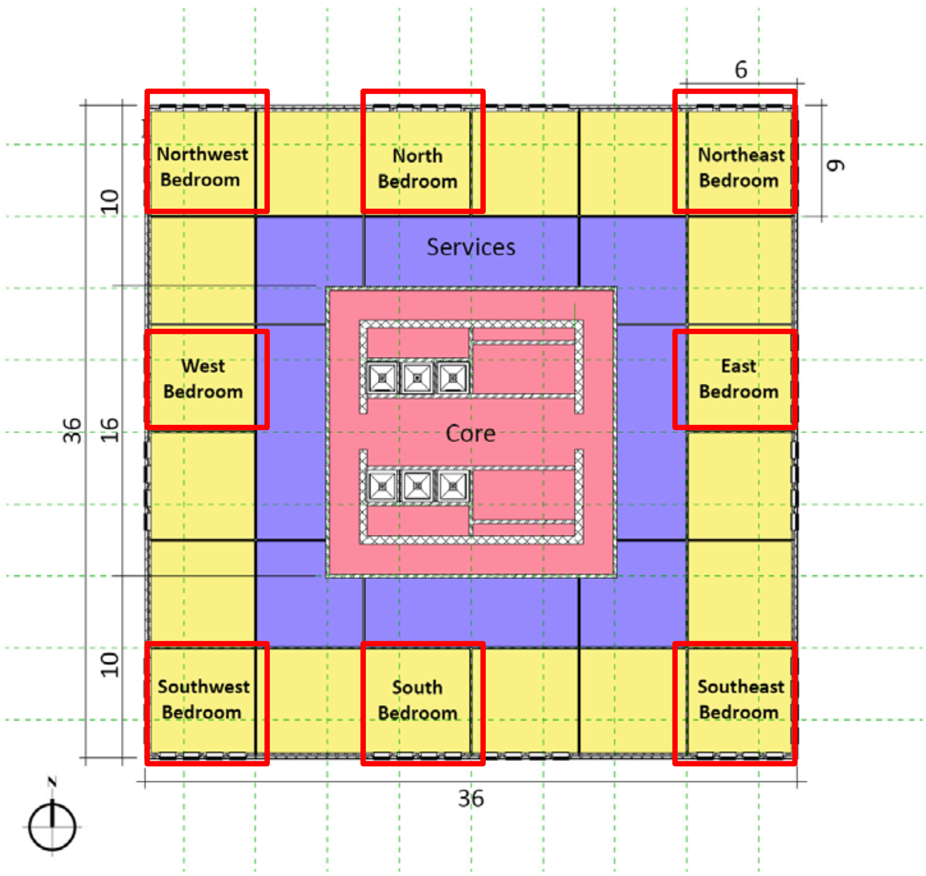


Figure 5-2 The base case typical residential floor plan showing the 8 simulation zones

5.2.2 The Simulation Assumptions

Since the aim of the simulations was to determine the difference in the performance of the various building fabric combinations under the same conditions, the same simplified model and assumptions were kept for all the simulations to allow for a better understanding of their outcomes. The only changes were the external wall and window construction type and the numbers of windows for glazing percentages whilst the internal walls, floor and roof were kept the same.

The assumptions considered the building model as a tall building following the local codes of the Gulf Region with an intense use of air conditioning. The estimated assumptions adopted were as follows:

I. Weather: The weather file for Jeddah, containing the hourly data for the year 2005, obtained from EnergyPlus was used in the simulation.

II. Calendar: Since active cooling is used throughout the year to maintain a unified room temperature and relative humidity, summer and winter months were not considered in the calendar. The calendar was set based on the days of the week only.

III. Internal Gains: No internal gains were assumed in this simulation.

IV. Ventilation and Infiltration: The infiltration rate was assumed at a rate of 0.57 ach[21] for 24 hours in line with The Saudi Building Code Energy Conservation Requirements (SBC 601). No ventilation was assumed as air conditioning is used.

V. Comfort Temperature Range: The thermostat was set according to the benchmark suggested by Dubai’s Green Building Regulations (Table 5 in section 4.1.1.2), where the comfort ranges between 22.5-25.5 °C.

VI. Thermal Zones: As Figure 5-2 shows, the simulation model was built and divided into three thermal zones: the air-conditioned zones adjacent to the building façades, services zones and the unconditioned core zone. The division of the model into different zones according to their relation to the building envelope facilitated detailed identification of differences in temperature between the zones due to the different orientation and specific envelope adoption.

VII. Heating: No heating was assumed.

VIII. Cooling: Active cooling through air-conditioning systems were used in the simulation for all the zones adjacent to the external building envelope, running for 24 hours. The thermostat was set in accordance with the above mentioned thermal comfort range.

5.3 Engineering Parameters Simulations

In this parametric study, the building envelope parameters in the two sets of simulations were categorized based on Baker and Steemers (1996) classification of the building factors as ‘building-design’ parameters and ‘engineering’ parameters. The design parameters interact with many other parameters and have an impact on the building’s form and performance, while the engineering parameters can take on values independently of other parameters. In the first set of simulations, the selected ‘engineering’ parameters were wall

[21] Air changes per hour.

construction (U-value), glazing composition (shading coefficient) and glazing ratio, while the second set of simulations focused on shading elements.

5.3.1 Input Parameters

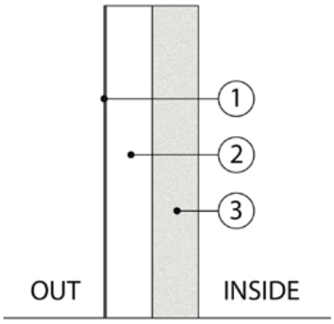
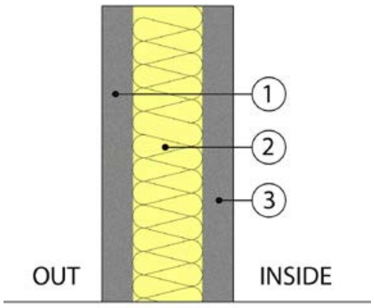
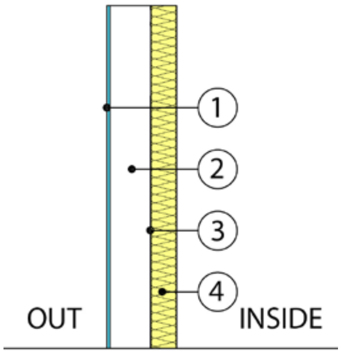
The selection of the engineering parameters used in the simulation was based on the elements for the design of energy efficient building envelopes prescribed in the Saudi Building Code Energy Conservation Requirements (SBC 601) and the Green Building Regulations and Specifications in the Emirate of Dubai (GBRS) (Section 3.1.6). Both building codes set minimum prescriptive building envelope requirements for glazing U-value and U-value for ceilings, floors and exterior walls based on the window area of the gross exterior wall area, all of which are considered 'engineering' parameters. The values of the parameters were derived from existing representative case studies built in Jeddah and Abu Dhabi (examined in the Characteristic Table), since they are widely employed in current practice for residential tall building design in the Gulf Region.

The methodology adopted consisted of adding a degree of improvement to the selected engineering parameters. The improvement of the opaque building envelope elements was done through the addition of thermal insulation products to reduce thermal transmittance. As for the transparent elements, the degree of improvement was achieved by optimizing both shading coefficient and thermal insulation to reduce thermal transmittance and solar gains.

Since the focus of the simulation was an investigation of building envelope elements, the floor and roof were kept the same as a common concrete floor construction. As for the wall build-ups, the three chosen types were determined by a review of the most common construction methods for residential tall buildings in the Gulf Region (as discussed in the Characteristics Table). Each wall type is described in Table 5-2 with relevant thermal characteristics. The U-value for the total wall was obtained through manual calculation. The spatial and thermal specifications of the construction materials were obtained from similar products in the market.

The first wall type, Unventilated Cavity Wall (UCW), where insulation products are not applied, is commonly used in low-rise residential buildings in Saudi Arabia, and in some tall buildings. Although the Ministry of Municipal and Rural Development Affairs announced that installation of thermal insulation systems was mandatory for all new tall buildings in 2014, there is still a lack of enforcement from the local municipalities (Arab News, 2014). The wall construction method for the 27-storey Corniche Dreams Tower in Jeddah was employed as a representative construction method of tall buildings with exterior cladding and gypsum blocks towards the interior. The second type, the Thermal Blocks Wall (TBW), is often used for opaque elements in residential tall buildings in Dubai and Abu Dhabi. The specifications for this wall type, according to local market suppliers, consider Estidama specifications in terms of wall thermal transmittance with (160mm) expanded polystyrene insulation. The third type, Shadow Box Spandrel Glass (SSG), is widely used in tall buildings in the Gulf Region to provide aesthetic unified glass façades; The Gate District Tower in Abu Dhabi is a good example of this wall type. SSG involves the use of glass that has no opacifier, combined with a separate light blocking assembly, typically a rigid foil backed insulation material that is taped to the surrounding framing system to block out the light (PPG Industries).

Table 5-2 Wall Construction Types for the simulation

Wall Construction Types	U-value[22]	Section
a. Unventilated Cavity Wall (UCW) Total thickness 204mm Layers from outside to inside: 1. Aluminium Cladding (4mm)[23] 2. Unventilated Air Cavity (100mm)[24] 3. Gypsum Blocks (60x60x10cm)[25]	1.13 W/m^2K	
b. Thermal Blocks Wall (TBW) (as per Estidama specifications)[26] Total thickness 300mm Layers from outside to inside: 1. Concrete block (70mm) 2. Expanded polystyrene (160mm) 3. Concrete block (70mm)	0.21 W/m^2K	
c. Shadow Box Spandrel Glass[27] (SSG) (The Gate District Tower in Abu Dhabi) Total thickness 137mm Layers from outside to inside: 1. Monolithic heat strengthened glass (6mm)[28] 2. Rigid powder coated aluminium (1mm) 3. Air cavity (80mm) 4. Rigid Rockwool Insulation (50mm)[29]	0.3 W/m^2K	

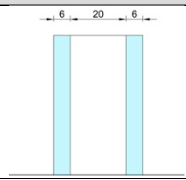
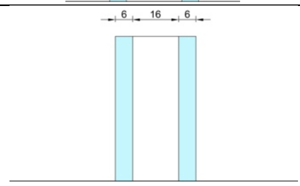
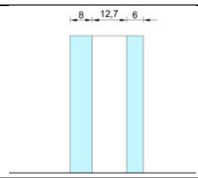
As with the wall-build ups, the glazing composition selection was determined based on the local practices reviewed in the Characteristics Table. Each type was copied from an existing building and together they represent the most common types in the Gulf Region. Table 5-3 illustrates the three glazing compositions used in the simulations – the (32mm) Double Insulating Glass (32 DIG) is the same glazing type used in Corniche Dreams. The other types, the (28mm) Double-glazing insulated units (28 DIG) and (26mm) Double-glazing insulated

22 The U-value for the total wall was obtained through manual calculation and might differ from Tas calculations.
23 Based on specifications from Viltabond Aluminium Composite Panels (R-value 0.0103 m^2K/W).
24 Based on Anderson (2006, p.11), Unventilated airspace cavities in wall constructions normally have a resistance of 0.18 m^2K/W.
25 Based on specifications for Gyproc WallBoard from British Gypsum (R-value 0.52 m2K/W).
26 Based on the specifications for thermal insulated (expanded polystyrene) sandwich block in Hussain Mohd. Abbas Block Factory.
27 Construction type and definition are based on the Glass Technical Document from PPG Industries
28 Specification based on Tinted float glass, blue, from Shanghai Pilkington Glass Group
29 Specifications based on Rainscreen Duo Slab from Rockwool

units (26 DIG) are used in the Landmark tower in Abu Dhabi and the Lamar Tower in Jeddah respectively. The unit configurations are similar in terms of being heat-treated air-filled double glazing units. The prominent factors that differentiate them are the thermal and visual specifications such as thermal and visible light transmittance and shading coefficient. Again, the specifications for these were copied from similar products in the market.

The selection of glazing ratios was based on the specifications outlined in SBC 601 and Dubai's GBRS in relation to the engineering parameters. Three glazing ratios were chosen: 20%, 40% and 60% (Figure 5-3). The glazing ratio was kept the same in all the simulated zones by following a certain grid for the window area. To better understand the simulation performed, the simulation matrix is explained in Table 5-4.

Table 5-3 Glazing compositions

Glazing composition	U-value	Shading coefficient	Visible light Transmittance	Section
a. 32mm Double Insulating Glass (32 DIG) - 6mm K-LITE -14 ON tempered - 20mm air space - 6mm EFG tempered Clear colour (Corniche Dreams, Jeddah)	2.7	0.23	13	
b. 28mm Double glazing insulated unit (28 DIG) - 6mm heat strengthened glass with solar/thermal protective coating - 16mm air space - 6mm laminated glass with PVB interlayer (Landmark Tower, Abu Dhabi)	1.4	0.3	50	
c. 26mm Double glazing insulating unit (26 DIG) - 8mm fully tempered - 12.7mm air space - 6mm Fully tempered Light and Dark Grey colours (Lamar Towers, Jeddah)	2.8	0.51	39	

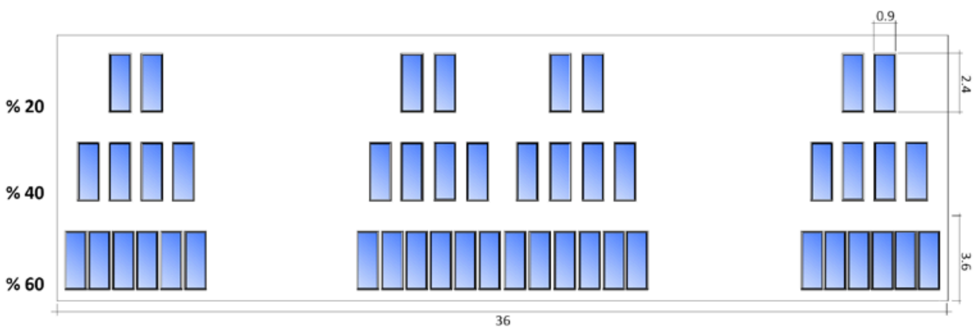


Figure 5-3 The variation in window glazing ratio tested in the simulation for each façade orientation

5.3.2 Simulation Matrix

Based on the previously discussed engineering parameters, the simulation matrix for the building envelope combinations was defined in Table 5-4. Each combination was named as shown in the table and the same name will be used to show the results. The first number refers to the glazing ratio, the letters refer to the wall type, and the final number signals the thickness of the glazing type. For example, the first set of simulation includes 20-ucw-32, 40-ucw-32, and 60-ucw-32, which test the impact of the three different glazing ratios (20%, 40%, 60%) while keeping the same wall and glazing type: Unventilated Cavity Wall (UCW) and 32mm Double Insulated Glass (32).

Table 5-4 The matrix for the first set of simulations testing the engineering parameters of the building envelope

Glazing Ratio	Wall Type	Glazing Type	Combination
20%	Unventilated Cavity Wall (UCW)	32 mm Double Insulated Glass (32 DIG)	20-ucw-32
		28 mm Double Insulated Glass (28 DIG)	20-ucw-28
		26 mm Double Insulated Glass (26 DIG)	20-ucw-26
	Thermal Blocks Wall (TBW)	32 mm Double Insulated Glass (32 DIG)	20-tbw-32
		28 mm Double Insulated Glass (28 DIG)	20-tbw-28
		26 mm Double Insulated Glass (26 DIG)	20-tbw-26
	Shadow Box Spandrel Glass (SSG)	32 mm Double Insulated Glass (32 DIG)	20-ssg-32
		28 mm Double Insulated Glass (28 DIG)	20-ssg-28
		26 mm Double Insulated Glass (26 DIG)	20-ssg-26
40%	Unventilated Cavity Wall (UCW)	32 mm Double Insulated Glass (32 DIG)	40-ucw-32
		28 mm Double Insulated Glass (28 DIG)	40-ucw-28
		26 mm Double Insulated Glass (26 DIG)	40-ucw-26
	Thermal Blocks Wall (TBW)	32 mm Double Insulated Glass (32 DIG)	40-tbw-32
		28 mm Double Insulated Glass (28 DIG)	40-tbw-28
		26 mm Double Insulated Glass (26 DIG)	40-tbw-26
	Shadow Box Spandrel Glass (SSG)	32 mm Double Insulated Glass (32 DIG)	40-ssg-32
		28 mm Double Insulated Glass (28 DIG)	40-ssg-28
		26 mm Double Insulated Glass (26 DIG)	40-ssg-26
60%	Unventilated Cavity Wall (UCW)	32 mm Double Insulated Glass (32 DIG)	60-ucw-32
		28 mm Double Insulated Glass (28 DIG)	60-ucw-28
		26 mm Double Insulated Glass (26 DIG)	60-ucw-26
	Thermal Blocks Wall (TBW)	32 mm Double Insulated Glass (32 DIG)	60-tbw-32
		28 mm Double Insulated Glass (28 DIG)	60-tbw-28
		26 mm Double Insulated Glass (26 DIG)	60-tbw-26
	Shadow Box Spandrel Glass (SSG)	32 mm Double Insulated Glass (32 DIG)	60-ssg-32
		28 mm Double Insulated Glass (28 DIG)	60-ssg-28
		26 mm Double Insulated Glass (26 DIG)	60-ssg-26

5.3.3 The Results

A total of 27 sets of simulations were conducted representing different building envelope combinations (Table 5-4). The results for the dynamic thermal simulations were examined according to the orientation of the eight simulation zones in terms of annual cooling loads and in relation to solar gains and conductive heat gain through the opaque and transparent elements of the building envelope.

Firstly, the best and worst combinations of glazing ratio, wall and glazing type were identified in order to understand the most influential parameter impacting the cooling energy loads in the building. Figure 5-4 compares the annual cooling loads per square meter for all the building envelope combinations for the eight simulation zones based on orientation. The analysis of the results shows that the combination 20-TBW-32 – highlighted in yellow – performed best in all the different orientations. As expected, the low glazing ratio (20%) and lower shading coefficient in the glazing type combined with the higher insulation of the thermal blocks for the wall type (following Estidama standards) contributed to the better performance. On the other hand, the un-insulated air cavity wall type (UCW) with 60% glazing ratio and higher shading coefficient (0.51) in glazing type, highlighted in red (60-ucw-26), performed worst, followed by the combinations of Shadow Box Spandrel Glass (60-ssg-26) due to the high solar gain through the large glazing area coupled with worse shading properties for the glazing type. Figure 5-4 also highlights that the corner zones (Southwest, Southeast, Northwest and Northeast) performed worst in relation to cooling loads due to the larger area of exposed walls and constant solar gain from west or east, while the North-oriented zones performed best in all the simulations.

Secondly, since the simulations aimed to investigate the most significant engineering parameter to impact the thermal performance of the tall building envelope, the results were analysed in relation to solar gains and external conduction gain through opaque and glazing elements. Looking closely at the results of the different orientations for each combination shows similar patterns in all the zones. The results for the Southwest zone will be used as an explanatory case since it was the worst performing zone. The charts in Figure 5-5 show that in the case of UCW combinations, the conductive heat gain through opaque walls contributed most to cooling loads due to the lack of wall thermal insulation. The charts also show that as the glazing ratio increases from 20% to 40% and 60%, solar gains surpass conductive heat gains, especially in the glazing type with the higher shading coefficient which allow more solar gain into the zone. On the other hand, replacing the UCW wall type with TBW minimized heat gain, particularly in the combination 20-tbw-32 (as highlighted in Figure 5-6). Using thermal insulation significantly reduced the conductive heat gain through opaque element, while solar gains contributed most to the cooling loads in relation to the glazing types with higher shading coefficient (26 and 28mm glazing types). For the SSG wall type, it is clear that solar gain is the main contributor to the massive increase in cooling loads due to the excessive use of glass as a wall type (Figure 5-7). Ultimately, and as expected, the addition of thermal insulation to the opaque elements can significantly reduce conductive heat gain. Furthermore, adjusting shading coefficient for the glazing elements can contribute hugely to solar gains, even for higher glazing ratios. For example, the use of lower shading coefficient in 60% glazing ratio reduced the solar gain by up to 63% (as shown by the difference in solar gain between 60-TBW-32 and 60-TBW-26 in Figure 5-6).

Moreover, as can be seen in the figures below, comparing the results of heat gain through the opaque and glazing elements of the building envelope proves, in similar patterns, that heat gain through glazing elements is considerably higher than through opaque elements, with a direct connection to the glazing types with a higher shading coefficient (Figure 5-8, 5-9, 5-10, 5-11, 5-12, 5-13, 5-14, 5-15).

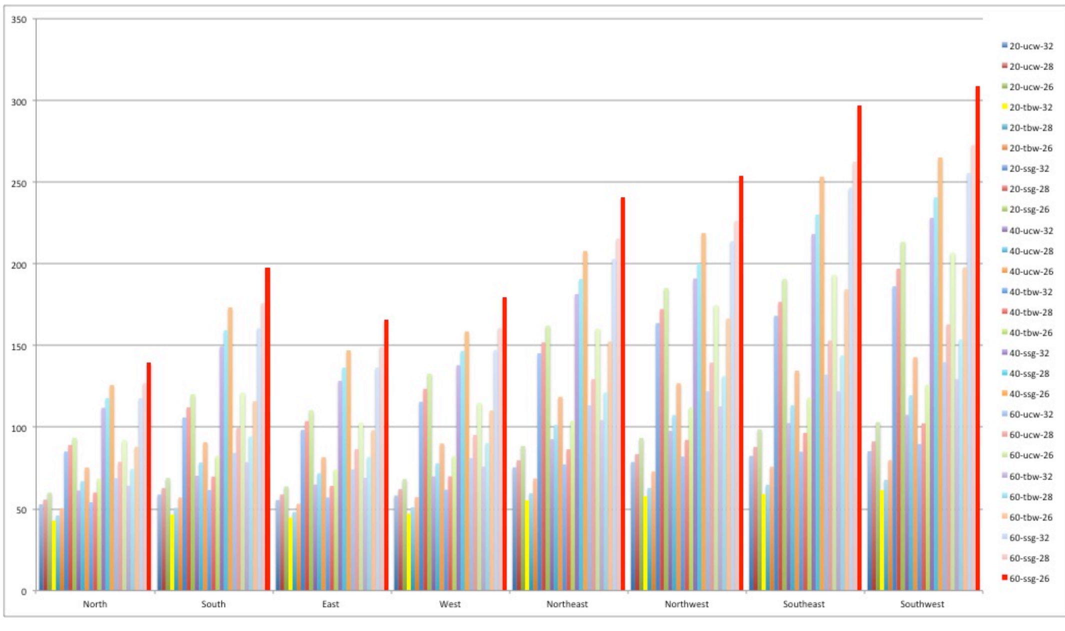


Figure 5-4 The results for the energy performance simulation for each orientation

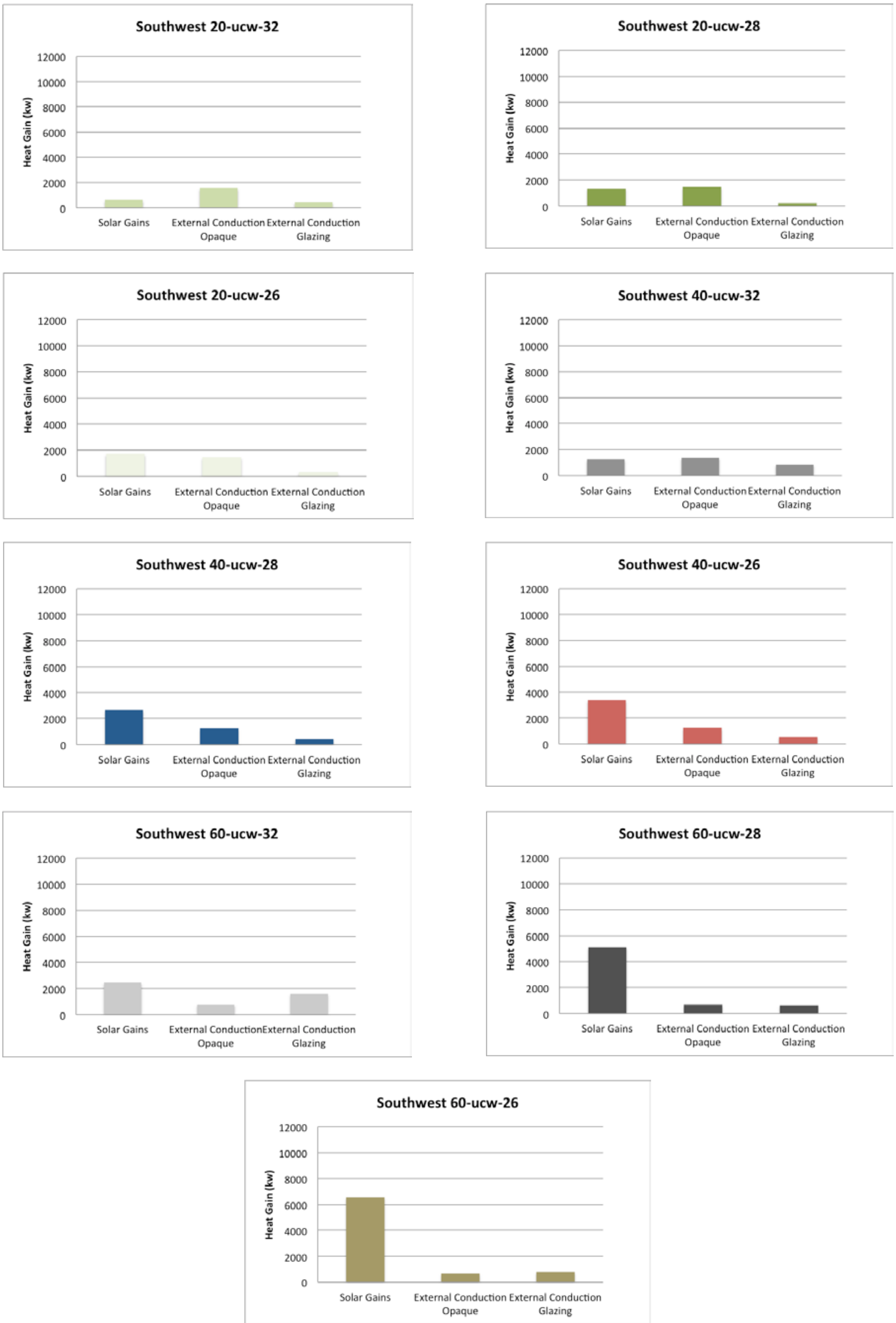


Figure 5-5 Heat Gains through the building envelope for the different glazing types and ratios for the Unventilated Cavity Wall type (UCW) in the Southwest Zone

Figure 5-6 Heat Gains through the building envelope for the different glazing types and ratios for the Thermal Blocks Wall type (TBW) in the Southwest Zone

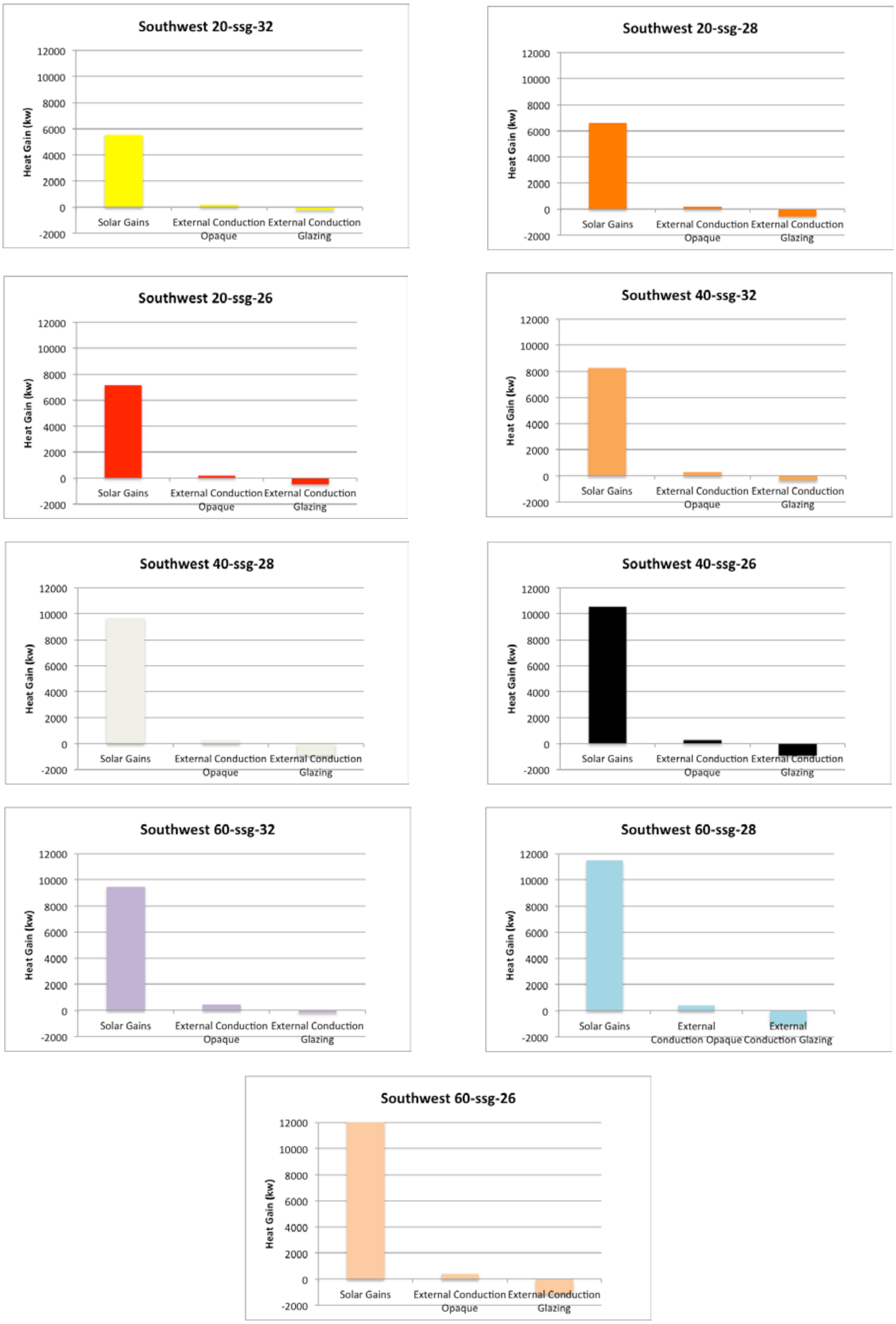


Figure 5-7 Heat Gains through the building envelope for the different glazing types and ratios for the Shadow Box Spandrel Glass Wall type (SSG) in the Southwest Zone

