بسم الله الرحمن الرحيم

In the name of God, Most Gracious, Most Merciful

Dedication

*I would like to dedicate this research to my beloved **parents**,*

Dr Ahmad Jaberansari and Mrs Marjan Rastegarpanah

for all their support throughout all my life… from the day I was born, got married, was blessed with a son and until now.

The effect of atrium configurations on energy usage in high-rise office buildings in semi-arid climate of Tehran

Marveh Jaberansari

School of Built Environment

University of Salford, UK

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Declaration

This thesis is submitted to the University of Salford rules and regulations for the award of a PhD degree by research. While the research was in progress, some research findings were published in conference papers prior to this submission.

The researcher declares that no portion of the work referred to in this thesis has been submitted in support of an application for another degree of qualification of this, or any other university or institution of learning.

Marveh Jaberansari

Email: Marveh.j@gmail.com

Aknowlegement

First and foremost I thank GOD as he is the one and only meaning of the universe.

I would like to thank and express my gratitude to my supervisor, Prof. Hisham Elkadi, for all his support, inputs, guidance, advice and patience in supervising me for this thesis. He has been truly a great supervisor as well as a great human being as he greatly understood my situation from the day I met him until now. May Allah bless him in his life. I also want to thank my co-supervisor Dr Yingchun Ji, for all his support through all these years. I also am in dept of my first supervisor Prof. Arto Kiviniemi, whom welcomed me in the university and helped me to strongly establish my first steps in this journey.

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Abbreviations

HVAC**:** Heating, Ventilating and Air Conditioning

NV: Natural Ventilation

Rec: Rectangular

SQ: square

N: North

E: East

W: West

S: South

NS: North South Aligned

EW: East West Aligned

DTS: Dynamic Thermal Simulation

ACS: Adaptive Comfort Standard

SBS: Sick Building Syndrome

CR: Constructive Research

DSC: Design Science Research

Abstract:

The building sector is responsible for at least 30% of energy use in most countries worldwide (UN environment, 2017) and around 33% of energy is used by HVAC systems in buildings (Salib & Wood, 2013). As a passive design element, an atrium has the potential to naturally provide heating and cooling, as well as adequate daylight, in arid and temperate climates. Moreover, a naturally ventilated atrium has also proven to be a useful environmental feature in tall building design (Moosavi et al., 2014; Salib & Wood, 2013; Sharples & Bensalem, 2001). This thesis investigated the impact of different configurations of atria on the energy performance of tall office buildings in Tehran. Despite having a rich history of climatic conscious design, the contemporary architecture of the Middle East, and Iran as one of the countries in this region, has witnessed excessive energy use (Holford & Hunt, 2003). The building sector in Iran consumes six times more energy in comparison to that of average European countries (Asgar, 2014a). Moreover, the HVAC sector in Iran uses 61% of the energy in office buildings (IFCO Iranain organization for Fuel Consumption Optimisation in the country, 2010). Providing thermal comfort via passive means is a challenge for tall buildings situated in semi-arid climates and therefore, the atria design for this region is of utmost importance.

In this thesis, different types of atria are incorporated into square and rectangular plan tall office buildings and their performances are examined when the buildings are only naturally ventilated throughout the year. The outputs are compared to when HVAC assists the naturally ventilated buildings, and for this, a Dynamic Thermal Simulation (DTS) tool, called Design Builder, has been used. This thesis utilises a Design Science research method. A number of scenarios were simulated with different atria configurations for square and rectangular plan buildings. The outcome of the simulation showed that the atria located on the north and west façades generally perform more efficiently in minimising heat loss. It was also concluded that rectangular plan models generally perform more efficiently than square plan models in terms of lowering energy load and ensuring fewer uncomfortable hours. Amongst the rectangular plan models, the lowest heating and cooling load prototypes had a reduction of 66.65% in energy load. Meanwhile, amongst the square plan models the lowest heating and cooling load prototype had a reduction of 33.71% in energy load.

CHAPTER 1: Introduction

1.1 Background

The percentage of energy used by the building sector in the world is around 30% (UN environment, 2017). The world's energy consumption is predicted to increase by 60% by 2030 and developing countries are accountable for two thirds of this growth (Schröder, Ekins, Power, Zulauf, & Lowe, 2011). Moreover, in the world today, one third of gas emissions are produced by the building sector and 80% is used when buildings are running, using heating, ventilating and air conditioning (HVAC), light, etc (Zawawi, 2016). Never the less, an agreement, called the Paris Climate Agreement, has been reached between many countries that aims to reduce greenhouse gas emissions. Therefore, the construction industry, like other contributing sectors, need to explore ways in which to reduce their emissions. One of the ways in which they can do this is by addressing high-energy consumption at the design stage.

Furthermore, as a means to assist thermal comfort to provide an acceptable indoor environment, HVAC contributes as much as 33% of the energy usage in tall commercial office blocks across the world (Salib & Wood, 2013). Moreover, according to Lombard, Ortiz, and Pout (2008), the largest energy end use in buildings around the world is HVAC. A comparison between the energy consumption of residential and commercial sector in the world between the years 1985 and 2015 (International Energy Agency, 2015) shows that the use of electricity (source of HVAC) in the commercial sector rose from 31% to more than half the energy consumed overall. This was a considerable amount higher than the electricity energy consumed in residential blocks which only had a rise of 10%. The importance of energy consumption for HVAC in office buildings has therefore been highlighted, and attention is needed to lower energy usage in the office and commercial sectors (International Energy Agency, 2015).

Thermal comfort is one of the most important parameters when designing buildings (Douvlou, 2003). Following the oil crisis in 1973, emphasis shifted to lower the energy usage of buildings as much as possible by incorporating energy efficient strategies into the designs without risking the comfort levels inside the buildings (Aldawoud, 2013). It is therefore important to try to achieve thermal comfort via natural means as much as possible and to lower the energy usage of buildings by incorporating energy efficient strategies into designs

(Aldawoud, 2013). High-rise offices, which are amongst the buildings with the highest energy consumption, have been emerging rapidly, especially in dense cities (Sauerbruch, Hutton, & Hinterthan, 2011), as they accommodate more people in a square meter of a land compared to low rise blocks.

Tall buildings tend to have an increasing appetite for energy especially in the provision of HVAC to maintain comfort levels (Holford & Hunt, 2003). Hence, it is important to design office buildings according to climate, because, when buildings are poorly designed, it leaves occupants no choice but to rely on HVAC as a mechanical means for providing thermal comfort. This results in the consumption of a lot of energy and money (Wahid, 2012).

Prior to the introduction of modern systems, ancient structures were designed to naturally provide thermally comfortable environments. Each climatic region developed its own particular and unique design of building that responded to the climatic needs of its specific place. The success of traditional buildings in meeting the particular climate and comfort needs of occupants has motivated architects to consider passive techniques to provide thermally comfortable environments in today's buildings. Nelson (2010) states that architects must approach climatic design by first looking into how successful traditional designs worked in order to create and select successful modern designs which provide thermal comfort and reflect the climate of the region. In the 1970's and 1980's, designers started to produce designs that considered natural ventilation, passive heating and cooling strategies, and energy conservation, and provided a healthier, more comfortable working environment (Salib & Wood, 2013). Some of the modern passive design strategies have been inspired by vernacular designs. It is important to use these passive modern designs in regions where they can be effective. By comparing the vernacular strategies of a particular region with the modern techniques available, a potential modern design strategy could be selected and investigated for that region.

1.2 Thesis Context

The building sector is a major energy consumption sector (40%) in Iran (Iranian Ministry of Energy, 2011). As mentioned previously, by 2030 this consumption rate will increase to 60% and developing countries, such as Iran, are partly accountable for this. In particular, the energy consumption of a housing and commercial unit has almost risen to double the amount in almost a decade in Iran (E.C.C, 2010). Furthermore, buildings in Iran consume more that of

European countries; for example, the annual energy consumption in buildings of Iran is 369 kwh/m2, which is more than most European countries (table 5.6). Moreover, offices in Iran consume an average of 350 kwh/m2, which according to Bagheri, Mokarizadeh, and Jabbar (2013) is a very high energy index. As such, it is important to tackle the problem of high-energy consumption in the office buildings of Iran.

The HVAC systems in Iran, like the rest of the world, have the largest energy end use in both residential and non-residential sectors (Lombard et al., 2008). This is due to the increasing number of high-rise buildings which rely on HVAC systems for the majority of the year (Shekarchian, Moghavvemi, Motasemi, & Mahlia, 2011). Indeed, almost 60% of the energy used in buildings in Iran is for heating and cooling (Riazi & Hosseyni, 2011). This is almost double the amount of energy used for HVAC internationally (33%) (Salib & Wood, 2013). In order to cool or heat buildings in Iran, two sources of fossil fuel are used: electricity (60% produced from gas) and gas (an irreplaceable source) (US energy Information Administration, 2015). By using these fuels, greenhouse gases are produced and since HVAC has a large share in the energy consumption of buildings in Iran, the greenhouse gas emissions they produce are considerable. Although Iran is the 158th densest country in the world (50 p/km2), in 2012 it was ranked the 15th country with the most greenhouse gas emissions (Carbon Brief, 2015) (Table 1.2). As such, Iran has pledged to decrease its greenhouse gas emissions by 4% by 2030, in accordance with the Paris Agreement (Department of Environment Islamic Republic of Iran, 2015). Therefore, it is essential to reduce energy consumption in this sector and reduce the reliance on HVAC in providing comfort in the buildings (including offices) of Iran.

Table 1.2: most countries with gas emission (Carbon Brief, 2015)

Rank	Country	Share of 2012 greenhouse gas emmision
1	China	23.7%
2	USA	12.1%
3	EU	8.9%
4	INDIA	5.7%
5	BRAZIL	5.7%
6	RUSSIA	5.3%

7	JAPAN	2.8%
8	CANADA	1.9%
9	CONGO	1.5%
10	INDONESIA	1.4%
11	AUSTRALIA	1.4%
12	SOUTH KOREA	1.28
13	MEXICO	1.2%
14	BOLIVIA	1.1%
15	Iran	1%
16	SAUDI ARABIA	1%

One of the most populated cities of Iran is Tehran (Barati, Rahbar, & Shaibani, 2010), which, in 2017, was ranked the 24th most populated city in the world, with almost 8.5 million reported as living in the urban area (Mayors, 2017). The pace of high rise building construction in Tehran has increased due to a combination of rapid population growth, large migration, a strong attraction to centralization, favourable economic conditions, changes in lifestyles, access to modern construction technologies, new housing policies, the shortage of inhabitable places, and an increase in the price of land. Furthermore, 70% of all services in the country are centralized in Tehran (Tehran Municipality, 2014), which affects the average energy consumption rate in this country. For example, the annual electricity consumption rate in Tehran is 9% while the annual average rate is 6%. Hence, attention should be paid to lowering the energy consumption of the rapidly emerging high-rise office buildings in Tehran.

Most buildings in Iran, including Tehran, have not yet been successful in responding to climate design needs. Moreover, they do not give the impression of being borne of their traditional design roots nor from their exclusive climatic place. Indeed, Khodabakhsh and Mofidi (2001) emphasised that modern Iranian buildings are actually designed in contrast to their climate conditions, despite having a history of strong traditional climatic architectural design. Moghaddam, Amindeldar, and Besharatizadeh (2011) state that, in Iran, the poor design of office blocks, with highly glazed façades, are increasingly common. Khodabakhsh and Mofidi (2001) and Moghaddam et al. (2011) mention that, because of poor design, HVAC systems have been used throughout most of the year to provide thermal comfort; this is a result of designers neglecting the vernacular knowledge of buildings in the region. Farahi

(2012) and Maleki (2011) claim that the practical problem of modern Iranian architecture is that it has embraced western designs without thinking about climate responsiveness, and has failed to establish its own technique and theories of high-rise buildings based on the success of past vernacular design. Maleki (2011) further adds that natural heating and cooling systems in the multi-storey buildings of Iran is needed and should be reviewed. However, Moghaddam et al. (2011) believe that, with good design, natural ventilation may be sufficient to ensure acceptable comfort levels in blocks. The above discussion shows that there is a design generation gap between the successful passive design buildings of the past to the non-climatically orientated design of the tall modern buildings of today in Tehran.

A number of Iranian architects have attempted to bridge the gap between old and new designs. However, the examples of their work do not cover high rise structures, but instead self-funded, lowrise dwellings. Furthermore, little attention is paid to lowering the energy consumption of buildings through passive design (Nasrollahi, 2009). This lack of attention to lowering energy consumption in practice is potentially due to three factors: firstly, subsidized energy and low energy costs which means there is less motivation to explore ways to reduce energy use. Secondly, the Iranian currency has been downgraded, which means that customers prefer to buy cheaper buildings, Finally, there is a lack of building regulation and enforcement of legislation, which could officially stipulate the consideration of energy reduction strategies.

In order to address the problem of high energy consumption due to the poor design of office buildings and the subsequent excessive use of HVAC, it is important to develop a reasonable modern passive strategy and modify the designs according to the climate, which, in this case is the semi-arid climate of Tehran. As Nelson (2010) states, architects must approach climatic design by first looking into how successful traditional designs worked in order to create and select successful modern designs which provide thermal comfort and reflect the climate of the region. One of the iconic features of Iran’s vernacular architecture, which is also a successful passive design strategy, is the courtyard.

The concept of the atrium was partially inspired by the courtyard, which was an old tactic for climate control (Abel, 2000b; Medi, 2010). Atria have many similarities in performance with courtyards and solar chimneys. The similarities between atria and courtyards include the provision of: natural ventilation, natural light and shade, social interaction spaces, and better visual spaces. Moreover, both create the potential for gardens and greenery. Just as courtyards have the ability to compliment other passive methods, atria also have the potential for being used alone or in combination with other passive design systems. It can be argued that atria, with or without a roof in high-rise buildings, are the extrusion of courtyards in low-rise buildings. They can be a strategy to provide thermal comfort in buildings and thus use less energy than those without atria.

According to Sharples and Bensalem (2001), in the last 37 years, many commercial and office buildings have used some form of atrium, often as a central circulation core. Atria have generally become very popular choices for high-rise office buildings, since SOM (Skidmore, Ownings and Merrill LLP) architects, Norman Foster and Ken Yeang started to incorporate them into designs (Abel, 2010). They have proven to be significant in enabling energy saving throughout the year (Linden, Lane-SerD, & Smeed, 1990). Atria have been used in a wide range of climates (Norton, 1997) as they can help with cooling and heating loads as well as natural ventilation (just like courtyards), whilst providing other potential advantages. However, it is important to design atria according to precise climatic needs.

Unfortunately, the current motivation for incorporating atria into Iranian buildings, is more likely to be as an architectural feature and not for the purpose of saving energy. Atria in Tehran's office buildings have not been used to their full potential, and as such, it has been suggested that research needs to be conducted on the performance of atria in this region (Assadi, Dalir, & Hamidi, 2011). However, very little research has been conducted into passive design that optimises thermal comfort in the high-rise buildings of Tehran's semi-arid climate. There is also limited research on the incorporation of atria as a successful climatic strategy, and there are few published works on successful examples of buildings with atria in Tehran. Therefore, there is a need for more research in order to understand the energy performance of atria in high-rise buildings in Tehran's climate.

Nevertheless, there are a number of publications on traditional, low-rise dwellings that demonstrate successful examples of passive design. However, researchers who have investigated the performance of atria, have tended to focus on buildings with no more than four storeys and not in semi-arid climates.

This research looks into the different configurations of atria in high-rise office buildings in the semi-arid climate of Tehran in order to minimise energy consumption in providing thermal comfort. This thesis also examines how atria may influence the indoor environments of adjacent office rooms in a semi-arid climate.

1.3 Research Aim and Objectives

The aim of this thesis is to investigate the effect of different atria configurations on the thermal comfort and energy loads of open plan high-rise office buildings in semi arid climate and to develop guidelines for the design of tall office building with atria. Also the main objectives are:

1. To conduct a literature review in order to:
    a. Critically review the thermal comfort temperature range in a semi-arid climate.
    b. Examine the energy consumption statistics of office buildings using HVAC.
2. To simulate different typologies to test their energy efficiency and impacts.
3. To validate the base case prototypes (virtual models of a typical office building) using empirical data.
4. To optimise the configuration of atria in tall buildings.
5. To develop guidelines and recommendations for the design of atrium in tall office buildings in a semi-arid climate.

The research questions that this thesis intends to answer are:

1. How do different configurations of atria affect the thermal comfort of occupants in tall office buildings in Tehran?
2. How do different configurations of atria affect heating and cooling loads in tall office buildings in Tehran?
3. What are the impacts of different parameters on the energy load in buildings in different configurations?

1.4 Thesis structure and outline

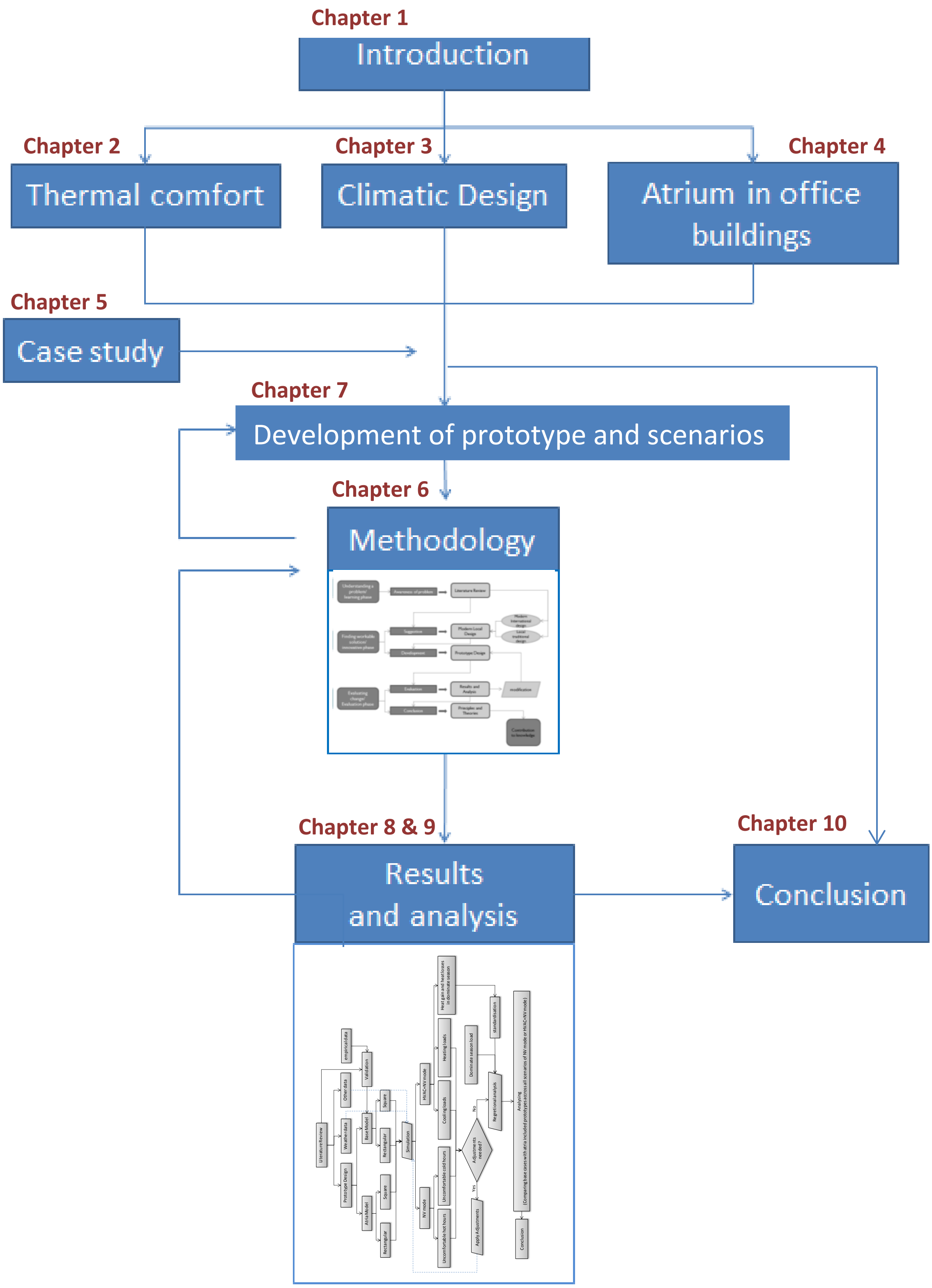


Figure 1.1: Thesis structure

This thesis consists of 10 chapters. The thesis structure illustrated in Figure 1.1, shows how the thesis is outlined and that which parts are covered in each chapter. The following explains what each chapter contains:

Chapter 1 provides an introduction and general summary of the research, including the thesis context, its aim, objectives and structure. Chapter 2 reviews the characteristics of thermal comfort in office buildings in different climatic conditions. Understanding thermal comfort and its parameters gives an idea as to what is important and should be taken into consideration in the simulation process. Chapter 3 highlights problems concerning the energy consumption in buildings and the importance of using climatic design. It also introduces different passive design techniques and justifies the use of atria for the prototype design. Moreover, Chapter 3 also expands on the factors that are important in the climatic design of buildings and some are considered in the prototype designs in later chapters. Chapter 4 explores atria design in more depth, including its history and advantages and disadvantages, and introduces basic atria and functionality types. These basic atria types are later selected for use in the prototype design. The chapter also gives information on how atria perform.

Chapter 5 covers all the subjects introduced in Chapters 2 to 4 (thermal comfort, energy consumption, passive climatic design and etc.) in relation to the case study of Tehran. This chapter explores the climate classification and thermal comfort temperature range in Tehran city. Knowledge of Tehran's thermal comfort range helps in the critical analysis of the results. The chapter then highlights the problem of energy consumption in buildings of Tehran. Chapter 6 describes and justifies the methodology used in the thesis. Chapter 7 provides a description of the selected prototype, including its characteristics, how it is formed, the software inputs, and a section on the comparison of the simulation base case scenario. It also outlines the empirical energy consumption data of existing office buildings in Tehran and compares this with the statistics in the literature review. Chapters 8 and 9 cover the simulation output results and the results analysis. Finally, Chapter 10 presents the discussion and conclusion which sums up the thesis overall. This chapter also considers the impact of costs on building design and gives guidelines and conclusions on the ways to reduce energy loads via passive atria design.