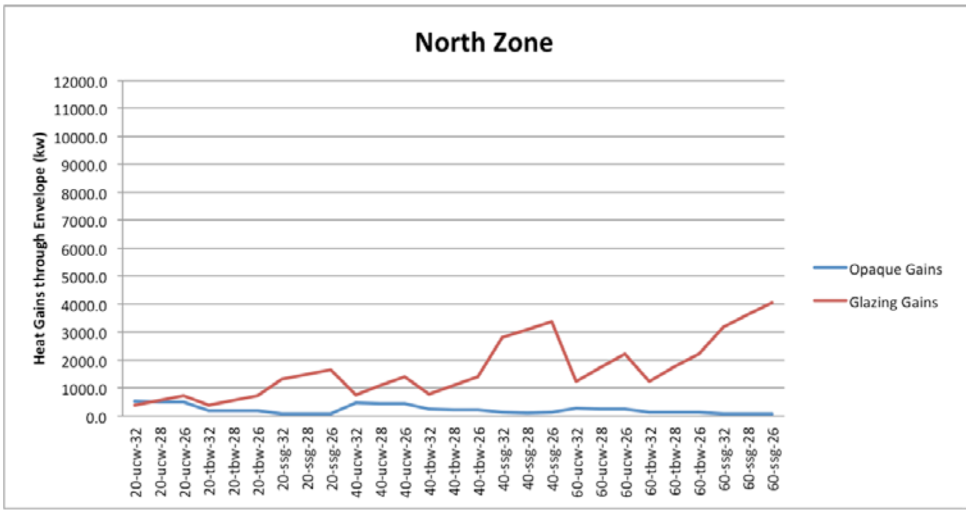


Figure 5-8 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the North Zone

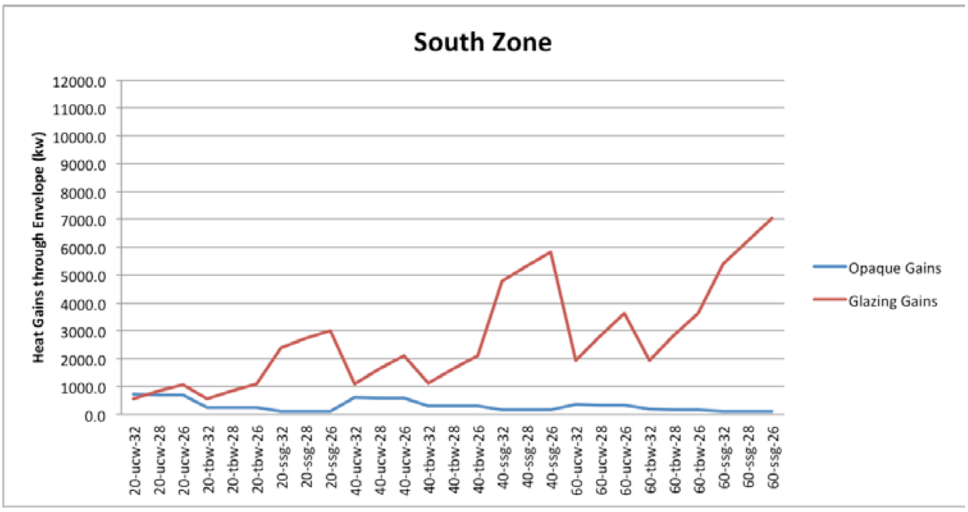


Figure 5-9 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the South Zone

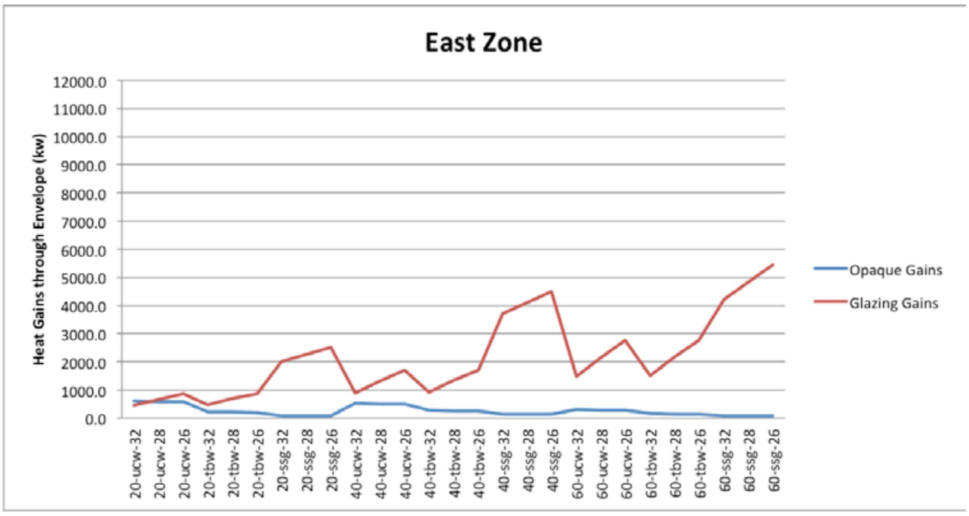


Figure 5-10 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the East Zone

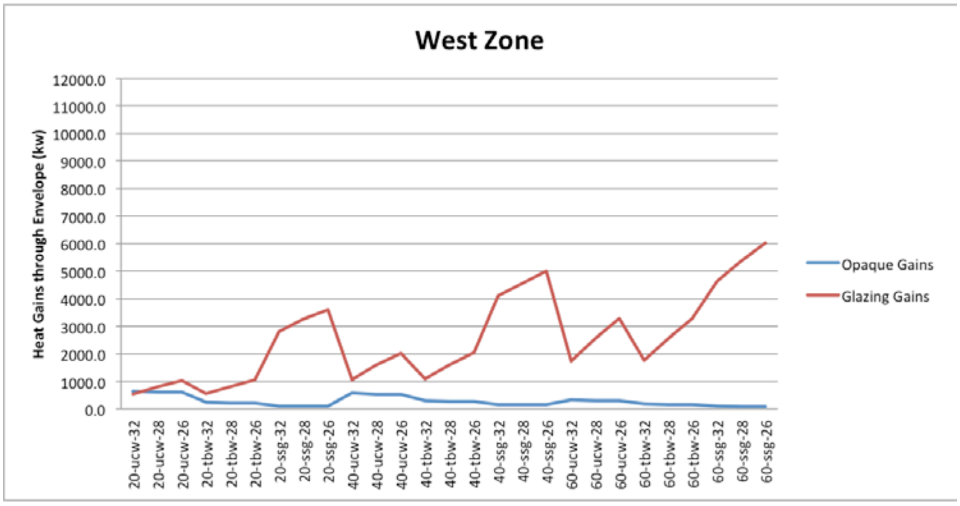


Figure 5-11 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the West Zone

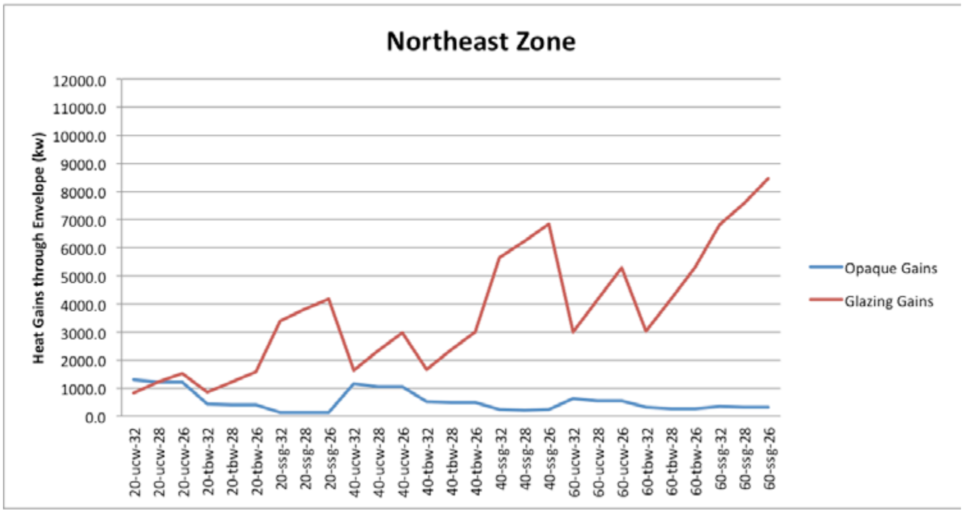


Figure 5-12 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the Northeast Zone

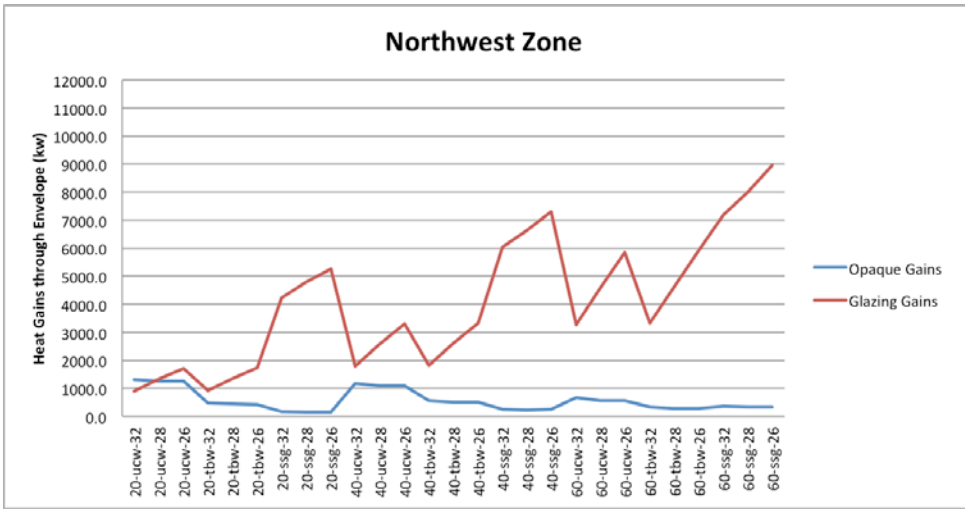


Figure 5-13 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the Northwest Zone

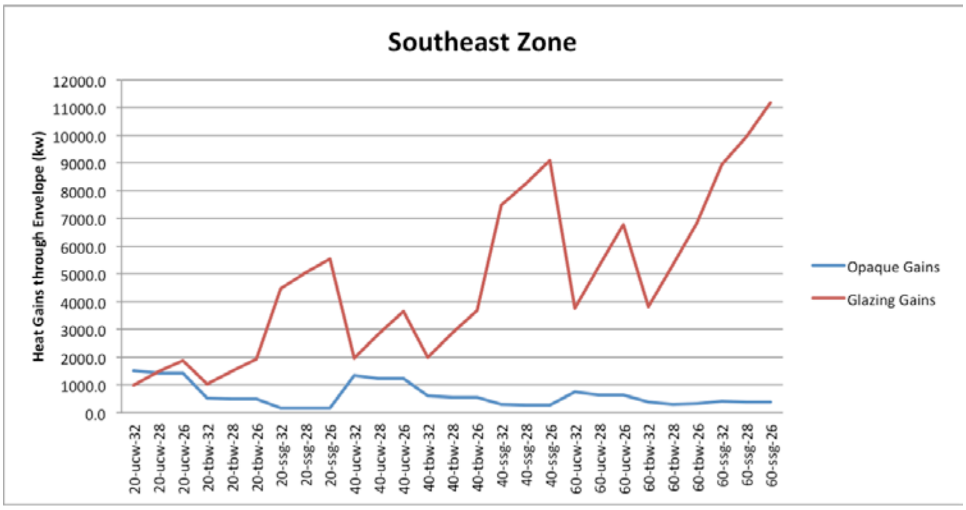


Figure 5-14 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the Southeast Zone

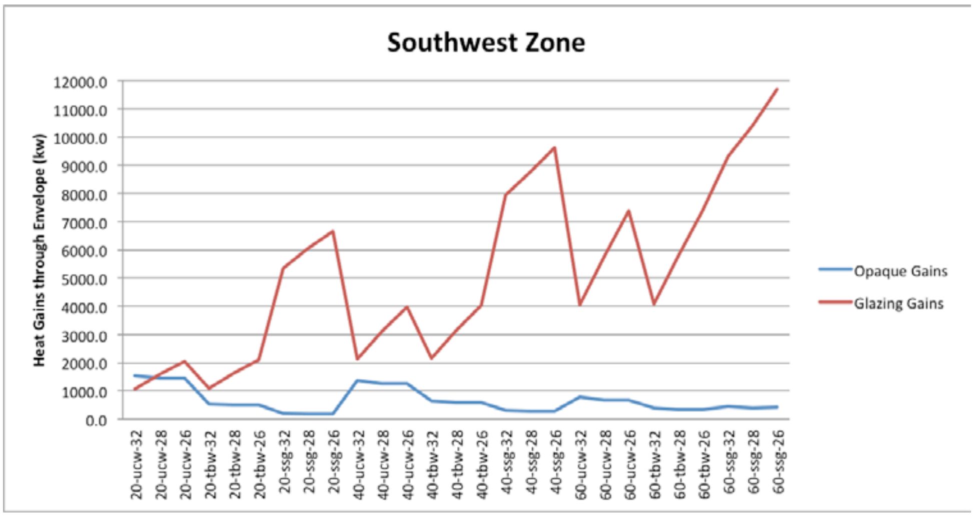


Figure 5-15 Comparison of the heat gain (kw) through the opaque and glazing elements of the building envelope for the Southwest Zone

Overall, as shown in Table 5-5, the difference between the best combination (20-tbw-32) and worst combination (60-ssg-26) reaches up to 80%, underlining the major role that building envelope parameters can play in terms of energy performance.

Table 5-5 he results of the energy performance simulations; the green row illustrates the best-case combination while the orange row shows the worst-case combination

Simulation Combination	North	South	East	West	Northeast	Northwest	Southeast	Southwest
20-ucw-32	52.88	58.82	55.46	58.19	75.43	78.70	82.47	85.32
20-ucw-28	55.71	62.74	58.85	62.12	79.82	83.59	87.98	91.35
20-ucw-26	59.97	68.93	63.83	68.25	88.51	93.47	98.66	103.14
20-tbw-32	**43.09**	**46.82**	**44.62**	**47.04**	**55.09**	**57.82**	**59.29**	**61.74**
20-tbw-28	46.00	50.69	48.05	51.00	59.60	62.84	64.85	67.82
20-tbw-26	50.40	56.99	53.16	57.27	68.59	73.00	75.81	79.90
20-ssg-32	85.11	105.96	98.29	115.55	145.28	163.72	168.19	186.26
20-ssg-28	89.15	112.18	103.73	123.51	151.92	172.34	176.75	197.07
20-ssg-26	93.53	120.22	110.45	132.84	162.19	185.18	190.73	213.49
40-ucw-32	61.27	70.33	64.91	69.89	92.66	97.77	102.52	107.54
40-ucw-28	67.00	78.44	71.84	77.93	101.39	107.44	113.48	119.56
40-ucw-26	75.38	90.83	81.72	90.09	118.60	126.93	134.67	142.88
40-tbw-32	54.10	61.56	56.99	61.76	77.23	82.02	85.02	89.75
40-tbw-28	60.02	69.82	64.10	69.97	86.48	92.25	96.59	102.39
40-tbw-26	68.57	82.39	74.17	82.30	104.05	112.06	118.10	126.02
40-ssg-32	111.84	149.45	128.36	137.98	181.50	191.01	218.20	228.11
40-ssg-28	117.84	159.40	136.51	146.65	190.69	200.10	230.17	240.69
40-ssg-26	125.82	173.32	147.07	158.62	207.87	218.82	253.37	265.15
60-ucw-32	68.79	84.25	74.17	81.14	113.34	121.99	132.18	139.78
60-ucw-28	78.85	99.57	86.59	95.30	129.48	139.56	153.01	162.91
60-ucw-26	92.20	121.08	102.74	114.99	160.35	174.76	193.41	206.92
60-tbw-32	64.15	78.63	69.08	75.92	104.35	112.76	122.00	129.42
60-tbw-28	74.48	94.32	81.82	90.39	121.33	131.22	143.92	153.71
60-tbw-26	88.00	115.97	98.14	110.24	152.44	166.60	184.45	197.82
60-ssg-32	117.73	160.54	136.47	147.25	203.03	213.82	246.56	255.64
60-ssg-28	126.91	175.88	149.08	160.63	215.41	226.25	262.52	272.71
60-ssg-26	**139.36**	**197.74**	**165.62**	**179.40**	**240.67**	**254.00**	**296.80**	**308.80**

5.4 Design Parameters Simulations

The results of the engineering parameters simulations showed that due to the high air temperature and abundant solar radiation in the Gulf Region, the thermal characteristics of the glazing type, especially its shading coefficient, is the dominant factor in reducing cooling energy loads in relation to solar gains; in other words, a lower shading coefficient can significantly decrease the solar gains even for large glazing areas. These results emphasize the fact that as solar gains are the highest contributor to cooling loads, the reliance on a prescriptive approach to the specifications of the engineering parameters for the building envelope will not necessarily achieve the required reductions in solar gains, and that the development of the 'design' parameters, such as shading elements, could have a significant impact on cooling energy loads.

Based on the classification of building factors devised by Baker and Steemers (1996), the façade's external shading devices can be considered a 'design' parameter since shading has an impact on the building's form as well as its performance in terms of daylight, heating and cooling, and natural ventilation. As discussed in Section 2.1.4, the importance of using shading devices as a passive environmental design strategy to enhance energy conservation in buildings is well documented (Brown and DeKay, 2001; Hausladen et al., 2008; Szokolay, 2008). The application of exterior shading devices is essential especially for façades with large glazed portions in hot climatic regions since they modify thermal exchanges through the glazed building envelope and decrease cooling loads by preventing the penetration of direct sunlight and solar radiation into the building. However, despite the obvious advice in the literature on the substantial impact of shading devices, the relevant guidelines in the local buildings codes in the Gulf Region tend to be generic in nature, difficult to navigate and thus time consuming for architects and designers, and without much emphasis on the benefits of shading devices in relation to visual and thermal performance or their implications for views, especially for residential tall buildings. This has led to very little practical application of shading devices in this building type in the Gulf Region. The current Dubai GBRS do recommend providing shading devices as a compliance alternative to orientating the glazed surfaces of the building façades to the north (Section 3.1.1), using the Vertical and Horizontal Shadow Angles technique to specify the minimum VSA for horizontal shading and HSA for vertical fins suitable for buildings in the city of Dubai. However, the Saudi SBC 601 only mentions shading elements as a 'window projection factor', a window specification used to determine the maximum solar heat gain coefficient and thermal transmittance of window assemblies, specifying neither recommendations nor guidelines regarding shading for any building type. Indeed, to the best of the researcher's knowledge, little has been done to examine the thermal performance of external shading devices for solar heat gain control in residential tall buildings in the region, especially for the latitude of 21° N of Jeddah in Saudi Arabia.

Based on the above argument, the second parametric study used simulation tools to assess the impact of external solar shading devices and their contribution to the building's overall energy performance in relation to cooling loads. The main objective of these simulations was to investigate the extent to which shading devices as a 'design' parameter can improve thermal performance in comparison to the 'engineering' parameters, with the aim of bridging a gap in the literature by introducing simple guidelines to help designers determine the thermal efficiency of external shading for residential tall buildings in the region. The next section details the main considerations that informed the selection and design of the external shading elements used in the second set of simulations.

5.4.1 Input Parameters

Shading devices vary according to their shape, mobility, or their location on the building's façade, and can be divided into two general groups: external and internal shading devices. External shading devices include fixed types (horizontal overhangs, horizontal and vertical louvres, and egg-crates that contains vertical and horizontal shading elements), and movable types such as deciduous plants. Internal shading devices include venetian blinds, vertical blind slats, and roller shades. The main advantage of external fixed shading devices is that they control and decrease solar ingress, which can significantly reduce cooling loads and prevent glare. However, they can block daylight and cause the need for artificial lighting, so it is important that proper consideration is given to location, time, daylight availability, thermal and visual comfort when selecting shading devices. As for internal shading devices, they are effective in providing privacy and visual and thermal comfort, but they can trap heat radiated from interior surfaces and increase cooling loads during overheating periods (Bellia et al., 2014; Kirimtat et al., 2016). As this research focuses on the building envelope, only external shading devices were considered in this parametric study as internal shading is mostly dependent on user behaviour and that falls outside the scope of this investigation.

As discussed earlier, finding a suitable strategy for shading can increase the energy efficiency of a building, reduce running costs, and minimise environmental effects. However, accurate and detailed information is needed to choose the right shading device and prevent inappropriate implementations (Kirimtat et al., 2014). The selection and design of shading devices for glazed façades depends on aspects such as location and latitude, local climatic conditions, building type and intended use, orientation, characteristics and form. According to Brown and DeKay (2001), to design effective external shading, the designer needs to know when to admit and when to block the sun, depending on the latitude and sun angles and the daily cycle of temperature for average days in each month. Moreover, Bellia et al. (2014) emphasise the importance of designing shading devices according to orientation, suggesting overhangs for south facing façades with the tilt angle of the slats equal to local latitude, and vertical louvres with various tilt angles for east and west facing facades. Meanwhile, Cho et al. (2014) have proposed alternative designs for external shading devices using equations to calculate the horizontal and vertical overhang depth based on the window area (height and width) and the vertical and horizontal shadow angle of the local location (Figure 5-16).

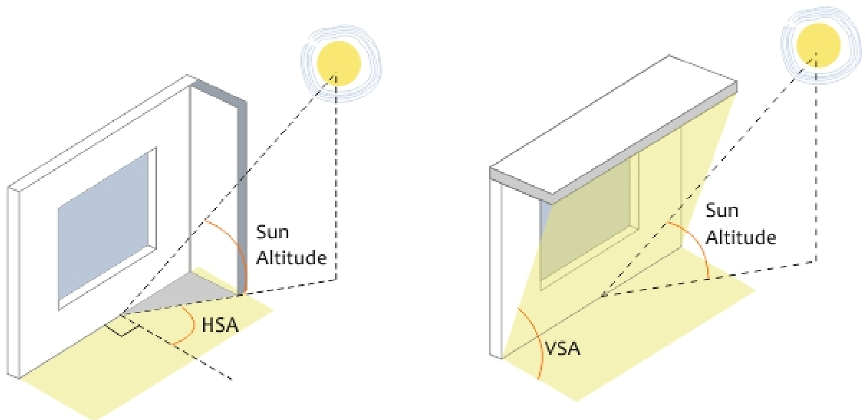


Figure 5-16 The shadow angles describe the length of the shadows on wall surfaces. The Horizontal Shadow Angle (HSA) is used for vertical shading device calculations while the Vertical Shadow Angle (VSA) is used for horizontal shading devices (Source: NZEB, n.d.)

In this parametric study, the design of the fixed external shading devices for the simulation alternatives was based on the design considerations mentioned above. First, an initial sun-shading analysis was carried out for each façade orientation using Autodesk Ecotect Analysis software. This showed the amount of solar radiation falling on each façade throughout the year, data which helped in determining when shading is desirable and most needed. Figure 5-17 compares the average total monthly incident solar radiation (kWh/m^2) falling on each orientation of a hypothetical base case located in Jeddah. It illustrates that the East and West vertical surfaces received the highest solar radiation during the hot summer months from April to September thus highlighting the importance of shading those façades in the hot season. On the other hand, although the South façade had the highest values for incident solar radiation, this was mostly received during the winter season making it less of a concern. Figures 5-18, 5-19, 5-20 and 5-21 show the average daily incident solar radiation values for each façade orientation, data which informed the selection of the external shading device type for each orientation depending on the daily cycle of temperature for average days in each month. Next, solar data for the location of Jeddah was derived from Autodesk Weather Tool 2011 (Table 5-6 and Figure 5-22), showing the vertical shadow angle (ε) and horizontal shadow angle (δ) for four key dates (Summer Solstice, Winter Solstice, Spring Equinox and Autumn Equinox). These were then used to calculate the depth of the shading devices following the methodology set out by Cho et al. (2014).

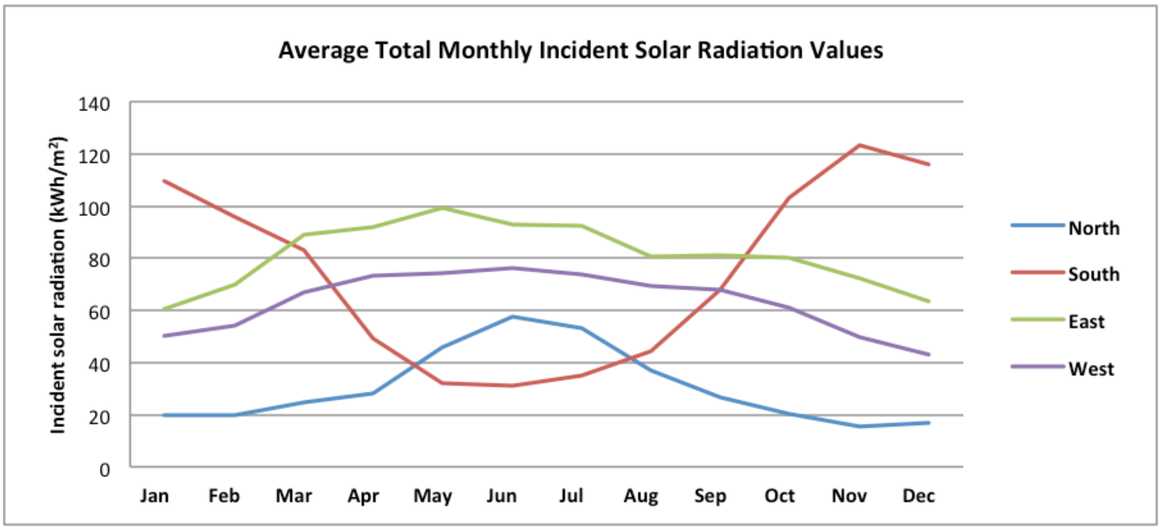


Figure 5-17 The average total monthly incident solar radiation falling on the four main orientations for the location of Jeddah, Saudi Arabia (Source: Author, plotted from Autodesk Ecotect Analysis)

According to this analysis, the North façade (Figure 5-18) received most radiation during the summer period from May to August, notably in June, in the morning and afternoon time. This can be addressed by installing vertical shading fins to block the northwest and northeast solar radiation. By contrast, the South façade received solar radiation throughout the day (as shown in Figure 5-19), therefore egg-crate shading devices were suggested, and the depth of the vertical fins (D_V) and horizontal overhangs (D_H) was set using the vertical and horizontal shadow angles for the Spring Equinox (March 21) since the highest radiation was recorded during this season. Moreover, vertical shading fins were proposed for both the East and West façades considering the Spring Equinox horizontal shadow angle between 7am-1pm for the East Façade, and the Spring Equinox horizontal shadow angle between 1-6 pm for the West façade (Figures 5-20 and 5-21).

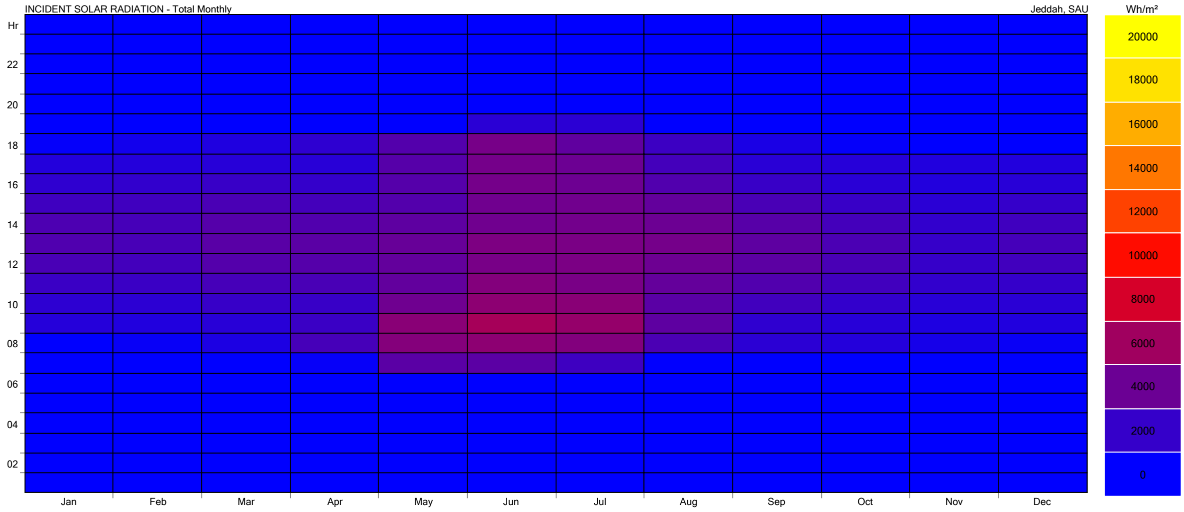


Figure 5-18 The average daily incident solar radiation falling on the North façade of a building located in Jeddah, Saudi Arabia. Note that the highest radiation is received during the summer months from May to August, especially during the morning time in June. (Source: plotted from Autodesk Ecotect Analysis)

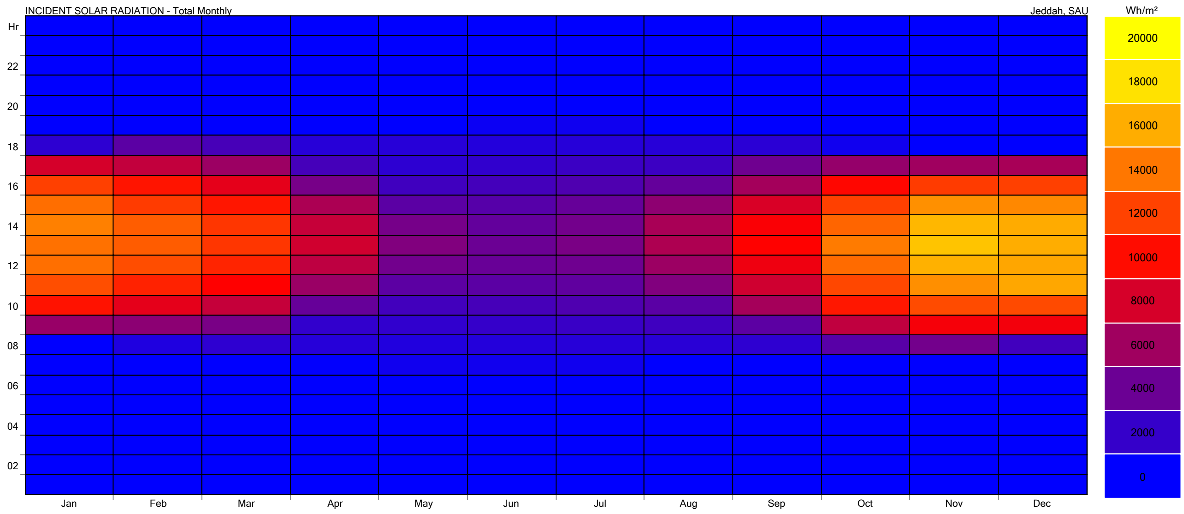


Figure 5-19 the average daily incident solar radiation falling on the South façade of a building located in Jeddah, Saudi Arabia. Note that the highest radiation is received during the mild winter months from October to March (Source: plotted from Autodesk Ecotect Analysis}