1.5 Thesis Scope

This research examines the impact of atrium configuration on energy performance of high rise office buildings during working hours only. The selected base cases of rectangular (1:2 ratio) and square configuration are the most used forms in tall buildings. This will be further explained in chapter 5. Convertible atrium prototype is used in the simulated models (in chapter 8 and 9), which is opened during the warm months and closed in the cool season.

The thesis examines the energy performance of the tall office buildings in Tehran's semi-arid climate. The results are therefore applicable within the Tehran climate. The results also depend on the thermal comfort range of the particular population of this region, since each region has its own thermal comfort range. The results of uncomfortable hours and the energy load (which explained in chapter 8 and 9) may therefore differ in other regions.

There are a number of factors that affect thermal comfort. This thesis neither look into personal factors (e.g. the effect of clothing) nor the air velocity (effect of air speed). The thesis focuses on the environmental factor (i.e.: impact of outside temperature and humidity on thermal comfort). More information on thermal comfort, passive deigns, atria and case study of Tehran are covered in the literature review in the chapters 2, 3, 4 and 5.

CHAPTER 2: Thermal comfort

2.1 The definition of thermal comfort

Thermal comfort is defined as the, "condition of mind that expresses satisfaction with the thermal environment" (ASHRAE Standard 55, 2013) "ASHRAE 55, ISO 7730 [and CIBSE are the] standards that define the local thermal comfort in an indoor environment, and its main indices and measuring procedures are described" (Orosa & Oliveira, 2012, p. 17).

Besides thermal comfort, acoustic environments, such as quiet service equipment, and visual comfort, involving artificial and natural illumination, are also part of the human comfort categories that need attention when designing buildings (Abdullah, 2007; Bansal, Hauser, & Minke, 1994). However, this research is mainly concerned with the thermal comfort of occupants in high-rise buildings, with an atrium. As stated by Douvlou (2003), thermal comfort is one of the most important parameters when designing buildings. It improves the mental performance as well as the health of the occupants of a building (Abdullah, 2007). Heidari (2009) states that designing with attention to thermal comfort has many advantages as it can result in better air quality in buildings, a reduction in sick building syndrome, lower energy consumption and less harm to the environment. It also represents a significant advantage in office spaces by encouraging more human productivity.

As this research examines high-rise office blocks, arguably more attention is needed in providing thermal comfort as the performances of employees who work in cold or hot environments are more likely to deteriorate than those working in perfect thermal conditions (Health and Saftey Executive, n.d.-a). Examples of some performance impacts are as follows:

- Taking shortcuts to get out of an uncomfortable environment
- In hot environments, employees may not properly wear their protective equipment and thus increase their health and safety risk
- The ability of workers to concentrate on a task may decrease substantially and therefore errors may be more likely to occur.

The Health and Saftey Executive (n.d.-a) explain that understanding and addressing the reason for these behaviours may increase productivity and improve employee health and safety as there is a limit to which a person can adapt to their environment, like removing or putting on clothing, without further affecting their comfort .

2.2 Factors affecting thermal comfort

The thermal balance of the body is of utmost importance in thermal comfort and this balance is influenced by several parameters. These parameters are categorised into two groups; personal and environmental factors (ASHRAE, 2013; Fanger, 1970; Health and Saftey Executive, n.d.-a) shown in dark and light grey in Figure 2. 1.

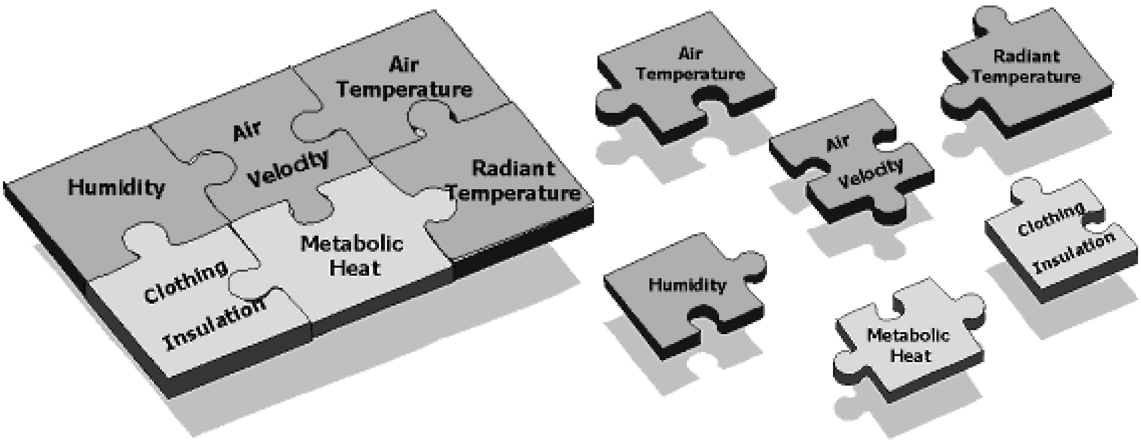


Figure 2. 1: Environmental factors in blue and personal factors in pink (Health and Saftey Executive, n.d.-a)

Personal factors, which can be controlled to some extent by occupants (Douvlou, 2003), are referenced by Fanger (1970), McIntyre (1980), R. Li (2007) and Design Builder (2015) as:

- **Activity level or metabolic rate (M):** the greater the activity level and the greater the internal metabolic heat production of the body, the greater the need to dissipate it from the body.
- **Thermal insulation** is provided by clothing and measured in clo: Different types of insulation in cloths affects the heat exchange through convection between the environment and the body surface.

Environmental factors, which can be controlled by the design team (Douvlou, 2007), are referenced by Fanger (1970), McIntyre (1980), R. Li (2007), Douvlou (2007) and Design Builder (2015) as:

- **Relative air velocity** (V): influences the thermal comfort via the convection process.
- **Mean radiant temperature** (T_r) is measured in MET: It affects the radiative heat exchange of all surroundings with the body.
- **Air temperature** (T_a): For most situations, this is the most important parameter to directly influence the heat exchange between the environment and the occupants. Also, Hensen (1990) believes that, among all thermal comfort parameters, air temperature is the most important environmental parameter with respect to thermal comfort. Furthermore, Douvlou (2003) only considered the effects of the changes in temperature with respect to thermal comfort as an important factor in thermal comfort.
- **Relative humidity** (RM): Douvlou (2003) believes that, if the humidity is in the range of 20% to 70%, and provided that the operative temperature (which takes into account air temperature, radiant temperature and air speed) is in the comfort range or thermal comfort zone, then the relative humidity does not have an appreciable effect and air temperature has the main effect on the thermal comfort of occupants. Douvlou (2003, p. 72) also states that "According to Macfarlane (1978), the use of dry bulb temperature is a satisfactory index and only in the humid tropics would humidity significantly affect the comfort rating of air temperature."

All these factors play a part in providing a comfort zone for occupants. Olgyay (1992, p. 18) defines a comfort zone as, "the zone where no feelings of discomfort occur". It is understood that, when a zone is known to be thermally comfortable, at least 80% of the population should be in what is called the acceptable zone (Douvlou, 2003). Although there is no exact limit for the comfort zone because it can, for example, depend on each person's activity or clothing, there is a need to develop and use standards or guidelines and limits for practical purposes.

Abdullah (2007) suggests that there is a difference in the comfort zone of people living in cold or moderate climates and those living in hot climates. Thus, knowing temperature to be an important factor, Givoni (1992) believes that for those who live in a moderate climate, the acceptable temperature range is 20°C to 27°C in still air in summer, and 18°C to 25°C in winter. However, this is relevant only if the humidity levels are not high (Douvlou, 2003). For those who live in a hot climate, the upper temperature limit can be increased by two degrees Celsius, making the overall acceptable range from 18°C to 29°C (Givoni, 1992). The exact application of this range to the case study in Tehran will be discussed later in chapter 5. Finally, methods have been proposed to measure occupant satisfaction regarding thermal comfort in buildings by using the factors mentioned in the following section 2.3.

2.3 Methods of defining and illustrating comfort and comfort zone

In order to enhance the understanding of occupants' thermal comfort, methods have been developed to evaluate thermal comfort levels of occupants. The Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) are the most common thermal comfort models used; these were developed by Fanger (1970) and stated in ISO7730 (2005). This standard uses 22 °C as the neutral temperature (T_{comf}) in winter and 24°C in summer (Taleghani, Tenpierik, & Dobbelsteen, 2012). PMV uses a seven point thermal sensation scale where +3 is hot and -3 is cold. Therefore, when the PMV is 0 it is in a neutral state, where thermal comfort is achieved for the majority of occupants (Abdullah, 2007; R. Li, 2007). The PMV is calculated using six basic variables, which are humidity, mean radiant temperature, air velocity, air temperature, clothing, and activity. The results agree with a number of tests involving a large population exposed to a wide range of given environments.

Moreover, PPD is another commonly used term, it is dependent on the PMV value and relates to the six main factors. PPD predicts the dissatisfaction of occupants that can be expected under certain conditions, or at each PMV. A total of 90% and 80% of people thermal satisfaction are calculated using the PPD model. The relationship between the PMV and PPD is illustrated in Figure 2. 2, which shows that, when the PMV is 0, the minimum value of PPD is no less than 5%. This means that, even if the environment is classified as thermally comfortable, there is never 100% satisfaction for all occupants and there are always some individuals who are dissatisfied with the comfort level that most other people seem to be fine with. This is because comfort evaluation differs from person to person. It is believed that the range of comfort is -0.5 to +0.5 in the PMV graph for 90% thermal satisfaction (Figure 2. 2) (Kim, Min, & Kim, 2013).

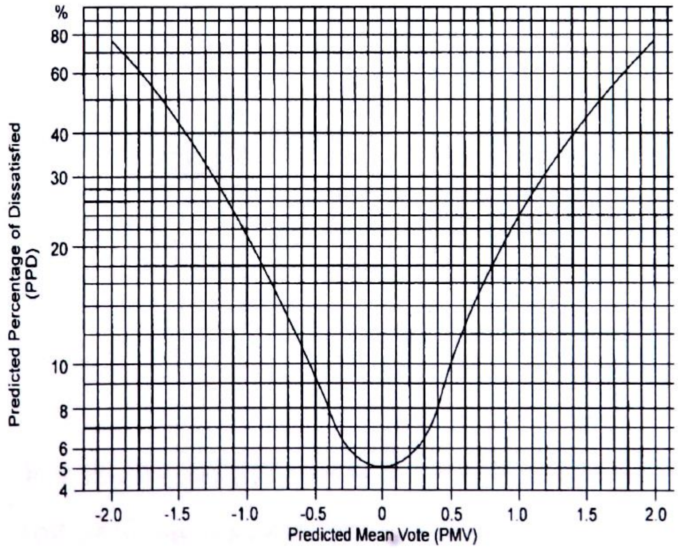


Figure 2. 2: Predicted Percentage of Dissatisfied (PPD) in relation to Predicted Mean Vote (PMV) (Fanger, 1970)

Kim et al. (2013) and Hussain and Oosthuizen (2013) state that the PMV indices are only applicable if used in HVAC or air conditioned buildings and are not adequate for naturally ventilated (NV) buildings. Furthermore, De Dear and Brager (2002) present examples that compare observed and predicted indoor comfort temperatures in an HVAC building as well as a naturally ventilated building, and confirm that the PMV index is more applicable to buildings with HVAC (Figure 2. 3 and Figure 2. 4).

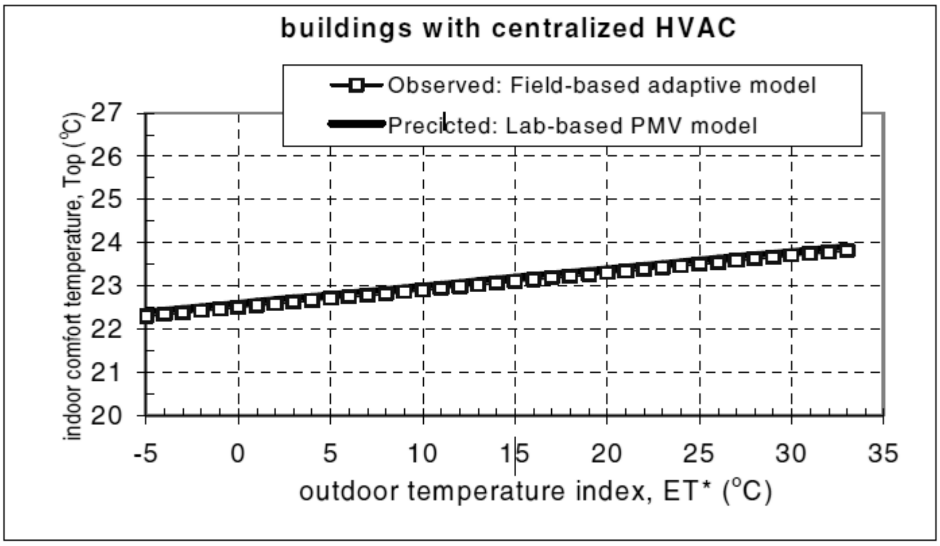


Figure 2. 3: Observed and predicted indoor comfort temperature for HVAC buildings (De Dear & Brager, 2002)

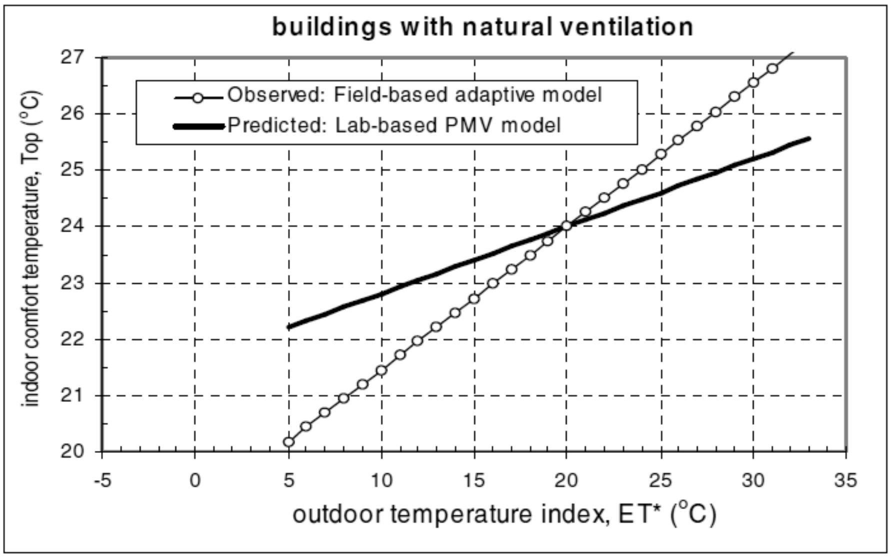


Figure 2. 4: Observed and predicted indoor comfort temperatures for naturally ventilated buildings (De Dear & Brager, 2002)

A comparison of Figure 2. 3 and Figure 2. 4 suggest that, in HVAC buildings, the PMV is successful in predicting the comfort temperature of occupants whereas in naturally ventilated buildings, it does not always predict the comfort of occupants correctly. Fanger and Toftum (2002) also agree that in warm climates, the occupants of a naturally ventilated building may observe the warmth as being less severe than the PMV prediction. Furthermore, De Dear and Brager (2002, p. 552) state that the occupants of an HVAC building, ”become more finely adapted to the narrow, constant conditions typically provided by mechanical conditioning, while occupants of NV buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns”.

By comparing Figure 2. 3 and Figure 2. 4, it becomes obvious that there should be another comfort index, which includes naturally ventilated buildings. Therefore in the new, revised ASHRAE Standard 55 (2013), another thermal comfort model was provided, named the ‘Adaptive Comfort Standard’ or ACS (Figure 2. 5).

The Adaptive Comfort Standard is developed from a global database where the comfortable neutral temperature in winter is 22°C, whilst in summer it is achieved via a formula (Taleghani et al., 2012). The average comfort range formula presented in the ASHRAE project is dependent on the outdoor dry bulb temperature (De Dear and Brager, 2002. This formula is acceptable when the average outdoor temperature is in the range of 10°C to 33°C in warm parts of the world (De Dear & Brager, 2002):

$T_{comf} = 0.31T_{a,out} + 17.8$ T_{comf} is the monthly average thermal comfort temperature

$T_{a,out}$ is the average outside monthly temperature

A total of 90% and 80% satisfaction amongst occupants are assumed at T_{comf} ±2.5°C and ±3.5°C respectively, respectively; this is illustrated in Figure 2. 5. The line in the middle is the neutral operative temperature, or the average comfort range. The 80% and 90% acceptable limit line on either side of the dotted middle line of the neutral temperature are the ±2.5°C and 3.5°C respectively.

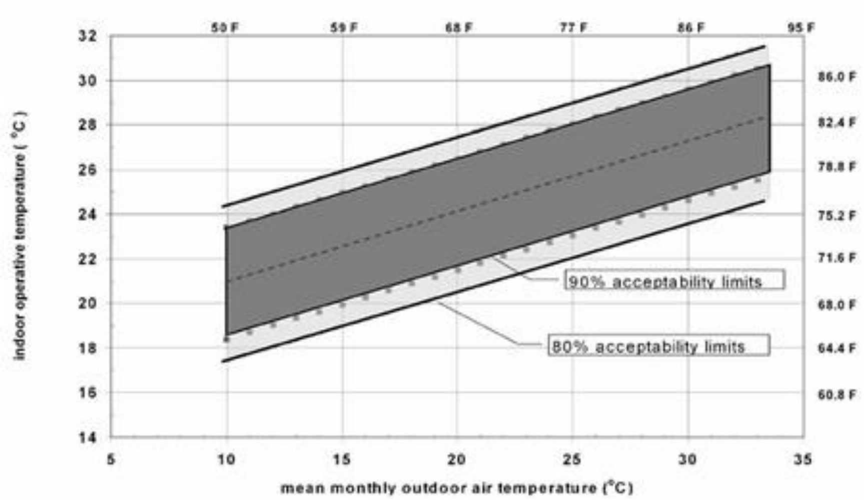


Figure 2. 5: Adaptive Comfort Standard graph (ASHRAE Standard 55, 2004)

According to previous formula, and as presented in Figure 2. **5**, when the outdoor temperature is 10°C the neutral temperature given by the formula is 20.9. Moreover, according to ASHRAE, ±3.5°C as the maximum and minimum acceptable range from the neutral temperature are also in the comfort range for 80% of occupants. Thus, 20.9 minus 3.5 equals 17.4, which is the minimum comfortable temperature. However, when the outdoor temperature is 33°C, the neutral temperature given by the formula is 28.03, which, when added to 3.5, is 31.53°C; this gives the maximum comfort temperature for 80% of the people in the building. So for 80% comfort, the range is almost 17.5°C to 31.5 °C, depending on the outside temperature.

Nevertheless, Fanger and Toftum (2002) believe that the adaptive comfort standard model has limitations as it is only applicable to mean monthly temperatures from 10°C to 33°C, and for large spaces.

> "[It] does not include [a variety of] human clothing or [a variety of] activity... [However,] the adaptive model predicts the thermal sensation quite well for non-air-conditioned buildings…located in warm parts of the world." (Fanger & Toftum, 2002, p. 533).

Since this research will be investigating passive ways of providing thermal comfort with the help of natural ventilation in large, open plan office buildings within a semi-arid climate, it is thus important to consider the ACS model in the analysis.

2.4 Summary of Chapter 2

In this chapter the importance of designing with attention to thermal comfort has been covered. Also amongst the personal factors and environmental factors effecting thermal comfort, the air temperature is highlighted as one of the most important parameters having a huge effect on thermal comfort of occupants. The methods of illustrating comfort zone is looked into and noticed that the methods differ if the building is purely ventilated by mechanical means and uses HVAC than those which make use of natural ventilation also. PPD and PMV are the two methods used for HVAC building and ACD is used for buildings using Natural ventilation also. The formula which indicated the comfort temperature of occupants based on outside temperature in warm season and large spaces for warm parts of the world has been also presented.

CHAPTER 3: Climatic Design and Passive strategies

3.1 Climatic Design

Climate is defined as “integration in time of a physical state of the atmospheric environmental characteristics of a certain geographical location” Edwards and Duplesis (2001 cited in Shokouhian et al., 2007). Buildings are manmade structures that act as shelters from this atmospheric environmental characteristic. Before designing a building, it is important to understand the climate of the area in which it will be located. This is because the design can influence the energy consumed in providing thermal comfort within the building. This thesis will study a region that is classified as a semi-arid climate (also known as semi-desert or BSK according to Koppen’s classification) which is explained in more detail in section 5.1.1.

This chapter reviews the development of climatic design approaches. “Climate-responsive design is a strategy that seeks to take advantage of the positive climate attributes of a particular location, while minimizing the effects of attributes that may impair comfort or increase energy requirements” (Broadbent & Brebbia, 2006, p. 99). Pourvahidi and Ozdeniz (2013) refer to design that addresses people’s climatic needs as bioclimatic design.

Climatic design emerged before modern technology developed. Prior to using any modern means to provide comfort, ancient structures were designed to naturally provide thermally comfortable environments. In the past, there was no air conditioning. Engineers and architects had to be innovative in providing a comfortable environment using natural means; bringing ventilation and daylight to all rooms of the building. After trial and error, they found ways to build structures that were able to bring benefit from the climate they were situated in, and to create the best comfortable environment that was naturally possible. For example, builders had to determine which shape would provide the most natural daylight and ventilation to the inside. Each climate region has therefore, its own particular and unique architecture as designers have had to respond to the climatic needs of that specific place. More analysis of vernacular architecture is provided in section 3.3.1. The success of traditional buildings in meeting the particular climate and comfort needs of occupants has motivated contemporary architects to consider passive techniques to provide thermal comfort environments.