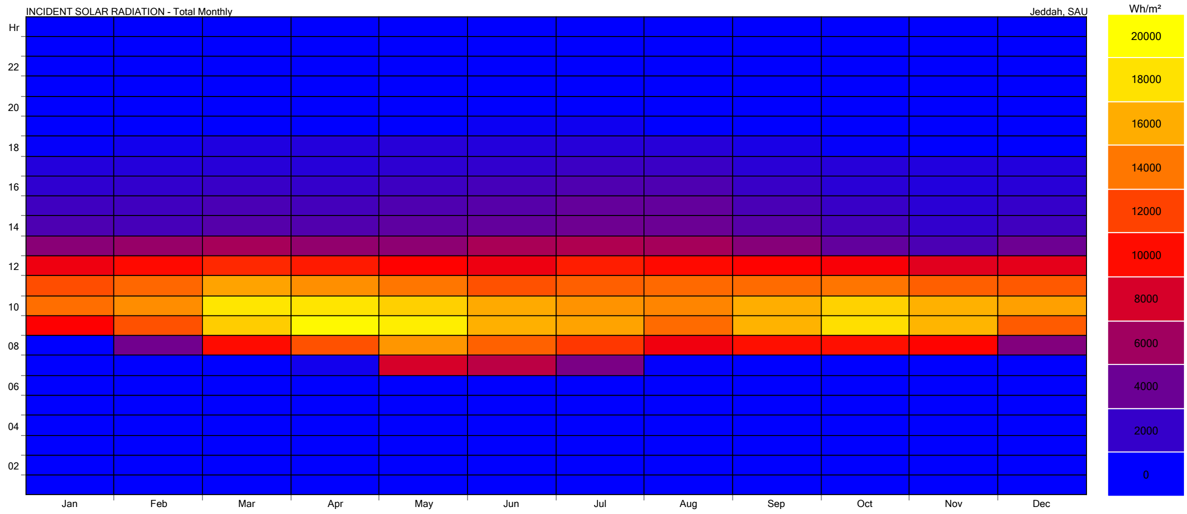


Figure 5-20 The average daily incident solar radiation falling on the East façade of a building located in Jeddah, Saudi Arabia. This orientation has the highest values for solar radiation in the early mornings for most of the year. (Source: plotted from Autodesk Ecotet Analysis)

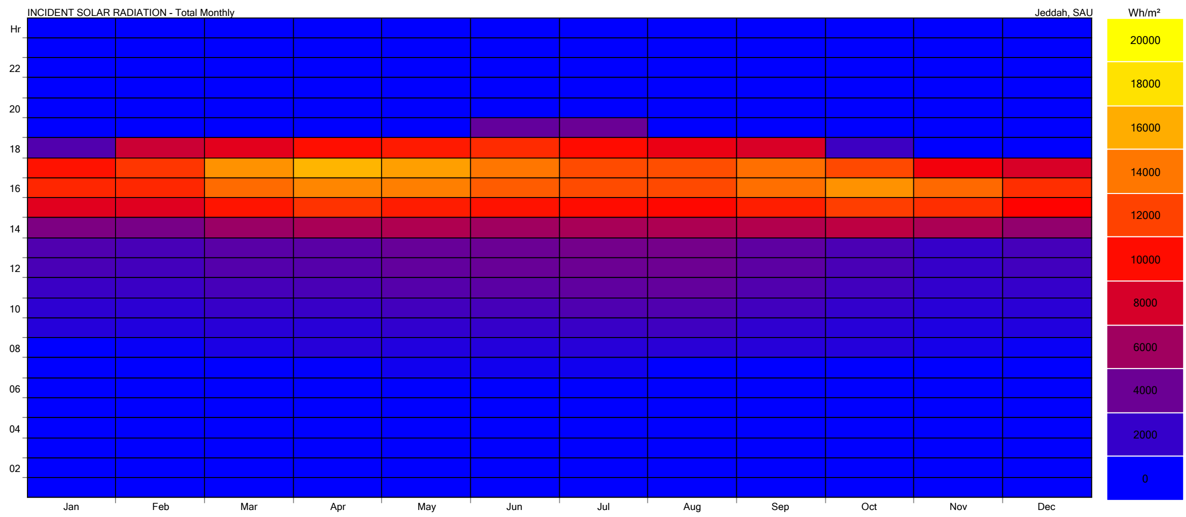


Figure 5-21 The average daily incident solar radiation falling on the West façade of a building located in Jeddah, Saudi Arabia. This orientation has high values for solar radiation in the afternoons for most of the year. (Source: plotted from Autodesk Ecotect Analysis)

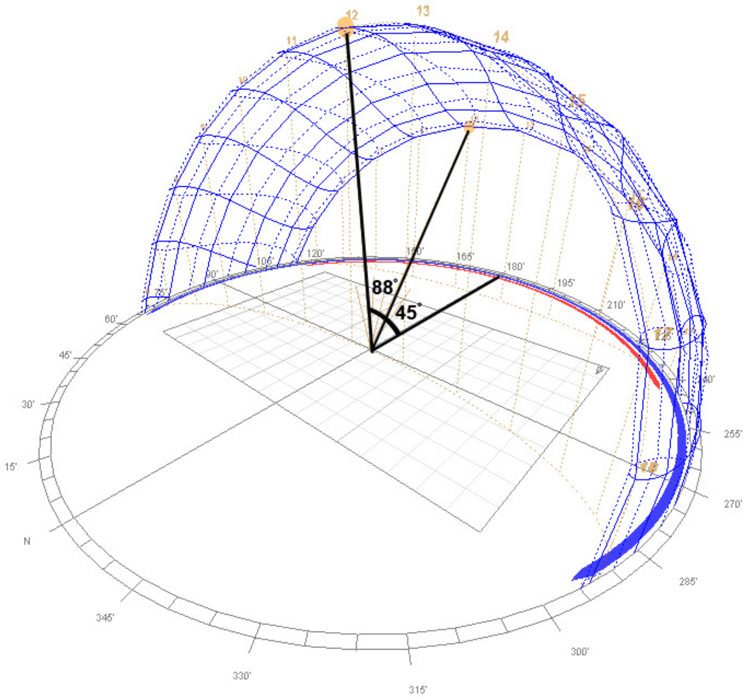


Figure 5-22 The annual sun path diagram for Jeddah, Saudi Arabia, highlighting the summer and winter altitude

Based on the given variables, the alternatives for the shading devices for this parametric study were set up using Equations 5-1 and 5-2, which considered the window area (2.4x0.9m) of the base case. The depth of the horizontal overhangs and vertical fins was calculated using the vertical and horizontal shadow angle range in Table 5-6, based on the time of day and the average daily incident solar radiation for each façade orientation. The results of the equations for the depth of the shading devices ranged from 0.12m to 6.3m; however, calculations were disregarded if the depth of the shading device exceeded 0.5m as this was judged to have a negative impact on the external appearance and structural load on the tall building façade. Finally, dynamic simulations were run for two types of shading devices on three façades with varying depths alongside the non-shaded base case. As Figure 5-23 and Table 5-7 show, egg-crate shading devices with a fixed depth of 0.2m were modelled for the South façade, while vertical fins to the left and right of the window with varying depths (0.15m, 0.3m and 0.5m) were installed on the East and West façades. As for the North façade, 0.2m deep vertical fins were tested in the simulations but the difference in results was insignificant so they were discarded in the results analysis.

$D_H = \tan(90 - \varepsilon) \times H_W$

$D_V = tan\ (90\text{-}\delta)\ x\ W_W$

Equation 5-2 and 5-2: The horizontal and vertical depths of external shading devices based on the window area of the base case model in addition to the local horizontal and vertical shadow angle (Source: Cho et al., 2014, p.773)

Where:

D_H = Horizontal overhang depth (m)

D_V = Vertical fin depth (m)

H_W = Window Height (m)

W_W = Window width (m)

ε = Vertical Shadow Angle (°)

δ = Horizontal Shadow Angle (°)

Table 5-6 The vertical shadow angle (ε) and horizontal shadow angle (δ) in Jeddah, Saudi Arabia

Jeddah 21.7 39.2	Shadow Angle	7:00 am	8:00 am	9:00 am	10:00 am	11:00 am	12:00 pm	1:00 pm	2:00 pm	3:00 pm	4:00 pm	5:00 pm	6:00 pm
The Spring Equinox	ε	113	112	112	112	112	112	112	112	112	112	112	113
	δ	93	98	106	116	132	160	-160	-132	-116	-106	-99	-93
The Summer Solstice	ε	41	64	77	83	86	88	88	86	82	75	61	35
	δ	70	74	77	80	80	71	-76	-80	-79	-77	-73	-69
The Autumn Equinox	ε	106	109	110	110	110	110	110	110	110	109	108	98
	δ	93	99.2	106	117	135	168	-151	-125	-111	-103	-96	-90
The Winter Solstice	ε	-179	157	145	139	136	135	135	137	141	148	163	-170
	δ	115	121	129	140	155	173	-167	-150	-137	-127	-119	-113

Table 5-7 The two types of shading devices used in the second set of simulations and their depths and orientations

Shading configuration	**Orientation**	**Depth (m)**	
		Horizontal	**Vertical**
No shading (NS)	All orientations	-	-
Egg-crate shading (ECS)	South	0.3	0.3
Vertical shading with fins on the left and right (VS)	East and West	-	0.15 – 0.3 – 0.5

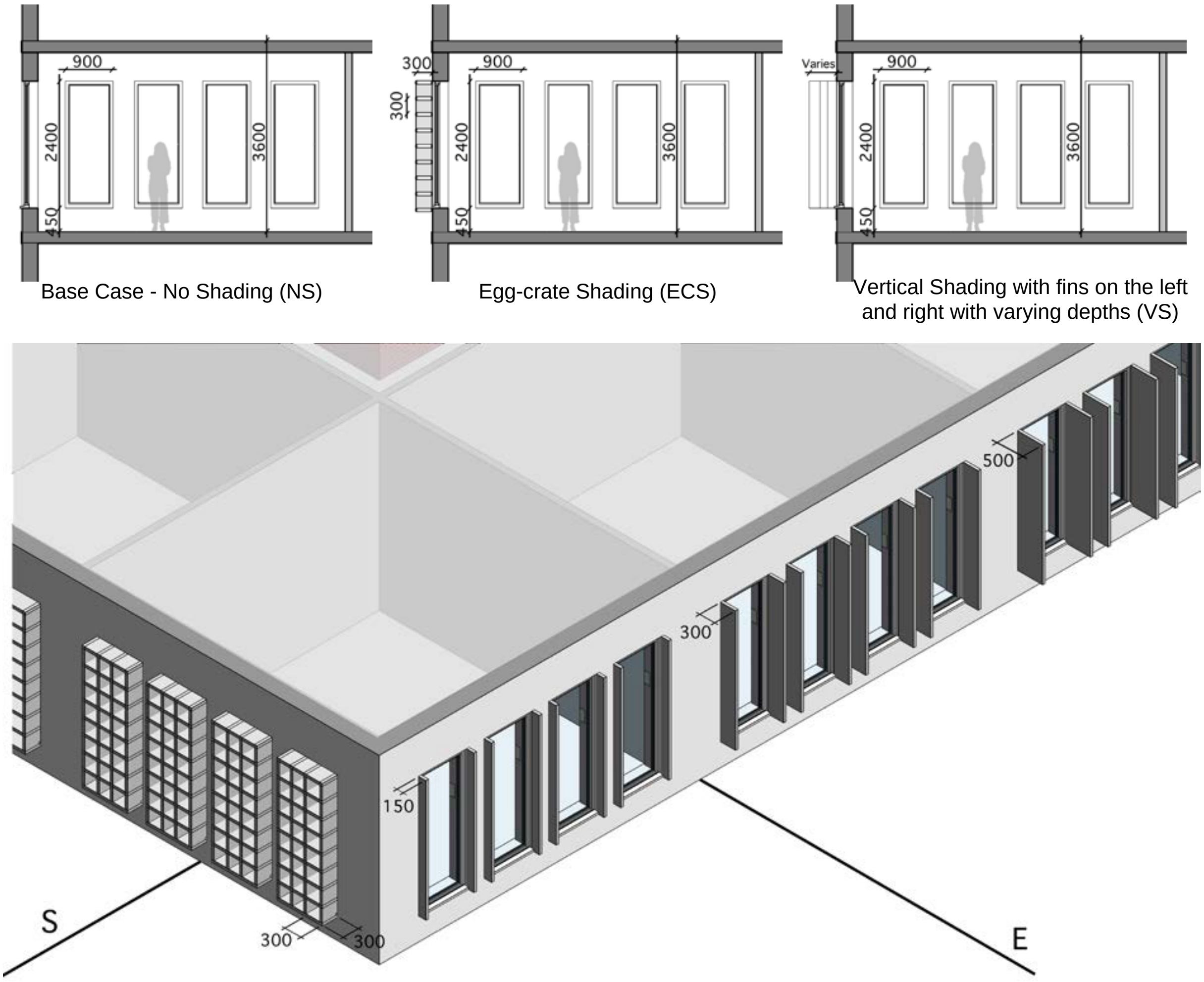


Figure 5-23 The main groups of shading configurations for the second set of simulations (dimensions in mm)

As for the base case model, the design described in Section 5.2.1 was used and simulations were run for the 18 building envelope configurations with 40% and 60% glazing ratios (as set out in Table 5-4) since the higher the glazing ratio, the more shading is needed. All other elements and assumptions remained the same as in the engineering parameters simulations in Sections 5.2 and 5.3.1. The design of the external shading was fixed for the four façades, altering depths only, and changing the configurations for the base case in relation to glazing percentage, glazing and wall type. This means that the base case thermal performance was reviewed both with and without shading devices. The next section will explain the simulation matrix used in the second parametric study.

5.4.2 Simulation Matrix

Following the results of the first parametric study, and based on the above-mentioned design considerations for the external shading devices, the initial set of simulations included 162 simulations carried out for the 18 base cases using Tas modelling software, with nine different cases of varying depths of the vertical shading devices on the East and West façades for each base case. Table 5-8 shows an example of the simulation matrix for the base case (40-tbw-32) and how the simulations varied the depth of the vertical fins on the East and West orientations. The first results showed very marginal differences between fixing the depth of the vertical shading for one orientation while varying the depth for the other orientation. For example, fixing the depth of the vertical shading on the West at 15cm while varying the depth between 15cm, 30cm and 50cm on the East-facing vertical shading had minimal impact on the solar gains or cooling loads, as will be further discussed in the Section 5.4.3. Consequently, the depth for the vertical shading on the East and West façades were fixed in the final matrix (Table 5-9).

Table 5-8 An example of the initial matrix for the second set of simulation testing the design parameters of the building

Base case configuration	**West (VS)**			**East (VS)**
	15	**30**	**50**	
18 base cases (e.g. 40-tbw-32)	(15-15)	(30-15)	(50-15)	**15**
	(15-30)	(30-30)	(50-30)	**30**
	(15-50)	(30-50)	(50-50)	**50**

Table 5-9 The final matrix for the second set of simulations testing the design parameters of the building envelope

Base case	Configuration
40-ucw-32	No shading
	(15-15)
	(30-30)
	(50-50)
40-ucw-28	No shading
	(15-15)
	(30-30)
	(50-50)
40-ucw-26	No shading
	(15-15)
	(30-30)
	(50-50)
40-tbw-32	No shading
	(15-15)
	(30-30)
	(50-50)
40-tbw-28	No shading
	(15-15)
	(30-30)
	(50-50)
40-tbw-26	No shading
	(15-15)
	(30-30)
	(50-50)
40-ssg-32	No shading
	(15-15)
	(30-30)
	(50-50)
40-ssg-28	No shading
	(15-15)
	(30-30)
	(50-50)
40-ssg-26	No shading
	(15-15)
	(30-30)
	(50-50)
60-ucw-32	No shading
	(15-15)
	(30-30)
	(50-50)
60-ucw-28	No shading
	(15-15)
	(30-30)
	(50-50)
60-ucw-26	No shading
	(15-15)
	(30-30)
	(50-50)
60-tbw-32	No shading
	(15-15)
	(30-30)
	(50-50)
60-tbw-28	No shading
	(15-15)
	(30-30)
	(50-50)
60-tbw-26	No shading
	(15-15)
	(30-30)
	(50-50)
60-ssg-32	No shading
	(15-15)
	(30-30)
	(50-50)
60-ssg-28	No shading
	(15-15)
	(30-30)
	(50-50)

60-ssg-26	No shading
	(15-15)
	(30-30)
	(50-50)

5.4.3 The Results

In order to understand the extent to which external shading as a design parameter can contribute to energy efficiency in residential tall buildings in the hot climate of the Gulf Region, a series of 72 dynamic simulations were run and the performance was evaluated by measuring the increase and decrease in annual cooling loads in relation to solar heat gain.

Firstly, to determine the impact of shading devices on cooling loads, simulations were run for the 18 base cases without any shading. Then, 0.3m deep egg-crate external shading devices were installed on the South oriented façade, and vertical fins with varied depths (0.15m, 0.3m, and 0.5m) were installed on the East and the West oriented façades. Each non-shaded base case was compared to the three different depths of vertical shading for eight zones representing the North, South, East, West, Northeast, Northwest, Southeast and Southwest orientations (as shown in Figure 5-2).

The results were analysed in relation to the reduction in cooling loads for the three variations of shading device depth by comparison with the tested base cases (Figure 5-24). This illustrates that a reduction of at least 4% in annual cooling loads could be achieved by using external vertical shading devices on the East and West façades and egg-crate devices on the South façades; furthermore, this could be increased to 17% by considering the glazing ratio and the thermal properties for glazing and external walls. In other words, the reduction in cooling loads was more evident in the base cases built with thermal blocks (TBW) or unventilated cavity walls (UCW) rather than spandrel glass (SSG). Moreover, external shading devices were more effective when used with glazing types with higher SC values (type 26 and 28 in Table 5-4), since they block excess solar radiation, thereby compensating for the lower shading quality of the glazing. On the other hand, the results also indicate that the glazing ratio is not necessarily a significant factor in relation to shading devices since the percentage reduction in cooling loads was similar for the base cases with 40% and 60% glazing ratios.

The next step was to compare the reduction in cooling loads across the eight zones for the 18 base cases in order to determine which orientation benefited most from external shading devices. The results in Figures 5-25, 5-26, and 5-27 demonstrate the effectiveness of the egg-crate shading devices on the South façades with up to 18% reduction in annual cooling loads. As for the vertical fins on the East and West façades, the efficiency of the shading is, as expected, dependent on the depth: the deeper the shading device, the greater the reduction in cooling loads. The 0.15m deep vertical fins achieved a maximum of 7% reduction, while the 0.3m reached between 11% and 12% on the East and West zones, and the 0.5m deep vertical fins reduced cooling loads by 18%, a significant 11% improvement on the 0.15m fins. The figures also highlight how the Southwest and Southeast façades, which performed worse in relation to cooling loads in the previous parametric study (Section 5.3.3), benefitted most from the reduction in cooling loads, especially when 0.3 or 0.5m deep fins were used.

In conclusion, the results of the second parametric study showed that egg-crate shading devices are most effective in reducing cooling loads in relation to solar gains. However, it is critical to assess the impact egg-crates have on views and visibility from the inside and on the aesthetic appearance of the façade design from the outside. Furthermore, although external shading devices can significantly improve both the thermal performance of the building envelope and the energy efficiency in residential tall buildings in the Gulf Region, their impact can be jeopardised if the thermal performance of the wall and glazing types is not carefully studied. Ultimately, it is important to integrate external shading as a design parameter with the engineering parameters of the building envelope, especially well-insulated walls and glazing types.

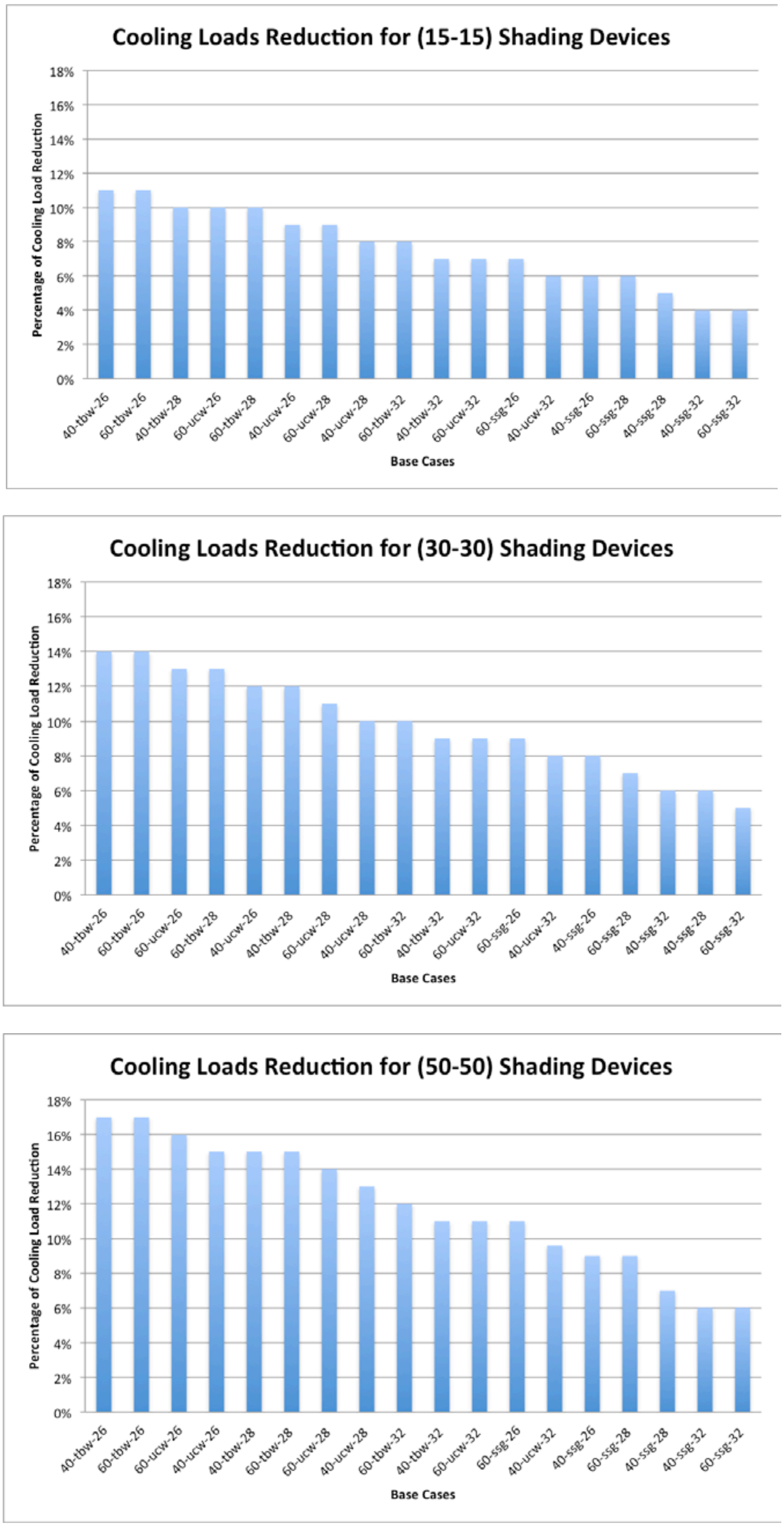


Figure 5-24 The results of the design parameters parametric study showing the percentage reduction in annual cooling loads for the 18 base cases, testing three different depths of vertical fins on the East and West oriented façades

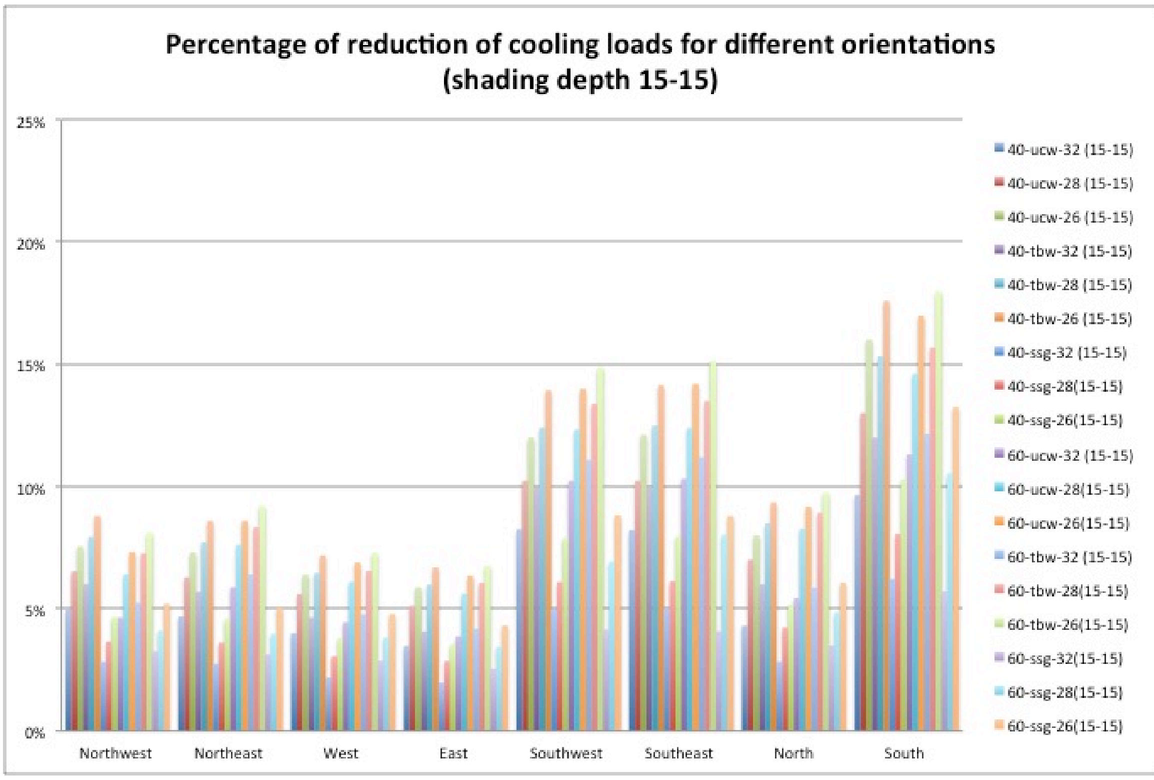


Figure 5-25 A comparison of the reduction in annual cooling loads between the different orientations of the 18 base cases, for vertical fins of 0.15m depth on East and West façades

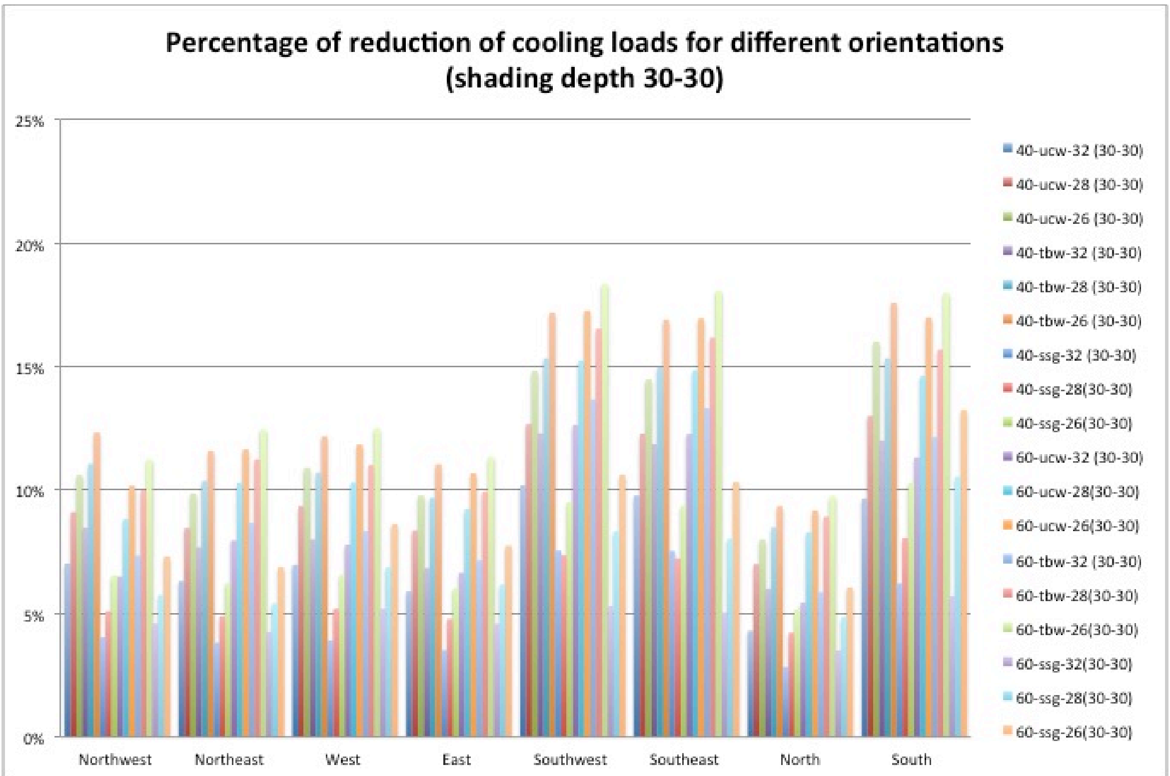


Figure 5-26 A comparison of the reduction in annual cooling loads between the different orientations of the 18 base cases, for vertical fins of 0.3m depth on East and West façade

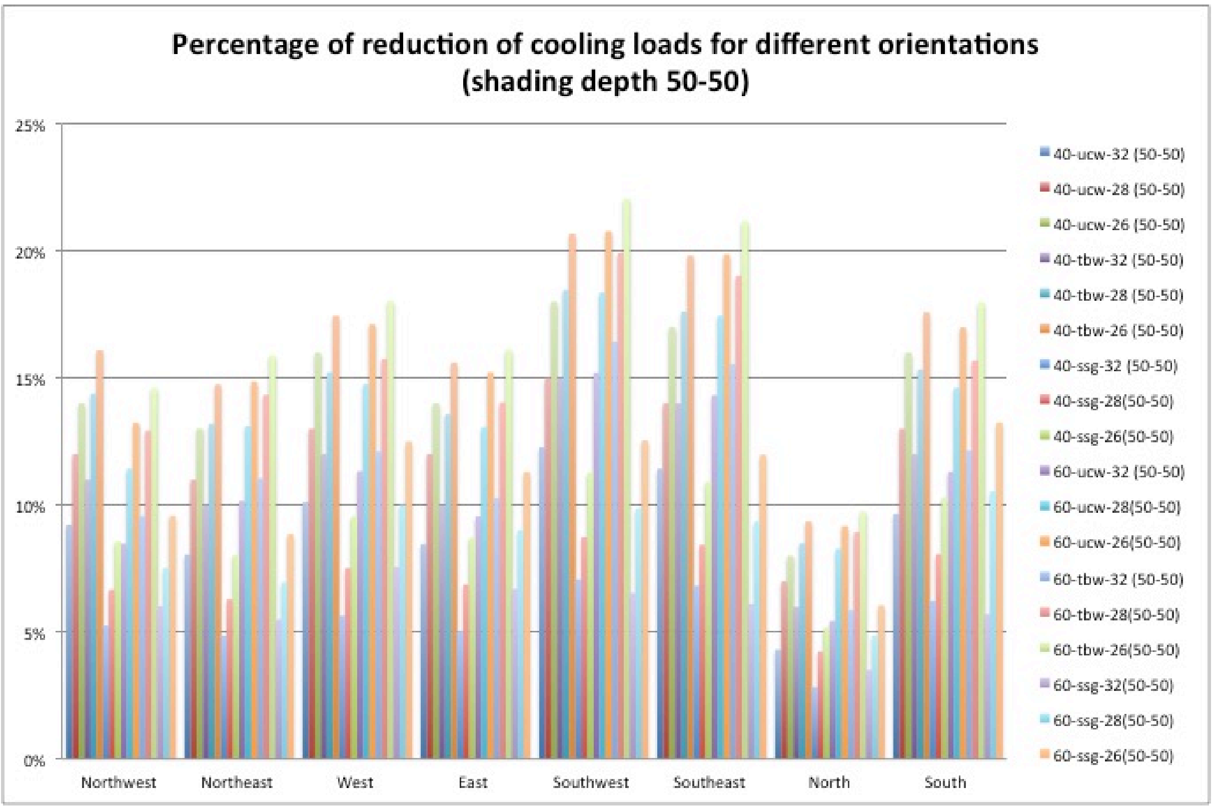


Figure 5-27 A comparison of the reduction in annual cooling loads between the different orientations of the 18 base cases, for vertical fins of 0.5m depth on East and West façades

5.5 Conclusion

This chapter aimed to identify the most influential building envelope parameter impacting the energy efficiency and cooling energy loads in residential tall buildings in the city of Jeddah in Saudi Arabia. In order to do that, two parametric studies were conducted through advanced dynamic simulation techniques using Tas modelling software: the first focused on the engineering parameters, selected based on the parameters specified in the local building codes and practices, and the second investigated the effect of external shading devices as a design parameter. The main objectives of the simulations were to evaluate and compare the impact of both the engineering and design parameters of different envelope combinations on thermal performance in order to determine the building envelope characteristics that deliver the best energy efficiency for the tall building typology.

The findings from the parametric studies showed that due to the high air temperature and abundant solar radiation in the region, solar gains make the greatest contribution to cooling loads. Hence, the reliance on a prescriptive approach to building envelope 'engineering' parameters specifications will not necessarily achieve the required reduction in solar gains, and the development of the 'design' parameters, such as external shading elements, could further reduce cooling energy loads.

The results revealed that lower shading coefficients, achieved either through glazing type or by using external shading devices, can significantly decrease solar gains, even across larger glazing areas. However, the choice of spandrel glass (SSG), commonly used to achieve an aesthetically unified fully glazed façade, had a significant negative impact on solar gain and cooling loads, regardless of whether shading devices were used or not. This suggests that it is important to integrate both the 'engineering' and 'design' parameters of the building envelope in order to achieve energy efficiency in residential tall buildings.

The next chapter tests this hypothesis and explores different options for building envelope parameters based on an existing case study of a residential tall building on the Corniche in Jeddah, Saudi Arabia.

CHAPTER 6: Thermal Simulations of Case Study: Corniche Dreams Tower

This chapter aims to test the hypothesis that integrating both the 'engineering' and 'design' parameters of the building envelope increases energy efficiency in residential tall buildings in the hot humid climate of Jeddah. In order to investigate this, this hypothesis was applied to an existing case study of a residential tall building located on the coast of Jeddah called Corniche Dreams Tower. Three parametric studies were conducted using dynamic thermal simulations to establish the extent to which the energy performance of the case study could be improved using both engineering and design parameters. The first study focused on the engineering parameters, while the other two considered the design parameters such as building orientation and shading devices. The main findings of the parametric studies emphasised the importance of integrating the engineering and design parameters from the early stages of the design process.

Chapter 6 THERMAL SIMULATIONS OF CASE STUDY: CORNICHE DREAMS TOWER

> *"Should we be building new buildings in the Middle East at all? Tall buildings are only economically viable due to the availability of cheap energy! So, what will be the future of those buildings in 50 years when the energy picture is different and we have moved away from the petroleum era, even in the Middle East?"*
>
> Joana Carla Soares Gonçalves in her book, 'The Environmental Performances of Tall Buildings', p.136, 2010
>
> *"Apprehension over the long-term viability of oil has challenged stakeholders in the region to attract new economic sectors with an emphasis on global placemaking and international tourism. Skyscraper construction has become a mechanism for generating value and identity within growing Middle Eastern cities, and has become the preferred method for boosting recognition and creating global destinations for these emerging municipalities."*
>
> Mounib Hammoud, CEO of Jeddah Economic Company, in the CTBUH 2016 Conference

As discussed in Chapter 1, Saudi Arabia is currently witnessing a rapid rate of urbanization and population growth, especially in major cities such as Jeddah. Indeed, Jeddah's population has increased over 100 times to reach 3.4 million people and is expected to grow at an annual rate of 2.2% (above the national average of 2%) to reach 5.6 million people by 2029 while its urban area has grown to 1000 times what it was six decades ago (Abdulaal, 2012). This urban expansion and population increase coupled with various kinds of economic progress within the city has resulted in urban sprawl, with scattered, unplanned developments, soaring land prices, and the proliferation of vacant plots and land far beyond actual demand for development. In addition to this poorly controlled expansion, Jeddah faces challenges such as the overdependence on cars, the increasingly congested roads, and inadequate infrastructure such as the water supply and sewage network that covers less than 25% of the existing built-up area (Jeddah Municipality, 2007; Abdulaal, 2012).

In order to respond to these challenges, the Municipality of Jeddah has developed a strategic growth plan for the city, expressed within the Jeddah Plan and associated Local Plan documents. At the same time, the Municipality has given approval to two types of large urban plans considering the development demands of the city: first, comprehensive urban mega projects on large-scale vacant areas, and second, regeneration projects aimed at rejuvenating unplanned settlements. The mega projects include typical mixed-use developments located in central locations dominated by high land prices and aim to build residential tall buildings to supply mid and high-end apartments for middle and high-income owners, given that the middle-income bracket covers 30% of Jeddah's population and the high-income bracket covers 13% (Abdulaal, 2012). Moreover, there is the ambitious plan to construct the world's tallest building, the kilometre-plus Jeddah Tower, as part of plans to develop the city as a means of reorienting the economy towards a global model based on business and tourism (Hammoud, 2016).

This tall building construction boom is associated with many environmental and ecological challenges that are linked with increased energy demand, especially the significant use of air-conditioning to cool indoor spaces (as discussed in the previous chapters). In Jeddah, tall building design has faced challenges on two levels, climatic and regulatory. First, the climatic conditions of high air temperature and abundant solar radiation in the city require careful selection of building envelope parameters to minimise heat gains and maximise heat losses. Second, despite governmental efforts, the scattered energy conservation plans have been ineffective due to factors such as limited enforcement of local building energy codes and lack of awareness and information. Therefore, the previous chapter investigated the effectiveness of local building energy efficiency regulations and concluded that the current reliance on a prescriptive approach to building envelope 'engineering' parameters specifications will not necessarily achieve the required reduction in cooling loads, especially in relation to solar gains. Instead, a holistic cross-disciplinary design approach that involves careful planning, integration and optimisation of both the 'engineering' and 'design' parameters of the building envelope should be incorporated into these regulations.

Based on this discussion, this chapter aims to test the hypothesis of integrating engineering and design parameters as a design strategy for tall building envelopes and compare it to current common practice and to local building codes and regulations. To achieve this aim, three parametric studies through dynamic building simulation, using Tas software by EDSL, were conducted to evaluate the thermal and energy performance of the building envelope for a representative existing case study of a residential tall building in Jeddah, Corniche Dreams Tower. This particular tower was chosen for three main reasons: first, for familiarity and ease of access since the author's relatives live in the tower. Second, the architectural and building envelope characteristics of the tower are representative of residential tall buildings in Jeddah, and third, the tower required environmental improvements in relation to its orientation, lack of thermal wall insulation and large glazing ratio.

The following sections first explain the existing case study of Corniche Dreams Tower, the scope and method of each set of simulations for the three parametric studies, and, finally, the analysis of the results of the cooling energy demands that were compared to other cases based on the findings of the analysis in Chapter 5.

6.1 The Case Study: Corniche Dreams Tower

The base case building for the parametric study is the Corniche Dreams Tower, located in Jeddah, Saudi Arabia, and overlooking the Red Sea across the Corniche Road (Figure 6-1). The tower is situated in a coastal resort area that is considered a popular attraction to visitors, featuring recreation areas, pavilions and large-scale civic sculptures (Wikipedia, 2017). The following sections introduce the formation of this case study, and the main considerations for the parametric study.

6.1.1 Building Information

According to the 'Jeddah 1450 Tall Buildings Guide', buildings between 19 and 30 storeys are defined as 'Very Tall Buildings' since they are as tall as the city's current tallest buildings and will be visible from across the city (Jeddah Municipality, 2007). Therefore, the 27-storey Corniche Dreams Tower, completed in 2011, is considered a very tall residential tower. The tower was locally designed by Ahmed Saleh Kaki Sons Company Ltd, who is also the real estate developer of the project.

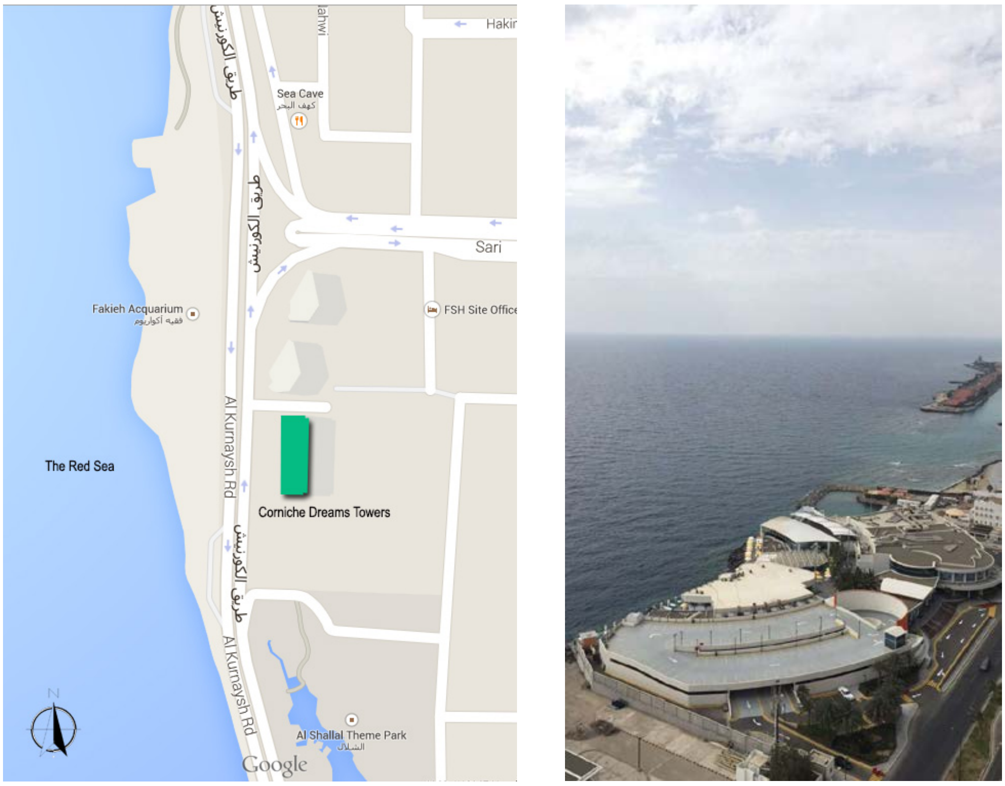


Figure 6-1 The location of Corniche Dreams Towers (on the left) overlooking the coast of the Red Sea in Jeddah, Saudi Arabia (on the right), (Source: modified from Google Maps, 2017).

As shown in Figure 6-2, the building is divided into four joined 'towers' each with a separate core serving a single flat per floor. The total gross area for the outer edge flats (Flat 1 and 4) is 685m^2 each, while the internal flats (Flat 2 and 3) are 640m^2 each, and the total gross external area for the whole typical floor plan is 2650m^2. Like many residential tall buildings along the Corniche in Jeddah, these towers supply high-end apartments and flats for high-income owners, thus it is considered typical to have large flats that occupy a whole floor area with its private lift core. Table 6-1 summarises the main architectural characteristics of Corniche Dreams Tower (as shown in the Characteristics Table in Chapter 4).

The tower has a predominantly north-south axis orientation and the main façade faces west to take full advantage of the Red Sea views (to boost the marketing of the residential flats) while the East elevation faces the city of Jeddah (Figure 6-3). However, this orientation is not favourable in this climate due to the high values of incident solar radiation falling on the vertical surfaces of the East and West façades, an issue exacerbated by the high glazing ratio on the East (48%) and West (55%) elevations (Figure 6-4; 6-5) and the absence of any shading treatment.

Figure 6-2 A typical floor plan for Corniche Dreams Tower, consisting of four joined towers each with a separate core serving a single apartment per floor

Figure 6-3 The main elevations for Corniche Dreams Tower: East elevation (Left), West elevation (Middle), and South elevation (Right)

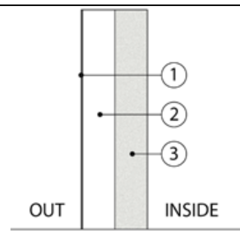
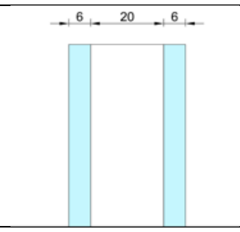
In relation to the main construction materials, the building is a steel structure and the external walls are made of two layers of 60x60x10cm gypsum blocks with 20cm unventilated air cavity between them with no insulation material. Meanwhile the glazing material is made of 32mm double insulating glass composed of two 6mm tempered glass panels with 20mm air space between them. Table 6-2 lists the thermal properties of the construction materials for Corniche Dreams Tower as obtained from the building's management. Note that although the Saudi building code has mandated thermal insulation against heat for all new buildings since 2010 (as mentioned in Chapter 1), Corniche Dreams Tower was completed in

2011 without proper insulation. And, as with all buildings in Jeddah, the luxurious residential Corniche Dreams Tower is entirely dependent on air-conditioning systems for cooling and ventilation.

Table 6-1 The main architectural characteristics for Corniche Dreams Tower in Jeddah (Source: obtained from architectural drawings provided through the building's management)

Parameter	Information
Height (m)	112
No. of floors	27
Typical floor plate net internal area (m^2)	2096
Typical floor plate gross external area (m^2)	2650
Flat 1 and 4 net internal area (m^2)	540
Flat 1 and 4 gross external area (m^2)	685
Flat 2 and 3 net internal area (m^2)	508
Flat 2 and 3 gross external area (m^2)	640
Typical floor plate width and length (m)	82 x 33
Typical flat width and length (m)	33 x 20
Floor to floor height (m)	3.6
Floor to ceiling height (m)	3.4
Core location	Exterior core
Core area (m^2)	108
Typical floor plate efficiency (%)	80
Exposed skin area for Flat 1 and 4 (m^2)	277
Exposed skin area for Flat 2 and 3 (m^2)	140
Glazing ratio of total exposed skin area for Flat 1 and 4 (%)	46
Glazing ratio of total exposed skin area for Flat 2 and 3 (%)	53

Table 6-2 Corniche Dreams Tower's main construction materials

Main Frame	Steel structure	
Floor/ ceiling	200mm lightweight concrete	
Walls	External: Unventilated air cavity wall[30]: Total thickness 204mm Layers from outside to inside: 1. Aluminium Cladding (4mm)[31] 2. Unventilated Air Cavity (100mm)[32] 3. Gypsum Blocks (60x60x10cm)[33] - U-value 1.13 W/m^2K[34]	
Windows	Double Insulating Glass[35] Total thickness 32mm 1. 6mm K-LITE -14 on clear tempered glass 2. 20mm air space 3. 6mm EFG on clear tempered glass - U-value 2.7 W/m^2K - Shading Coefficient 0.23 - Visible light transmittance 13%	

[30] Information provided by Mr. Syed Zubair Jaffery, the maintenance manager in the Tower.
[31] Based on specifications from Viltabond Aluminum Composite Panels (R-value 0.0103 m^2K/W).
[32] Based on Anderson (2006, p.11), unventilated airspaces cavities in wall constructions normally have a resistance of 0.18 m^2K/W.
[33] Based on specifications for Gyproc Wall Board from British Gypsum (R-value 0.52 m2K/W).
[34] The U-value for the total wall was obtained through manual calculation and might differ from Tas calculations.
[35] Information provided by Mr. Mohammad Hisham Kaki, the developer of Corniche Dreams Tower.

Figure 6-4 The main front elevation for Corniche Dreams Tower facing west (Source: Building Management)

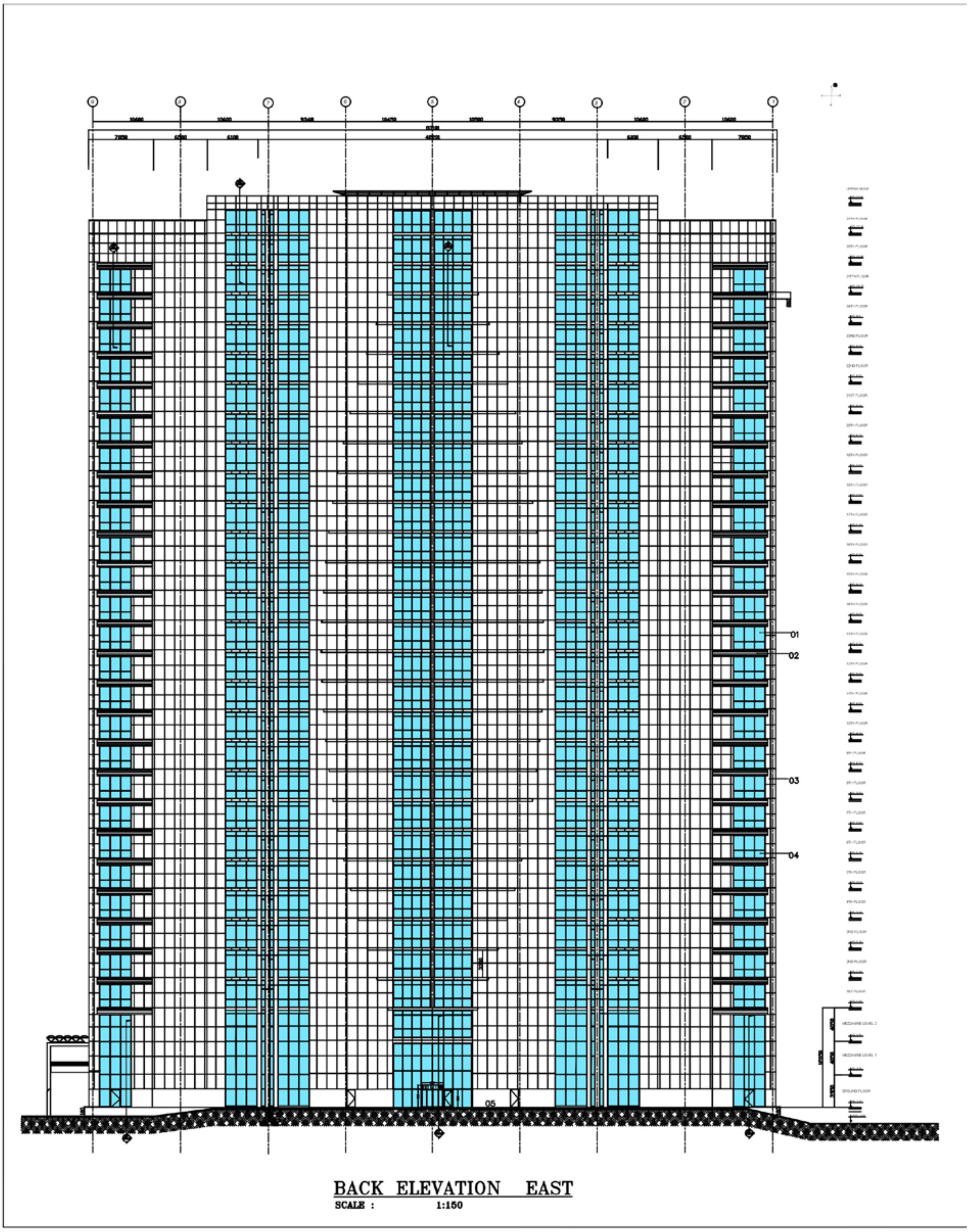


Figure 6-5 The back elevation for Corniche Dreams Tower facing east (Source: Building Management)

6.1.2 Monitored Data and Onsite Measurements

In order to evaluate the thermal performance of the existing building envelope of Corniche Dreams Tower, continuous monitoring of dry bulb temperature and relative humidity was undertaken for an empty flat on the 25th floor of the tower using four data loggers. The instruments used were one Tinytag Plus 2 data logger, designed for indoor and outdoor use, and three Tinytag Ultra 2 loggers, designed for indoor use (Tinytag, 2017). They were set to measure air temperature and relative humidity every 5 minutes for a whole year from the 1st August 2014 to the 15th August 2015.

The flat type is similar to the design of Flat 4 shown in Figure 6-2, with south, east and west facing orientations. The flat was unoccupied for the duration of the monitoring and isolated from the impact of active cooling equipment or internal gains. Therefore, the results should give a reasonable indication of the thermal performance of the building envelope in relation to conductive and solar heat gains through the external walls and glazing system. The locations of the data loggers were set according to orientation; the Tinytag Plus 2 logger was placed outside on the west facing balcony to record external air temperature and relative humidity, while the three Tinytag Ultra 2 loggers were placed in the East bedroom, the West bedroom, and the Southwest sitting room to monitor the indoor air temperature and relative humidity inside the flat (Figure 6-6, 7, 8, 9, 10).

The author had access to the flat through personal connections, and relatives who live in the same building were able to download the measurements data whenever they had access. However, due to logistic and technological constraints, some data were missing for a few weeks (as shown in Table 6-3). Nevertheless, since the measurements were recorded for more than a year, they still gave a fair representation of the thermal conditions in the flat.

Table 6-3 Days when data from the monitored zones was not recorded in the flat in Corniche Dreams Tower

Zones	Missing days	Duration
West facing balcony	22 and 23 September 2014	2 days
	18 November 2014 to 26 February 2015	14 weeks
	8 April 2015	1 day
	4 to 20 June 2015	2 weeks
East bedroom and Southwest sitting room	22 and 23 September 2014	2 days
	18 November to 10 December 2014	3 weeks
	4 to 26 February 2015	3 weeks
	8 April 2015	1 day
	4 to 20 June 2015	2 weeks
West bedroom	22 and 23 September 2014	2 days
	18 November 2014 to 26 January 2015	10 weeks
	26 February	1 day
	8 April	1 day
	4 to 20 June 2015	2 weeks

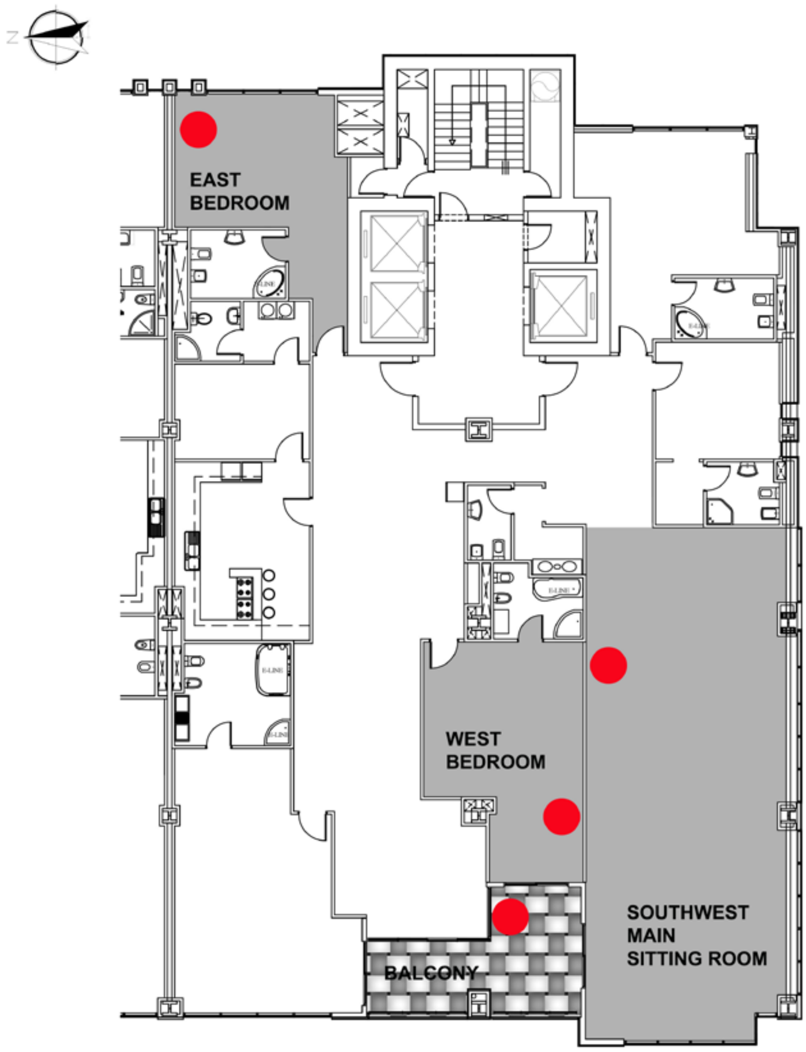


Figure 6-6 The locations of the data loggers in the flat on the 25th floor of Corniche Dreams Tower

Figure 6-7 The Southwest main sitting room in the flat on the 25th floor of Corniche Dreams Tower, and the Tinytag Ultra 2 data logger that recorded indoor air temperature and relative

Figure 6-8 The west facing balcony and the Tinytag Plus 2 data logger that recorded external air temperature and relative humidity in Corniche Dreams Tower

Figure 6-9 The East bedroom in the flat on the 25th floor of Corniche Dreams Tower

Figure 6-10 The West bedroom in the flat on the 25th floor of Corniche Dreams Tower

Certain factors were considered during the analysis of the measurements from the data loggers. First, due to the missing data, the results were plotted for the months with available full data, and then divided based on seasons as follow: Autumn (September, October and November 2014), Spring (March, April, May 2015) and Summer (July and August 2015). Second, since the data loggers recorded measurements every 5 minutes, there were around 105,000 reading for each location, which was challenging to interpret. Therefore, the data were combined into 24 hours periods to make them easier to read and analyse. Finally, although the flat itself was empty, those above and below it were occupied and presumed to be air-conditioned most of the time, which might have affected the stability and reduction of the air temperature in the monitored flat since it benefited from the colder air-conditioned spaces adjacent to it.

The available results for the external air temperature in Figure 6-11 showed high similarities when compared to the monthly diurnal average air temperature in Jeddah obtained from the Regional Climate Centre in the Presidency of Meteorology and Environment for the period between 1970 and 2011, and the hourly data for one year (2005) from EnergyPlus (See Chapter 1). This comparison validated the recordings for both sources. The results indicated a difference of up to seven degrees between the average monthly air temperature in the colder and hotter months, reflecting the slight seasonal difference in such climates.

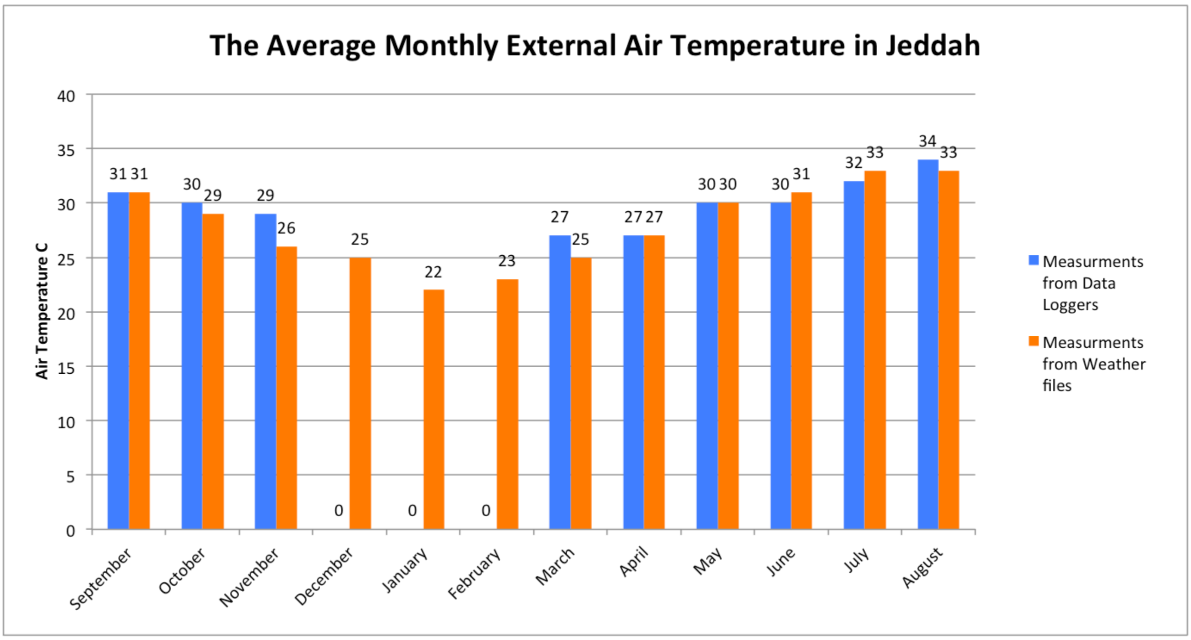


Figure 6-11 Comparison of the average monthly external air temperature for Jeddah as obtained from the data loggers between September 2014 to August 2015 and the accumulated data from the Presidency of Meteorology and Environment for the period between 1970 and 201

Comparing the results for the external and internal zones, the graphs in Figure 6-12, 6-13 and 6-14 illustrate the dry bulb temperature readings from the data loggers in the four specified locations. The results showed that in all three monitored seasons, the difference between the external and indoor air temperature was minimal with a maximum fluctuation of four degrees. The Southwest sitting room performed worst, especially in the cooler autumn season, with its internal air temperature rising up to three degrees more than the external air temperature, while the West bedroom performed slightly better in relation to reduced air temperature. This might be due to factors such as the larger exposed walls in the Southwest sitting room on two orientations with larger glazing ratios of 54% (west) and 65% (south), while the West bedroom has a smaller exposed wall onto the balcony with 47%

glazing ratio that is also shaded by the balcony above. As for the East bedroom, it had similar readings to the Southwest sitting room, especially in the hot summer season, which may also be due to its higher glazing ratio of 54% (as shown in Table 6-4).

The main findings from this data analysis revealed that the lack of thermal insulation in the external walls adversely affected one of the main functions of the building envelope: sheltering the internal spaces from Jeddah's hot humid climate. In other words, the thermal conditions for both the external and internal spaces were similar, and in some spaces, the internal conditions were worse than the external for an extended period of time. Moreover, the larger exposed walls and glazing areas also contributed to the higher dry bulb temperature, especially in the southwest facing rooms, which highlights the importance of considering the thermal properties of the opaque and transparent building envelope elements in parallel.

Following this analysis of the impact of the thermal properties of the building envelope and building orientation on the thermal conditions in a representative flat in Corniche Dreams Tower, the next section discusses the same impact in relation to energy performance using thermal simulations.