3.1.1 Energy consumption and Importance of Climatic design

Poor design, and not designing according to climate, results in the consumption of a lot of energy and money. Indeed, some towers in the world are designed poorly because they do not incorporate climatic design (Wood, 2008). A significant number of office blocks look similar as a result of derivative designs from iconic structures, rather than developing a unique design born from their particular location (Wood, 2008). Figure 3. 2 is an example of such case provided by Wood (2008) which shows three buildings with very similar designs in the two different climatic locations of Seoul and Jakarta.

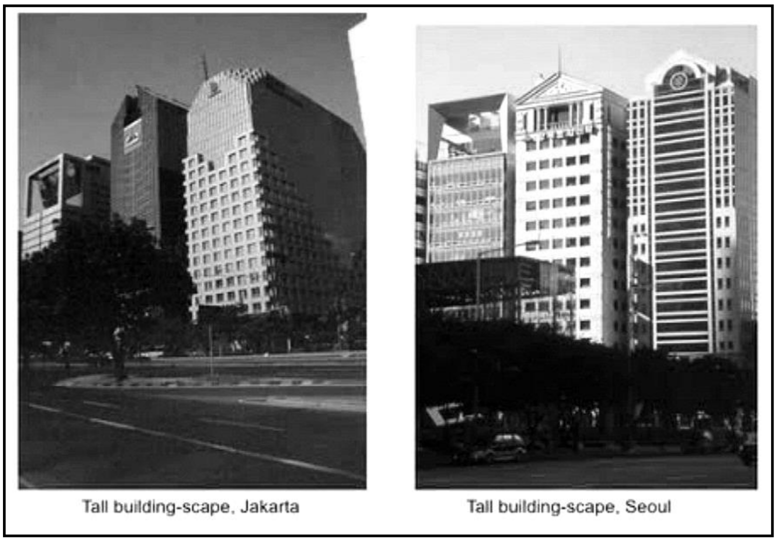


Figure 3. 2: similar looking office blocks (Wood, 2008)

Most copied structures are offices that ignore the impact of the local climate (Santamouris, Papanikolaou, Koronakis, Georgakis, & Assimakopoulos, 1998), have resulted in the excessive use of mechanical heating, ventilation, and air-conditioning (HVAC) systems. Using HVAC was easily affordable at the beginning of 20th Century (Wood, 2008), which meant that designing structures according to climate, didn't seem vital at the time. Following the oil crises in1970's and 1980's airtight dwellings were designed to minimise the heat loss through ventilation however, in order to provide thermal comfort, one of the basic human needs, mechanical and HVAC systems had to be used (Wahid, 2012). These systems can cause other discomfort, such as sick building syndrome, which will be discussed later. It also affects the comfort range of occupants and ultimately can result in more energy consumption. This is the result of dwellings not being designed and built for specific local climate conditions (Salib & Wood, 2013). Thus, designing buildings according to climate has to be given more attention and improved across the world; this also applies in the developing countries of the Middle-East. After the emergence of air conditioning and prior to the energy crises (before the early 1970's), structures were free from any restrictions regarding form, material or design, as there seemed to be no necessity to provide natural ventilation when air conditioning could provide perfect temperatures at a low cost (Douvlou, 2003).

Moreover, in some developing countries, architects, adapted their style of buildings, especially tall structures, from the west, thus importing western style models (Wong & Hassell, 2009). This meant that, even though these western styles might have been designed according to their climate, the building styles might not have necessarily responded appropriately to different climate regions. Therefore, copying styles from western countries without attention to the climate needs of another country and area or city would cause complications.

Similarly, problems could also arise as a result of not considering cultural and social effects, regional architecture, and differing lifestyles (R. Li, 2007). For instance, the majority of the high-rise buildings in the world have large glazing façades which are open to the outside (Hashemi, Fayaz, & Sarshar, 2010). However, such features would be less appropriate in other climates with differing amounts of sunlight, such as the Middle-East. Whilst western buildings can open up to views and sunlight because they face less risk of constantly overheating, the culture and climate of the Middle-East requires a more private and protected design where there is very little glazing on the outside. This also contributes to minimising the cooling and heating loads, by using openings on the inside; for example by including courtyards and gardens (Hashemi et al., 2010; Sozer, Clark, & Elnimeiri, 2011).

After the oil crises in 1973, it was important to lower the energy usage of buildings as much as possible by incorporating energy efficient strategies into the designs without risking the comfort levels inside the buildings (Aldawoud, 2013). It is still important to lower the energy usage in buildings. Indeed, some statistics on energy consumption around the world, and in particular in developing countries, are as follows:

- The percentage of global energy used by the building sector in developed and developing countries is almost 30% (UN environment, 2017) (and out of that 30%, inappropriate structural design is accountable for 40% of the energy consumption in developing countries (Holford & Hunt, 2003).

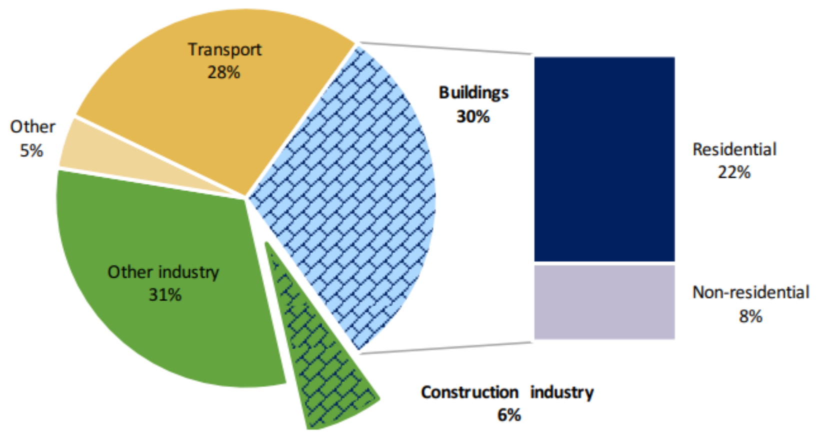


Figure 3. 3: Share of global final energy consumption by sector in 2015

- The building sector's greenhouse gas emissions is almost one third of the global production (Zawawi, 2016). Furthermore, 80% of the gas emissions are usually produced when the buildings are in use; for example, when using heating, cooling, lighting appliances or other applications. Hence it is important to address this at the design stage. This research explores lowering the use of HVAC via natural means, which could also be beneficial in lowering gas emissions.

- Moreover, the world's energy consumption is predicted to increase by 60% by 2030 and developing countries are accountable for two thirds of this (Schröder et al., 2011). Thus, it is important to lower the energy consumption of buildings on a worldwide scale and this can be achieved by addressing these issues on a smaller scale within these developing countries to which this research contributes.

In order to highlight why office design requires particular attention, a comparison in energy has been drawn between residential and commercial buildings between the years 1985 and 2015 (International Energy Agency, 2015) (Figure 3. 4). This figure shows that in both residential and commercial sectors the overall electricity and gas usage has risen considerably in three decades time, however, commercial sector had more overall percentage gas and electricity energy rise compared to residential buildings:

A comparison between the energy consumption of residential and commercial sector in the world between the years 1985 and 2015 shows that the use of electricity and gas (source of heating and cooling) in the commercial sector rose 19% having 75% share of the overall energy consumed in 2015. This is a considerable amount higher than the electricity and gas energy consumed in residential blocks which had a rise of 13% having 43% share of the overall energy consumed in 2015. Therefore, the importance of energy consumption for heating and cooling in office buildings has been highlighted, and attention is needed to lower energy usage in the office and commercial sectors.

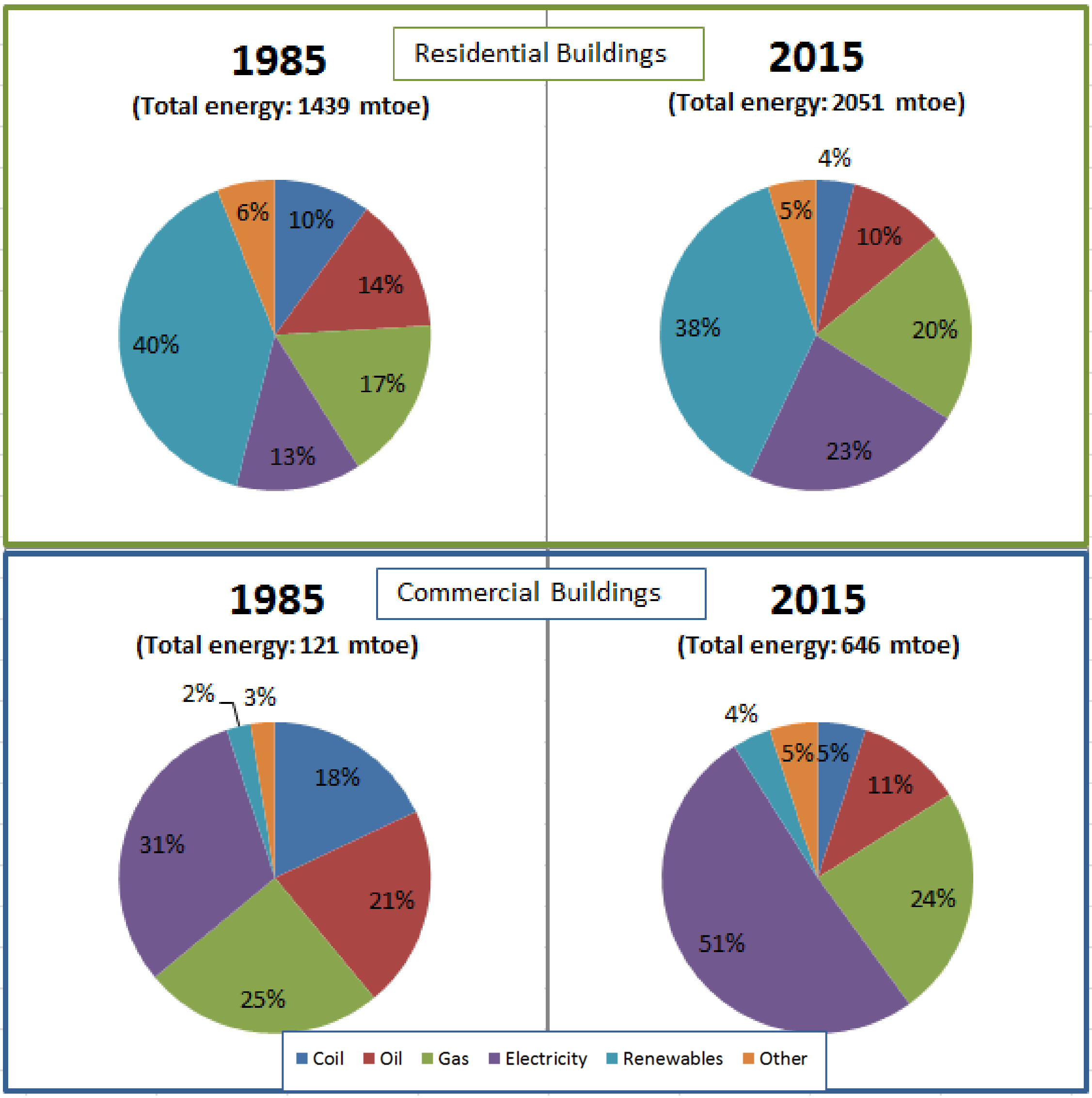


Figure 3. 4: Total final buildings energy consumption (International Energy Agency, 2015)

Nevertheless, Chapter 5 discusses the finding that almost 61% of the overall energy usage is in general employed for heating and cooling buildings in Tehran. Thus, it is important to strike a balance in building design that enable occupants to first use free natural resources as much as possible, and then use HVAC as the only remaining option.

Abdullah (2007) believes that the most common concern amongst architects and engineers lies in how to reduce the energy consumed by HVAC systems. He also adds that, passive low energy design techniques are a practical way to address this, claiming that low energy design techniques are the most effective way to develop low-energy buildings. These are strategies that provide occupant comfort through solar radiation and natural heating and cooling, and thus minimise lighting, heating and cooling energy requirements.

Using passive design elements and natural heating and cooling are not only concerned with lower energy consumption, but also the wellbeing of the occupants. As research shows, the consequences of only relying on mechanical ventilation, especially in airtight buildings, has a negative impact on the comfort and health of occupants. “Sick Building Syndrome” emerges as a result of poor indoor air quality which means the spread of diseases and a basic lack of fresh air (Salib & Wood, 2013). This affects both the productivity and performance of staff in office blocks. In addition, Cook and Shpritz (2010) concluded that fresh air is a simple solution to improve employee health and the working environment. Omrani, Garcia-Hansen, Capra, and Drogemuller (2017) claim that natural ventilation can provide an acceptable internal environment with good thermal comfort and satisfactory air quality. Similarly, Moghaddam et al. (2011) mention that natural ventilation is used in modern public buildings to minimise the non-renewable energy consumption as well as to improve the air quality. Moreover Ji and Lomas (2009a) and Webb (2011) state that, of all the techniques available, natural ventilation provides the most effective method to reduce carbon emissions and achieve carbon-neutral buildings.

To summarise, the advantages of providing a comfortable environment via natural means lie in (Abdullah, 2007; Frazier, 2015; Heidari, 2009):

- Reducing energy consumption
- Reducing resource depletion
- Reducing harmful impacts to the environment because of pollution caused by energy production
- Reducing costs
- Reducing the incidence of Sick Building Syndrome (SBS) where symptoms include: headaches and dizziness, nausea, aches and pains, fatigue, poor concentration,

shortness of breath or chest tightness, eye and throat irritation, irritated, blocked or running nose, and skin irritation (skin rashes, dry itchy skin) (NHS, 2017).

- Improving human productivity because of healthier environments, unlike some buildings which create SBS, partially as a result of using HVAC,(heating ventilating and air conditioning) in tight buildings
- Providing fresh air

Therefore, passive ventilation is a beneficial technique and, as a result, in the 1980’s and 1990’s, designers started to produce designs that considered natural ventilation (NV), passive heating and cooling strategies and energy conservation, and provided a healthier, more comfortable working environment (Salib & Wood, 2013). Sobek (2011) also states that, in the coming years architects will focus on producing designs that provide greater comfort levels, increased natural light supply, better fresh air supply, and energy conservation in cooling or heating air. Therefore, this research will focus on the provision of thermal comfort by using passive design and passive ventilation techniques as a means to provide natural heating and cooling in high-rise buildings with the help of atria (more discussion on atria is in chapter 4) and ultimately lowering energy consumptions.

3.1.2 Factors influencing climatic design

Douvlou (2003) claims that designers who are inspired to develop low energy, comfortable buildings and climate responsive designs need to take into account the following steps.

1. Understand the climate region
2. Understand basic human thermal comfort
3. Improve comfort through the use of thermal mass
4. Enhance visual comfort but also control the sun heating effect
5. Carefully select a strategy to provide space conditioning which is climate responsive

This thesis does not investigate to improve comfort through the thermal mass nor to enhancing visual comfort, however, the other steps have been addressed in this study.

Douvlou (2003) classifies the factors that affect climatic design into two groups: site related factors and architectural factors (Figure 3. 5).

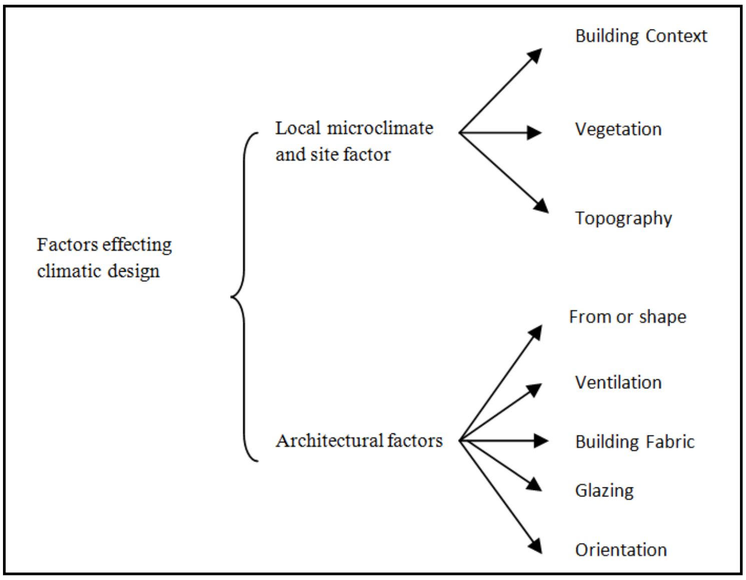


Figure 3. 5: Factors influencing climatic design

The first group investigates the local microclimate and the site factors that might influence on the building's environmental conditions. These are (Douvlou, 2003):

1. **Building context (**nearby buildings)**:** For example, buildings in an open plan area and the free spaces between blocks provide better ventilation. This is because, in high density blocks, the wind speeds at ground level and access to wind flow is reduced (Abdullah, 2007). Therefore, in order to have more chance of natural ventilation for occupants in all buildings, high-rise structures should be spaced at wider distances. In addition, Givoni (1976) believes that the spaces between buildings, the height of the structures, the orientation of street network, and the size of the gardens and their distribution, influence the design of a building with a successful internal environment.

2. **Vegetation** (pattern of growth, location, mass, height)**:** vegetation could improve the microclimate of buildings by providing shading and fresh air. They also filter the air and provide moisture(Yeang, 2006). In addition, vegetation alone, or with the use of water, could create a pleasant atmosphere, minimising the use of HVAC, cutting costs and helping to avoid overheating problems in building spaces (Abdullah, 2007).

3. **Topography** (ground surface conditions, hills and valleys, slopes, elevation)**:** for example, buildings on a high ground may have a better chance of catching wind for natural ventilation than those located in valleys.

The second group are the architectural design factors, which Douvlou (2003) believes to consist of four main categories, namely: the shape of a building, ventilation, a building's fabric/material and its fenestration/glazing. However, Brien, Pearsall, and O'Keefe (2010) believe that orientation is also one of the design factors that produce an efficient passive low energy design for a naturally thermally comfortable environment. As such, the five different factors are:

1. **Form or shape** (building height, surface to volume ratio)**:** The form of the building could affect its efficiency and is defined by the climate conditions (Rashdi & RashidEmbi, 2016), the functionality of the building and the socio-cultural requirements (Douvlou, 2003). For example, climate conditions might determine whether cross ventilation is needed and, as such, deep plan buildings will not be as efficient as narrow plan buildings when it comes to cross ventilation for cooling (Abdullah, 2007). The ventilation factor is described in detail later in this section. Also, a flat roof shape could be an advantage in some parts of the world in winter, when it can act as insulation if covered with snow. High ceilings also provide an advantage in hot climates where heat can rise well above head height (Abdullah, 2007). Moreover, Rashdi and RashidEmbi (2016) states that the lower ratio of surface to volume will help passively in reducing cooling loads in a

2. **Building fabric** (materials and construction, thermal mass and thermal insulation)**:** Thermal mass and thermal insulation could control the amount of heat gain and heat loss in wall, roofs or floors (Reardon, McGee, & Milne, 2013). When used in buildings, heavyweight materials, such as earth, stone, solid concrete or brick, are known to be of high thermal mass and can store the heat of the sun during the day to release it slowly during the night. The greater the mass, the slower the temperature exchange between out and indoors; This helps in not losing heat in winter, whilst in summer it helps to heat up gradually and slowly; On the other hand, materials that are light react rapidly to the changes in temperature and are known to be suitable for rooms that need rapid heating or cooling (Douvlou, 2003; Reardon et al., 2013). Moreover, materials with thermal insulation could affect the spread of heat between the indoors and outdoors, which could be an advantage if used correctly. For example,

they could help with thermal comfort and ensure significant energy savings, as they can be effective in keeping the heat inside the building when it is cold outside or the heat outside when it is hot, therefore, this helps to control the temperature of the building. Finally, the fabric colour of the inside or outside façades also has an impact on heat gain. The darker the colour, the greater the heat absorption (Yeang, 2006).

3. **Orientation**: The orientation of a building is important in relation to climatic design. For example, if the building is orientated towards the south in a northern hemisphere, and towards the north in a southern hemisphere, it allows maximum sunshine in winter and protects from peak heat in summer (Abdullah, 2007). Also, if the long elevation faces the sun, more heat gain could occur than when a smaller façade is exposed in winter. In summer the sun angle is high and its best to have small façade on east and west where sun angle is low. By avoiding the exposure of interiors to direct sunlight, cooling loads and the need for mechanical air conditioning devices, such as HVAC are reduced. Therefore, a correct orientation can help to control the cooling and heating in buildings (Brien et al., 2010). In cases where an appropriate orientation is not possible, devices, such as shades, could be of help in blocking harsh direct sunlight from the interior.

4. **Glazing** (window size, position, glass material and shading devices)**:** This is an effective way to provide warmth and light, allowing sun penetration inside. The amount of glazing and its position is important as it has an important role on the energy consumption of buildings (Abdullah, 2007). The more the glass, the more sun rays can enter and generate more heat gain, therefore, the balance between sufficient heat gain and sufficient natural ventilation should be considered in the design stages of a building (Abdullah & Wang, 2012). Such decisions will depend on the climate of the region and on the fact that the buildings may need more help with heating loads in a cool season or with cooling loads in a warm season. However, care must be taken to provide shading in circumstances where heat is not welcomed. Shades and solar blinds help minimise heat absorption (Holford & Hunt, 2003). Creating shade has been important, especially in the vernacular architecture of the Middle-East (Michell & Grube, 1995). The vernacular structures were designed to create shade for semi-open places, such as courtyards, bazars and narrow streets (Weyland & Oncu, 1997). Overhangs also have a useful effect in blocking the summer high angle sun rays. This prevents overheating whilst at the same time allows the low angle sun penetration in

winter and welcomes solar heat gains to help with heating loads (Abdullah & Wang, 2012).

5. **Ventilation** (natural ventilation)**:** As explained in the first point the choice of ventilation technique influences the design shape of the building in the early stages. It is advised that architects and engineers should choose the option that maximises the amount of acceptable natural ventilation for occupants' potential needs in buildings (Abdullah, 2007).