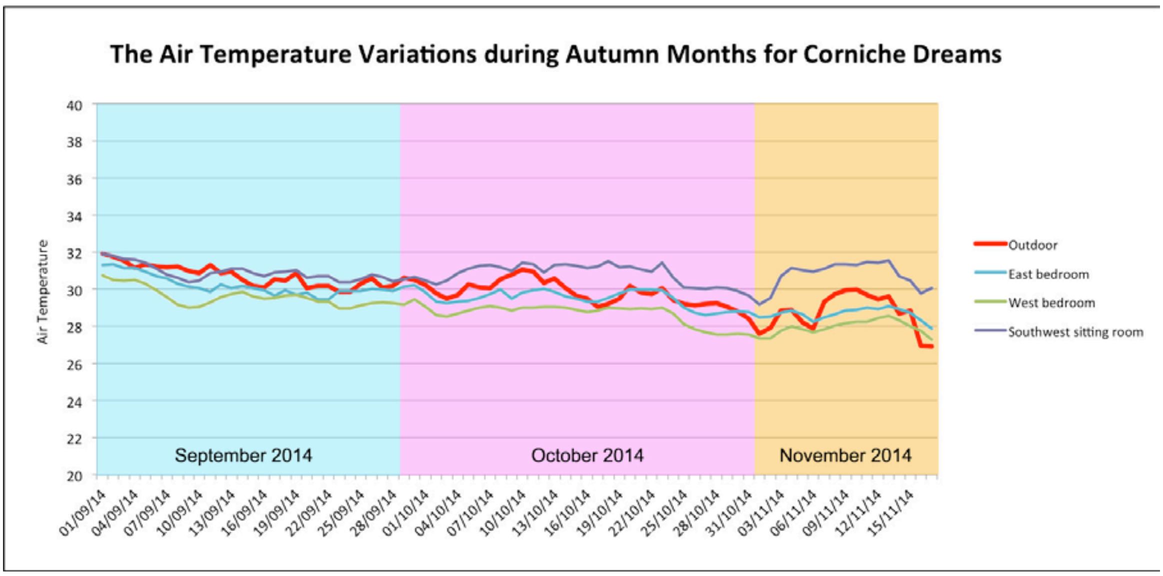


Figure 6-12 The readings for air temperature variations during the autumn season for the Southwest sitting room, West and East bedrooms and the external temperature obtained from the west facing balcony in Corniche Dreams Tower

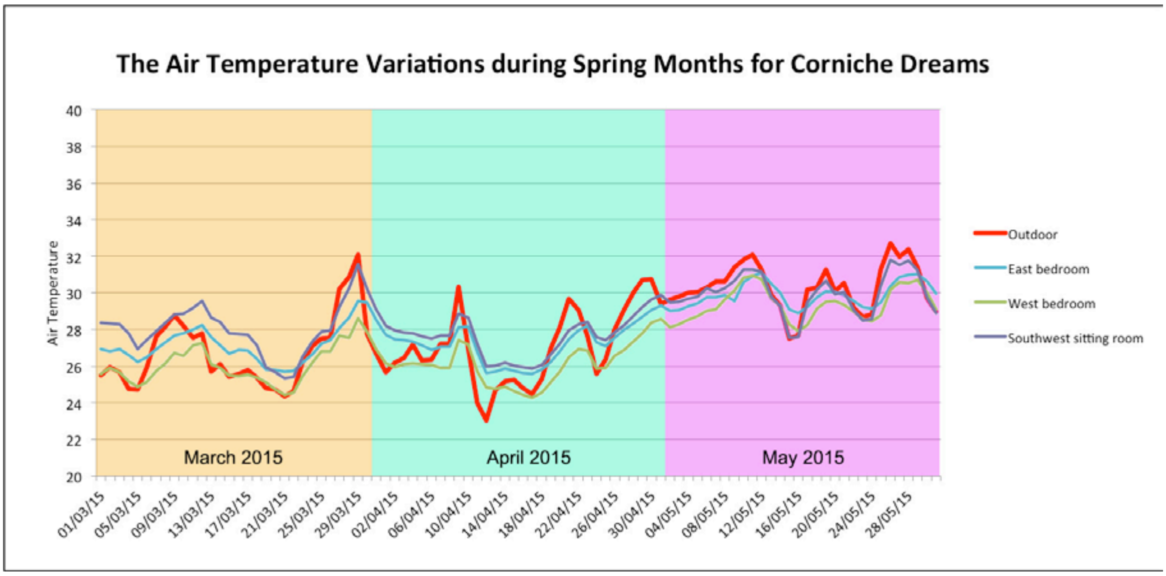


Figure 6-13 The readings for air temperature variations during the spring season for the Southwest sitting room, West and East bedrooms and the external temperature obtained from the west facing balcony in Corniche Dreams Tower

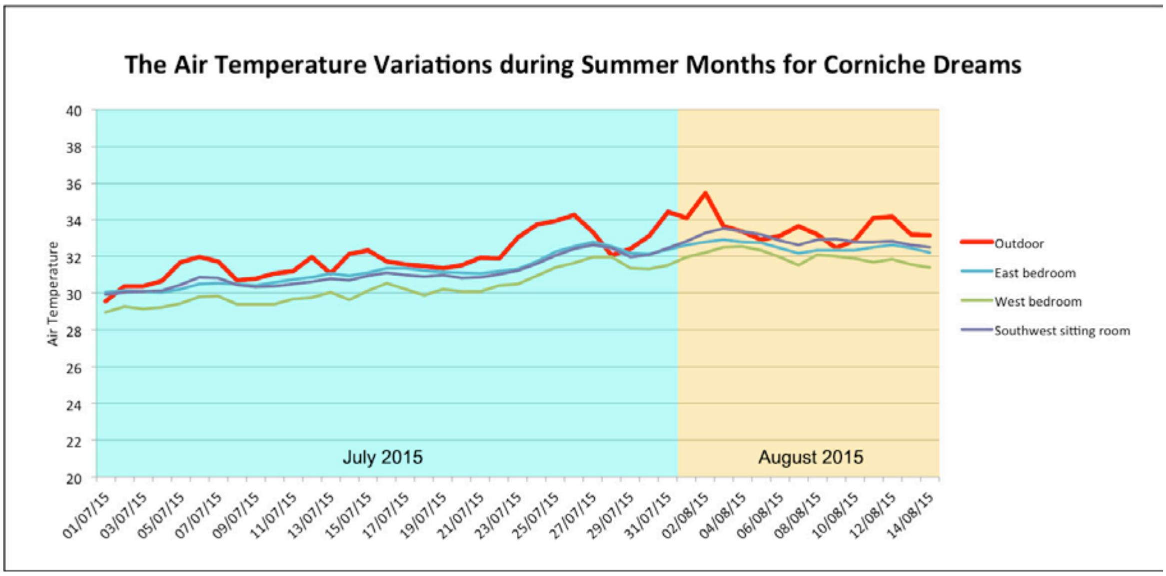


Figure 6-14 The readings for air temperature variations during the summer season for the Southwest sitting room, West and East bedrooms and the external temperature obtained from the west facing balcony in Corniche Dreams Tower

6.2 Thermal Simulation

The analysis of Jeddah's climate in Chapter 1 concluded that the high solar altitude and the clear cloudless sky characteristic of the local climate allows the abundant solar radiation to cause surface heating which raises the air temperature. Moreover, the findings from the parametric studies in Chapter 5 showed that, due to these challenging climatic characteristics, solar gains are the highest contributor to cooling loads. Therefore, lowering the shading coefficient, either through glazing type or by using external shading devices, can significantly decrease the solar gains even with larger glazing areas.

In the case of Corniche Dreams Tower, a qualitative environmental analysis revealed minimal climatic considerations in the design of the tower. First, as mentioned earlier, the current north-south axis orientation is not advisable in such a location. Next, the lack of insulation material in the external walls allows conductive heat gain through the opaque walls contributing to higher indoor air temperatures (as shown from the monitored data in Section 6.1.2) which in turn increases cooling loads. However, the low shading coefficient in the transparent glazing elements can positively reduce solar heat gain, even with the high glazing ratio of 48% (for the outer edge flats) and 53% (on the internal flats), and this could be further improved by installing external shading devices, especially on the main East and West façades.

Given these considerations and the hypothesis that combining both 'engineering' and 'design' envelope parameters could improve energy efficiency, a parametric study through dynamic building simulation was undertaken in order to identify to what extent an alternative approach could improve the environmental performance of Corniche Dreams Tower. The simulations investigated three main aspects in relation to building envelope parameters, the engineering parameters of the building envelope, building orientation, and external shading devices, and aimed to address the following questions:

I. To what extent can relying on the engineering parameters of the building envelope reduce cooling loads in Corniche Dreams Tower in the hot humid climate of Jeddah?
II. What is the impact of building orientation and external shading devices on both the energy performance and the views from the building?
III. To what extent can combining both engineering and design parameters improve the energy performance of Corniche Dreams Tower?

The following sections describe the basis for the three parametric studies and explain the base case, the input parameters, the simulation matrix and the results for the simulations investigated in this chapter.

6.2.1 Simulation Model Formation and Assumptions

For the purpose of this simulation, the existing 27-storey Corniche Dreams Tower was simplified into five mid floors with only the middle floor considered for data analysis (Figure 6-15). The results were plotted for the main perimeter zones only since they will reflect the thermal performance of the building envelope (Figure 6-16). The perimeter zones in Flat 3 and Flat 4 were selected as they mirror Flat 1 and 2, except that Flat 4 faces south and Flat 1 faces north. The south facing flat was selected as it represents the worst-case scenario in terms of energy performance, so any improvement there would also be effective for the north facing flat. Moreover, it matched the flats monitored by data loggers in Section 6.1.2. The selected zones are highlighted in Figure 6-17 and their main architectural characteristics are listed in Table 6-4. In Flat 3, the selected zones were the west facing main sitting room, west facing main bedroom, west facing bedroom and west facing sitting room, and two east facing bedrooms. Meanwhile Flat 4 had a west facing main bedroom and a smaller west facing bedroom, a west facing sitting room and a southwest facing main sitting room, a southeast bedroom and an east facing bedroom. Table 6-4 shows that even though the total glazing ratio for the West elevation is 55%, the individual glazing ratios for the west facing zones are higher, reaching more than 75% in rooms such as the main sitting room in Flat 3, which might count towards the high solar gains in these zones.

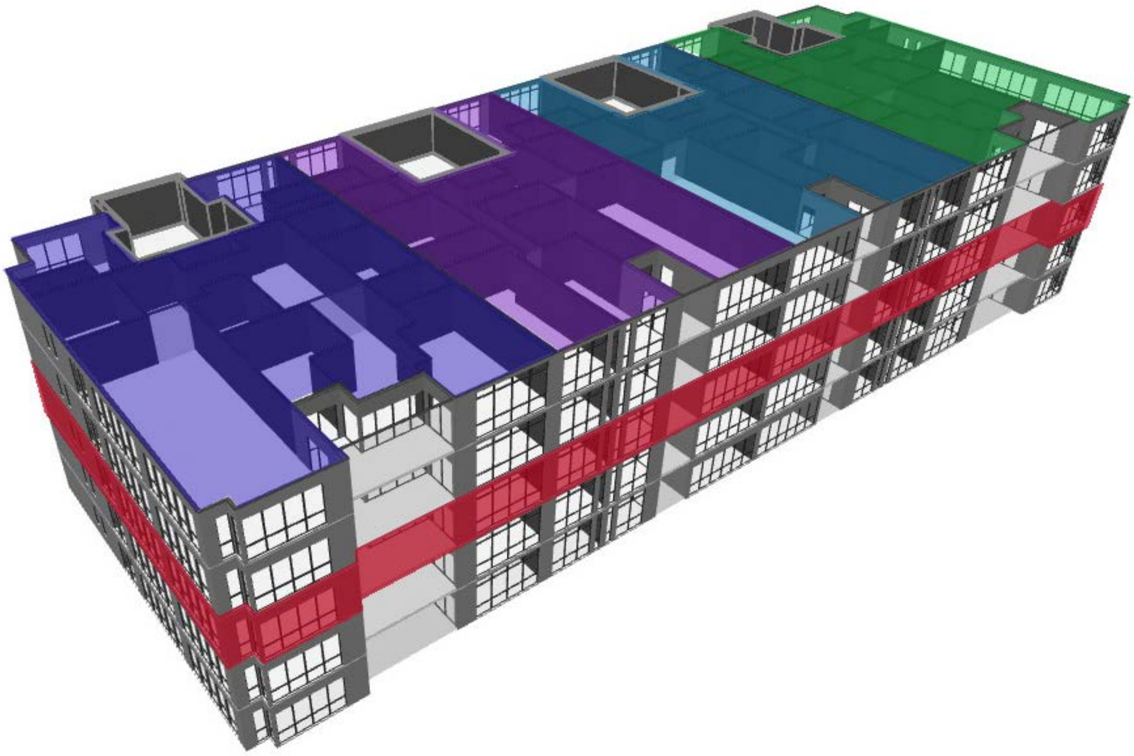


Figure 6-15 The 3D simulation model of Corniche Dreams Tower. The middle floor (highlighted in red) represents the analysed base case floor plan

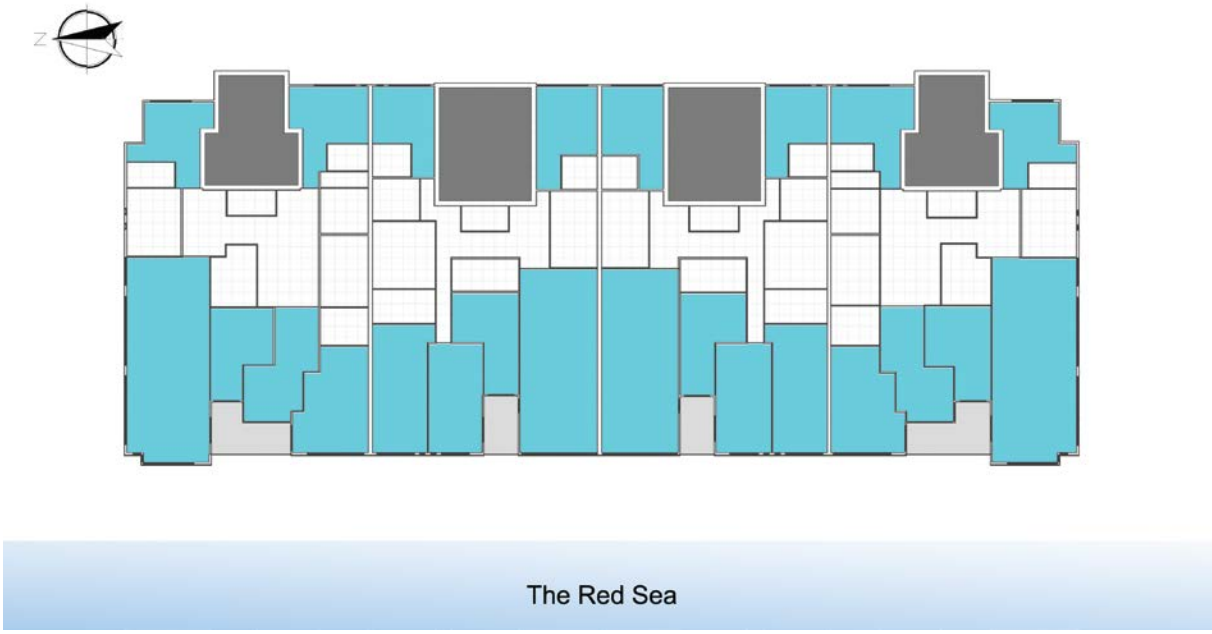


Figure 6-16 The perimeter zones, highlighted in blue, for Corniche Dreams Tower

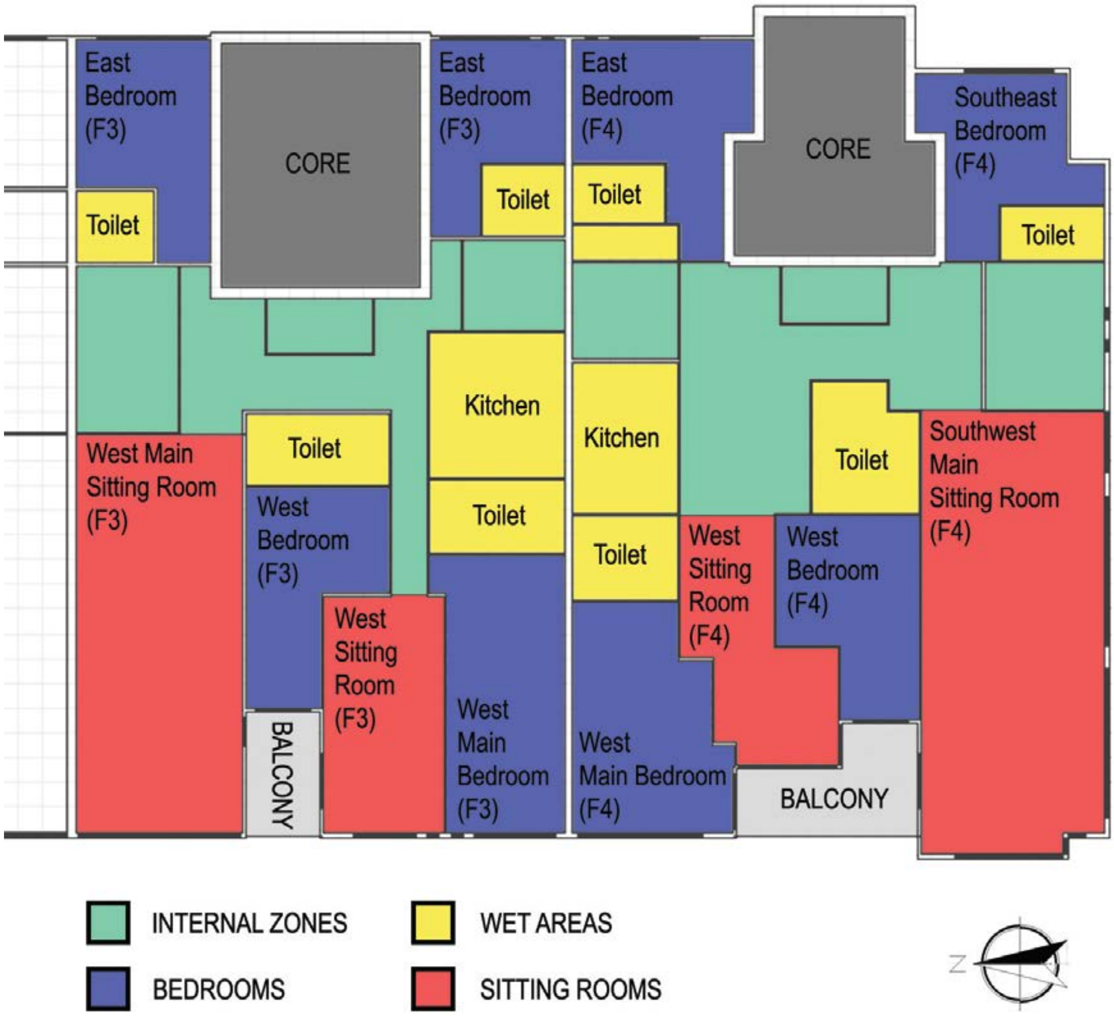


Figure 6-17 The internal organisation of Flat 3 and 4, showing the selected perimeter zones (sitting rooms and bedrooms), analysed in the thermal simulations

Table 6-4 The main architectural characteristics for the selected zones in Corniche Dreams Tower

Zones	Floor Area (m^2)	Exposed wall area (m^2)	Glazing orientation	Glazing area (m^2)	Glazing ratio (%)
Flat 3					
West Main Sitting Room	109.35	42.12	West	18.48	76.6
West Bedroom	39.2	10.8	West	5.28	48.8
West Sitting Room	46.25	35.38	West	9.9	57.3
West Main Bedroom	55	16.9	West	12.54	74.2
East Bedroom	35.6	19.44	East	14.85	76.4
East Bedroom	35.6	19.44	East	14.2	73
Flat 4					
Southwest Main Sitting Room	131.5	64	South	41.72	65.2
		26.28	West	14.28	54.3
West Bedroom	39.7	11.16	West	5.28	47.3
West Sitting Room	43.9	14.76	West	9.6	65
West Main Bedroom	52	23	West	16.5	71.7
Southeast Bedroom	35.9	18.36	South	0	0
		22.68	East	10	44.4
East Bedroom	42.4	26.28	East	14.2	54

Since the aim of the simulations was to determine the level of improvement in energy performance which could be achieved by changing the existing design and engineering parameters of Corniche Dreams Tower under the same conditions, the simplified model and assumptions were kept the same for all the simulations to allow for a better understanding of the outcomes of the simulations. The only changes were to the external wall thermal insulation, the building orientation, and shading devices, whilst internal walls, floor and roof were kept the same.

As in the simulations in Chapter 5, the considered assumptions followed the local building codes of the Gulf Region and the internal conditions for the simulated zones were set for an air-conditioned space with an infiltration rate of 0.57 ach for 24 hours. The estimated assumptions adopted were as follows:

IX. Weather: The weather file for Jeddah, containing the hourly data for the year 2005, obtained from EnergyPlus was used in the simulation.

X. Calendar: Since active cooling is used throughout the year to maintain a unified room temperature and relative humidity, summer and winter months were not considered in the calendar. The calendar was set based on the days of the week only.

XI. Internal Gains: no internal gains were assumed in this simulation.

XII. Ventilation and Infiltration: The infiltration rate was assumed in a rate of 0.57 ach for 24 hours in line with The Saudi Building Code Energy Conservation Requirements (SBC 601). No ventilation was assumed as air-conditioning is used.

XIII. Comfort Temperature Range: The thermostat was set according to the benchmark suggested by Dubai Green Building Regulations (Table 5 in section 4.1.1.2), where the comfort ranges between 22.5-25.5 °C.

XIV. Thermal Zones: As shown in Figure 6-17, the simulation model consisting of the two flats was built and divided into three zones: the main perimeter air-conditioned zones adjacent to the building façades (which include the sitting rooms and bedroom), the internal air-conditioned zones, and the wet area of kitchens and toilets. The division of the model into different zones according to their relation to the building envelope facilitated detailed identification of the differences in temperature between the zones due to the different orientation and specific envelope adoption.

XV. Heating: No heating was assumed.

XVI. Cooling: Active cooling through air-conditioning systems running for 24 hours was used in the simulation for all the zones. The thermostat was set according to the above-mentioned thermal comfort range.

As mentioned earlier, the focus of the simulation was to explore the extent to which the energy performance in Corniche Dreams Tower could be improved in relation to the engineering and design parameters of the building envelope, while taking into consideration the results from the monitored data in the previous section and the results from the parametric studies in Chapter 5. In order to achieve this, three sets of simulations were conducted to investigate three main aspects in relation to building envelope parameters: engineering parameters, especially wall thermal insulation, building orientation and external shading devices. The following sections discuss the input parameters, simulation matrix and results for each set of simulations.

6.2.2 First Parametric Study: A Comparison of the Engineering Parameters of the Building Envelope

a. Input Parameters and the Simulation Matrix

Based on the results from the monitored data which emphasised the importance of thermal insulation, the first set of simulations studied the impact of engineering parameters to determine to what extent wall thermal insulation could reduce cooling loads in Corniche Dreams Tower. In order to do this, the same methodology as in the first parametric study in Chapter 5 was followed. The selected engineering parameters were the U-value of wall and glazing, shading coefficient (SC) for glazing, and the façade glazing ratio (%). Each parameter was changed one-at-a-time with the aim of identifying the most influential parameter in relation to cooling loads for the perimeter zones in the Corniche Dreams Tower case study.

Two types of walls were selected and compared: the Unventilated Cavity Wall type (UCW), which is the existing wall type for Corniche Dreams Tower, and the better-performing Thermal Blocks Wall that follows the Estidama standard (TBW) (See also Table 5-2). The

Shadow Box Spandrel Glass wall type (SSG) was discarded since it performed worst in relation to cooling loads and solar gains, contradicting the aim of the simulation to improve energy performance. As for glazing types, the three glazing compositions with different thermal transmittance values (described in Table 5-3) were selected and compared, noting that (32 DIG) is the existing glazing type for Corniche Dreams Tower. The wall and glazing types were alternated between three glazing ratios; 20%, 40% and 60% (Figure 6-18). And even though the existing base case of Corniche Dreams Tower has 48% glazing ratio on the East and 55% on the West elevations, the glazing ratio was simplified - in terms of the name only - to 40% for the purposes of the simulation.

Moreover, further comparison was undertaken with the prescriptive compositions of the engineering parameters outlined in the local energy efficiency building regulations for Saudi Arabia (SBC 601), Dubai GBRS, and Abu Dhabi Estidama system (discussed in Chapter 3), which specified certain values of U-value and SC depending on the glazing ratio.

Following that, the matrix for the first set of simulations consisted of 23 combinations for the building envelope build-ups (Table 6-6). The base case representing the case study as built is highlighted and labelled (40-ucw-32) meaning a 40% façade glazing ratio, Unventilated Cavity Wall type and a 32mm thickness double insulated glazing make-up. The matrix also included two simulations based on the SBC 601, and three simulations following Dubai GBRS standards, each with a different glazing ratio. To represent the SBC 601 standard of a wall U-value ranging between 0.3-1.8 W/m2K, Concrete Masonry Unit (CMU) was selected in the building envelope build-up with a U-value of 1.4 W/m2K. As for Dubai GBRS, thermal wall type with U-value of 0.52 W/m2K was tested for all glazing ratios, while double insulated glazing with U-value of 2.2 W/m2K was set for the 20% glazing ratio, and double insulated glazing with U-value of 1.9 W/m2K was set for the 40% glazing ratio, as specified in the regulations.

Table 6-5 The prescriptive minimum envelope requirements in SBC 601 and Dubai's GBRS

Glazing Ratio (%)	Building codes and regulations	Roof U-value (W/m^2K)	External wall U-value (W/m^2K)	Glazing Elements		
				Shading Coefficient	**U-value (W/m^2K)**	**Visible light transmittance**
20	**SBC 601**	**0.18 – 0.2**	**0.4 – 1.8**	**0.57 – 0.8**	**2.8**	**Not specified**
	DGBRS	**0.3**	**0.57**	**0.4 (max)**	**2.1**	**0.25 (min)**
40	**SBC 601**	**0.18 – 0.2**	**0.3 - 1.4**	**0.4 – 0.8**	**2.2**	**Not specified**
	DGBRS	**0.3**	**0.57**	**0.32 (max)**	**1.9**	**0.1 (min)**
60	**SBC 601**	**Not specified**				
	DGBRS	**0.3**	**0.57**	**0.25 (max)**	**1.9**	**0.1 (min)**

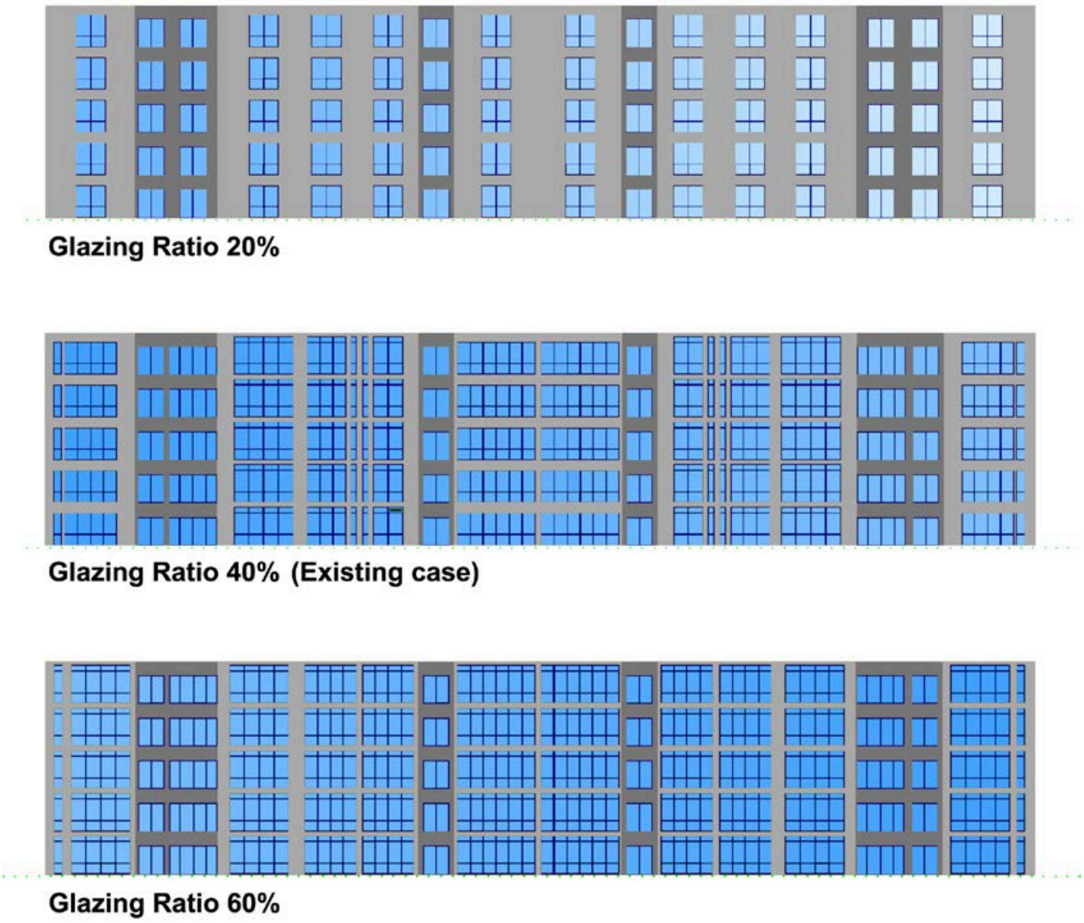


Figure 6-18 The variations of window glazing ratio for the main West façade of Corniche Dreams Tower tested in the simulation

Table 6-6 The matrix for the first set of simulations testing the engineering parameters of the building envelope for Corniche Dreams Tower. The highlighted row shows the existing base case of the tower

Glazing Ratio	Wall Type	Glazing Type	Combination	Notes
20%	Unventilated Cavity Wall (UCW)	32 mm	20-ucw-32	
		28 mm	20-ucw-28	
		26 mm	20-ucw-26	
	Thermal Blocks Wall (TBW)	32 mm	20-tbw-32	
		28 mm	20-tbw-28	
		26 mm	20-tbw-26	
	Concrete Masonry Unit (CMU)	26 mm	20-sbc 601	Saudi SBC 601
	Thermal Blocks Wall (DTBW)	24 mm	20-dtbw-24	Dubai GBRS
40%	Unventilated Cavity Wall (UCW)	32 mm	40-ucw-32	Corniche Dreams Tower
		28 mm	40-ucw-28	
		26 mm	40-ucw-26	
	Thermal Blocks Wall (TBW)	32 mm	40-tbw-32	Wall type following Estidama standard
		28 mm	40-tbw-28	
		26 mm	40-tbw-26	
	Concrete Masonry Unit (CMU)	26 mm	40-sbc 601	Saudi SBC 601
	Thermal Blocks Wall (DTBW)	24 mm	40-dtbw-24	Dubai GBRS
60%	Unventilated Cavity Wall (UCW)	32 mm	60-ucw-32	
		28 mm	60-ucw-28	
		26 mm	60-ucw-26	
	Thermal Blocks Wall (TBW)	32 mm	60-tbw-32	Wall type following Estidama standard
		28 mm	60-tbw-28	
		26 mm	60-tbw-26	
	Thermal Blocks Wall (DTBW)	24 mm	60-dtbw-24	Dubai GBRS

b. Energy Performance Results

A total of 23 sets of simulations were conducted comparing four wall types, four glazing type build-ups, and three glazing ratios to the existing base case scenario (40-ucw-32). Following the same analysis techniques as in Chapter 5, the best and worst combinations of glazing ratio, wall and glazing type were identified in order to understand the most influential parameter impacting the cooling energy loads in Corniche Dreams Tower. The output metric to express the results was the annual cooling load per square metre of floor area (kWh/m^2).

Figure 6-19 compares the total annual cooling loads for the perimeter zones in Flat 3 and 4 for all the 23 sets of simulations. Both flats acted similarly in relation to the worst and best combination, with a difference of up to 15% between the two flats, which was expected since Flat 4 is slightly larger and is exposed to the south as well as to the west and east. As in the results in Section 5.3.3, the insulated thermal blocks wall following Estidama standards represented in the combination (20-tbw-32) performed best due to the excellent thermal performance of the wall type in addition to the low glazing ratio (20%) and lower shading coefficient (0.23) in the glazing type. Meanwhile the combination (60-ucw-26) that consisted of un-insulated air cavity wall type (UCW) with 60% glazing ratio and higher shading coefficient (0.51) in the glazing type performed worst. Comparing the base case of Corniche Dreams Tower (40-ucw-32) with the other cases by changing one building envelope parameter at a time revealed that adding thermal insulation to the external walls (40-tbw-32) could improve cooling loads reduction by 10%. Furthermore, decreasing the glazing ratio (20-ucw-32) could reduce cooling loads by 22%, and improving the SC of the glazing type could significantly reduce cooling loads by 28%.

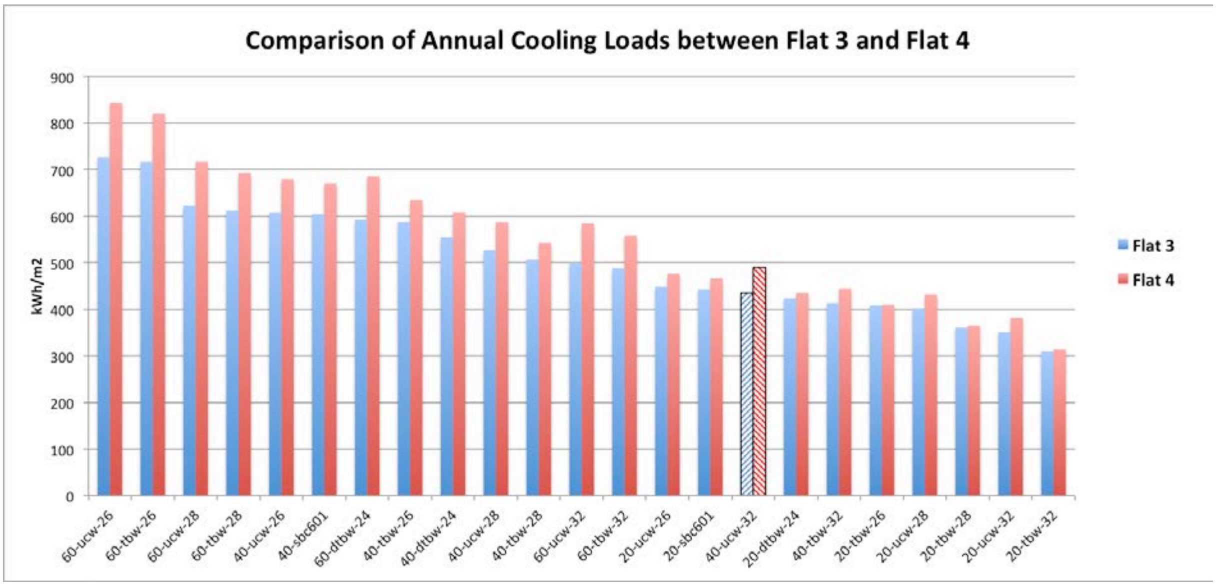


Figure 6-19 Comparison of the total annual cooling loads for the perimeter zones in Flat 3 and 4, showing the worst and best performing base case in relation to cooling loads. The existing base case (40-ucw-32) is marked differently.

After determining the best and worst building envelope combinations in relation to the total annual cooling loads for the perimeter zones in Flat 3 and 4, the second analysis focused on comparing the energy performance of the different perimeter zones. Figure 6-21 and 6-22 illustrate that the West bedroom in both Flat 3 and 4 performed best in relation to annual cooling loads in all the simulated base cases, regardless of the difference in the engineering parameters of the building envelope. This could be due to the smaller exposed wall area and glazing percentage in comparison to the other zones (as shown in Figure 6-17 and Table 6-4). On the other hand, the West sitting room in Flat 3 performed worst due to the larger exposed wall area in relation to the floor area. As for Flat 4, the Southwest main sitting room and Southeast bedroom performed worst as both zones are exposed to two different orientations with a larger exposed area and glazing ratio on both sides. These findings are further explored in relation to heat gains in the coming paragraphs. Please note that even though the graphs in the figures are complex and difficult to read in detail, their intention is to establish and understand the trend of the energy performance in the analysed zones rather than to focus on the detailed numbers.

In order to understand the most significant engineering parameter impacting the thermal performance of Corniche Dreams Tower, the results were then analysed in relation to solar gains and external conductive gains through the opaque and glazing elements for the 23 sets of simulations, the five perimeter zones in Flat 3 and the six perimeter zones in Flat 4.

Comparing the heat gains through the building envelope for the 20% base cases (Figure 6-22) showed that since the solar heat gain was minimal due to the small glazing ratio, the conductive heat gains through the unventilated cavity wall (UCW) were the highest contributor to cooling loads. However, in the cases of glazing types with higher SC (28 and 26 glazing types), solar gains surpassed conductive heat gains through opaque walls. In the cases of thermal blocks wall type (TBW), the wall insulation reduced the conductive heat gains, therefore, the solar gains were, relatively, the highest contributors despite the small glazing ratio. As for the 40% base case (Figure 6-23), solar gains were the highest contributor to cooling loads in all cases except those with the glazing type (32), which has the lowest SC specifications. This emphasised that lower SC for glazing can significantly reduce solar gains and consequently cooling loads even for higher glazing areas. On the other hand, in the 60% base cases (Figure 6-24), solar gains were the highest due to the larger glazing ratio as was expected. However, in the cases of glazing type (32), although the lower SC specifications reduced solar gains, the higher U-value resulted in higher conductive heat gains through the glazing which contributed to the cooling loads of the zones.

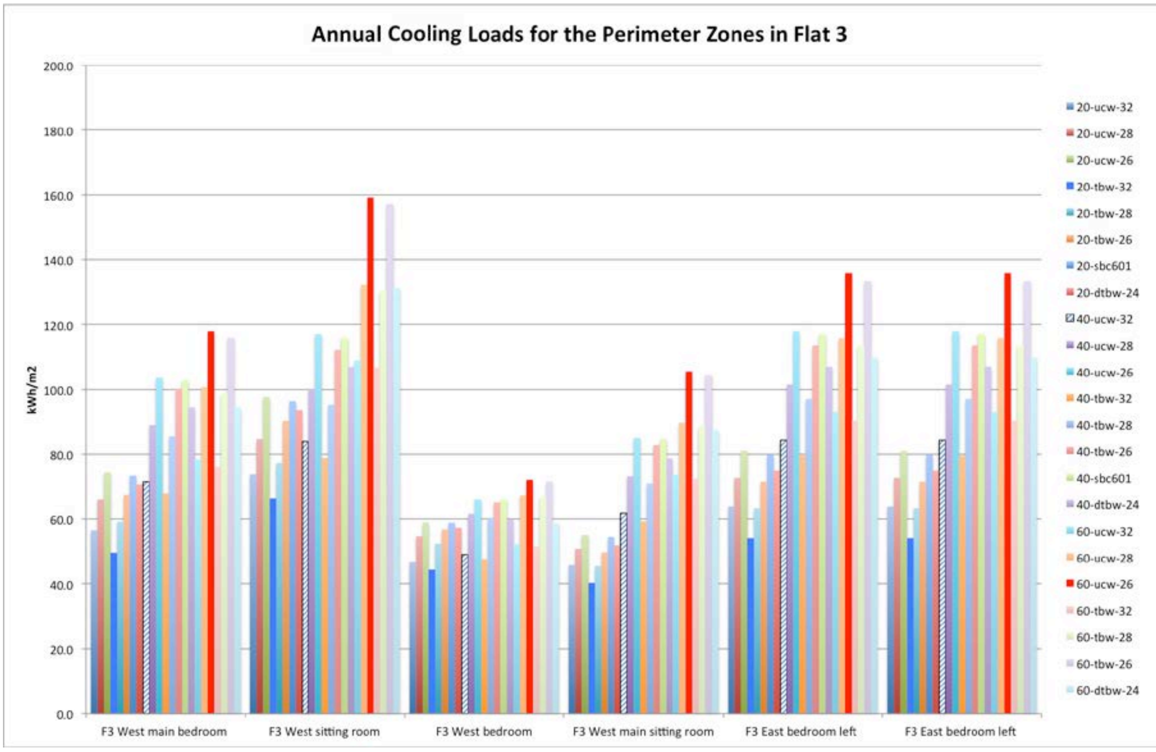


Figure 6-20 The results for the energy performance simulation for the different zones and orientations in Flat 3. Note the best case (in blue), worst case (in red) and the existing base case of Corniche Dreams Tower (marked)

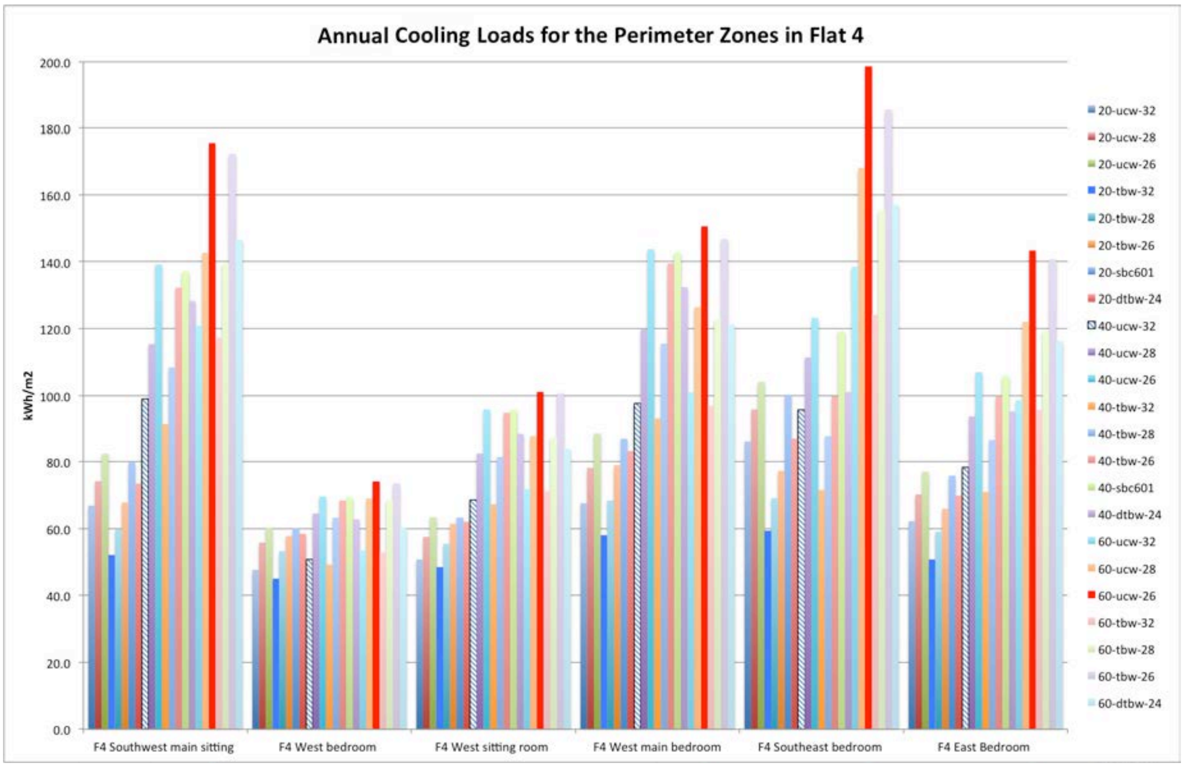


Figure 6-21 The results for the energy performance simulation for the different zones and orientations in Flat 3. Note the best case (in blue), worst case (in red) and the existing base case of Corniche Dreams Tower (marked)

After comparing all the simulated combinations, and since the aim of this first parametric study was to determine to what extent cooling loads could be reduced in Corniche Dreams Tower, the existing case study (40-ucw-32) was further analysed (Figure 6-23). Focusing on the worst performing zones in relation to cooling loads, the heat gains analysis for Flat 3 showed that the conductive heat gain through the external opaque and glazing wall elements contributed most to the higher cooling loads in the West sitting room, even with added thermal insulation in the (40-tbw-32) case. This confirmed the impact of the larger exposed wall area in relation to the floor area as mentioned earlier. As for Flat 4, solar gains were highest in the Southwest main sitting room due to the large glazing ratio of both the west and south facing walls, which exceeded 50% on both sides. Meanwhile in the Southeast bedroom, the conductive heat gain through the opaque walls was higher. However, adding wall thermal insulation significantly reduced the conductive heat gains in the case (40-tbw-32) (Figure 6-23). Nevertheless, solar gains were still the highest contributor to increased cooling loads in all the perimeter zones.

Further to that, the existing case study of Corniche Dreams Tower was compared with the base cases that followed the local energy efficiency building regulations. The analysis of this comparison showed that the annual cooling loads in the case (40-tbw-32) were reduced by 10% as a result of insulating the external walls following Estidama standards, thereby reducing the conductive heat gains through the building envelope. However, the cases (40-sbc601) and (40-dtbw-24) performed worse than the existing case study in relation to annual cooling loads (Figure 6-22) as a result of the much higher solar gains due to the higher SC values in the glazing types that met the minimum building envelope requirements of Dubai GBRS and Saudi SBC 601.

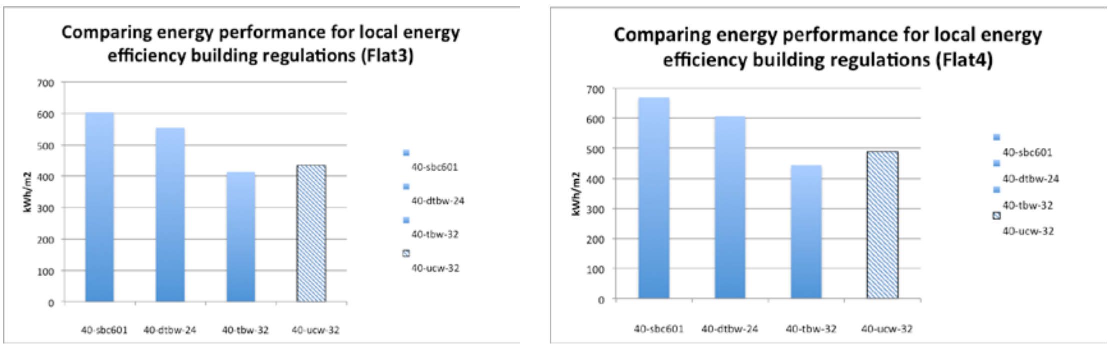


Figure 6-22 Comparing the existing case study of Corniche Dreams Tower (40-ucw-32) with the base cases that followed the local energy efficiency building regulations in relation to annual cooling loads

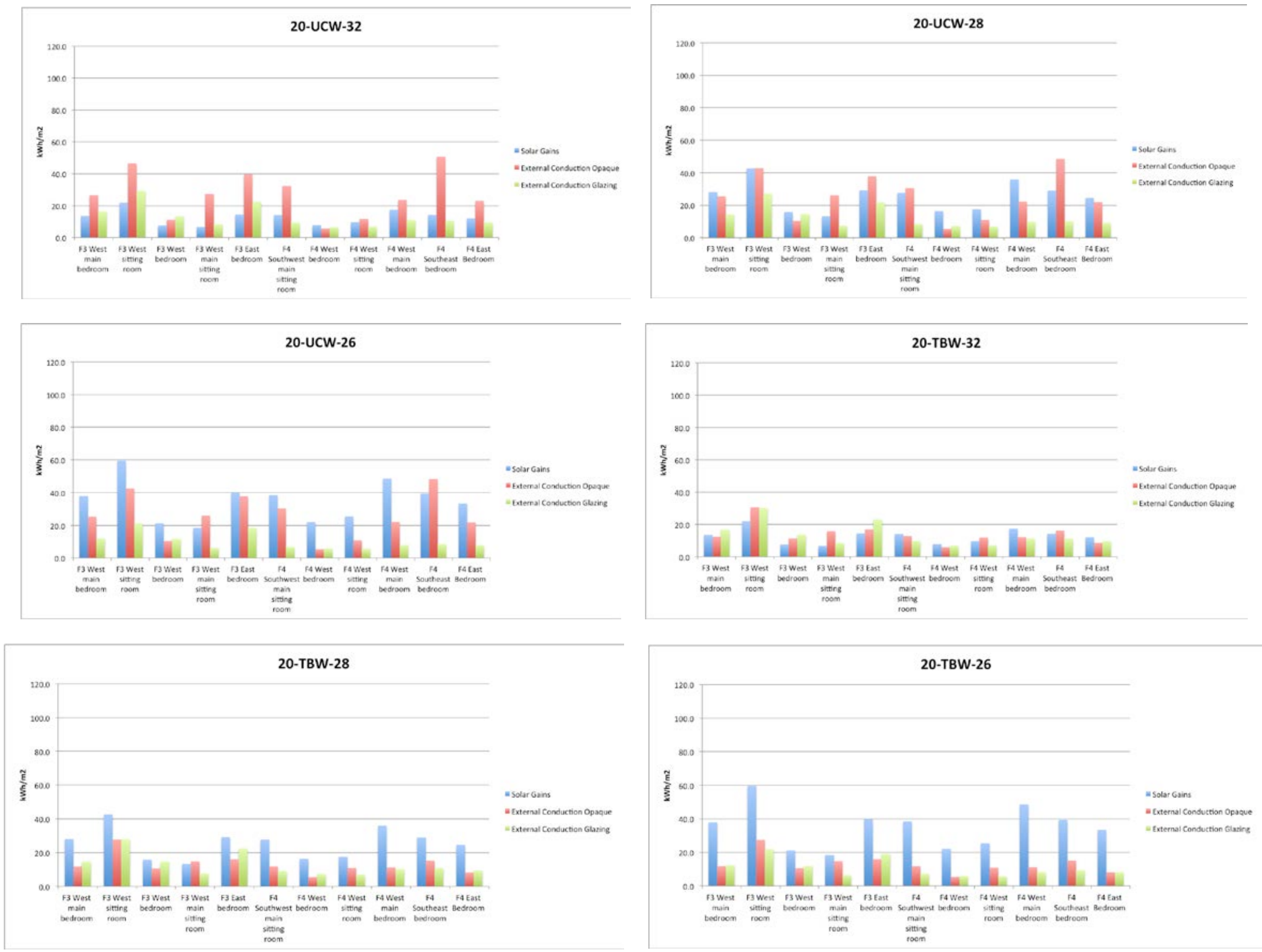


Figure 6-23 Heat gains through the building envelope for the 20% glazing ratio and different glazing and wall type combinations in the perimeter zones in Flat 3 and 4 in Corniche Dreams Tower

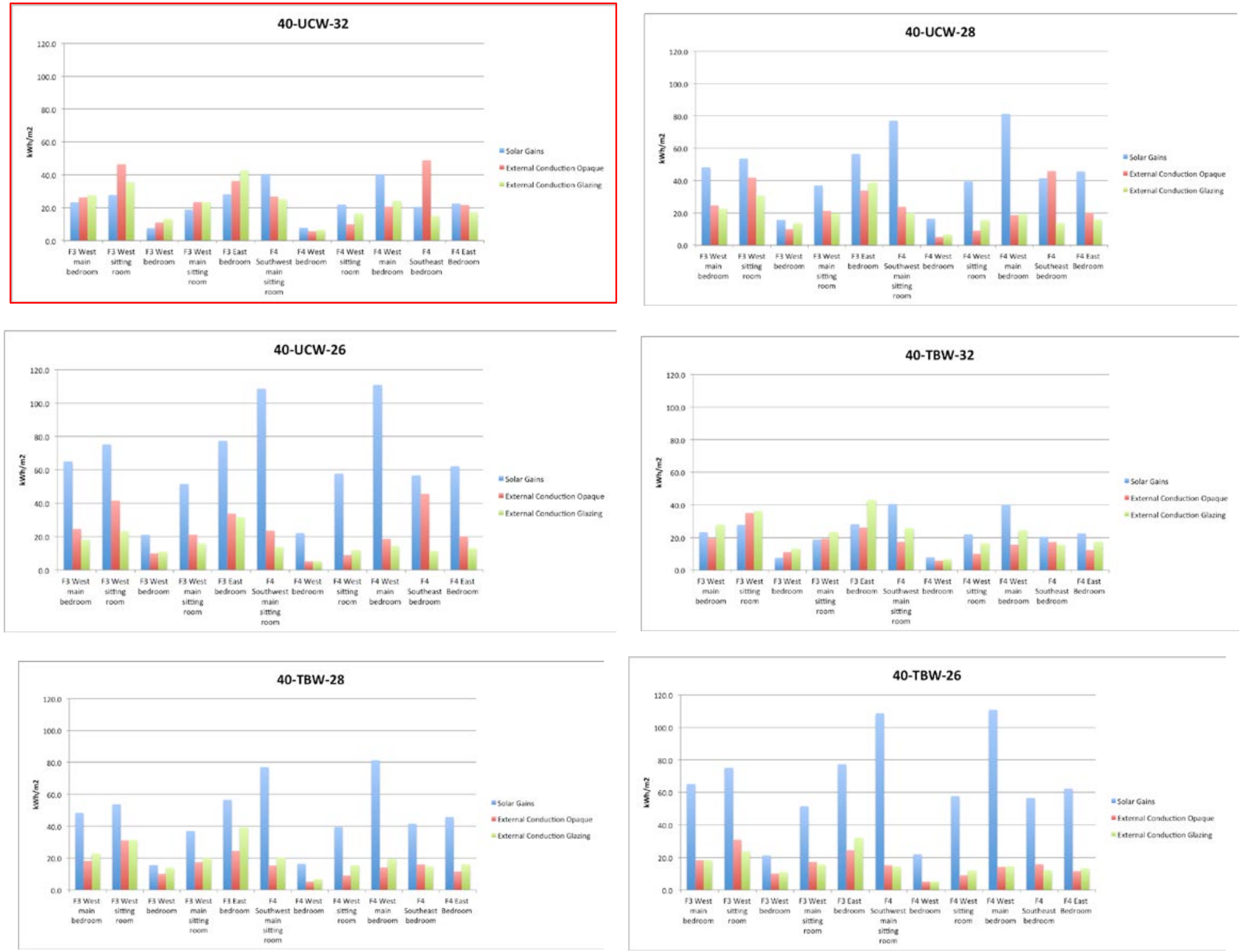


Figure 6-24 Heat gains through the building envelope for the 40% glazing ratio and different glazing and wall type combinations in the perimeter zones in Flat 3 and 4 in Corniche Dreams Tower

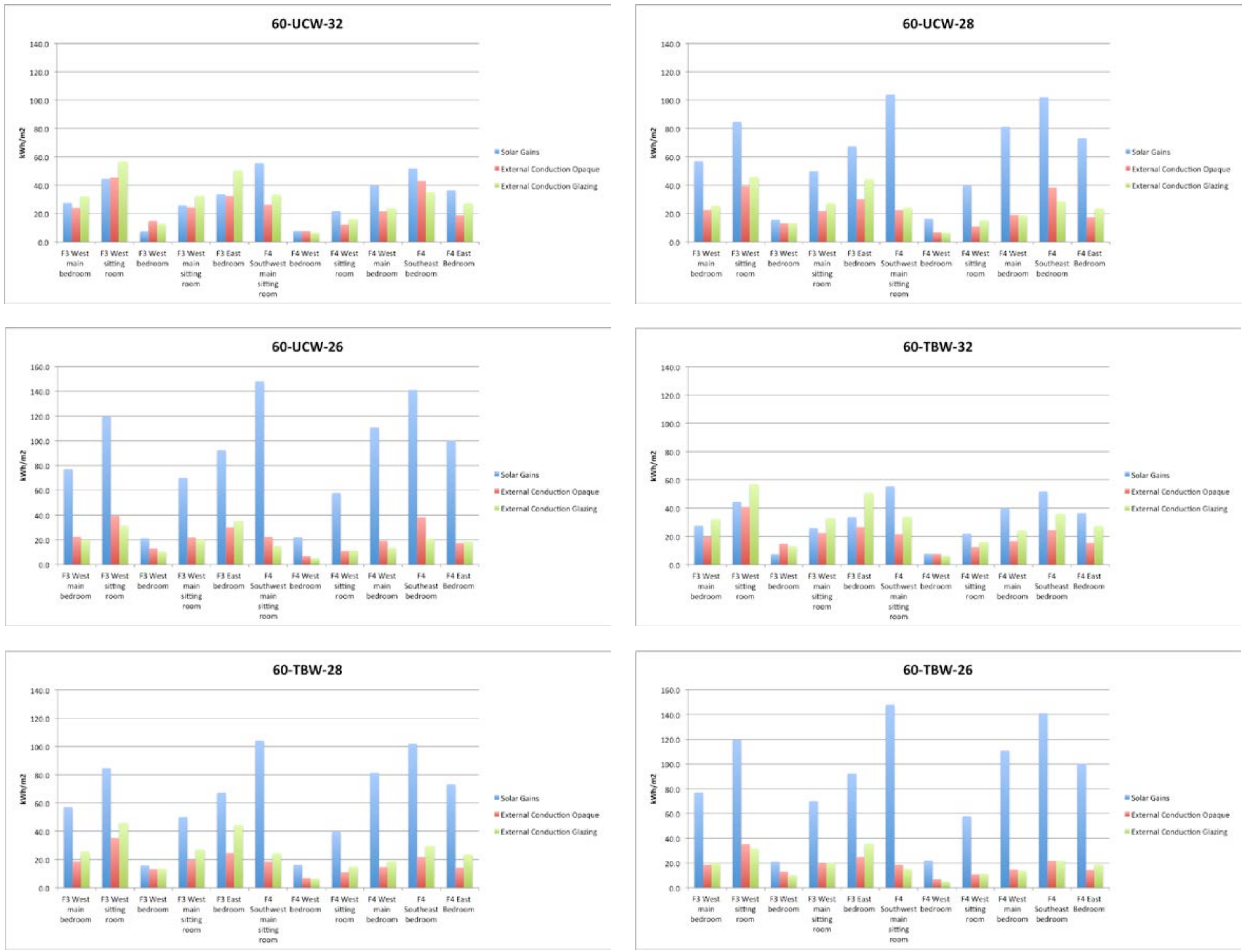


Figure 6-25 Heat gains through the building envelope for the 60% glazing ratio and different glazing and wall type combinations in the perimeter zones in Flat 3 and 4 in Corniche Dreams Tower

In conclusion, the results of this first set of simulations indicated the following:

- In general, solar gains are the highest contributor to heat gains, which is directly linked with larger glazing ratios and higher SC. However, even in cases with smaller glazing ratios, higher SC will produce higher solar gains. Therefore, the SC for glazing is the main influencing parameter in relation to cooling loads.
- Conductive heat gains through opaque walls increase notably where the ratio of exposed wall to floor area is large or the zones have exposed walls on two orientations; hence, further considerations should be given to thermal insulation.
- Adding thermal insulation for the external walls can reduce cooling loads by 10%, while glazing ratios can impact cooling loads by more than 20%. However, improving the SC of the glazing type can reduce cooling loads by nearly 30%.
- In relation to the existing building envelope parameters of Corniche Dreams Tower, the glazing type with lower SC considerably reduced solar gains and cooling loads. Furthermore, the thermal performance of the un-insulated external walls was slightly improved by adding insulation following the Estidama standards.
- Regardless of the low SC of the glazing type, the south and west facing zones received the highest solar gains; therefore, further investigation of the impact of building orientation follows in the next section.

6.2.3 Second Parametric Study: Investigating the Impact of Building Orientation on Cooling Loads

The previous set of simulations investigated the impact of the engineering parameters of the building envelope on the energy performance in Corniche Dreams Tower, concluding that a reduction of 10% in cooling loads could be achieved by adding thermal insulation to the external walls. However, the parametric study also showed the crucial role of solar gains in increasing the cooling loads, thereby emphasising the need for further design considerations to minimise solar gains through the glazing elements of the building envelope.

Based on those findings, and since the aim of these parametric studies was to determine to what extent combining both engineering and design parameters could improve the energy performance of Corniche Dreams Tower, two additional parametric studies using thermal simulations were conducted to test the impact of the design parameters of the building envelope. One study focused on building orientation while the other explored the effectiveness of external shading devices. The following sections explain the input parameters and results analysis of those two parametric studies.

a. Input Parameters

As discussed in Section 5.4.1, the year-round high solar altitude in Jeddah combined with the apparent daily movement of the sun from east to west has resulted in east and west orientations receiving high solar radiations (especially in warmer seasons) while north and south orientations receive much less. Moreover, in the case of Corniche Dreams Tower, the long axis of the building orientation runs from north to south with the main elevation facing west towards the Red Sea. Hence, the main zones with large glazing ratios face either west or east, resulting in higher solar gains which have a negative impact on the building's energy efficiency, as shown in the results of the previous parametric study.

It is well documented in the literature that the two most common methods to resolve solar overheating in hot climates are often broken down into building orientation and shading controls (Kiamba, 2016). Both methods are considered to be design parameters based on Baker and Steemers (1996) categorisation of the building factors that influence energy use, since they interact with other parameters and have an impact on both the form and performance of the building.

Based on those considerations, the second parametric study focusing on building orientation aimed to test the impact of changing the main axis of Corniche Dreams Tower on heat gains and cooling loads. In the simulation, the long north-south axis was turned 90^{o} to run from east to west instead (Figure 6-26). Thus, all the main perimeter zones facing east and west became north and south facing, which is the recommended building orientation to reduce solar heat gains. Consequently, in this simulation, the west facing zones have become north facing, while the east zones now face south (refer to Figure 6-17 and 6-27). This is the only parameter that was different from the previous simulation; all the estimated assumptions concerning the building envelope and the internal conditions remained the same.