   There are different ways to achieve cooling in spaces (Ghiabaklou, 2010; Salib & Wood, 2013): for example, cooling the building fabric, cooling and refreshing indoor air by incorporating outdoor air (this is useful when the outdoor air temperature is lower than inside), and by cooling the occupants directly through convection and evaporation. However the efficiency of the last option depends on the speed of the air movement, known as the air flow rate. Salib and Wood (2013) confirms that even in high temperatures, the psychological cooling effect achieved through the convection and evaporation cooling method, can minimise occupant discomfort with high speeds of 1-2 metres per second. Norton (1997) states that cooling via convection accounts for 30% and evaporation for 25% of body heat loss in normal comfort conditions. Behbood, Taleghani, and Heidari (2010) also suggest that air temperature in combination with air movement affects the speed of warm air taken away from the body and the body temperature. Moreover, the use of night coolness to bring down the temperature of the mass material helps towards the cooling loads on the following day (Abdullah & Wang, 2012; Holford & Hunt, 2003). Therefore, night time ventilation helps to improve thermal comfort and reduce cooling demands (Hussain & Oosthuizen, 2013). Hussain and Oosthuizen (2013) state that this technique has been successful in many low energy passively cooled office buildings. He also adds that night time ventilation is at its most effective in terms of cooling when the temperature difference between day and night is large. This is because it helps to eliminate the warm air that has built up inside the building space and in the building fabric during the day and thereby cool the building fabric in order to enable it to act as a heat sink for the following day.

   In addition, it is important to know how air movement is generated in spaces. Three main types of ventilation are: single-sided, cross-sided and stack ventilation. Single-sided ventilation works sufficiently if the depth of the room is less than 2.5 times its height, whereas for effective cross ventilation, the maximum depth of the room can be five times its height (Irving, Ford, & Etheridge, 2005).

Advance natural ventilation methods are also used via incorporating features such as light wells or atria (more description on these features are presented in section 3.2.2. Ji and Lomas (2009a) mentions that advance natural ventilation methods are classified as " Edge-in, Centre out (EC), Centre-in, Edge-out (C-E), Edge-in, Edge-out (EE) and Centre-in, Centre-out (C-C). Existing examples of ANV buildings which have used one or more of the above ventilation strategies include: the Queens Building at De Montfort University, Leicester, where the E-C strategy was used…; and the Frederick Lanchester Library at Coventry University where the C-C and C-E strategies were used ... The Harm A Webber Library for Judson College, Illinois, near Chicago, uses a hybrid approach, in which both the C-E and E-E strategies are used in combination with mechanical cooling to combat the warm humid summers and the cold winters…"

Stack ventilation, and other forms of air movement through a building, is caused by pressure differences (Awbi, 2003; N. Khan, Y. Su, & S. Riffat, 2008b; Moosavi, Mayhyuddin, Gharfar, & Ismail, 2014). These pressure differences (stack effect) are either due to temperature differences between the two zones (buoyancy effect) or due to the wind effects (Daemei, Limaki, & Safari, 2016):

- **Buoyancy induced ventilation**: "Buoyancy is the upward force exerted on an object when it is immersed, partially or fully, in a fluid" (NPL, 2010, para. 1). It is believed that buoyancy driven ventilation causes the stack effect ; "The stack effect is when warm air moves upward in a building" (NC State Extension, n.d., para.2) (Figure 3. 6).

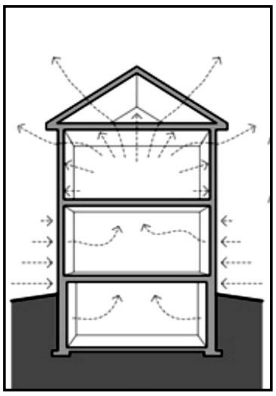


Figure 3. 6: Air movement in building with the help of buoyancy force (Straube, 2007)

The buoyancy driven ventilation performance is dependent on a difference in temperature between the outside and inside spaces (Hussain & Oosthuizen, 2013). Moreover, according to Moosavi et al. (2014), factors that influence buoyancy driven ventilation are; lower level inlets, higher outlet openings, and heat. One of the natural heat sources is solar radiation, which helps in enhancing natural ventilation in spaces through the buoyancy effect. Even though the penetration of solar radiation by daylight through glass or a roof has been the most significant factor in temperature discomfort in buildings (R Li & Pitts, 2006), careful strategic building designs can also prove beneficial in enhancing the thermal and ventilation performances of spaces such as atria by assisting the stack effect.

Also when the outside air temperature is lower than the inside air temperature, an inward airflow is guaranteed. Buoyancy induced ventilation is specifically helpful in maintaining the indoor temperature at night (Moosavi et al., 2014). This type of ventilation generally works more efficient when indoor temperatures are greater than the outdoor temperatures (N. Khan, Y. Su, & S. Riffat, 2008a).

However, if this situation is reversed, air may enter through high level vents and discharge at low level vents. According to Hussain and Oosthuizen (2013), outside temperatures have a major effect on inside thermal performances. When the outdoor temperature is below 30°C, the buoyancy effect can be utilised as a natural ventilation technique in order to reach the thermal comfort level defined by ASHRAE standards. However, if it is above this degree, other ventilation techniques (such as HVAC) have to support the situation in order to achieve the same thermal comfort level.

- **Wind induced ventilation**: Wind induced ventilation can also increase the stack effect (Chan, Riffat, & Zhu, 2010). It can create negative and positive pressure on the windward and leeward sides of a building, which has an effect on natural ventilation (Mahmoudi & Mofidi, 2008). These outside pressure differences, along with the pressure differences on the inside, lead to the drive of air flow in the building (Moghaddam et al., 2011) (Figure 3. 7). Moosavi et al. (2014) explain that the positive pressure is created on the inlet opening, which is towards the wind (the windward side) and the negative pressure is on the outlet opening (the leeward side). They confirm that the pressure field around the building changes when the wind direction varies causing the inlet openings to experience a change of pressure from positive to negative and therefore act as an air outlet or as a vent exhaust. As such Ghiabaklou (2010) confirms that there are two types of pressure difference caused by wind; namely steady or unsteady. He explains that the steady pressure difference occurs when there is a strong prevailing wind which leads to cross ventilation. In contrast, when the wind is unsteady, turbulence ventilation takes place where the air inside does not have a steady cross flow.

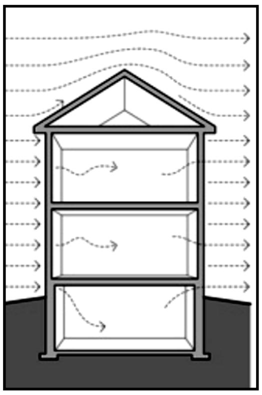


Figure 3. 7: Air movement in building with the help of wind force (Straube, 2007)

In all climates, but especially where the temperature of the interior does not differ much from the exterior (N. Li, Zhang, & Zhang, 2009), it is important to use the combination of wind induced force with the buoyancy force in order to provide a better indoor environment and to optimise natural ventilation. This is because buoyancy alone may not be sufficiently strong and efficient to provide thermal comfort in buildings especially those with an atrium (Moosavi et al., 2014). The strength, the resistance of the flow path and the direction of these forces determine the ventilation rate (Allocca, Chen, & Glicksman, 2003). Moreover, if the air passes through narrow sections it can speed up and provide more surface contact whilst helping to cool the thermal mass of the building fabric (Maleki, 2011).

In order to apply an appropriate design strategy to modern buildings in a region, and to design according to the environment, it is important to learn lessons by studying the vernacular architecture of that region that has been successful in addressing thermal comfort temperatures inside buildings. Later on, an investigation could be conducted into modern passive design techniques in tall buildings in order to identify the most similar stategy with the vernacular architecture of the region. This can provide a further indication as to what modern passive design elements might work for assisting heating and cooling loads in a natural way inside high-rise blocks.

3.2 Design strategies

Despite the high-energy consumption of buildings today, the historical vernacular strategies avoided excessive energy consumption and used nature as much as possible. In order to design comfortable indoor environments based on natural means, it is important to understand the different passive design techniques available in traditional and modern architecture. Moreover, Nelson (2010) states that architects must approach climatic design by first looking into how successful traditional designs worked in order to create and select successful modern designs which provide thermal comfort and reflect the climate of the region. Below are some examples of vernacular architecture as well as some modern design strategies that have been inspired by vernacular designs. Finally, by comparing the vernacular strategies of arid regions with modern techniques inspired from this vernacular architecture, a potential modern design strategy could be chosen that would benefit the occupants of semi-arid climates.

3.2.1 Vernacular passive heating and cooling design strategies (case study of Iran)

Vernacular architecture is known as an ideal source of sustainable design because it aims to achieve thermal comfort temperature via passive low energy strategies (Wahid, 2012). The ways to achieve a comfortable temperature can differ from place to place depending on the culture and climate. Tehran, the capital of Iran, has been selected as a case study for this research. According to Roaf (1997), Iran has buildings from antiquity and a rich diversity of types due to its geographic location and climate diversity. It is thus one of the most architecturally fascinating regions. To achieve comfortable passive ventilation and thermal conditions in the historical architecture of the arid regions of Persia, the flow of air, or water and air was used (Castle, 2012). Naciri (2007) suggests that the techniques are discovered and applied slowly to modern forms of today. Soleymanpour, Parsaee, and Banaei (2015) have conducted research into the vernacular techniques used in Iran and have presented a sample graph that summarises its application (Table 3. 1 to Table 3. 4).

Table 3. 1: Analysing climate comfort vernacular houses of Yazd city, a hot and dry city of Iran

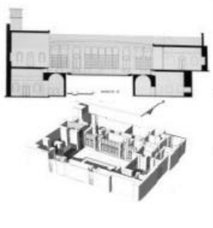
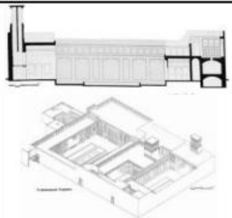
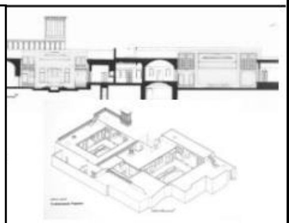
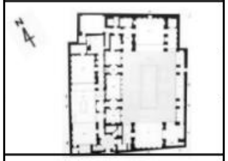
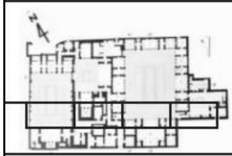
Climate component	Architectural Strategies	Rasulian house	Arabha House	Golshan house
The use of heat capacity of the soil to air cooling	the ground floor level lower than street levels			
	using basements			
enhancement of air turbulences	using wind towers			
	Windows toward courtyard			
Increasing indoor heat in the winter	Orientation to south-eastern			
	The dense settlement pattern			
Reducing high difference of the temperature between day and night	using materials with high thermal capacity and heavy external and internal walls			
Increase humidity	water pool and trees in the courtyard			

Table 3. 2: Analysing climate comfort vernacular houses of Bushehr city, a hot and humid city of Iran

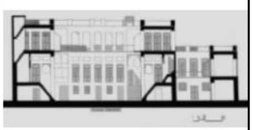
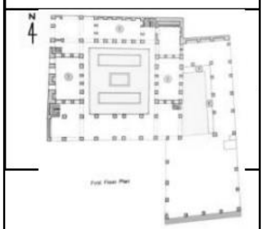
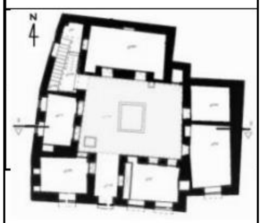
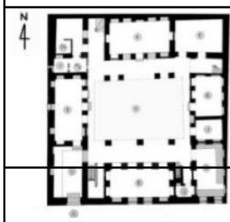
Climate component	Architectural Strategies	Mehraban house	Mokhtarzade	Tabib house
exclude direct sunlight	cover extensive deep verandas			
	small central courtyards			
enhancement of air turbulences	high ceiling and wide windows			
	windows on both sides of single-banked rooms			
	minimum joint walls with neighbors			
	oriented towards the wind from the sea			
preventing excessive absorption of heat	Indigenous materials with the low thermal capacity			
	brightly colored exteriors			

Table 3. 3: Analysing climate comfort vernacular houses of Rasht city, a temperate and humid city of Iran

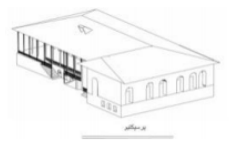
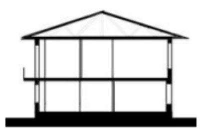
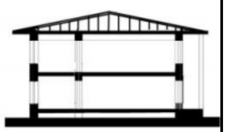
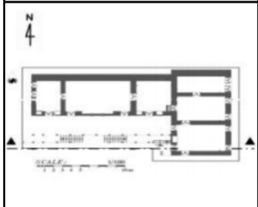
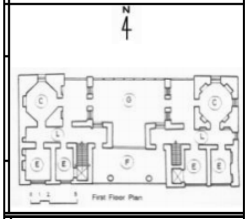
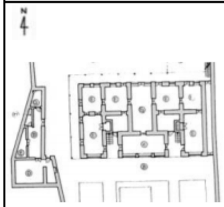
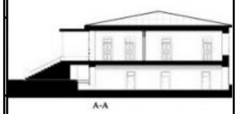
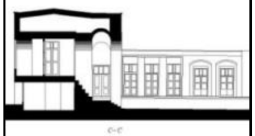
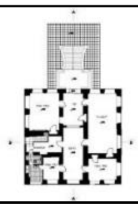
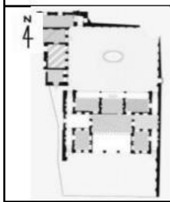
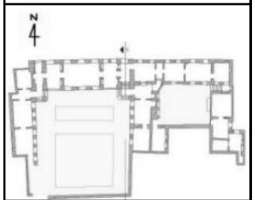
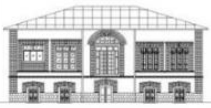
Climate component	Architectural Strategies	Avadis house	Samiei house	Abrishami house
Disposal of rainwater	extending gable roof over balconies			
No moisture absorption	Ground floor's slab upper than the ground level			
Heating in the winter	Orientation toward South			
	spread Open and wide settlement pattern, Plan proportions 1 to 3			
enhancement of air turbulences	deep continues balcony			
	material with minimum thermal capacity			
	large number of openings			

Table 3. 4: Analysing climate comfort vernacular houses of Urmia city, a cold city of Iran

Climate component	Architectural Strategies	Majidi Afshar house	Hedayat House	Ansari house
Disposal of rainwater	gentle sloped roofs			
absorption of heat	Ground floor lower than a natural ground level			
	small verandas			
	Introverted Buildings with southern courtyard			
	Using thermal mass			
temporary provision for air movement	using windows to enhance air movement			
Receive solar radiation in winter	Located according to the sun radiation, Plan proportions 2 to 3			
	large windows in the southern Front of building			

As mentioned, Soleymanpour et al. (2015) outline the vernacular architecture of different climates of Iran. Whilst there are no vernacular buildings specifically listed for semi-arid climates, the mixture of cold and arid climates would give an idea as to what needs to be considered for a semi-arid climate. The information in the above tables show that in most climates of Iran, the courtyards are part of the vernacular design strategy, especially in hot and cold climates. Moreover, the building is generally orientated to the south so that windows can benefit from the south sun in cold climates (the cool season is also the dominant season in the Tehran case study, which is explained in chapter 8 and 9). Nevertheless, Pourvahidi and Ozdeniz (2013) state that there is a slight difference in the vernacular architecture of hot and dry climates and the climate zone classified as hot and dry with cold winters (semi-arid climate). Although the vernacular design is similar, the main difference "is the provision of more open spaces... [In hot dry climate as oppose to hot dry with cold winters, a] Central courtyard is very suitable for summer to keep the coolness and humidity of night and give refreshment during the summer days. It is also suitable for winter to protect the rooms from winter winds" (Pourvahidi & Ozdeniz, 2013, p. 13).

Moreover, the materials ideally need to have a high thermal capacity, both in dry and cold climates, and wind catchers are experienced as useful in dry hot climates (Pourvahidi & Ozdeniz, 2013; Soleymanpour et al., 2015) (this is particularly the case for warm seasons in the case study of Tehran).

The features of the courtyard and wind tower, which are the iconic features of Iran's vernacular architecture are explained in more detail:

- **Badgir or wind catchers**: These are chimney like structures above roof level designed to catch the fresh, less dusty air, or used as means to extract exhaust air (Figure 3. 8). They are one of the masterpieces of Iran's architecture, and reflect the understanding of predecessors in working with climate design and in providing an example of clean energy (A'zami, 2005) which provides natural ventilation and cooling (L. Li & Mak, 2007).

Figure 3. 8: Baghe Dowlatabad windcatcher (Neoh, 2015)

According to Roaf (1997) these structures date back to 2000 BC in the Middle-East and the central plateau of the city of Yazd in Iran. However, Maleki (2011) claims that the first historical evidence of their use date back to 4000 BC, and were found by a Japanese expedition to a house in the north east of Iran at the site of Teppeh Chackmaq. Regardless of date, it is apparent that these structures were born in Iran in the Middle-East and are perfectly suited the climate conditions. The greatest Badgirs are allocated in Yazd, and date between 1868 and 1900, with the most elaborate example being Baghe Dowlatabad (Roaf, 1997) shown in Figure 3. 8 and Figure 3. 9.

Figure 3. 9: Below the dome of Baghe Dowlatabad (Najafi, 2015)

Badgirs work by mainly taking fresh air into the building and exhausting hot, polluted air (Moghaddam et al., 2011). In large towers, the temperature difference between the top and bottom of the shaft can be 2°C (Roaf, 1997). In some situations, it has been seen that the cool air in the basement, guided by the wind tower, can have a temperature difference of 9°C when the outside air is 32°C (Maleki, 2011).

There are also different types of wind catcher; for example, wind towers differ in height, placement, and the number of openings at the top. Wind catchers have an inlet and sometimes an outlet, which is a division of the wind tower shaft. Sometimes the outlets are placed somewhere other than a division in the wind tower; such as the outlet vents on the dome (Figure 3. 9) or skylights (Bahadori, 1978).

The sucess of windcatchers is due to the effect of wind and bouyancy, which helps to maintain natural ventilation through the living spaces (Moghaddam et al., 2011). There are two scenarios, namely; when there is wind, and when there is no wind. Moghaddam et al. (2011) explain these as follows:

- Scenario 1- Wind assisted ventilation in wind catchers: When the wind hits the internal blades of the wind catcher, since the density of the air is thick, it creates positive pressure and descends into the room. However, the other hole (or holes) of the wind catcher, which are on the leeward side, have a negative pressure and act as a sucking machine releasing the hot and exhausted air from the building to outside.

- Scenario 2- Buoyancy assisted ventilation in wind catchers: The wind catcher functions even when there is no wind, whether day or night. In the day, the sun hits the wind catcher on the southern façade causing the air to heat and rise acting as a solar chimney. Also, the hot air inside the room rises up to escape through the vent (Norton, 1997). This creates a suction effect which helps to draw the cool air inside the room from the porch, or as Naciri (2007) claims, the cool air can be sucked in from the northern section of the wind catcher and enable comfort through evaporation and air motion (Maleki, 2011). However, if the outside air is warmer than inside, the cool air stays inside the room keeping the occupants more comfortable (Norton, 1997).

  Nevertheless, when there is no wind at night, the cold night air moves down, gets warmed up again, and goes up to be released. Although, this air circulation continues until the temperature of the outside and inside walls become equal, it is usually daylight before that is achieved. Roaf (1997) summarises that the wind catcher's purpose is to cool down the building structure at night and to help cool down the occupants through natural ventilation during the day.

Moghaddam et al. (2011) claim that the principles of wind catchers can be adopted in new buildings in order to create thermally comfortable environment. It will be explained in section 3.2.2.3 that the contemporary use of wind catcher technique in high rise buildings is wing walls as it is a technique to capture wind in high rise buildings. Also thermal flue is the contemporary version of a solar chimney used in high rise buildings also mentioned in section 3.2.2.4. Last but not least, wind catchers are also used in conjunction with courtyards, which are another beneficial strategy in providing a thermally comfortable temperature.

- **Courtyards**: are one of the typical traditional architecture features of Iran with all the other building spaces surrounding their open rectangular space. They have both an environmental and social function, and act as a source of fresh air, light and heat (Cho & Mohammadzadeh, 2013). Figure 3. 10 illustrates an example of a courtyard in Kashan, one of the cities of Iran.

Figure 3. 10: Tabatabaee house in Kashan (Iran) (Kashan.today, n.d.)

Courtyards have been used in different places (Norton, 1997) because they are energy efficient in all climates, but particularly in those that are hot-dry and hot-humid (Aldawoud & Clark, 2008). Furthermore, they play several roles and provide several advantages. One of their most important characteristics is that they act as a reservoir of cool air and are an excellent thermal regulator (Cho & Mohammadzadeh, 2013; Heidari, 2010b). In order to maximise their efficiency, courtyards should be sufficiently deep compared to the height of the walls so that they can stay shaded for most of the day (Norton, 1997). Donham (1960) believes that this allows more ‘heat dissipation’ from surrounding indoor rooms and ensures less thermal impact from the sun. Heidari (2010b, p. 20) adds that courtyards, especially those central placed that are surrounded by the building on all four sides, “introduce the outdoor into the heart of the building core and maximise the thermal interaction between them”.

In terms of their summer night functionality, the cold air sinks into the centre courtyard and the fabric of the building is cooled down, hence the rooms’ temperatures surrounding the inner court drop substantially (Naciri, 2007; Sozer et al., 2011). This night cooling technique, along with the courtyard being shaded for most of the day, helps the walls and floors to hold the coolness throughout the hot day and provides comfort to occupants. Norton (1997) states that it is important that the house has no, or limited, external openings on the outer façade so that the cool air can stay in the base of the yard, enabling the courtyard to functions as a reservoir of coolness.