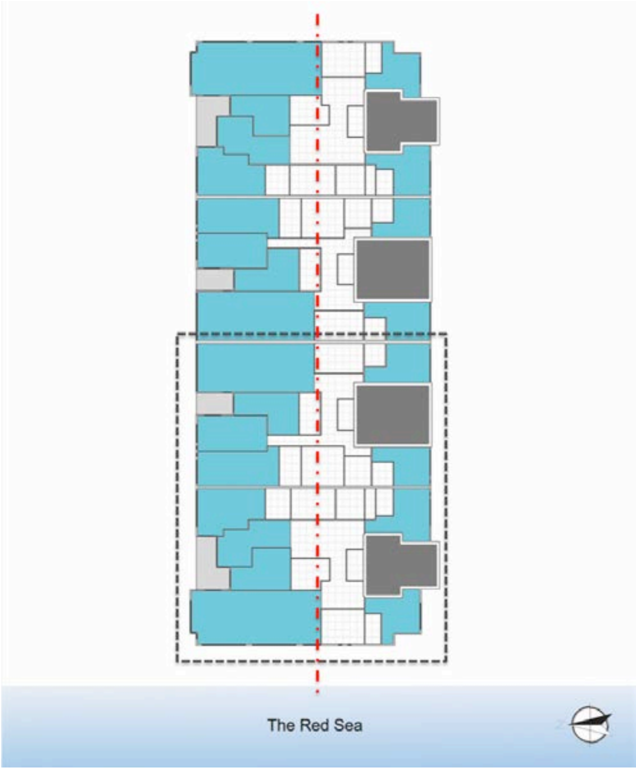


Figure 6-26 The new orientation of Corniche Dreams Tower with the long axis running from east to west and the main elevation facing the north (refer to Figure 6-16)

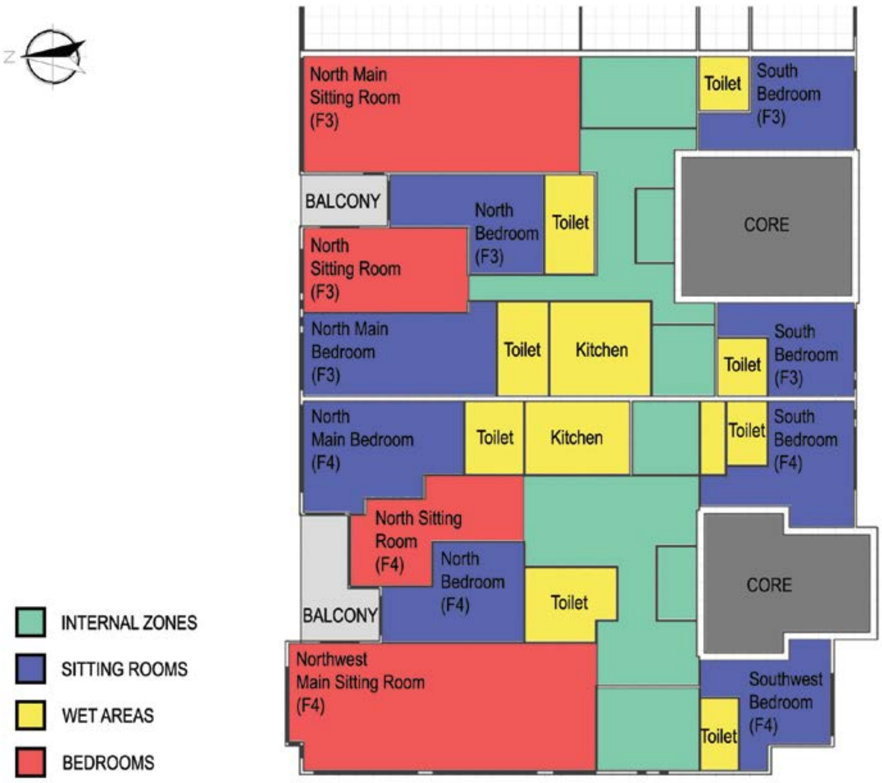


Figure 6-27 The selected perimeter zones (sitting rooms and bedrooms) in Flat 3 and 4 as they appear in the new orientation (refer to Figure 6-17)

b. Energy Performance Results

Since the aim of this second parametric study was to determine the impact of changing the building orientation on the energy performance of Corniche Dreams Tower, the results of the simulations were first analysed in relation to cooling loads and heat gains for Flat 3 and 4. Generally, changing the orientation of Flat 3 and 4 from facing east and west to facing north and south resulted in around 16% reduction in the total annual cooling loads. While solar gains were reduced by 20%, conductive heat gains fell by more than 50% in total.

In order to further understand the impact of orientation in each perimeter zone, Figure 6-28 and Table 6-7 compare the cooling loads and display the percentage difference in heat gains for each zone in Flat 3 and 4 for both orientations. Note that the West main bedroom in the original case study has changed to become the North main bedroom, and so on. Also, the black font percentage shows the percentage improvement in energy performance while the red font indicates a decline in performance.

The graph in Figure 6-28 shows that cooling loads in the perimeter zones in Flat 3 were more efficient than the zones in Flat 4, especially the north facing zones. For example, the cooling loads of the West Bedroom, the worst performing zone in the previous simulation, improved by more than 20% with a 47% reduction in solar gains. The table reveals that this was due to the significant reduction in external conductive heat gains through both opaque and glazing elements since much less solar radiation fell on the north facing surfaces than on the west façade, which reduced the surface temperature and, consequently, the heat gains through the building envelope (refer to Figures 5-18, 19, 20 and 21). By contrast, the worst performing zone in Flat 4 (the Southwest main sitting room that changed to face the northwest) experienced only a marginal improvement in relation to cooling loads and heat gains. Meanwhile, the South and Southeast bedrooms, which were turned to face south and southwest, performed worse in relation to cooling loads due to an increase in solar gains of more than 15% (highlighted in red in Table 6-7).

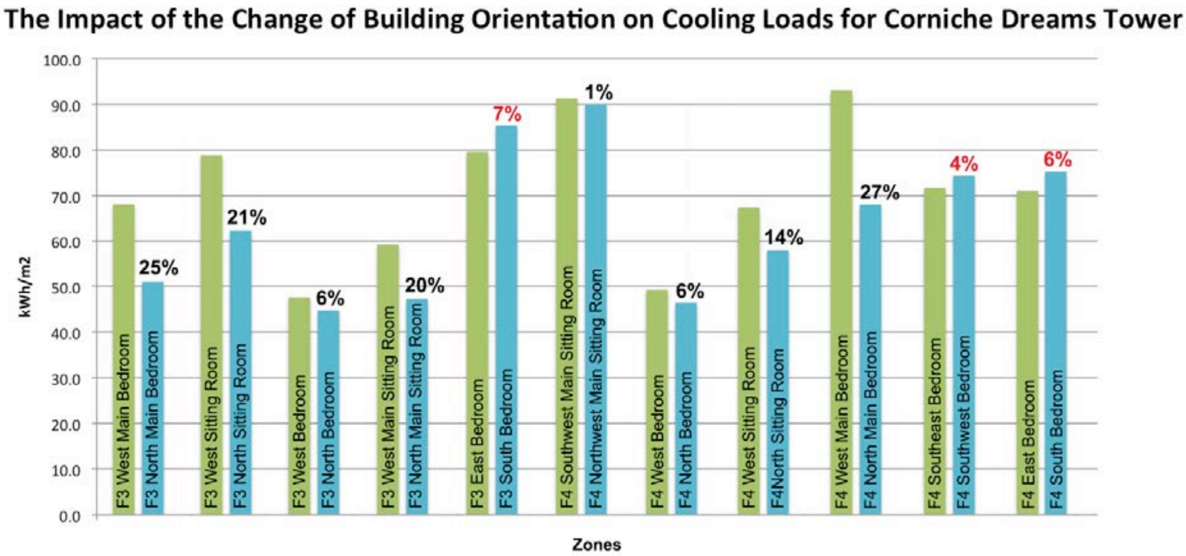


Figure 6-28 Comparing the impact of changing the orientation of Corniche Dreams Tower. The black font reflects a positive impact in relation to decreased cooling loads, while the red font highlight worsening energy performance

Table 6-7 The percentage of difference between the east-west orientation and the north-south orientation for the perimeter zones in Corniche Dreams Tower. Note that the red percentage denotes a worse performance than the original orientation

	Zones	Solar gains	Opaque conductive gains	Glazing conductive gains
F3	West main bedroom[36]	57%	68%	65%
	North main bedroom[37]			
	West sitting room	47%	60%	62%
	North sitting room			
	West bedroom	18%	52%	53%
	North bedroom			
	West main sitting room	54%	62%	64%
	North main sitting room			
	East bedroom	19%[38]	44%	47%
	South bedroom			
F4	Southwest main sitting room	3%	4%	4%
	Northwest main sitting room			
	West bedroom	23%	6%	7%
	North bedroom			
	West sitting room	36%	14%	15%
	North sitting room			
	West main bedroom	52%	29%	26%
	North main bedroom			
	Southeast bedroom	14%	7%	3%
	Southwest bedroom			
	East bedroom	18%	10%	6%
	South bedroom			

In conclusion, rotating the axis of Corniche Dreams tower 90° to achieve the recommended orientation for the hot climate of Jeddah notably decreased the heat gains for the internal flats, especially with the main zones facing north instead of west. However, the outer edge

[36] The green rows show the original north-south orientation.
[37] The blue rows show the new east-west orientation.
[38] The red font highlights the worse performing zones.

flats that changed to face west, north and south instead of south, east and west, did not benefit much from the change of orientation and the corner zones actually performed worse than in the original orientation.

Ultimately, building orientation should be determined during the early stages of the design process, influenced by factors such as plot location, road layout and view requirements (Kiamba, 2016). In the case of Corniche Dreams Tower, these factors have overridden those of solar control, especially the views toward the Red Sea. Hence, the use of external shading is deemed necessary. The third set of simulation looked at the option of applying external shading devices to reduce solar gains and cooling loads.

6.2.4 Third Parametric Study: Investigating the Impact of External Shading Devices on Cooling Loads

After defining the role of thermal insulation, as an engineering parameter, and building orientation, as a design parameter, in reducing heat gains and cooling loads for residential tall buildings in the hot climate of Jeddah, further investigation was conducted to determine to what extent combining both engineering and design parameters can improve energy efficiency. In order to explore this, the base case (40-tbw-32) was chosen for the thermal simulation since the wall type is insulated following the Estidama standards which improved the engineering parameter of the building envelope. As for the tested design parameter, external shading devices were applied to the glazing elements of the building envelope.

The following sections explain the input parameters and the analysis of the results for the third set of simulations.

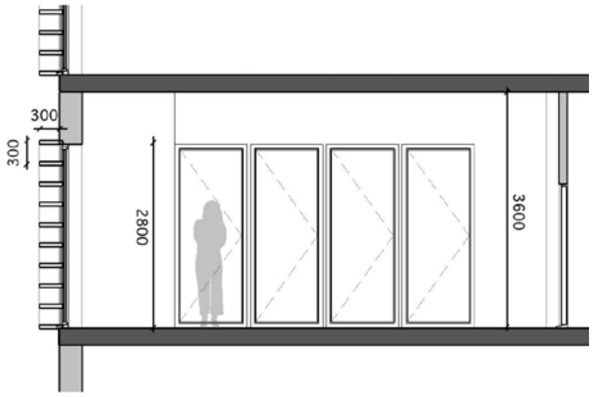
a. Input Parameters and the Simulation Matrix

The selection and design of shading devices depends on aspects such as location, local climatic conditions, building orientation, characteristics and form. In this parametric study, the design of the shading devices for Corniche Dreams Tower was based on the main findings and followed the same methodology as in Chapter 5, since the location, latitude, climatic conditions and building engineering characteristics were the same for both base cases. First, the types of the shading devices were selected according to orientation: vertical fins of various depths for east and west facing orientations and egg-crates for south facing façades. Second, the depths of the external shading devices were calculated following the methodology set out by Cho et al. (2014), which set up the alternatives for the shading devices using Equations 5-1 and 5-2 (See Section 5.4.1), considering the window areas of the case study of Corniche Dreams Tower and using the vertical shadow angle (ε) and horizontal shadow angle (δ) for the four key dates (Summer Solstice, Winter Solstice, Spring Equinox and Autumn Equinox) as stated in Table 5-6.

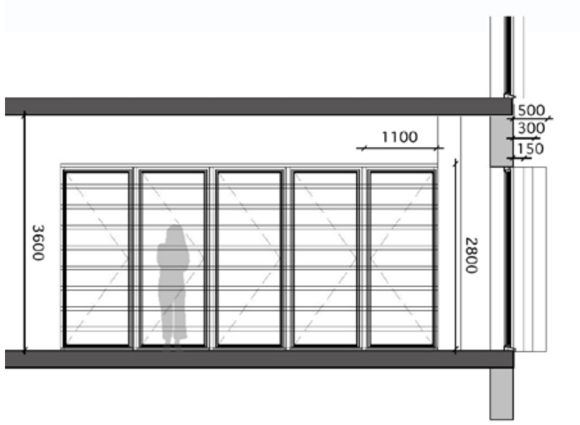
Following that, the depth of the vertical fins (D_V) and horizontal overhangs (D_H) for the South egg-crate shading devices was set using the vertical and horizontal shadow angles for the Spring Equinox (March 21) since the highest radiation was recorded during this season. Meanwhile, the vertical shading fins proposed for the East and West façades considered the Spring Equinox horizontal shadow angle between 7am-1pm for the East façade, and the Spring Equinox horizontal shadow angle between 1-6 pm for the West façade. As for the window area considered in the equations, the challenge was that the windows for Corniche Dreams Tower were of different widths and heights; however, the difference in calculations was not significant and therefore it was discarded in the matrix. Furthermore, the results of the equations for the depth of the shading devices that exceeded 0.5m were also excluded since they were judged to have a negative aesthetic and structural impact.

Eventually, the same depths for the shading devices used in Chapter 5 were selected for the shading simulation matrix in this parametric study: egg-crate shading devices with a fixed depth of 0.3m were modelled for the South façade and vertical fins to the left and right of the window with varying depths (0.15m, 0.3m and 0.5m) were installed on the East and West façades, as shown in Figure 6-29. As for the simulated model, the base case (40-tbw-32) was chosen (as mentioned above) with all the assumptions remaining the same to allow for a clear interpretation of the impact of the external shading devices on cooling loads.

Based on the above-mentioned design considerations for the external shading devices for Corniche Dreams Tower, the third set of simulations included four sets of simulations comparing the base case (40-tbw-32) with the three different shading device depths on the West and East façades (Table 6-8). The results of these simulations are compared and analysed in the next section.



Egg-crate shading for the south orientation



Vertical shading fins on the left and right with varying depths for the east and west orientation

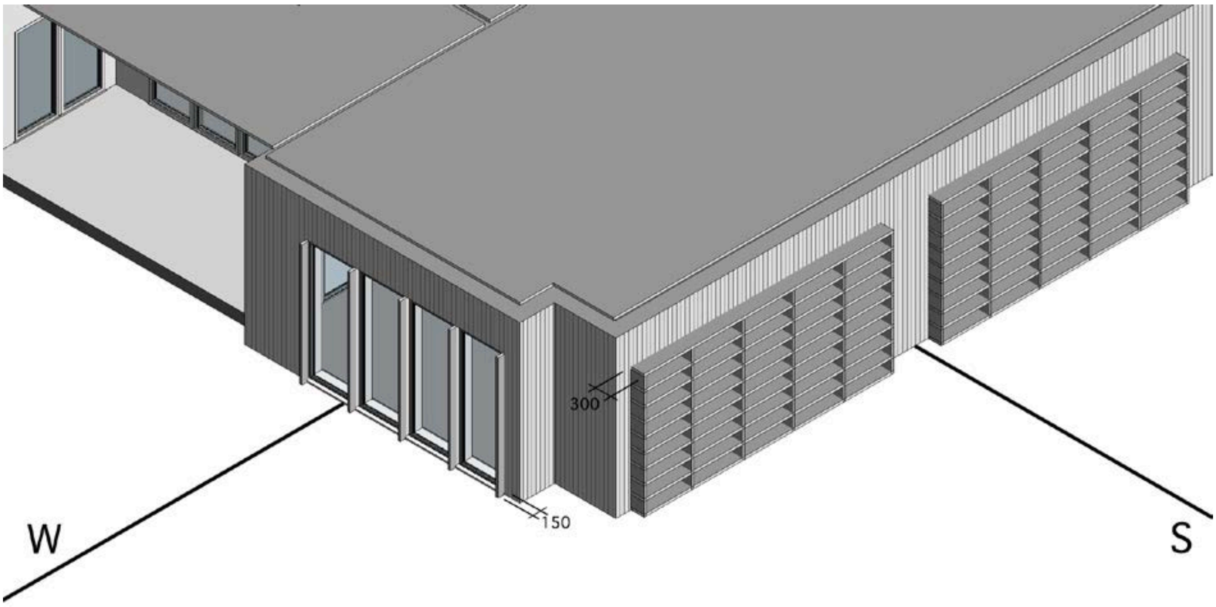


Figure 6-29 The shading configurations used in the third set of simulation for Corniche Dreams Tower (dimensions in mm)

Table 6-8 The matrix for the third set of simulations testing shading devices as a design parameter for the building envelope of Corniche Dreams Tower

Base case	Configuration
40-tbw-32	No shading
	(15-15)
	(30-30)
	(50-50)

b. Energy Performance Results

In order to define the impact of external shading devices on the energy performance of Corniche Dreams Tower, the results of the simulations were first compared and analysed in relation to the reduction in cooling loads and solar gains. This showed a reduction of up to 8% in the annual cooling loads when shading was applied as a result of up to 20% reduction in solar gains. The results also showed the increased efficiency of the shading devices with the increased depths of the vertical fins, as was expected. However, an increase in the depth of the vertical fins of 70% would be required to reduce solar gains by 50%, which means using large and deep external shading devices that might restrict the views from within the building and compromise the external appearance of the building façade.

Next, the reduction in cooling loads and solar gains was compared across the perimeter zones for Flat 3 and 4 in order to determine which orientation benefited most from the external shading devices (Figure 6-30). Focusing on the worst performing zone from the previous simulations, the results showed that solar gains were reduced by 16% in the West sitting room in Flat 3. However, compared to the other zones in the flat, this room still performed worst, especially as solar gains were reduced by nearly 30% in the East facing bedrooms. As for Flat 4, the worst performing zones - the Southwest main sitting room and the Southeast bedroom - benefited most from applying vertical fins on the East and West façades and egg-crate devices on the South façades, with solar gains reduced by more than 20% in each zone. Overall, the results emphasised that the impact of shading devices was more substantial on the south and east orientation, while the west zones were least affected in relation to cooling loads reduction. Furthermore, the reduction was most visible when using the 50cm deep vertical fins, while the smaller fins had a minimum impact of 2-3% only.

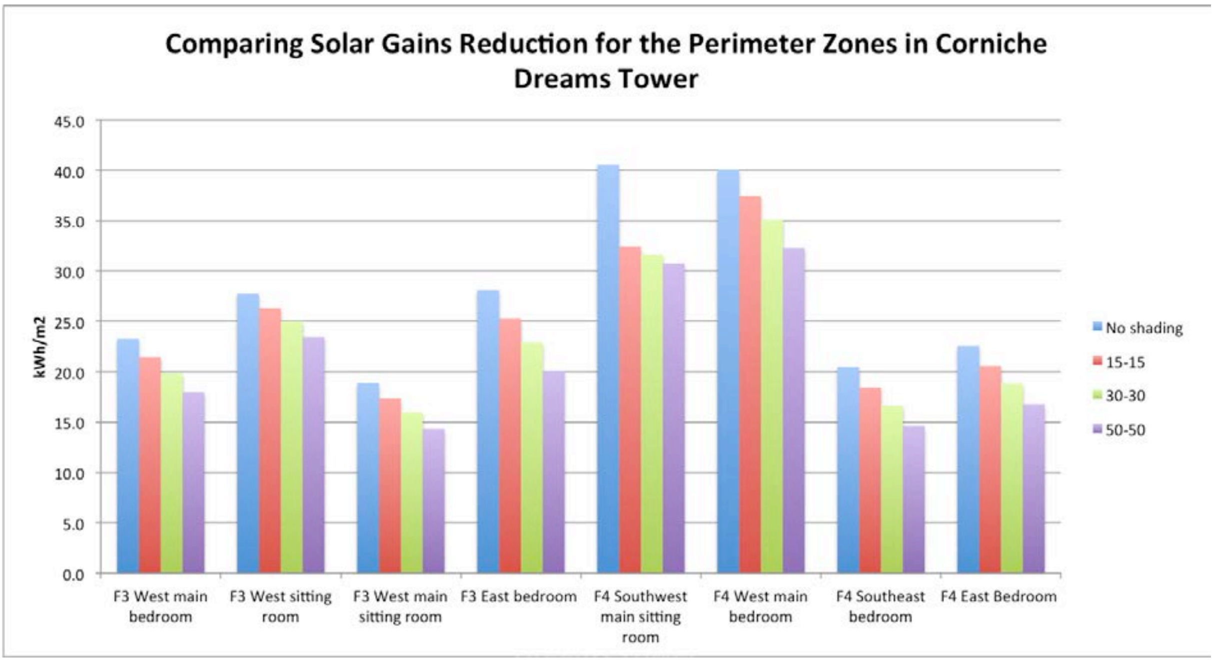


Figure 6-30 Comparing the solar gains reduction in the main perimeter zones in Corniche Dreams Tower for the tested base cases with different shading devices of different depths

In conclusion, comparing the reduction in cooling loads and solar gains for both design strategies (change of orientation or shading devices) revealed that in the case of Corniche Dreams Tower, changing the orientation by 90^{o} had a more significant impact on the west facing zones since they became north facing, which is the preferred orientation in such a climate. On the other hand, the east and south zones benefited most from applying shading devices with nearly 30% reduction in solar gains, especially when using the 50cm deep vertical fins on the East and West façades.

Table 6-9 Comparing the percentage of solar gains reduction between the existing case study with no shading and the three tested shading device depths in the main perimeter zones in Corniche Dreams Tower

The main perimeter zones	15-15	30-30	50-50
F3 West main bedroom	8%	15%	23%
F3 West sitting room	5%	10%	16%
F3 West main sitting room	8%	15%	24%
F3 East bedroom	10%	19%	29%
F4 Southwest main sitting room	20%	22%	24%
F4 West main bedroom	7%	12%	19%
F4 Southeast bedroom	10%	19%	29%
F4 East bedroom	9%	17%	26%

6.3 Conclusion

This chapter aimed to test the hypothesis developed in the previous chapter regarding the integration of the engineering and design parameters of the building envelope as a design strategy to achieve energy efficiency in tall buildings. In order to attain this aim, a representative case study of an existing residential tall building in Jeddah, Corniche Dreams Tower, was chosen, and three parametric studies through dynamic building simulation were conducted to evaluate and compare the impact of both engineering and design parameters on the thermal and energy performance of the case study.

The first parametric study explored to what extent relying on the engineering parameters could reduce cooling loads and compared the performance of the building envelope of the existing case study with that of the prescriptive composition of the engineering parameters outlined in the local energy efficiency building regulations. The results of the study showed that a reduction of up to 10% of cooling loads could be achieved by adding thermal insulation to the building envelope. The results also emphasised the fact that solar gains through the building envelope were the highest contributor to cooling loads, especially for the south and west orientations. These results formed the basis for two further parametric studies that aimed to investigate the impact of building orientation and external shading devices on reducing solar gains.

Next the existing base case with added thermal simulation was further tested to determine to what extent combining both engineering and design parameters could improve the energy performance of Corniche Dreams Tower. The second parametric study focused on the energy impact of rotating the main axis of the building from a north-south orientation to an east-west orientation; this significantly decreased the heat gains, notably in the main zones which had been west facing but now faced north. However, the south and east facing zones required further design consideration in order to reduce solar gains and cooling loads, leading to the application of external shading devices on the east, west and south facing zones in the third parametric study.

The third study compared the modified existing case study with three alternatives of shading devices including fixed egg-crate shading devices on the south façade and vertical fins of varying depths on the windows facing east and west. The results showed the positive effect of shading devices in reducing solar gains on the south and east orientations, especially when the larger 50cm deep vertical fins were applied.

Ultimately, in the case of Corniche Dreams Tower, the engineering parameters of the building envelope could be improved through the use of thermal insulation for the external walls following Estidama standards. Moreover, installing shading devices on the East, West and South façades could further improve energy efficiency and reduce solar gains. However, significant enhancement could only be achieved by using deep shading devices; these might impact the building façades aesthetically and structurally from one side, and impede the views across the Red Sea from the other side. However, the building orientation proved to have the most substantial impact in terms of improving energy efficiency and reducing cooling loads and solar gains, underlining the importance of considering these matters at the early stages of the design process.

In conclusion, the main findings from this chapter suggest that combining both engineering and design parameters of the building envelope can be an effective way to achieve energy efficiency in residential tall buildings in the hot humid climate of Jeddah. However, as mentioned in Chapter 2 and 3, such an approach should be carefully integrated from the early stages of the design process. Moreover, comparing the specifications in local energy efficiency building regulations with residential tall building practice in the region revealed major areas for improvement, especially for the Saudi SBC 601, as following the prescriptive compositions of the engineering parameters outlined in the regulations led to worse energy performance results than those of the existing case study, Corniche Dreams Tower.

Finally, this chapter established the crucial role of building orientation in achieving energy efficiency in residential tall buildings. Based on that, the next chapter introduces a method that helps designers in the early design stages to choose the most appropriate engineering and design parameters for the building envelope, considering the environmental requirements for each façade orientation while also addressing the specific challenges of this desirable Jeddah location in relation to sea views and marketing demands.

CHAPTER 7: Energy Efficiency Strategies for Building Envelope Design

This chapter is based on the findings of the previous chapters that emphasised the importance of integrating both the engineering and design parameters of the building envelope in order to reduce solar gains and achieve energy efficiency in residential tall buildings in Jeddah, Saudi Arabia. In order to draw meaningful recommendations from those findings, a set of energy efficiency strategies is proposed incorporating a comparative tool to help designers make informed decisions regarding the building envelope in the early stages of the design process. This chapter aims to fulfil the main outcome of this work by describing how the proposed energy efficiency strategies could serve to enhance the effectiveness of local energy efficiency building regulations in Saudi Arabia.

Chapter 7 Energy Efficiency Strategies for Building Envelope Design

"My purpose in writing this book is to help architectural designers who are not energy experts understand the energy consequences of their most basic design decisions and to give them information so that they can use energy issues to generate form rather than simply as limits that must be accommodated."

G. Z. Brown and Mark DeKay in their book, 'Sun, Wind & Light: Architectural Design Strategies', 2001, p. xvi

This study has been focused around the development and adaptation of the local building codes and standards as a key tool to reduce energy use and improve the energy efficiency performance of residential tall buildings, especially in the hot Gulf region and in Saudi Arabia in particular. One of the main aims of this work was to contribute to the energy efficiency regulations for this building type by enhancing the efficiency measures and design benchmarks for the building envelope, as the main architectural feature used in the development of environmental strategies determining a building's energy use.

The previous chapters established that the glazing elements are the most influential components of the building envelope in relation to energy use and thermal performance. This is particularly accurate in the Gulf region due to the high air temperature and abundant solar radiation, which make solar gains the greatest contributor to cooling loads. Therefore, shading coefficient can have a significant impact on the energy performance of the building envelope and should be carefully considered, either as an engineering parameter solution (glass coatings) or as a design parameter solution (shading elements).

However, most studies about the building envelope in Saudi Arabia have focused only on engineering parameters, and current energy efficiency building regulations rely on a prescriptive approach to the specifications for the engineering parameters of the building envelope, mostly the thermal properties of the opaque and transparent elements. This approach was questioned, studied and investigated in the previous chapters, and the findings established the validity of the hypotheses that integrating both the engineering and design parameters could provide a more effective means to reduce heat gains and achieve energy efficiency in residential tall buildings. Furthermore, the research indicated that such integration should take place in the early stages of the design process.

With this in mind and based on the findings from the last two chapters, this chapter introduces a manual method or set of guidelines to help designers determine the thermal performance and energy use impact of selected engineering and design parameters on a typical residential tall building in the hot climate of Jeddah, Saudi Arabia. These parameters can be reviewed, discussed and integrated during the early stages of the design process, requiring just a few simple parameters for data input purposes.

The following sections explain these guidelines, considering the environmental requirements and the specific challenges associated with residential tall buildings in Jeddah, Saudi Arabia.

7.1 The Development of the Energy Efficiency Strategies for the Building Envelope

The guidelines are based on the results of the dynamic thermal simulations conducted as part of the parametric studies in Chapters 5 and 6. These considered both the engineering and design parameters of the building envelope: the engineering parameters were the wall type (focusing on the U-value and thermal transmittance), glazing type (focusing on SC), and glazing ratio, while the design parameters were building orientation and shading devices.

Three wall types were selected and compared: un-insulated wall type (UCW), which was based on the existing Corniche Dreams Tower in Jeddah; thermally insulated wall type (TBW), that followed the Estidama standards; and a spandrel glass type (SSG), which was based on existing residential tall buildings in the Gulf region. As for the glazing types, they too were all selected based on existing case studies of residential tall buildings in the region. The three selected glazing ratio (20, 40 and 60%) followed the classifications specified in the local energy efficiency building regulations. On the other hand, the design parameters were designed specifically for the latitude of the city of Jeddah in Saudi Arabia, considering its particular climatic and environmental conditions and the structural and architectural requirements of residential tall buildings in that location.

The parametric studies were conducted on two case studies: the first building was a hypothetical case study, which aimed to test the above-mentioned input parameters in isolation from the location requirements, while the second was an existing residential tall building in a specific location in Jeddah, Saudi Arabia. All the parametric studies were analysed in relation to cooling loads, solar gains and conductive heat gains through the building envelope.

The main findings of those parametric studies showed that the trends of the results were fairly similar for both case studies. However, building orientation was identified as a significant factor. In order to understand the impact of those results, the findings are summarised in relation to orientation as follows:

1. As was expected, the north orientation is most desirable in relation to cooling loads and heat gains since, due to the northern latitude and high solar altitude of Jeddah, it receives the lowest average daily incident solar radiation compared to the other orientations. Hence, the main building façade should have a predominantly north orientation and at least 60% of the total glazed surface area should be north facing. Based on the practical guidance of Dubai GBRS - which can be applied to buildings in Jeddah due to the similarities in climatic conditions (as discussed in the previous chapters) - a 'north' orientation encompasses the 150 degree angle from East towards North West.
2. Due to the high solar altitude for Jeddah, the south orientation receives slightly lower incident solar radiation in the hot summer months when compared the other orientations. Nevertheless, the south facing zones in the simulations showed higher values for solar gains as they receive solar radiation from morning till evening most of the year. Therefore, it is advisable to minimise the glazing ratio on the south facing façades. However, if larger glazing ratios of 40 and 60% are used due to design considerations and the demand for panoramic views, solar protection is needed. As discussed in Chapter 5, this should be achieved by using glazing with lower SC or by installing egg-crate shading, the most suitable and efficient external shading type for south facing glazed surfaces and capable of reducing cooling loads by up to 20%.
3. The east and west orientations receive the most solar radiation, especially in the summer months, which makes it critical to protect them from solar gains. Applying smaller glazing ratios to nearly solid façades is usually the best solution to achieve energy efficiency in such situations; however, as Jeddah faces the Red Sea to the west, residential tall buildings tend to be oriented westward in order to provide the

best sea views and solid west façades avoided completely. Although glazing with lower SC can reduce solar gains and cooling loads, deep vertical fins should also be used to achieve reductions in cooling loads of up to 20% (as mentioned in Chapter 5).

4. The northeast, northwest, southeast and southwest corner zones have external exposure from two sides, contributing greatly to heat gains and making them the worst performing zones in relation to cooling loads. Of these, the southeast and southwest zones receive the highest levels of solar radiation, causing surface heating on both façades and increasing both solar gains and conductive heat gains. However, if the above-mentioned strategies (smaller glazing ratios, lower SC of glazing type, and external shading devices) were applied, a significant reduction in cooling loads could be achieved.
5. Reflecting on the tested inputs of the engineering and design parameters, the most influential parameters in relation to decreasing heat gains and cooling loads are those directly connected to solar gains, namely the SC of the glazing type and external shadings for the building envelope. These parameters are also associated with building orientation.

These findings were used to develop an understanding of the impact of solar heat gain in a typical residential tall building sited along latitude 21^{o} N. Following that, and in order to make meaningful recommendations from the findings, especially in relation to reducing solar gains, the average monthly solar heat gain coefficient (SHGC) values for the tested external shading types were derived for the main building orientations and correlated to projection factor (PF) ratios using the hypothetical base case study in Chapter 5. The following section explains the steps and results for this analysis and how it informed the creation of the energy efficiency strategies for the building envelope.