The most important factor of the courtyard design is the height of the surrounding walls, which affect the air velocity in the central yard. Olgyay (1992) also states that it is important that the courtyard is also the optimum shape, namely rectangular, to maintain a more successful climate response. Heidari (2010b, p. 25) concludes that the, “air flow pattern in courtyard[s] are the function of their depth to width ratio”. He also states that the smaller the size of courtyard, the better it is in warm seasons to achieve shade during the day and minimise the thermal impact.

Courtyards also have the role of connecting rooms as well as serving as a gathering area for families. These common spaces are likewise the source of daylight (Sozer et al., 2011). Khodabakhsh and Mofidi (2001) state that, in traditional countries of the Middle-East, the attitude towards daylight and views are very different from western cultures. They believe that the people of this region do not openly invite sunlight due to the risk of overheating. Moreover, privacy is part of the culture (Naciri, 2007) and so buildings opening up to light from their inner courtyards present an acceptable solution culturally as well as environmentally. As the openings concentrate on the inside, courtyards provide views and often offer garden and fountain sights for the rooms surrounding them (Saatci, 1997).

Water features in courtyards, provide a significant advantage for managing temperature (Castle, 2012). In summer, they help with cooling by producing an evaporative cooling effect to decrease temperature and increase comfort level (Castle, 2012). Oliver (1997) also indicates that traditional houses that have pools or fountains in the yard help significantly in reducing the heat. This is achieved via cross ventilation over the water, which impacts on the surrounding rooms and spaces, functioning as an additional cooling system.

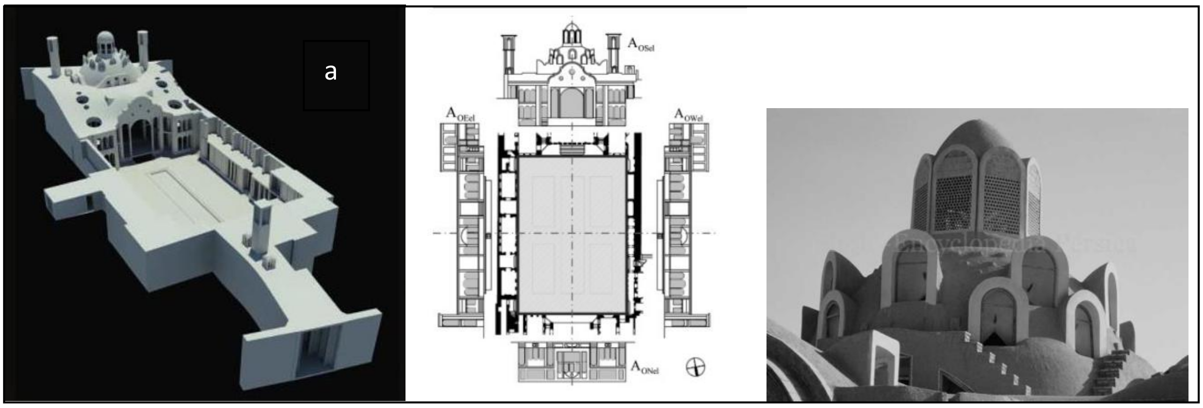


Figure 3. 11: Boroujerdi-ha house using a courtyard, wind catchers and roof vents (a) 3d view, (b) elevation view, (c) the roof (Gharleghi & Sadeghy, 2012)

Boroujerdi-ha mansion in Kerman is an example that uses a few of the techniques described, such as domes, water, courtyards and wind catchers, to ventilate and cool inside spaces (Figure 3. 11). Wind passes through the courtyard and over the water, which helps the air to cool down. It then enters the building, gets warmed up and is pushed up by the fresh cool air entering the space. Gharleghi and Sadeghy (2012) explain that the hot air rises up to the high ceiling of the dome in the central part of the house, which is built intentionally high to guide unwanted hot air above the living level area, and exhaust air through openings at the top of the dome. They add that Boroujerdi-ha house also has three wind catchers, which catch cooler air from above, channel it down into the rooms, and cool it via evaporation and convection.

Depending on the climate, exhaustion is achieved either by the courtyard, for the rooms not connected to the dome, or via the vents on the dome in the main gathering room of the house.

Never the less, it is important for the courtyards to be narrow enough to maintain shaded area during summer and wide enough to receive solar radiation during cool season to help with heating loads (Donham, 1960; Givoni, 1976). In such case there is seasonal movement in living spaces for occupants between warm season and cool season in order to respond to climate conditions (Memarian & Sadoughi, 2011). This means that with the house enclosed from outside and opening to the courtyard, the sunny side of the courtyard houses which is the north is used during cool season and the shaded side which is the south is used during warm season (Soflaei, Shokouhian, & Mofidi, 2015). Most of courtyard houses in desert climate are along the north-south direction or northeast–southwest, or northwest–southeast, to maximise the use of summer and winter living (Ghobadian, 2006, cited in Soflaei, Shokouhian, & Mofidi Shemirani, 2016). Never the less, Soflaei et al. (2016) believes that in desert climates "The south–north or west–east direction without a rotation angle can be considered the appropriate orientation for courtyards. However, the local geographic and environmental conditions, as well as the latitudinal location, cannot be neglected."

Other techniques also used in arid countries around the world are as follows:

1. Mashrabiyya: grills over the window openings providing shade and permitting air circulation, often in hot, humid climates (Earls, 1997).
2. Pierced walls: Cross ventilation between large windows facing inner courtyards and small, eye-level windows facing outside; these are usually used in India (Ganapathi, 1997).
3. Vents or coral slabs: vents allowing air to enter at the top, pass through the cavity wall, and enter the room at floor level (Zandi, 1997).
4. Double skin roof: ventilated space between the outer roof and inner ceiling that prevents thermal gain; these are used in Bojnordiha house in Iran (Castle, 2012).
5. Air funnel: the entrance lobby acts as a wind tunnel cooling the rooms in contact with it and directing air to the courtyard, which acts like the lungs of the house (Ganapathi, 1997).
6. Water (Ghanat and water features): Ghanats are vertical shafts in the ground, often used to supply water and to help with cooling the air when it passes above. Roaf (1997) claims that many traditional buildings have these tunnels in order to provide comfort.

7. Use of domes: domes are usually situated above a main square room in the house with small air vents to draw hot air out of the space. They are often seen in the houses of Yazd in Iran (Naciri, 2007).
8. Kasbah: tall walls with very small windows built closely to each other, and mostly in North Africa, to protect occupants from extremely sunny days (Figure 3. 12). The plan of a Kasbah usually combines a major atrium inside, typically referred to as courtyard, which is an important asset in climate control within these houses (Naciri, 2007).

Figure 3. 12: Kasbah (Naciri, 2007)

9. Covered streets: this method draws in the cool air, stored in the shaded streets between dwellings, to the courtyards via convection (Figure 3. 13). It helps the exteriors of north African houses to stay cool during the day (Naciri, 2007).

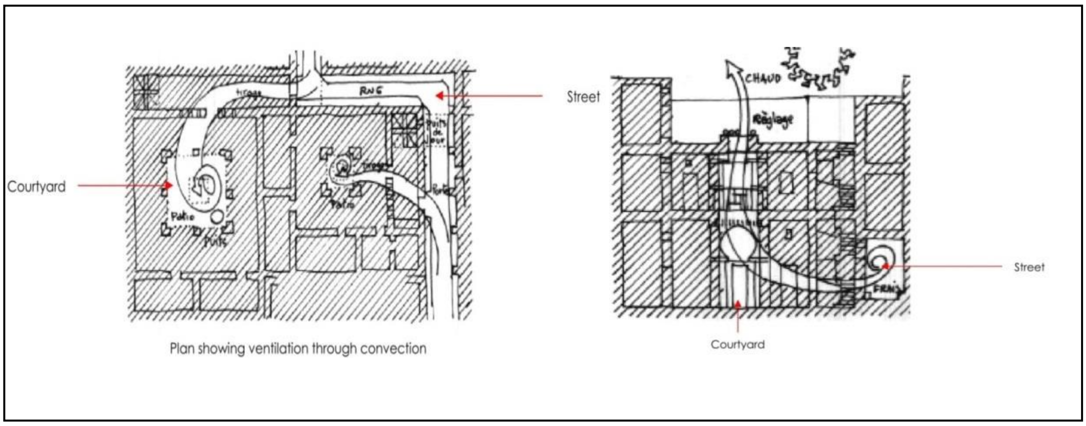


Figure 3. 13: Air flow from covered streets to courtyard (Naciri, 2007)

10. Passive downdraft evaporative cooling: this technique is mostly seen in India where a fine mist of water is released at the top of three large intakes located above the atrium or courtyard. The mist helps to cool down the air, which then descends slowly and helps occupants to achieve thermal comfort. An example of this is Torrent Research Centre in Ahmadabad, which achieves 72% of its human comfort through this technique, with 6 to 9 ac/h on different floors in summer (Wahid, 2012).

All of these traditional systems have been effective when there is a need to provide natural ventilation or to control any discomfort temperature. Soleymanpour et al. (2015) claims that the climate comfort of buildings today have decreased because of their dependence on new technologies. This is not a good solution for all climates and therefore suggests a lack of human-oriented design. Consequently, research is needed into how to incorporate as well as translate old strategies into modern tall buildings considering the seasonal variations of semi-arid climates.

3.2.2 Modern Passive heating and cooling Design strategies in world

This thesis focuses on modern tall buildings. The reason why some modern buildings are built as tall structures is that they accommodate more people in a square metre of a land compared with low rise blocks (Sauerbruch et al., 2011). In some dense cities, where land is limited and expensive, high-rise structures seem to present a good solution. Also, among other advantages, high rise structures create a lower carbon footprint compared with low-rise structures (Sauerbruch et al., 2011) and use less material for usable floor space, which Sobek (2011) believes is important in reducing energy loads. They also share natural energy between floors (Salib & Wood, 2013); for example, in cold seasons the hot air rises towards the ceiling and helps the above floor with its heating loads. As a result of these advantages, high-rise buildings are being built more often; however, it is important to design them according to the climatic needs of the place.

Until now, vernacular techniques have been overlooked that provide good thermal comfort temperatures, especially in the arid climates of Iran. However, as mentioned previously, one should also look at these passive design techniques for inspiration for the high-rise design structures of today. As a result, the most similar strategy between old and new, namely the successful vernacular strategy of the region and modern passive strategy for today's tall buildings, could be chosen as a possible solution that might work for a semi-arid climate. This strategy could have the potential to be successful in energy saving by bringing down cooling and heating loads on hot and cold days.

Salib and Wood (2013) believe that modern passive design techniques have been inspired by traditional solutions, and the basic principles used for many years for inside ventilation are being relearned by individuals. Also, there have been some passive design options for designing buildings, such as using double skin façades (pressure rings), dynamic or porous envelop materials, wind turbines, sky courts, atria, wing-walls, and/or solar chimneys (sometimes known as thermal flues). These strategies have been used in today's tall structures in order to respond to climate needs. The atrium and sky courts, wing-walls, and solar chimneys are explained in this thesis because they are the most similar technique to the iconic features of Iran's vernacular architecture of courtyards, wind catchers and open top domes, which are iconic features of Iran's vernacular architecture; Therefore, more detail about these features and their functionality in modern buildings will be provided with examples, as described below.

3.2.2.1 Atrium (open and closed top)

The concept of an atrium was partially inspired by courtyard, which was an old tactic for climate control (Abel, 2000b; Medi, 2010) and it can be used in different climates (Norton,1997). Shokouhian, Soflaei, and Nikkhah (2007) also believe that courtyards can inspire designs that respond to different climate conditions. This is because they can be designed to be narrow enough to contribute to the shading of space in summer and wide enough to absorb solar energy from the sunrays inside the area in winter. It can be argued that atria are somehow the extrusion of courtyards with or without a roof. Atria were usually used as spaces to provide light and circulation, especially in offices and commercial buildings (Medi, 2010). However, after the energy crises of the 1970s, some architects started designing atria in a more sustainable way and as means to help with passive ventilation.

Some architects think that having an atrium to assist with the thermal comfort temperature provides a considerable advantage. For example, Salib and Wood (2013) believe that, in architecture designs, and especially in deep plan offices, atria help with insubstantial additional pressure over the height to provide a buoyancy effect. However, it should be mentioned that wind passing over the top of the tower also creates suction at the outlets and negative pressure. This helps the buoyancy effect, which relies on temperature difference between inlets and outlets.

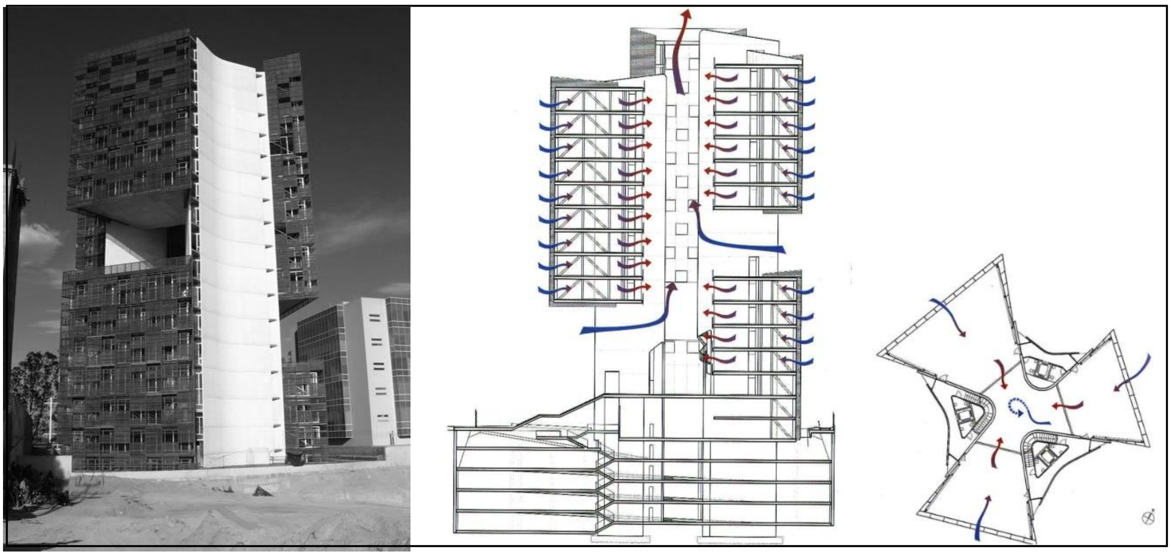


Figure 3. 14: Cube Tower in Mexico, section and plan of the natural ventilation flow (Al-Kodmany, 2015)

Some buildings, such as Torre Cube in Mexico, have achieved success in naturally providing a comfortable thermal temperature (Figure 3. 14). This building is designed to provide 100% natural ventilation throughout the year without the need to use HVAC or any other artificial system (Al-Kodmany, 2015). The tower has a central atrium, which is roofless and interacts perfectly with the climate that it sits within. In fact, the atrium, being an open void, is the key element of the design. It is open from the top as well as in the façades of each office wing, also creating porches. The porches allow for greater air circulation and provide social spaces. Natural air flow in the offices comes from the external windows, to the windows open to the atrium. The exhausted air is drawn out of the office by the additional uplift as a result of negative pressure in the atrium. The wing design takes advantage of each office floor opening in four directions, thus it can directly capture almost every wind flow direction (Figure 3. 14). It also helps to funnel air into the central void. Moreover diaphanous screens, located on the external façade, provide solar protection as well as control over the amount of air flow entering the office. However, this building has been specifically designed for this hot climate. Salib and Wood (2013, p. 98) explain that, "This building works because of its 17-story height and almost consistent climate, it is unlikely to work with buildings of greater height or larger annual temperature." One of the reasons for this could be that the atrium, or porches, are always completely open to outside air and there is no shutter or vent on the porches' façades or at the top of the atrium to control the air flow according to a more significant annual climate change, hence it has been designed in this way for an almost consistent climate.

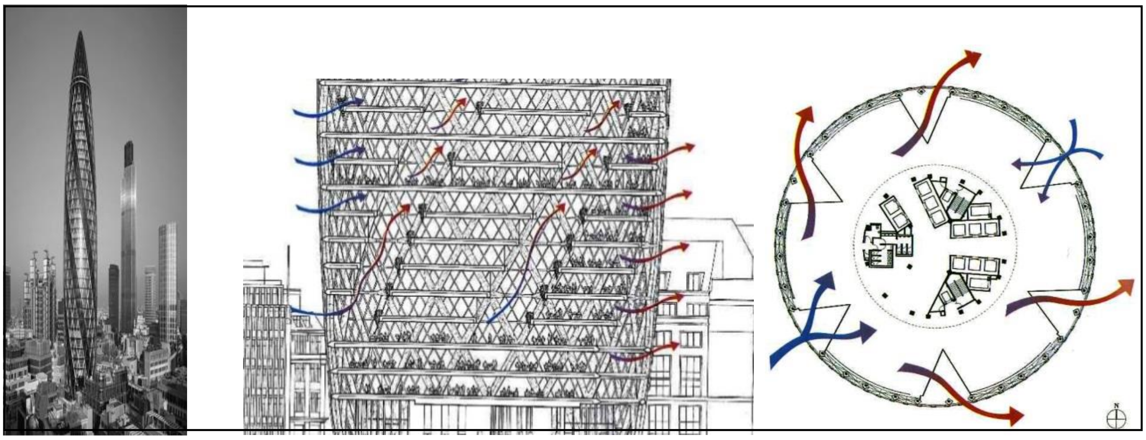


Figure 3. 15: Swiss Re tower, segmented atria section and air flow plan (Salib & Wood, 2013)

In addition, atria, with attention to climate conditions, can be shaped and placed in different positions in the buildings and can be closed as well as opened to outside air. For example, Norman Foster designed 30 St. Mary Axe with spiral atria located on the façade (Figure 3. 15). This building is naturally ventilated for 40% of the year (Jenkins, 2009). The windows, which are open to the windward atrium, invite air in, whereas those open to the leeward exhaust it. Furthermore, single sided ventilation is used for the offices that are only open to one atrium,.

The key role of the natural ventilation strategy in 30 St. Mary Axe is the segmentation of the rotated atria on almost every sixth floor. Segmentation helps substantially in controlling the wide range of pressure difference due to wind or buoyancy or both, and in preventing extreme stack flows, creating smooth air flow and minimizing draft and noise development (Lepik, 2004). Consequently, the large pressure difference between the bottom and top can be resolved to a reasonable extent. This technique allows each segment to be ventilated independently and thus the pressure reduces significantly; this is why the method has also been used in other high buildings with atria. Moreover, (Ross, 2004)believe that, if the height of the atrium is reasonably extensive, it creates a problem with extreme stack flows and pressures, where a typical door at the top or bottom of the building might not be easy to close or open. Also, due to the wind and buoyancy, the driving pressure is large and with a wide range that makes control difficult (Salib & Wood, 2013).

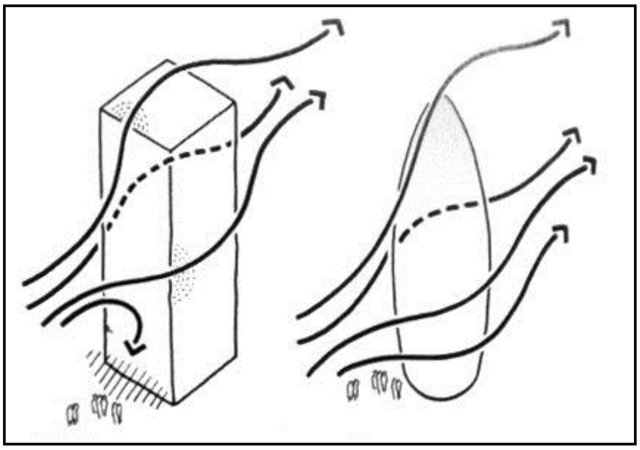


Figure 3. 16: Drawing by Norman Foster showing the wind conditions near the building (Lepik, 2004)

It is also important to point out that the similarity of the shape of the building to a gherkin, means that Foster has developed a structure with the lowest resistance to wind compared with any other shape; this is of help in lowering the danger of strong downward winds as well as lowering the high demands of load-bearing structures (Figure 3. 16) (Lepik, 2004).

3.2.2.2 Sky courts

Sky gardens are usually horizontal cuts in building elevations, which create a platform for air inlets as well as a social gathering place (they are like mini courtyards). In some cases, this takes advantage of good air quality and temperatures. Heron Tower in London is an example of a block that uses 11 north-facing, independent sky courts (segmented) by a three-story height (Figure 3. 17).

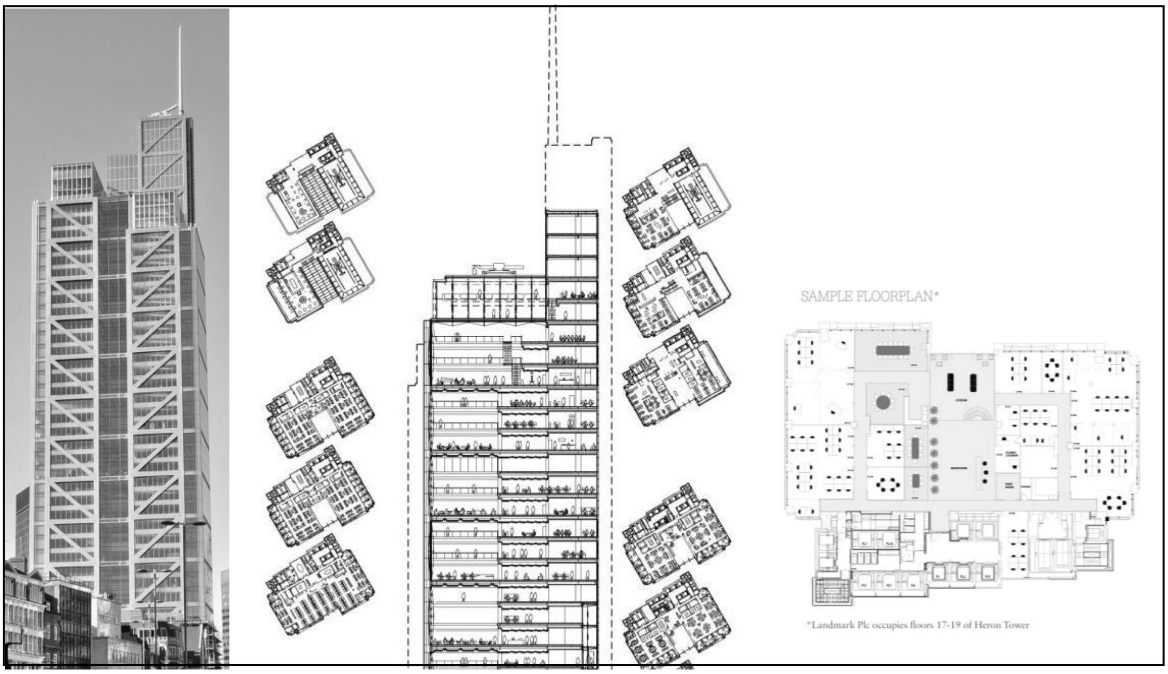


Figure 3. 17: Heron Tower, section and plan (sky gardens) (KPF, 2018)

Commerzbank in Germany is another example that takes advantage of the combination of atria with sky gardens (Figure 3. 18). The difference between sky-courts in Commerzbank and porches in the Cube Tower is that the latter has porches that are always open to the outside and do not close up to the exterior. However, in the Commerzbank, sky-courts, may not be entirely open to outside air and thus more control can be exerted over them according to the specific climate.