7.1.1 Estimating Solar Heat Gain Coefficient (SHGC) Values

The SHGC values (expressed as a percentage, in decimals between 0 to 1) are used to account for the amount of solar gain due to direct and diffuse shading on a window surface, and indicate the effectiveness of the external shading devices. In the hot climate of the Gulf region, where minimising solar heat gain is a priority, the lower the SHGC value the better (Kiamba, 2016).

For the purposes of this analysis, the total SHGC of the fenestration system ($SHGC_{total}$) was calculated using three variables as shown in Equation 7-1 (BSEEP, 2013, p.114):

$$SHGC_{total} = SHGC_{external} \times SHGC_{glazing} \times SHGC_{internal}$$

Equation 7-1: Total Solar Heat Gain Coefficient (Building Sector Energy Efficiency Project – BSEEP, 2013, p.114)

Where:

$SHGC_{total}$ is the energy reduction per year (kWh/year)

$SHGC_{external}$ is the Solar Heat Gain Coefficient of external shading devices (1, if no external shading device is used)

$SHGC_{glazing}$ is the Solar Heat Gain Coefficient of glazing

$SHGC_{internal}$ is the Solar Heat Gain Coefficient of internal shading devices (1, if no internal shading device is used)

Since the focus of this analysis is on external shading devices and no internal shading devices were used, the $SHGC_{internal}$ was left constant and had a value of 1 for all the conducted calculations. The $SHGC_{glazing}$ was set according to the three tested types of glazing in the engineering parameters inputs (32, 28 and 26), which have $SHGC_{glazing}$ values of (0.2, 0.26 and 0.44) respectively. As for the $SHGC_{external}$, it was estimated taking into account the effect of the application of external shading devices of varying depths and configurations.

The calculations of the $SHGC_{total}$ were conducted using the configurations of the hypothetical case study in Chapter 5 considering the wall type (TBW) and excluding the other wall types since the efficiency of external shading devices and reduction in annual solar gains is not related to the wall type. Moreover, as explained by Kiamba (2016), the shading coefficient for each orientation would vary due to the relative movement of the sun throughout the day and the year. Therefore, in order to limit the results, the average SHGC values for all the daylight hours were calculated for the 21st day of each month of the year (ASHRAE, 2013a), as listed in Table 7-1.

Table 7-1 The selected days of a typical year used for the SHGC calculations

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Day of the year	21	52	80	111	141	173	202	233	265	294	325	355

The results of the SHGC calculations were derived for each of the three glazing types and correlated with the various PF ratios for the vertical and egg-crate shading devices in the eight main orientations (north, south, east, west, northeast, northwest, southeast, and southwest). The PF is a simple ratio used to define the relationship between the shading element depth and window size as shown in Equation 3-3 (SBC 601, 2007) in Chapter 3, and illustrated in Figure 7-1 (Kiamba, 2016, p. 355). As for egg-crate shading, a combination of both horizontal and vertical PF should be considered. The window dimensions were set using the standard window type in the hypothetical base case profile of 2.4m high and 0.9m wide for all calculations. The PF ratios derived for the selected shading configurations are shown in Table 7-2.

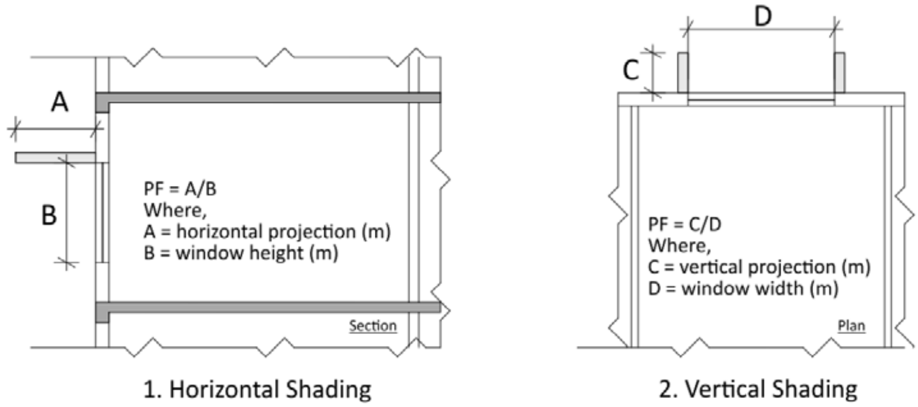


Figure 7-1 Projection factor ratio for horizontal and vertical shading elements (Source: Kiamba, 2016, p.361).

Table 7-2 The PF ratios derived for the selected shading configurations

Shading configuration	Shading Device Depths (cm)		Corresponding PF Ratio	
	Horizontal	Vertical	Horizontal	Vertical
Egg-crate shading (ECS)	0.3	0.3	0.125	0.3
Vertical shading with two fins on the left and right (VS)	-	0.15 – 0.3 – 0.5	-	0.2 – 0.3 – 0.5

7.1.2 The Results of the SHGC Analysis

The analysis of the SHGC values was derived from the solar gains results from the parametric study simulation in Chapter 5, which used the hypothetical base case representing a residential tall building in Jeddah. The analysis followed Equation 7-1 and considered the SHGC of the three glazing types (32, 28, and 26), and the SHGC of the 0.3m deep egg-crate shading on the South façade and the varied-depth vertical fins (0.15, 0.3, and 0.5m deep) on the East and West façades, for the 12 chosen days (as set out in Table 7-1).

Firstly, the average SHGC values for the external vertical fins were compared across all the zones in order to observe the trends in variations between the different orientations. Table 7-3 shows that the variations in SHGC values were minor between the opposite orientations, i.e. east and west, northwest and northeast, and southeast and southwest. The values for the north and south zones were constant since the north zone was not shaded in any case, while the south zone had a fixed egg-crate shading type. As was expected, the results confirmed that the east and west zones had the highest SHGC values, especially with the minimum depth of 0.15m for the vertical fins, as these receive the highest solar radiation (as discussed in previous chapters). On the other hand, the South oriented zones had the lowest SHGC values due to the effective use of egg-crate shading devices. This vertical and horizontal shading type made a positive reduction, even in the southwest and southeast zones, while the non-shaded North oriented zones suffered from higher SHGC impacting the northwest and northeast zones. However, the increased depth of the vertical fins on the east and west façades made a major impact in reducing the SHGC values (as shown in Table 7-3 and 7-4).

Table 7-3 The variation of SHGC values due to external shading for the different orientations, the red colour indicates higher values while the green is lowest

	Northwest SHGC	Northeast SHGC	West SHGC	East SHGC	Southwest SHGC	Southeast SHGC	North SHGC	South SHGC
(15-15)	0.83	0.84	0.86	0.87	0.76	0.75	0.80	0.66
(30-30)	0.76	0.77	0.74	0.75	0.71	0.70	0.80	0.66
(50-50)	0.68	0.70	0.61	0.63	0.65	0.65	0.80	0.66

In Table 7-4, the SHGC values of the vertical fins were calculated for the correlated PF ratios for the six orientations that they were applied to: northwest, northeast, west, east, southwest, and southeast. Additionally, curve fits were presented for the various PF ratios for the orientations in Figure 7-2, which showed highly positive correlation factors indicated by the R^2 values. This provided a very close estimate of the SHGC value from any PF values for external shading applied to the simulation of a typical residential tall building.

Table 7-4 SHGC values for vertical fins based on PF ratios

PF Vertical	0	0.2	0.3	0.5
Northwest	1	0.83	0.76	0.68
Northeast	1	0.84	0.77	0.70
West	1	0.86	0.74	0.61
East	1	0.87	0.75	0.63
Southwest	1	0.76	0.71	0.65
Southeast	1	0.75	0.70	0.65

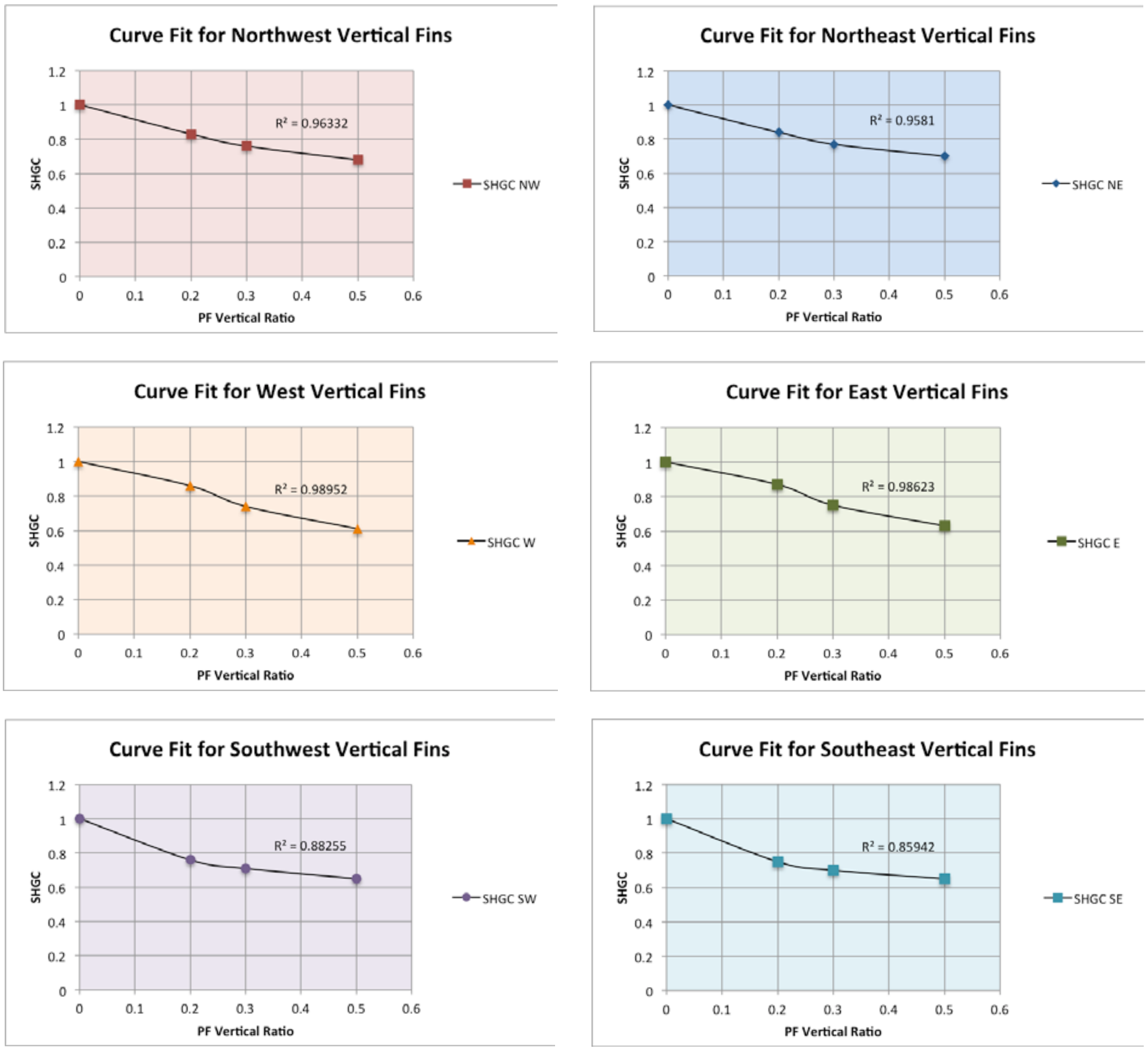


Figure 7-2 SHGC Curve Fits for vertical fins for Northwest, Northeast, West, East, Southwest, Southeast orientations.

The results of this analysis showed that the improvement in SHGC indicating reduced solar gains was more visible on the east and west orientations with the application of vertical fins. Moreover, the SHGC with egg-crates was lower than with vertical fins due to the greater shading masks this type creates on building façades.

In terms of solar gains and cooling loads reduction, the SHGC results were found to reflect the performance analysis for the parametric studies carried out in Chapter 5 and 6, where it was noted that the deeper the external vertical fins on the east and west orientations, the greater the reductions in solar gains.

As for the $SHGC_{total}$ for all the tested cases, the findings from the results considering both the $SHGC_{external}$ for external shading and $SHGC_{glazing}$ for glazing type indicated that the glazing types with lower SC achieved the lowest $SHGC_{total}$, as was expected and discussed in the previous chapters.

Overall, the results of this SHGC analysis were found suitable to be used as an indicator of the impact of various shading and glazing types. Hence, they can be used as a helpful reference for designers during the early design stages to predict the potential impact of the SHGC on reducing solar heat gains and, consequently, reduce cooling loads in residential tall buildings in Jeddah, Saudi Arabia.

7.2 The Energy Efficiency Strategies for Building Envelope

Based on the findings from the previous chapters and the above-mentioned SHGC analysis, a set of energy efficiency strategies was proposed in the form of a comparative tool to assist designers and architects in the early stages of the design process of residential tall buildings in the hot climate of Saudi Arabia. This tool aims to compare energy efficiency performance considering both the engineering and design parameters of the building envelope and taking into account the recommendations of the local energy efficiency building regulations.

Accordingly, the comparative tool focused on reducing solar heat gains through glazing ratios, SC of glazing type, and SHGC due to the use of external shading devices. As for the opaque elements of the building envelope, the tool presumed the application of Estidama standards regarding the thermal transmittance of external walls, assuming that both the occupants and the building systems function in an optimum mode. Moreover, it is worth noting that this tool is developed for and limited to preliminary comparative studies, and could be used for testing and comparing the relative performance of a number of design options so that overall trends and workable design solutions can be identified.

Having said that, the comparative tool is divided according to the orientations of the building's perimeter zones since this study has identified building orientation as the key element impacting solar gains and the perimeter zones suffer most from conductive heat gains and solar heat gains through the opaque and transparent elements of the building envelope. It simultaneously compares the three main envelope parameters that impact the reduction of cooling loads through the reduction of solar gains: the glazing ratio, PF representing external shading, and SHGC of glazing type.

The tool is presented in Table 7-5 below. This highlights the trends in energy performance in relation to cooling loads of a typical residential tall building located in Jeddah. The dark green colour indicates reduced cooling loads and good energy performance moving through light green and orange to red as cooling loads increase. This is also indicated in the values for the PF and SHGC: green shows better performance and red worse performance. For example, the north zone with a 40% glazing ratio, a projection factor of 0.5 and a SHGC value of 0.2 is dark green indicating a good performance, while the same zone with a larger glazing area of 60%, 0 PF (no external shading), and SHGC of 0.4 is a light shade of orange, signifying increased cooling loads and a worse energy performance.

This colour-coded comparative tool can be used as part of an energy efficiency strategy to give a fair representation of the energy performance patterns of a typical residential tall building located in Jeddah, Saudi Arabia. The following steps explain how it should be used:

1. Determine the perimeter zones and their orientations on the floor plan.
2. Choose the glazing area of each zone, noting that the total glazing ratio for the whole façade of the building differs from the glazing ratio for the individual zone, which can have a significant impact on the energy performance (as discussed in Section 6.2.1).
3. Based on the zone's orientation and glazing ratio, identify the most suitable shading type for the glazing area. This can be done using the methodology in Section 5.4.1.
4. Calculate the PF for the chosen shading type based on the method in Section 7.1.1.
5. Determine the SC or SHGC of the glazing type by following the prescriptive recommendations in the local energy efficiency building regulations or based on the specific requirements of the project.
6. Using the tool in Table 7-5 input the considered values for the glazing ratios, PF and SHGC for glazing. The values for these parameters can be changed according to the specific requirements of the building as long as they follow the same ascending pattern.

7. Compare the relationship between the different configurations of the building envelope to identify trends in relation to energy performance. This should help designers to reach an informed decision based on the established trends.

The input parameters for the tool should be simple enough to be integrated into the early stages of the design process. The tool can be used to compare the energy performance of the different configurations of the building envelope in order to reach an informed decision based on the established trends. It can also be used as an analytic tool to compare the results of energy performance simulations for a typical residential tall building. This was the case with the parametric study of Corniche Dreams Tower in Chapter 6 where the tool helped in determining the percentage of improvement between the different configurations of engineering and design parameters in relation to solar gains and cooling loads.

An important factor to consider when designing residential tall buildings in Jeddah are the views from the interior, the main selling and marketing point for this building type, which can be jeopardised by deeper external shading. Table 7-6 shows how this comparative tool can be used to determine the optimum building envelope configuration considering both energy performance and view requirements. For instance, in the case of a 40% glazing ratio, and a well preforming glazing type with SHGC of 0.2, the difference in energy performance between 0.2 and 0.3 PF is minimal, hence selecting a shallower external shading device should not have a major impact on energy efficiency.

Based on the predictions obtained using this tool, the designers would have useful information with which to weigh the advantages and disadvantages of applying these strategies in order to achieve energy efficiency in residential tall buildings.

Table 7-5 The comparative tool proposed as part of the energy efficiency strategies for the building envelope, considering the building envelope parameters that impact solar gains and cooling loads. The green colour indicates better performance while the red indicates higher cooling loads and worse performance

Orientation	Glazing Ratio	Projection Factor (PF)				SHGC Glazing
		0	0.2	0.3	0.5	
North	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
South	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
East	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
West	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
Northeast	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
Northwest	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
Southeast	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4
Southwest	40					0.2
						0.3
						0.4
	60					0.2
						0.3
						0.4

Table 7-6 An example considering view restrictions in relation to external shading depths

Orientation	Glazing Ratio	Projection Factor (PF)				SHGC Glazing
		0	0.2	0.3	0.5	
West	40	*	*	**	***	0.2
		*	*	**	***	0.3
		*	*	**	***	0.4
	60	*	*	**	***	0.2
		*	*	**	***	0.3
		*	*	**	***	0.4

7.3 Conclusion

The parametric studies in the previous chapters identified the building envelope parameters that had the most significant impact on the energy performance of residential tall buildings in the city of Jeddah. The results showed that due to the high air temperature and abundant solar radiation characterising the local climate, parameters that affect solar gains, such as glazing ratio, SHGC of glazing type and external shading, are the dominant factors in reducing cooling energy loads. The findings also showed that the reliance on a prescriptive approach to the specifications for the engineering parameters of the building envelope did not achieve the required reduction in solar gains whereas the integration of design parameters led to a significant improvement in reducing cooling energy loads.

Based on this, this chapter has examined the application of these findings in a step-by-step approach that can help designers test the impact of applying energy efficiency strategies in residential tall buildings in the hot climate of Jeddah, Saudi Arabia. The main focus of this design intervention is to significantly reduce solar gains and consequently cooling loads for this building type.

In order to draw up these energy efficiency strategies for the building envelope, the findings from the parametric studies in Chapters 5 and 6 were combined in a comparative tool that connected the three main building envelope parameters impacting solar gains: glazing ratio, external shading, and glazing type. The glazing ratio was directly dependent on the orientation of the perimeter zones, while the external shadings were represented by the PF after being correlated with the SHGC for shading. As for the glazing type, the SHGC values were used to express the solar properties of the material.

The comparative tool is intended to be simple enough to be integrated into the early stages of the design process, requiring few input parameters to compare the trends in energy performance of the different configurations of the building envelope. However, it is flexible enough to be incorporated into the later stages of the building design simulations in order to assist the designers to reach informed decisions regarding building envelope design. Furthermore, the tool also considers the need for panoramic views in relation to the design and marketing process of residential tall buildings, an essential requirement in costal Jeddah.

In order to test its applicability, the comparative tool was tested on the existing case study of Corniche Dreams Tower. The results showed that its predictions were accurate enough to help designers make informed decisions regarding the most appropriate energy efficiency measures to incorporate into the building envelope.

Ultimately, these energy efficiency strategies, including the comparative tool, should be incorporated into the design guidelines and recommendations in the local energy efficiency building regulations, especially in Saudi Arabia. This would enhance the effectiveness of these building codes and regulations for the designers and architects who aim to deliver residential tall buildings that consider both the local environmental and the specific energy efficiency requirements of the region.

CONCLUSIONS AND FURTHER WORK

CONCLUSIONS AND FURTHER WORK

Over the last four decades, the energy consumption in the Gulf Region has been increasing sharply as a result of the rapidly growing population and the expansion in industrialization and diversifications plans that ironically aimed to reduce the reliance on the oil-based economy, only to produce more energy-intensive mega-scale projects. These diversification plans were strongly associated with tall buildings construction boom that played an essential role in building a future economy based on financial services, global placemaking and international tourism. In Saudi Arabia, this active construction of tall buildings is focusing more on the residential and mixed-use types, in order to meet the increasing demand of housing and residential units to accommodate the growing urban population. Moreover, the building sector is a major consumer of energy, particularly in the harsh hot climate of Saudi Arabia, where residential buildings account for over 50% of all energy consumption across the country. And the intensive use of air-conditioning to cool the indoor spaces accounts for more that 70% of the electricity consumed in these residential buildings. Bearing in mind that power-generating plants in the country are dependent on fossil fuels, this identified residential buildings as a major contributor to carbon dioxide emissions.

The climatic analysis of the main coastal cities in the Gulf Region showed that the climate is predominantly hot, coupled with abundance solar radiation and high relative humidity, making minimising heat gains a prime consideration. Yet, the majority of the residential tall buildings in the region are designed and built with no regard to the local climate showing an excessive use of completely sealed and fully glazed facades, and relying completely on active cooling systems to overcome the impact of uncomfortable climate conditions. The building envelope is regarded as the key aspect in designing climate responsive buildings, especially for tall buildings, determining energy use and influencing as much as 30% of the cooling loads. The properties of the opaque and transparent elements of the building envelope have a major impact on the energy balance of the building, for example, in the hot climate of the Gulf Region, solar gains through glazing can be as high as 85% of the incident radiation. Which reflect how the window and glazing properties, namely the SHGC and glazing ratio, are influential in relation to energy consumption and thermal comfort.

The design of the building envelope is not a single process but a holistic cross-disciplinary deign process that considers the outdoor environment and climatic conditions, the building form and orientation, and functional and systems requirements. Careful planning and integration of all those aspects during the early design process of the building envelope is the key to produce energy efficient buildings. Nevertheless, most studies about the building envelope in the Gulf Region focused on the engineering parameters – as classified by Baker and Steemers (1996)- rather than the integration and planning of the building envelope within the design process.

On the other hand, several studies have shown that developing and adapting the building codes and regulations to work with rather than against the harsh climate of Saudi Arabia and the Gulf Region are considered a high priority when it comes to increasing energy efficiency in buildings, achieving up to 70% reductions in energy demand. However, amongst the countries of the Gulf Region, only UAE and Qatar have pioneered in developing exclusive building codes that address sustainability and green building construction following the international standards. Moreover, very few studies have evaluated the effectiveness or the applicability of these energy efficiency regulations measures in relation to tall buildings design.

Based on this discussion, an evaluation of the current energy efficiency codes and building regulations in the Gulf Region in relation to the energy performance of residential tall buildings were carried out comparing between Saudi Arabia's SBC 601, Dubai's GBRS, Abu Dhabi's Estidama PBRS, and Qatar's GSAS. The comparison revealed that those building regulations either provide minimum requirements for the engineering parameters of the building envelope (U-value, SC or SHGC) or refer to the engineering parameters in the ASHRAE Standards, with little or no mention of the design parameters. Parallel to this comparison, informal interviews were conducted at three major engineering practices in London with designers and engineers who have a vast experience regarding the design of tall buildings in the Gulf Region. The interviews emphasised on the climatic and regulatory challenges in relation to tall building design in the region. Concluding how the careful planning and integration of a hierarchal design approach that involves the optimisations of the key design features throughout the design phases can overcome the climatic challenge.

Such an approach can be adopted in the energy efficiency building regulations to achieve energy efficiency in residential tall buildings. However, in addition to the limitation of the local building codes, many of these conservation efforts have been ineffective due to different regulatory factors such as bureaucracy and governance challenges, lack of awareness, information, enforcement, and lack of market incentives and political support.

In views of these factors, this research aimed to find and prioritise building envelope design solutions that can reduce high energy consumption and cooling loads while maintaining indoor environment for residential tall buildings in the Gulf Region in general and Saudi Arabia in particular, which can enhance the effectiveness of the local building codes and energy efficiency regulations in relation to this building type. In order to achieve that, a mixed method approach was followed including literature review, data collection, dynamic building simulations and parametric analysis.

Firstly, a comparative analysis was carried out to evaluate the energy performance of the building envelope for a selected number of residential tall buildings in the Gulf Region in order to identify and quantify the main parameters that affect the overall building energy performance. The architectural characteristics and properties of the building envelope of 11 residential tall buildings in Dubai, Abu Dhabi, and Jeddah were compiled and compared in a Residential Tall Buildings Characteristics Table. And the collected data was analysed to obtain the total heat gains through the building envelope using the two manual calculation techniques proposed by Brown and DeKay (2001). The main findings of this analysis established an initial understanding of the issues and trends of the characteristics of the building envelopes in the region, which were used to generate hypothesises about the parameters that impact the thermal performance of the building envelope. These parameters determined the different building envelope build-ups and configurations that established the matrix for the dynamic building simulations. While the main architectural characteristics of the compiled buildings were used to define the common design considerations for a hypothetical base case representing a residential tall building located in Jeddah, Saudi Arabia, which were used for the simulations as well.

Following that, two parametric studies were conducted through advanced dynamic simulation techniques using Tas modelling software. These studies aimed to evaluate and compare the effect of both the engineering and design parameters of different envelope combinations, in order to identify the most influential building envelope parameters impacting the cooling loads and energy efficiency in residential tall buildings in the hot climate of Jeddah. The first parametric study focused on the engineering parameters, namely wall U-value, glazing SC, and glazing ratio, which were all selected based on the parameters specified in the local building codes and practice, while the second parametric study investigated the effect of shading devices as a design parameter. The findings from those studies showed that due to the high air temperature and abundant solar radiation characterising the local climate, solar gains make the greatest contribution to cooling loads. And that following a prescriptive approach relying on the specifications of the engineering parameters of the building envelope will not necessarily achieve the required reduction in solar gains. Therefore, the development of the design parameters, mainly external shading devices, can significantly reduce cooling loads.

In order to test this hypothesis of integrating engineering and design parameters as a design strategy for tall buildings envelope, another three parametric studies were conducted to evaluate the thermal and energy performance of the building envelope for Corniche Dreams Tower, an existing case study of a residential tall building located in the city of Jeddah. The first parametric study explored the engineering parameters and compared it with the local energy efficiency building regulations. The results emphasised that solar gains through the building envelope are the highest contributors to cooling loads, especially for the South, East and West orientations, while the thermal properties of the wall type can reduce up to 10% of the cooling loads. The findings from this parametric study laid the basis for the last two parametric studies that investigated the impact of the design parameters such as building's orientation and external shading on reducing solar gains. In the second parametric study, the rotation of the main axis of the Corniche Dreams Tower by 90^{o} from a north-south orientation to an east-west orientation has significantly reduced cooling loads by 25% and solar gains by 60% for the north orientated zones. As for the last parametric study, three alternatives of shading devices were tested including fixed egg-crate shading devices on the South facing windows and vertical fins with varied depths on the West and East windows. The results showed a reduction of up to 30% in solar gains, especially where the deeper vertical fins were applied.

Lastly, the main findings from these parametric studies emphasised how combining both engineering and design parameters of the building envelope can be an effective way to achieve energy efficiency in residential tall buildings in the hot climate of Jeddah. And more importantly, such as approach should be carefully integrated from the early stages of the design process. Based on this, the final chapter introduced a set of guidelines that can help designers to determine the thermal performance and energy use of a typical residential tall building in the early stages of the building's design. These guidelines incorporate a comparative tool that interconnected the three main building envelope parameters impacting solar gains, which are the glazing ratio, external shading, and glazing type. The glazing ratio was directly dependent on the orientation of the perimeter zones, while the external shadings were represented by the PF after being correlated with the SHGC for shading, and SHGC values were used to express the solar properties of the glazing material. Ultimately, these guidelines aim to be incorporated as part of the design guidelines and recommendations in the local energy efficiency building regulations, especially for Saudi Arabia, to enhance the effectiveness of those building codes and regulations in relation to the energy efficiency of residential tall buildings.

Stepping back to reflect on the bigger picture, this research defined the main challenges in applying energy efficiency for residential tall buildings in the region, which can be overcome by the planning and integration of the engineering and design parameters of the building envelope in the early design stages. The specific climatic challenges in relation to solar gains can be addressed through the careful designing of the building envelope. For example, in the case of Corniche Dreams Tower, the total glazing ratio for the building façade is around 40%, which is reasonable considering solar gains reduction and views recommendations. However, the glazing ratios for the individual zones, facing west and east, can reach up to 80% as shown in Table 6-4. Which contributed hugely to the high solar gains and cooling loads for these zones. Therefore, the glazing ratio should be calculated for each perimeter zone and not only for the entire façade, and based on it, the requirements of the shading devices and the thermal properties of the glazing type, especially SHGC, can be selected accordingly. This integrated approach considering many parameters can be supported using the comparative tool introduced in this research.

As for the challenges on the regulatory level, comparing the specifications in the local energy efficiency building regulations in relation to residential tall buildings revealed major areas for improvements, especially for the Saudi SBC601. Which can be easily solved through the right implementation of the agreed cooperative plan on establishing common building standards incorporated into the national legislation in each country of the Gulf Region. This research highlighted few examples that supported this idea in relation to building envelope design; for instance, the specifications of the thermal properties of external walls in Abu Dhabi's Estidama Pearl Rating System can be applied in the building regulations in Saudi Arabia. Moreover, the design guidelines regarding external shading devices mentioned in The Green Building Code in Dubai can be effectively implemented in the design of residential tall buildings in the hot climate of Jeddah.

In summery, this research aimed to investigate the possibilities of improving energy efficiency in residential tall buildings in Saudi Arabia - as one of the largest contributors to the high energy consumption in the country- by finding and prioritising building envelope design solutions and strategies. The practical approach employed in the execution of this work aimed to enable easy translation of the interlocked findings into the local building codes and practice. Moreover, this structural method provided specific guidelines that can be used as a helpful reference for designers enabling them to make informed decisions in relation to the envelope deign for residential tall buildings in Saudi Arabia.

One of the main limitations of this study was the lack of architectural and structural documented information for residential tall building in Saudi Arabia, especially the locally designed towers. Consequently, the researcher was required to collect a significant amount of empirical data for analysis proposes, which was time-consuming. In addition to the logistic challenge since the researcher was resided in UK while the reviewed case studies were located in the Gulf Region, which also affected the relatively short period of the field study for the case study of Corniche Dreams. Hence, it would be useful to have more site-base examination into the energy performance of local residential tall buildings in Jeddah, including the investigation of actual energy use using electricity bills for example. This will allow more comparison options that enable higher level of accuracy and validations.

Furthermore, additional testing and revision of the proposed guidelines including the comparative tool should be conducted using a number of proposed and existing local residential tall buildings, in order to validate the effectiveness and fully understand its potential impact on heat gains and cooling loads reduction. Moreover, further analysis regarding the influence of these guidelines on the views and marketing requirements of these high-rise towers. However, the extensive work of this research enabled the publication of a series of papers that will serve the availability of high quality research in this area.

In conclusion, and as predicted by the national director responsible for Jones Lang LaSalle's tenant and landlord services across Saudi Arabia; "*What I see is the market here are becoming more diverse and more sophisticated. We're going to see increasingly more high-rise, more high-quality projects and more mixed-use projects, which reflect the changing market*." Therefore, as long as tall buildings and high-rises will continue to be built, the necessity to increase their energy efficiency and reduce their consumption will remain a vital responsibility on both the regulatory and the design industry level.

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APPENDICES