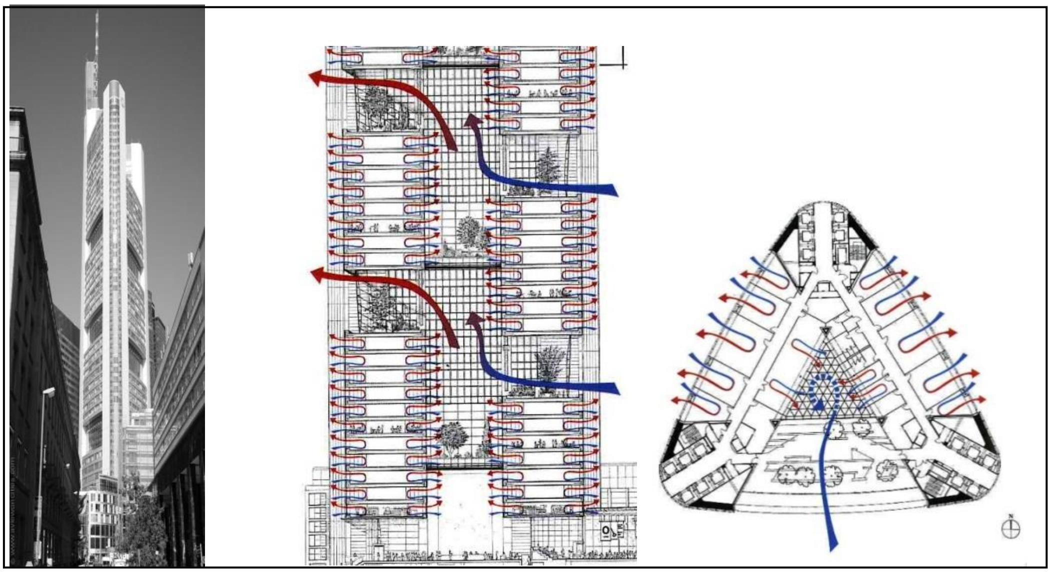


Figure 3. 18: Commerzbank tower section and plan (air flow in sky court + atrium) (Al-Kodmany, 2015)

Wells (2005) believes that Commerzbank tower is one of the most ecological tall buildings ever built. It was built with the aim of being the first naturally ventilated, naturally lit tall building in the world (Lepik, 2004). The office blocks are naturally ventilated for 80% of the year in the temperature climate of Frankfurt. In addition, this building uses a heat recovery system besides other innovative technologies which greatly reduces the energy consumption of the building compared with other traditional high rise structures (Lepik, 2004). It is known to save 30% more energy than fully air-conditioned offices in Germany (Giavazzi, 2010). It also includes a central atrium with sky gardens connected at three different angles. There are two types of ventilated office; external offices, which ventilates through a double façade, and internal offices, which ventilates through the central atrium throughout the year (Al-Kodmany, 2015).

Commerzbank also uses the segmentation technique for a better performance in the building in terms of ventilation and energy efficiency; its atrium is segmented into four sections with each being 12 levels in height. The ventilation in the atrium flows from the sky gardens to the central atrium and out through another sky garden. The plan is in a shape of a triangle so that the internal windows on the other two inner elevations are always looking outside, towards the city as well as the gardens in the sky-courts (Wells, 2005). In addition, because of the triangular plan, there is always a windward and leeward sky garden to enhance the pressure driven ventilation (McCallum, 2009). The internal movement of air caused by wind and buoyancy is partially controlled by the glass screens enclosing the sky-courts. Even though the combination of sky courts and the central air shafts help to maximise natural ventilation in all seasons (Abel, 2000b), the key element of this design is the sky court. As well as being the controllers of air movement, the sky courts act as extraction chimneys in summer, to help with cooling loads, and as solar collectors in winter to help with the heating loads (Salib & Wood, 2013).

3.2.2.3 Wing walls

Another system is to use wing-walls. Their performance are similar to wind catchers in that they also capture wind. Wing walls are literally vertically shortened walls expanding over the height of the building that capture a wide range of wind to redirect the air flow inside (Yeang, 2007). For example, UMNO building (Figure 3. 19) designed by Ken Yeang, is situated in Penang. Yeang (2007) state that the UMNO tower in Malaysia was the first to use this strategy to enhance natural ventilation, and the first in Malaysia to provide 100% natural ventilation for its inhabitants. It is also believed that this method is used in a climate where the temperature is mostly hot throughout the year and saves 25% more energy compared to fully air conditioned buildings of the same type in the region (Salib & Wood, 2013). This technique was used in UMNO tower because the building could not rotate to the direction where the prevailing wind blew; this was due to the need to gain maximum natural light (Yeang, 2007). It was also used because the generation of high air change rates was needed in order to achieve comfortable conditions through air movement. Considering the low average wind speed of 2.6 m/s in this city, wing-walls have become a crucial element in improving the flow rate. Airlocks and adjustable windows control the amount of air, or the flow rate entering the void.

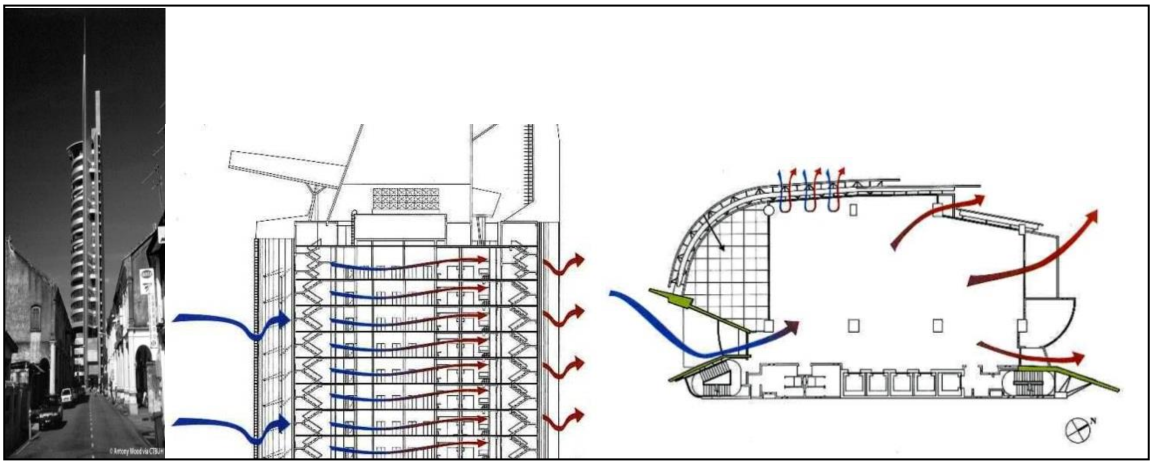


Figure 3. 19: UMNO tower, section and Plan (wing wall technique) (Salib & Wood, 2013)

Moghaddam et al. (2011) emphasise the importance of this feature by claiming that, in using wing walls the average indoor air speed rises by 25%. Even though they are effective in terms of providing natural ventilation inside but they block the sunlight in other parts of the building.

Some structures also combine this technique with atria for better passive results. An example is the Post Tower (Figure 3. 20), which has two wing walls; one encourages positive pressure while the other boosts negative pressure. These are on the east and west elevations with a linear atrium connecting them (Moghaddam et al., 2011). In Post tower the combination of wind wall and atria is used as an extract chimney for the exhaustion of office air in summer. The exhausted air from offices is poured into the atrium whilst the wing wall helps to strengthen the cross vent across the atrium in order to release that air to the outside. Thus, as the wind is captured, it is forced into the openings at the lower levels, and guided through the atrium. It then rises up the other side with the help of the negative pressure force, and is then dragged out the top level of the atrium. Wells (2005) also states that, in cool weather, the fresh air is warmed in the atrium before being introduced to the office rooms, and ultimately the exhausted air is vented at the top of the atrium. The techniques saves 79% on heating and cooling energy compared to other German offices with fully air conditioned strategies (Salib & Wood, 2013). Even though the offices do not use this strategy as an air intake but rather as an outlet, the atrium is 100% naturally-ventilated throughout the year (Al-Kodmany, 2015).

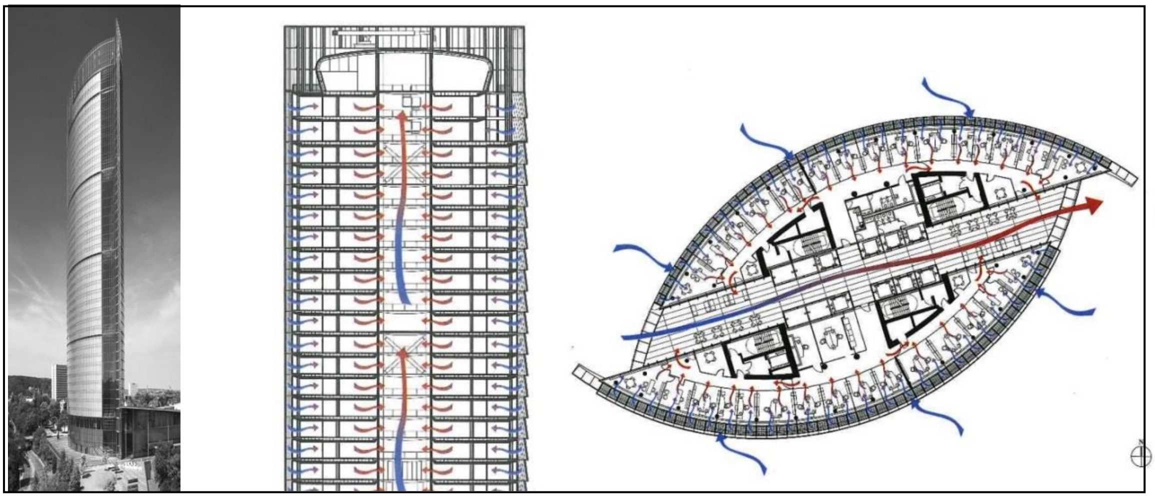


Figure 3. 20: Post tower, section and plan (wing wall + atrium) (Al-Kodmany, 2015)

Finally, segmentation has also been applied to the design. As for the post Tower building, it is segmented into four parts, each nine stories tall. This verifies the importance of this strategy in tall buildings.

3.2.2.4 Thermal flue (double skin façade solar chimney)

A thermal flue is a form of solar chimney with a typical dimension length of an entire elevation. It is used as an outlet and has almost the same effect as traditional chimneys. It acts in a similar way to the outlets on the top of the building domes. Alternatively, it acts in a similar way to the wind catchers; when there is no wind, the warm air is collected above the habitat area and sucked out from the highest point in the wind catchers (which act as outlets).

The thermal flue technique usually consists of a double skin façade at one end of the elevation, which is designed as a continuous gap without any divisions, where the height rises above the floor levels of the building. The thermal flue is usually situated on the warm elevation in order to build up heat inside the space. This is beneficial both in cool and warm seasons. In warm season it helps with the stack effect flow which draws air out from the top level openings of the floors. This stack vent encourages the air out in three ways; either through the buoyancy effect or through the negative pressures created by wind on the top, which sucks the warm air out, or through both techniques. This space can be entirely open from the bottom to encourage air flow and help the speed of the exhausting air, which is introduced into this gap and released at the top.

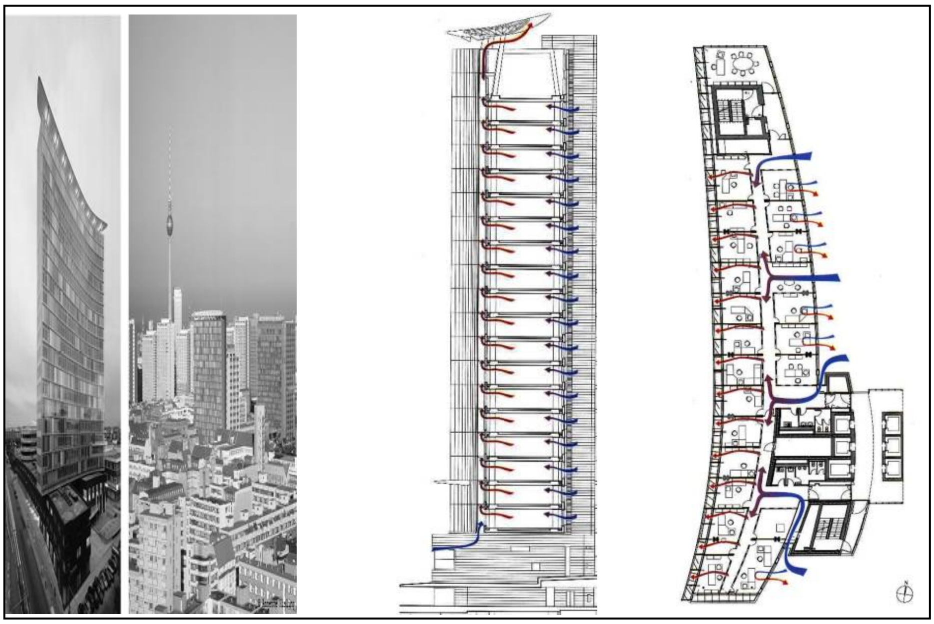


Figure 3. 21: GSW Tower, section and plan with the thermal flue on the west (Salib & Wood, 2013)

GSW headquarters in Germany (Figure 3. 21) is an example of successful thermal flues that provides natural ventilation for 70% of the year (Salib & Wood, 2013). However, the offices are totally naturally ventilated when the temperature is between 5^{o}C to 25^{o} C. It also saves more than 30% energy for heating and cooling compared with other fully air conditioned office buildings in Germany (Bream, 2015). On top of the thermal flue, on the roof another element, called a wing roof, is installed in order to build up the negative pressure by accelerating the wind passing over the flue. Therefore, when air is invited into the office rooms from the eastern elevation, it passes through the depth of the office floors and is exhausted from the thermal flue on the western elevation. However, there is a risk of back flow of air. In order to avoid this, it has been calculated that a 10-degree temperature difference is essential between the top and bottom of the thermal flue. In order to maintain this, the temperature difference raises open the dampers at the bottom to let air in, and when it falls, the dampers are closed to trap the air in the flue. Night cooling also takes place to cool down the building before the next day.

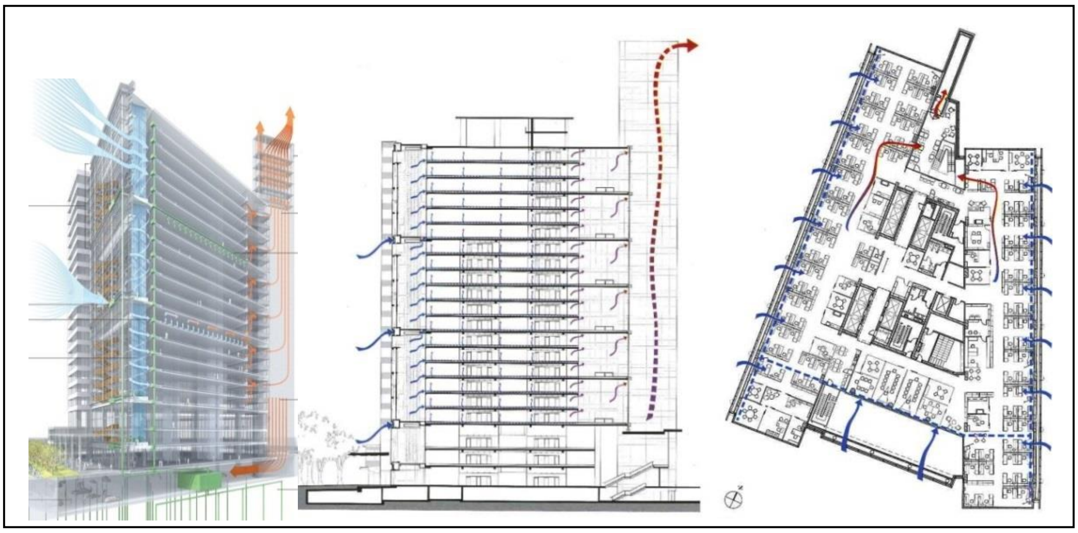


Figure 3. 22: Manitoba Hydro tower, section and plan (solar chimney + atrium) (Salib & Wood, 2013)

This method also is combined with atria, and the most vivid example of this is Manitoba Hydro place (Figure 3. 22) in Canada. This building is situated in Winnipeg where its extreme climate varies from -35^{o} C to +35^{o} C. However, the climate classification is cold. For such a climate, the building has done remarkably well in remaining naturally ventilated for 35% of the year, saving 73% energy compared with other, typical Canadian office buildings with HVAC. It has two atria on opposite sides of the building and both are segmented; those on the south that invite in air are six storeys high whilst those on the north that exhaust the air are three storeys high. Fresh air enters the south atrium and into the rooms, through the corridors and towards the north atria and then to the far north end of the building where the solar chimney is installed to collect and exhaust the warm air

(Carter, 2010). The 115 metre solar chimney raised above the top of the building on the north side is the key element to the passive ventilation system which draws air out of the building during the shoulder season and summer months. This building won the America's "best (design) tall building 2009 awards" by the Council of Tall Buildings and Urban Habitat (CTBUH).

3.2.3 Potential passive design strategy in modern buildings of Tehran

(via comparing vernacular strategies in Iran and some modern strategies in the world)

Even though the modern techniques that provide passive ventilation, described in section 3.2.2, are impressive, all examples have used techniques that complement the climate needs of their own region. For instance, in some examples the façade consists mostly of glass, or the position of the atrium is situated in such a way as to invite as much light and heat as possible into the rooms. Whilst this might suit the particular climate it has been designed for, it might not be a suitable solution for other areas. Therefore, copying existing structures without attention to the climate needs of the place in which the building will be built might cause an increase rather than a reduction in energy consumption. Thus, it is important to pick a reasonable modern passive strategy and modify the designs according to the climate, and in this case for the semi-arid climate of the Middle-East.

The examples explained in sections 3.2.1 and 3.2.2 show that an atrium has traditional roots, and that atria are inspired from courtyards. Atria also play an important role in passive ventilation, like courtyards in arid climates. Atria have a lot of similarities with courtyards; for example, both, provide natural ventilation, natural light and shade, social interaction spaces, better visual spaces, and create the potential for gardens and greenery. Moreover, atria have the extended potential of being used alone or in combination with other passive cooling design systems, just as courtyards have the ability to compliment other passive methods. Atria have also been used in a wide range of climates (as the examples in section 3.2.2 shows as well as Appendix 10), and courtyards have also been used in different climatic zones (Norton, 1997).

Finally, Fathy (1986) states that old Islamic houses have used courtyards to maintain coolness without air conditioning and to admit light without glare; he believes that the same principles can easily be incorporated into high-rise buildings in similar climates. Also Gharleghi and Sadeghy (2012) believe that Fathy (1986, pp., para.20) views are still relevant today;

> " ...The architects must renew the architecture from the moment when it was abandoned. They must try to bridge the existing gap in its development by analysing the element of change (climate), applying modern techniques to modify the valid methods established by our ancestors and then develop new solutions that satisfy modern needs."

So in order to narrow the gap between old successful passive designs and new high-energy consuming designs in today's tall buildings in semi-arid climates, the correct use of atria is recommended as they have similarities with courtyards. Also, their flexibility in summer and winter and potential for combination with other modern passive designs suggest that atria can be picked as a potential passive design solution, with traditional roots for semi-arid climates that cover cold winters to hot summers. Therefore, in Chapter 4, atria, their history and application are studied in more detail.

3.3 Summary of Chapter 3

Poor design of buildings causes excessive amount of energy consumption. 40% of global energy is used by buildings. 55% of energy used in office buildings is used to provide thermal comfort by using HVAC. Therefore, passive design in order to provide natural ventilation and heating and cooling are of importance. The factors effecting passive design in buildings are described in detail in this chapter. Moreover, vernacular architecture of semi-arid region has been studied and in order to select the best modern passive design for semi-arid climate. Atria is the potential passive design that can work in semi-arid climate due to its principle similarities with courtyards and wind catcher, the two mostly used passive design elements in vernacular architecture of arid climates of Iran. It also can be beneficial in both hot and cold season as extract chimneys in summer and solar collectors in winter. In addition the chapter looks into some successful examples of modern buildings using atria design to help lowering the use of HVAC.

CHAPTER 4: Atria configuration and impacts

Chapter 3 discussed the reasons why atria were selected for further analysis. This chapter will provide more detailed information on atria, the history of their development, and discuss examples found in Tehran's semi-arid climate.

4.1 The History of Atria

The word 'atrium' is derived from the Latin word 'āter',which means dark, and refers to a central space surrounded by rooms that, in the traditional houses of Rome, used to have dark black soot covered walls (Moosavi et al., 2014) allowing fire smoke to escape and daylight to enter (Moosavi et al., 2014). Hung and Chow (2001, p. 285) defines atria as "a tall indoor open space, with part of it connected to the outside" . These spaces were known to be used initially in the Mesopotamian area (Moosavi et al., 2014) (Figure 4. 1).

> "*Mesopotamia (from the Greek, meaning 'between two rivers') was an ancient region in the eastern Mediterranean bounded in the northeast by the Zagros Mountains* [in the west and south-west of Iran] *and in the southeast by the Arabian Plateau, corresponding to today's Iraq, mostly, but also parts of modern-day Iran, Syria and Turkey.* "(Mark, 2009, para.1).

However, Bednar (1986) believes that the history of atria is known to have begun with the archaeological remains of a Malaysian courtyard house in 3000 BC. Later on, the central uncovered roof houses were found in ancient Greek and Roman cities (Moosavi et al., 2014) (Figure 4. 2).

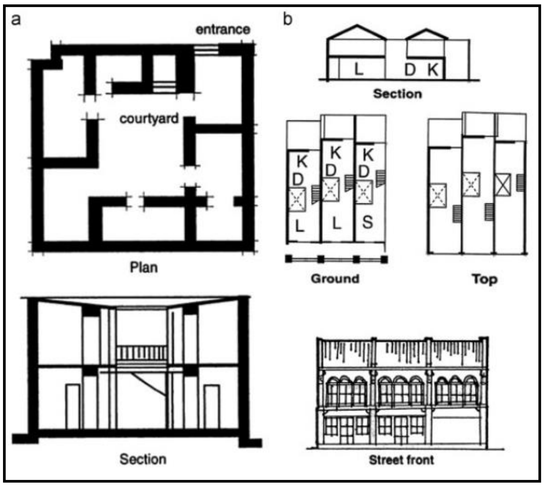


Figure 4. 1: section and plan of house of Ur, Mesopotamia (Rasdi, Tajuddin, & Ahmad, 2000)

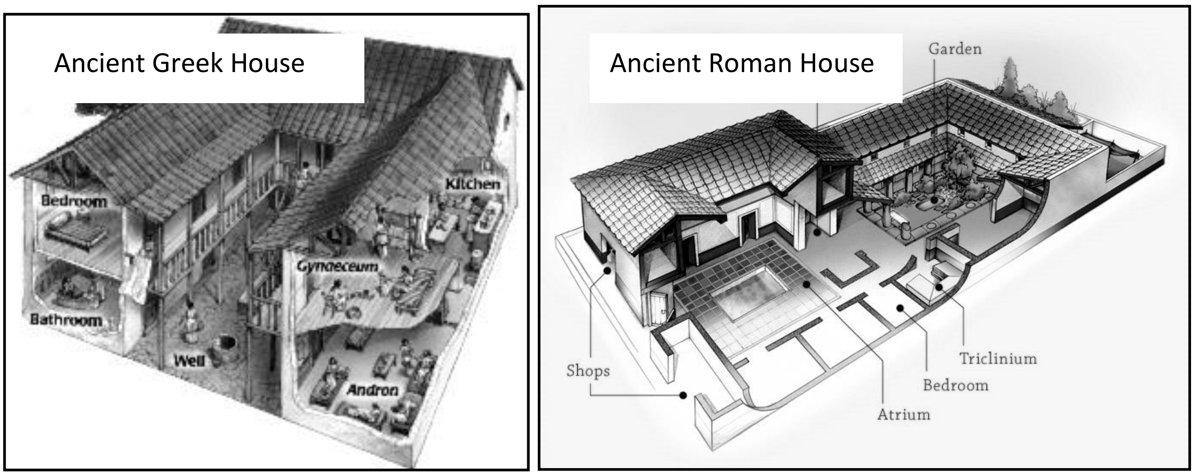


Figure 4. 2: Typical ancient Greek house (left picture) and typical Roman house (right picture)

As Hung and Chow (2001, p. 286) mentions "In roman cities these large central spaces were open to the sky. "The roman atrium was composed by a grand entrance space, a focal courtyard and sheltered semi-public area… The roman houses were isolated from outside but with some interaction…The house left the façade blank and turned inward to the courtyard where noise and dirts were isolated…inhabitants in houses opened to the atrium needed to pass through that common space to go inside or outside." It is believed that this form was extended in the Middle-East to as a larger courtyard space for individual houses (Sharples & Bensalem, 2001). The development of their design can be divided into four periods:

- Early 19th century: the atrium was used as cover courts or covered galleries. For example with the new technology of iron and glass, John Nash first developed a roof over a picture gallery in 1806 (Figure 4. 3). Also appearing early 19^{th} century was greenhouses, utilizing the solar radiation passing through glass, as a glass enclosures which hugely influenced the development of atrium buildings (Hung & Chow, 2001).

Figure 4. 3: Attingham park picture gallery in Shrewsbury

- Late 19th century: During the late 19th Century, industrial materials (glass steel and iron) became more widely available. Moosavi et al. (2014) also state that, during the industrial revolution a new era in atria design started; these spaces were usually created in non-residential buildings and as a common or circulation space. The atria were covered with a glass roof and sometimes with glass walls, connecting stories and galleries within the whole building (Moosavi et al., 2014). According to Hung and Chow (2001) this new type of atrium emerged in the late 19th century in America as Burham and Roots Rookery atrium in 1886 in Chicago (Figure 4. 4) was converted from an ordinary light well to a interior street with shops at mezzanine and ground floor (Figure 4. 4). Moreover, Abel (2000b) mentions that the first known western architect who designed a building by taking out its core and replacing it with a top-lit atrium-cum-circulation space was George H. Wynman. His building was completed in 1893 in L.A. and was called Bradbury (Figure 4. 4).

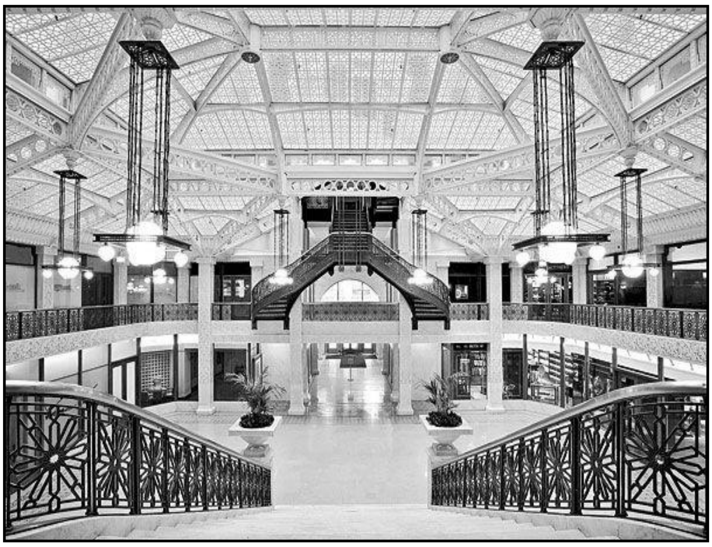



Figure 4. 4: Burham and Roots Rookery atrium (left) and Bradbury building (right)

- Early 20th century: Larkin office building by Frank Lloyd Wright created a full height atrium in Buffalo in 1905 (Figure 4. 5). Abel (2000b) believes this to be the “first major deviation” to impact the design of office buildings. Larkin office space introduces four open side levels around a sky lit court and the whole building is turned inwards and away from the city. This gives the office workers and uplifting space. Frank Lloyd Wright paid attention to the flow of space between the levels and he was the only one using this concept at the time (Hung & Chow, 2001).

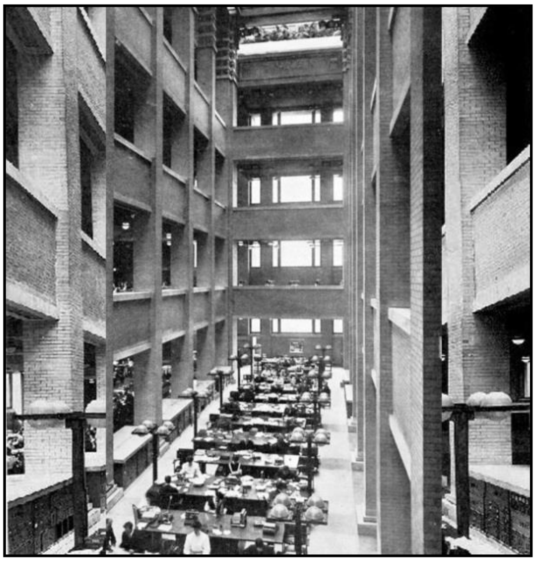



Figure 4. 5: Larkin building (left) and Lever house building (right)

With the design of Lever House (Figure 4. 5) in 1952, Gorden Bunshaft gave glass skyscrapers their definitive form, and through the use of air conditioning, these buildings could be inhabited in all weathers (Abel, 2000b). Abel (2000b) states that this was the "second major deviation" to impact the design of office buildings.

- Late 20th century: As building technology advanced longer distance enclosure spaces were built. By the late 1950's and early 1960's, modern atria were gradually becoming common (Atif, 1994). However, Hyyat Regency Hotel (Figure 4. 6) announced the next revival of atriums. Hyyat Regency Hotel by John Portman built in 1967 in Atlanta, is one of the first modern tall buildings (Saxon, 1994). Hung and Chow (2001, p. 286) states that the architect "intended to provide a socially stimulating environment. A sun and rain canopy was put over courts but with natural ventilation provided simultaneously. There are areas for catering and sight-seeing. On the other hand, Portman was also the pioneer to adopt the wall-climber elevator. That was not enclosed in a shaft, but exposed to the atrium, giving the atrium a dynamic quality as the lift cars travelling up and down. The Hyatt Hotel, introducing a sense of joy and spirit, deserved much appreciation on the entertaining atmosphere and had achieved great commercial success. Architects afterwards were inspired by Portman and tried to simulate the social atmosphere to their shopping mall design…At the same time, they made compact and multi-level atrium design to save money on climate control". Abel (2000b) calls this the "The third deviation" when high-rise buildings were designed for local climates and spaces.

Figure 4. 6: Hyyat Regency Hotel atrium by John Portman

An effective example of this is the National Commercial Bank (NCB) bank in Jeddah (Figure 4. **7**), which was designed by Bunshaft in SOM architects. Built in the early 1980's, this building was the first of its kind, in that it reflects the climate, and its design is specified to its location (Akbar, 1995). This building has since been the inspiration for both local and international architects in designing according to climate and, as a result, saving energy (Abel, 2000b). The building is further discussed;

> NCB was built thirty years after Bunshaft designed the Lever House, and the building gave glass skyscrapers their definitive form (Abel, 2000b). The design was based on the brief to create a structure that connected the latest technology of tall buildings with the special climate conditions of the local area (Lepik, 2004). NCB is built in the extremely hot desert climate of Jeddah and based on a triangular plan with 126 meters height and 27 storeys. This structure is covered with light colour travertine to reflect sunlight, has a completely windowless block on all outside external façade, with one square opening on one elevation and two on the other. This means the building has three landscape openings at different levels whilst the elevator and staircases are placed on the third elevation which mean that this elevation does not have any openings at all (Lepik, 2004) (Figure 4. 7).

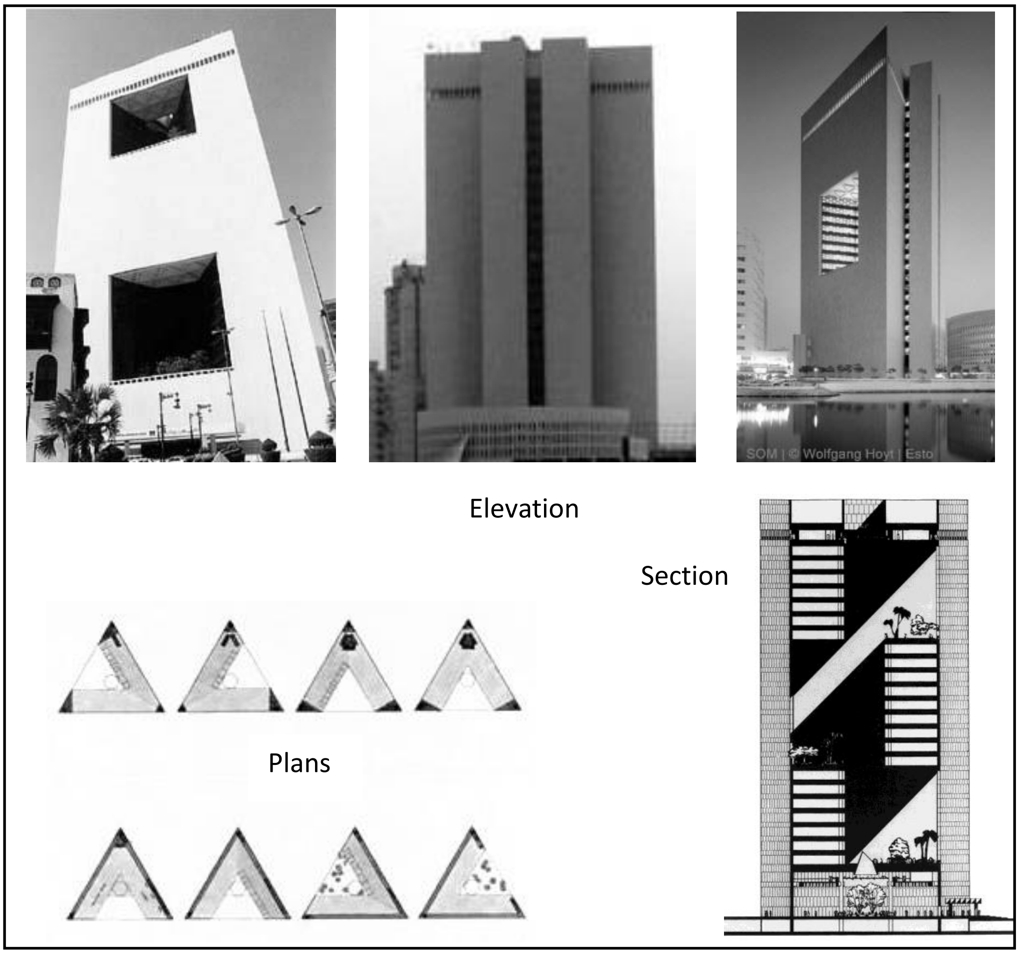


Figure 4. 7: NCB tower with its plans and section

The purpose of this type of atrium was to provide natural ventilation to the building as well as indirect light (Lepik, 2004). By paying attention to the traditional houses of Middle-East, it can be seen that the rooms and windows of a house are orientated inwards, towards an inner courtyard so they are protected against the sun and maintain the possibility of air circulation. The NCB has incorporated these traditional approaches into its modern techniques. The incorporation of atria in the core of the building and the inward orientation of these windows towards the atria, means the building represents a revival of courtyard houses (Abu-Ghazalah, 2006). Furthermore, the building has an energy saving form through merging modern techniques with a traditional design (Lepik, 2004).

Abel (2000a, p. 189) claims that this tower,

> "was the first to create a secondary ground level in a form of large external incision in the building and this single innovation, more than any other previous development, changed the relation of internal to external space for tall office buildings. No longer had occupants to look down, instead they could enjoy the well planted terra firma at close proximity".

He further states that NCB has seven wide and nine story high openings on two elevations (Figure 4. 7), which invite indirect sunlight to the inside void that office windows overlook, and protect against glare as well as create a platform for green courtyards and ventilation. In fact, these three sky-courts were designed to allow the building to be windowless from the outside, having all glazed surfaces facing inwards towards the three shaded sky courts which minimises the heat gain. Lepik (2004) also confirms that, apart from providing natural ventilation for the spaces, the openings are placed in such a way that only indirect sunlight can enter the office floors. Thus the NCB is one of the first buildings to highlight the importance of designing according to climate and that demonstrates the possibility for success in doing so. NCB shows that this is possible even in hot regions where it may not seem easy but where sensitive designs can still contribute towards the reduction of cooling loads and energy consumption.

4.2 Advantage and disadvantages of atria

In order to understand the importance of using atria, its advantages and disadvantages must be studied. The advantages are first mentioned in the list below:

- Providing Natural Ventilation:
  Atrium buildings offer the potential to utilise natural ventilation and reduce energy consumption and thermal loads (Abdullah & Wang, 2012; Assadi et al., 2011; Göçer, Tavil, & Özkan, 2006; Moosavi et al., 2014). Aldawoud (2013) also believes that a well-designed atrium should reduce the demand to condition the spaces artificially. For tall buildings with no atria there is little air pressure build up for buoyancy

induced ventilation; for effective air flow, there needs to be a reasonable temperature difference between the inlet and outlet. However, this is possible by creating voids, or atria, in the floor plates, enabling a large pressure field difference on the atrium's top and opening inlets (Salib & Wood, 2013; Sharples & Bensalem, 2001). Overall, Moosavi et al. (2014) strongly states that, the main potential environmental advantage of atria is natural ventilation.

- Provides solar gain:

  If positioned correctly towards the sun, atria can warm up a space and help with heating loads in winter; this is because the sun rays can provide heat to the space (Abdullah & Wang, 2012; Assadi et al., 2011). Bednar (1986) and Zhang (2009) also explain that an atrium can directly gain heat because of its greenhouse effect, which is when short waves enter the atrium, hit the face of objects, transform into long waves and ultimately become trapped in the closed space. The heat can be captured by controlling the atrium vent openings; in cold seasons this is advantageous as it reduces heating loads and heat loss. Hence, as previously mentioned, this passive design feature could work for different climates, including cold areas, as it similarly takes advantage of direct solar heat gains (Moosavi et al., 2014).

- Provides shelter and acts as insulation:

  Göçer et al. (2006) believe that atria act as buffer zones between the inside and outside, sheltering the indoor space from wind, snow, rain and other outdoor environmental factors while retaining desirable outdoor effects, such as fresh air, natural light and sunshine, as well as exterior views. For example, Hawkes and Baker (1983) state that using closed top glazed atria in cold climates is beneficial as they can act as a buffer zone between the indoor environment and harsh external climate conditions. Furthermore, they can be used as means to reserve heat during sunny days in cold climates and help with heating loads.

- Provides natural light:

  When an atrium is properly integrated within a building design, it complements the building's functionality and can provide deep penetration of light into the interiors of the building to provide a more vibrant space (Linden et al., 1990). Atria help in reducing the use of artificial lighting, and can reduce energy consumption (Abdullah

& Wang, 2012; Aldawoud & Clark, 2008; Assadi et al., 2011; Göçer et al., 2006; Moosavi et al., 2014; Sharples & Bensalem, 2001).

- Has the potential to provide better air quality:
  By using a plant-filled atrium, air could be filtered and particles removed when they enter the space (Barkkume, 2007).

- Has the potential to provide Water features: During cold days it can help to add moisture, and during hot days it can cool down the incoming air.

- Provides an attractive visual space:
  An atrium provides an attractive visual space that people can over look to the outside (Laouadi, Atif, & Galasiu, 2003). In some cases, the gardens or skycourts designed for atrium spaces, or even a distance view to another section of the building, can provide communication with different storeys of the building (Moosavi et al., 2014).

- Provides a social gathering and circulation area as well as a green space:
  It has been said that the future of tall buildings is moving towards the creation of community areas (Wood, 2008). This is important as there are usually large numbers of habitants in comparatively small structural foot prints (Pedersen, 2010), hence an atrium fulfils the requirement for a social gathering and circulation space (Medi, 2010) whilst also providing good air quality and comfortable temperatures. A number of authors also consider that atria have a significant impact on increasing socialisation and interaction amongst inhabitants (Bednar, 1986; Bryn, 1993; Gocer & Tavil, 2006; Saxon 1986). Furthermore, Moosavi et al. (2014) and Hung and Chow (2001) also agree that these gathering places can promote interaction amongst occupants and create a social environment to recover from any stress. Additionally, Stigsdotter (2003) suggests that these have the appositive effect on the stress levels of employees and raise the productivity of workforces. Morris (2003, p. 4) also believes that these, "Natural open spaces and well-designed green spaces provide a [space] for… social interaction" and have a positive effect on health and well-being. These benefits are significant in that it is generally believed that socialising has a positive effect on the physiology and psychology of citizens (Laouadi, Atif, & Galasiu, 2002).

Therefore, there are notable advantages in using atria as passive design elements for reducing energy consumption. Studies conducted on atria have proven, as stated, that they are significant in enabling energy saving throughout the years (Linden et al., 1990). Few examples of these studies are discussed below:

Laouadi et al. (2002) state that three out of four buildings in the USA have proven to use less energy compared to builidngs that have not incorporated atria in their design. Göçer et al. (2006) have researched office buildings in the warm climate of the Middle-East and claim that atria must be included as part of the energy saving strategy to help with cooling and heating loads, while caution must be exercised regarding the thermal climate of the atrium and the use of the building. Meanwhile, others believe that it depends on the height of the feature, stating that the energy performance of open top courtyards is more efficient in low rise buildings, and closed top atria perform more efficently in high rise buildings in all four climates (namely, cold, temperate, hot-humid and hot-dry) (Aldawoud & Clark, 2008). Hindrichs and Daniels (2007) also sugguests compact designs of buildings with core zones or atria in specifically hot-arid regions. Moosavi et al. (2014) agrees that an atrium is a climate modifier where the optimum balance between saving energy and increasing thermal comfort is to have an almost closed atria in winter and an open one in summer.

After identifying the advantages of atria, it is necessary to determine possible disadvantages in order to be aware of issues and, where possible, address them. Highly glazed atria designs present disadvantages, especially in cold climates where they can contribute towards heat loss (Göçer et al., 2006). Moreover, if an atrium is shaded it will need electrical lighting. In such cases, it will not have used the natural light to its full potential and will have required unnecessary energy consumption. In contrast, if the atrium is not shaded, there are studies that demonstrate the impacts of overheating. Göçer et al. (2006) add that too much solar heat gain in summer can mean significant energy consumption. Also air stratification takes place in an atrium and, in summer this might pose a problem when the heated air rises to the top and causes discomfort for occupants in the upper storeys of a building (Göçer et al., 2006). Therefore, designers have to be aware of the deep penetration of strong solar radiation and its unfavourable impact on thermal comfort (Douvlou & Pitts, 2001). Laouadi et al. (2003) state that if an atrium is not designed properly and absorbs a considerable amount of heat when it is not needed, its running will be expensive. In such cases, including atria in buildings might actually prove to be considerably energy consuming throughout the year. Hence, it is important to design atria with careful consideration to energy consumption.

4.3 Atrium basic shape typology

The climate conditions of a region should affect the design of buildings with atria (Linden et al., 1990). Apart from climate conditions, other factors, such as the functionality of buildings, the expected level of thermal comfort, and the incorporation of architectural experimentation also define the design of an atrium (Moosavi et al., 2014). Nevertheless, the placement of an atrium and its different forms (namely; atria type) are the main factor determining the advantages that it brings to a building (Moosavi et al., 2014).

In terms of the main categories of atria, four different shapes have generally been recognised (Hung & Chow, 2001; Moosavi et al., 2014), although by including the two-sided atrium, Saxon (1986) believes there are five types. Different names are given to each shape, and these are known to be the simple generic forms of the feature (Figure 4. 8 to Figure 4. 12):

1. One-sided atrium (single-sided, conservatory atriums, attached atrium, open-sided atrium): adjoins one side of the occupied portion of the structure.

Figure 4. 8: Generic form of a one-sided atrium building on the left (Saxon, 1986) with Law Courts, Vancouver as a one sided example on the right (Halbauer & Company, 2009)

2. Two-sided atrium (open-sided atrium): touches two sides of the occupied portion of the structure.

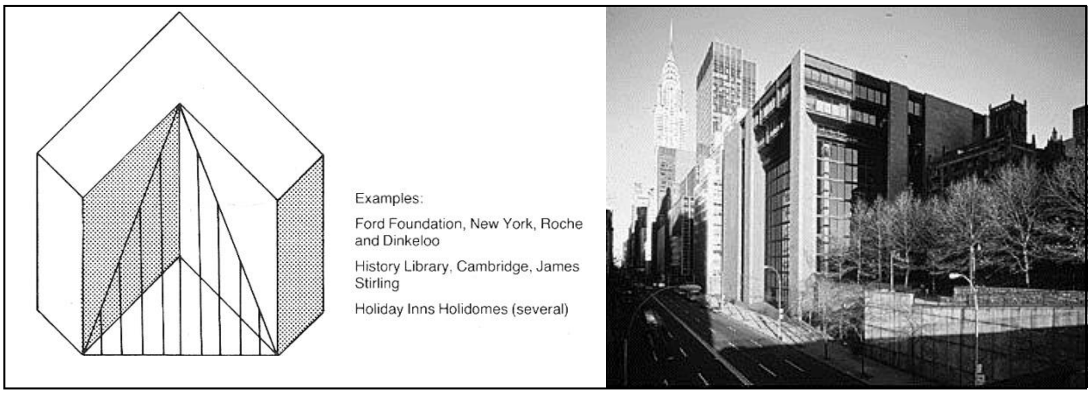


Figure 4. 9: Generic form of a two-sided atrium building on the left (Saxon, 1986) with the Ford Foundation, New York as a two-sided example on the right (Bednar, 1986)

3. Three-sided atrium (open-sided atrium, integrated): adjoins three sides of the occupied portion of the structure.

Figure 4. 10: Generic form of a three-sided atrium building on the left (Saxon, 1986) with an example of Hercules plaza, Wilmington as a three-sided example on the right (Bednar, 1986)

4. Central atrium (closed atrium, core atrium, four-sided atrium): is a standard type with four sides surrounded by occupied zones. The ground plan could be rectangular, circular, triangular or other shapes.

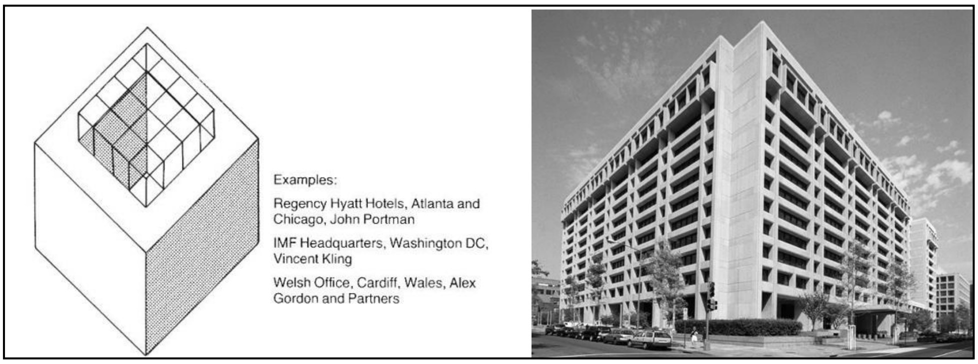


Figure 4. 11: Generic form of three-sided atrium building (Saxon, 1986) on the left with an example of IMF headquarters on the right (Michael, 2014)

5. Linear atrium: is where occupied zones hold positions on opposite sides of the atrium. The ground area is often rectangular shaped.

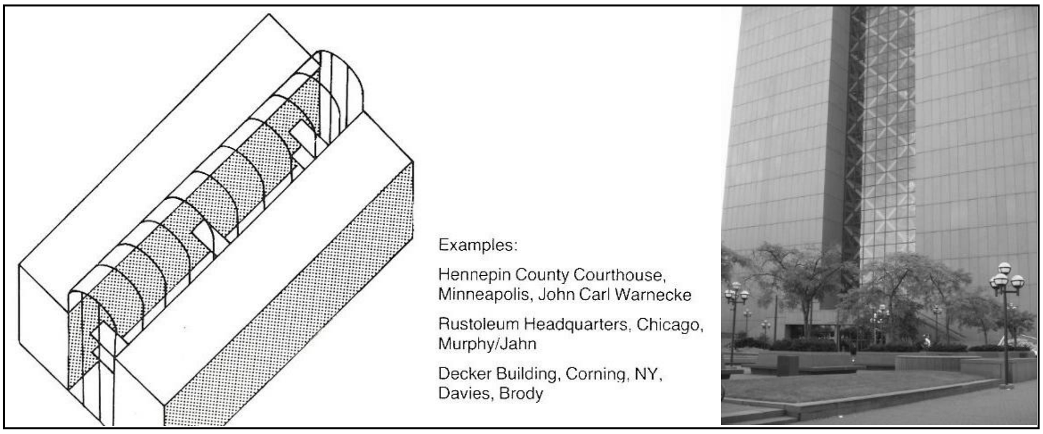


Figure 4. 12: Generic form of three sided atrium building on the left (Saxon, 1986) with example of Hennepin County Government Centre, Minneapolis-linear atrium on the right (Bednar, 1986)

One-sided atria have been used in temperate climates as a glazed façade in order to enable more solar heat gains in winter as well as attractive views during the rest of the year (Moosavi et al., 2014). However, linear and centralised atrium positions are known to be most effective in high temperature climates and with humidity (Moosavi et al., 2014). This is because these two types of atria maintain more steady temperatures as well as minimise temperature fluctuations in temperate and hot periods (Ho, 1996; Moosavi et al., 2014). Hung (2003) believes that central and linear atria are more beneficial in terms of daylight access compared to other types. A list of buildings with atria is shown in Appendix 10 where it can be seen that atria are used in different climate regions and in different typologies.

Abel (2010) claim that atria, regardless of form, have generally become very popular choices for office towers, since SOM (Skidmore, Ownings and Merrill LLP) architects, Norman Foster and Ken Yeang first led the way. According to Sharples and Bensalem (2001), in the last 37 years, many commercial and office buildings have used some form of atrium and often as a central circulation core. Reid et al. (1994) also add that atria are popular with large office headquarters as well as commercial buildings and shopping malls. Salib and Wood (2013) similarly agree that, during the 19th Century, many large office blocks used atria because of the advantages they brought.

Moreover, atria have been used in a wide range of climates as they can help with cooling and heating loads as well as natural ventilation whilst providing other potential advantages. However, it is important to design them according to climate needs; thus, different types of atria functionality are covered in section 4.4.

4.4 The role of atria in passive heating and cooling

“An atrium is a central feature of many modern naturally ventilated building designs” (Holford & Hunt, 2003, p. 409). When designing atria buildings, it is important to consider ambient conditions, such as solar radiation, outdoor temperatures, and wind direction and speeds as these have a direct effect on the climatic environment of buildings with atrium and thus occupants’ comfort (Moosavi et al., 2014). In terms of thermal comfort and the functionality of atria, three types are recognised, namely the warming, cooling, and convertible atrium, where the final type is a combination of the previous two. However, the decision as to which atrium design is suitable really depends on the climate where the building is situated. The following section discusses three types of atria in more detail.

4.4.1 Warming atria

This type of atrium is used in places where there is more need for heat in buildings. The ventilation mode in this type is called “Atria to Building”; which means the atrium absorbs lots of solar heat, causing its temperature to rise higher than the parent building, thus the air flows from the atria to the inside block (J. Q. Li, 2004). Bednar (1986) and Zhang (2009) explain that the atrium can be a direct heat gain space because of its greenhouse effect, namely the effect when short waves enter the atrium, hit the face of objects, transform into long waves and ultimately get trapped in a closed space.

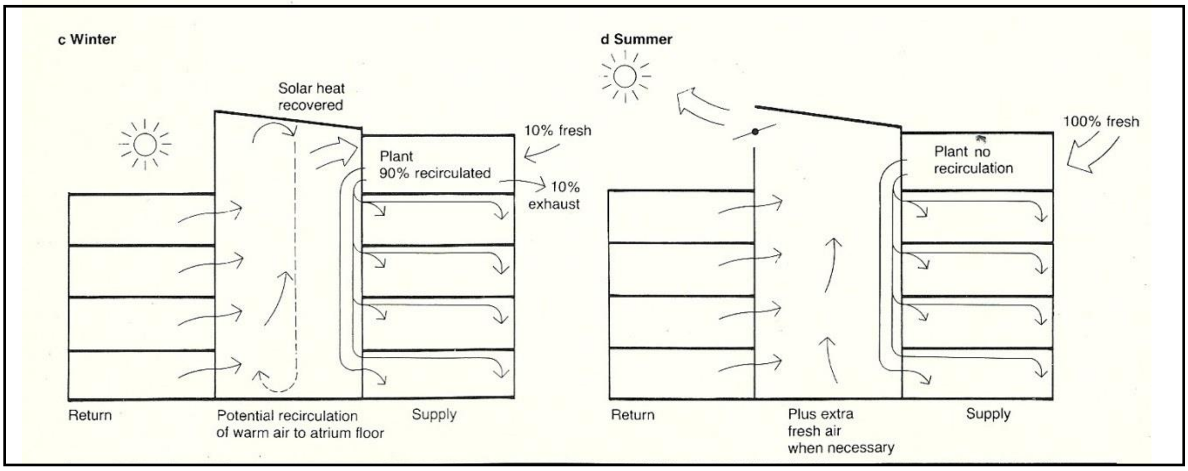


Figure 4. 13: An example of a warming atrium strategy

Figure 4. 13 illustrates an example of a warming atrium. As shown, warming atria tend to have closed roofs because, according to simulations by Taleghani, Tenpierik, and Dobbelsteen (2014), when an atrium is open from the top, the building’s surface to volume ratio is higher. This results in more exposure of the building to outside conditions and inevitably more heat loss; this results in a greater consumption of energy to supply heating demands. Thus, closed top glazed atria make the indoor environment warmer compared to other open top atria. In addition, “ the surface to volume ratio relates to heating demand of a building to its’ outdoor environment” (Taleghani et al., 2014, p. 492). As a result, the lower the surface to volume ratio, the lower the heating demands will be. Taleghani et al. (2014) state that there is even greater heat loss in open top courtyards or atria in the cold days of winter compared to buildings with no atria, and this is due to a higher façade exposure to outside conditions. They believe that a building with no atrium could decrease the heating

demands compared to a building with a open top atrium. Thus, it is important to have the top of the atria closed in warming atria.

4.4.2 Cooling atria

These atria are also known as a method to help with cooling loads (Bednar, 1986). They are called “cooling atria” as they have the opposite functionality of warming atria. Cooling atria focus on lowering the heat gains, therefore, it is advised to have the glazing polar orientated away from excessive sunrays, minimised or shaded (Bednar, 1986). There is a lot of research into how atria are ventilated and how they help with the ventilation inside adjacent rooms. Two driving forces are crucial in creating air flow in ventilated atrium buildings, namely: buoyancy driven ventilation and wind induced ventilation. These types of ventilation have been described in chapter 3; however, there is a need for them to be explained again in relation to buildings that incorporate atria in their design in order to ensure a better understanding of how natural cooling atria work.

4.4.2.1 Buoyancy driven ventilation in buildings with atria

Rooms that open on to open vertical spaces, such as an atrium or chimneys, benefit from the buoyancy effect. This is because the buoyancy driven ventilation that causes the stack effect has a considerable influence on the thermal conditions (Moosavi et al., 2014). Hussain and Oosthuizen (2013) add that acceptable comfort conditions in rooms can be maintained by relieving the exhausted air, poured from rooms into the atria and then to the outside using buoyancy effect. Nevertheless it is important to understand what related factors help with this effect.

Apart from temperature, the related factors connected with a better buoyancy effect are the height differences between the air’s low-level inlets and the high-level outlets of the atrium. This leads to an air exchange between the indoor and outdoor spaces (Moghaddam et al., 2011). Moosavi et al. (2014) also agree that the factors influencing buoyancy driven ventilation are; lower level inlets, higher outlet openings, and heat. Hence, the top of the atria is a great outlet opening position.

The element of height is important in helping with solar assisted ventilation (Holford & Hunt, 2003). Warm air is collected in the atrium and heated up through solar radiation also the glazed atrium attracts solar energy, moreover the solar radiation affects the roof temperature and therefore results in an increasing temperature on the atrium's upper layers (R Li & Pitts, 2006). These result in stack pressure and increase the upwards flow rate for exhausting hot air outside the building and replacing fresh air inside the rooms (Holford & Hunt, 2003). As such, the atrium performs in a similar way to the traditional solar chimneys in collecting and channelling warm air from the inside to the outside at the very top (Holford & Hunt, 2003).

However, there is a drawback in this system in that thermal discomfort that can be experienced amongst occupants on the top storeys of a building because the warm air collects at the top of the atrium.

4.4.2.2 Wind induced ventilation in buildings with atria

The wind force can cause pressure gradients between the inner atrium facing façades and the building's outer facades (Sharples & Bensalem, 2001). This pressure difference causes the air to flow through the building. The two most important factors in wind induced ventilation is the wind direction and its speed (Moosavi et al., 2014). Other factors that influence the direction the internal airflow and its magnitude are the shape of the roof over the atria, the pressure distribution inside and outside the building, the amount of façade leakage and the sheltering effect of the structures surrounding the area (Sharples & Bensalem, 2001). Horan and Finn (2008) also conclude that wind driven ventilation is effective in places where there are high wind speeds. They have found that the effect of the wind speed on the air change rate (ach) inside the atrium is linear. This means that the higher the wind speed, the greater the air change rate inside the atrium. Moreover, Moosavi et al. (2014) believe that wind can also help in ventilation of the rooms directly by opening external room windows. They state the faster wind speed increases the rate of the ventilation in the rooms with windward openings. The increased wind rate outside can also help ventilation in the leeward openings by generating suction or negative pressure outside the room's external windows or openings, which could lead to air flow from inside to outside and possibly draw in air from other openings with non-negative pressure (Moghaddam et al., 2011).

Finally, according to Abdullah and Wang (2012) analysis of an atrium, the increase of openings and wind speeds can reduce the vertical temperature gradient to a great extent and this may not guarantee a comfortable temperature. Also, the impact of the wind force is not as expected in the dense urban areas where the building exposure to wind is limited (Horan & Finn, 2008).

As explained in chapter 3, sometimes, and especially in extreme temperatures, neither buoyancy nor wind induced ventilation alone are effective enough. To maximise the ventilation in atria, and consequently in the building, often both buoyancy and wind induced ventilation can achieve the desired thermal comfort level, or at least help with the cooling loads (Liu, Lin, & Chou, 2009) (Figure 4. 14). Sharples and Bensalem (2001) also agree that both the wind force and stack effect caused by buoyancy are utilised in buildings to generate the flow of air in spaces and rooms adjoining the atrium well. They add that the atrium acts as a solar chimney to exhaust the warm air from the top openings in summer when there is no wind. At other times, when there is wind, the pressurised wind forces assist the stack effect and create a pressure difference (negative pressure) between the inside and outside causing a flow of air inside through the rooms and into the atria and outside the atria openings (a suction effect).

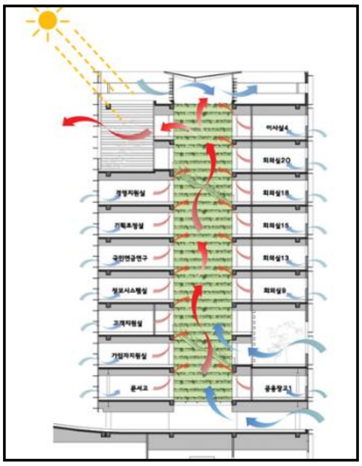


Figure 4. 14: An example of a cooling atrium using buoyancy and wind induced technique

To summarise, the functionality of cooling atria is as follows: the hot air on the top layer wants to escape through the top of the atria and thus draws air from the surrounding spaces to fill the vacuum and thereby set up the convective flows (or stack effect) (Bednar, 1986). This is where the “Building to Atria” ventilation flow takes place (J. Q. Li, 2004).

Moreover, Bednar (1986) states that during the day, the flow of air assists evaporation cooling to help skin temperature fall, and at night it helps to cool the whole building. At night the strategy of open-air courtyards, used in Islamic architecture, means that air in deep courts cools the walls, slowing the rate of heat build-up over the next day. The same strategy can be used in buildings with atria at night where the atrium can provide cold air over the night (Bednar, 1986).

4.4.3 Cooling and heating atria - convertible atria

The final type is convertible to cooling or heating atria (Figure 4. 15), depending on the situation. This type helps with cooling and heating loads. The Solar Energy Research Institute (SERI) building in Colorado is an example of such atrium. On extremely hot days, when the atrium is much warmer than the building itself, the atria space could run independently. The independent mode is when there is no contact between the air inside the atrium space and the occupancy space in the building. This helps to prevent warm air pouring inside the building from the atria, rising the temperatures, and adding to its cooling loads (J. Q. Li, 2004). It also allows the atrium to cool itself down with no openings to rooms and release its hot air to the outside environment. In the cold days however, the atria can be closed to the outside environment minimizing the heat loss and act as a buffer zone between inside and outside and in some having the effect of a greenhouse in order to help with lowering the heating loads.

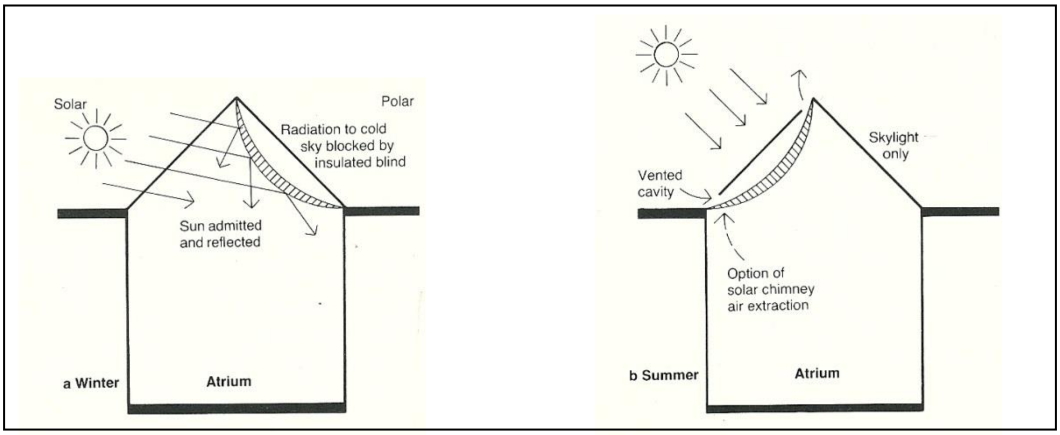


Figure 4. 15: An example of a convertible atrium in summer and winter with operable shading which can be moved to the sides

Between the three types of atria (heating, cooling and convertible atria) convertible atria would be more suitable for a semi-arid steppe climate where there is a need for cooling as well as heating. Therefore, in winter, buildings can take advantage of closed top atria to limit heat loss and in summer, in order to reduce overheating and assist with ventilation, atria top can open up. This technique has also been used within Taleghani et al. (2014) research. Taleghani et al. (2014) concluded that, in terms of the thermal comfort of occupants and the energy consumption due to cooling and heating demands, a convertible atrium helps to provide a more efficient building throughout the year compared to a building with no atrium. Their test was conducted on a climate where summer and winter were over the comfort threshold, and suggests that these types of atria could be beneficial in semi-arid climates. Since Tehran (the case study city) has semi-arid climate, convertible atria have been used for this thesis.

4.5 Summary of Chapter 4

This chapter covers the history of atria where the basic full height atria as known today started in the early 20th century. The advantages and disadvantages of using this features has also been mentioned. Advantages such as providing NV, solar gains, natural light, better air quality which can lower the energy consumed in buildings. But also attention needs to be payed to control the heat loss in winter and the overheating in summer. Moreover, five generic forms of atria have been introduced as the basic design forms that this thesis tends to later focus on. In addition, ambient conditions are known to be of importance when designing buildings with atria. Ambient conditions such as solar radiation, outdoor temperature and wind direction and speed have direct effect on atria climate environment. Last but not least, atria functionality has been divided into three types; warming atria, cooling atria and convertible atria. This thesis aims to look into convertible atrium which has the potential to help with lowering heat loss in winter by creating enclosed space, and opening up the ceiling in summer in order to get rid of excessive heat.

CHAPTER 5: Case study of Tehran as a semi-arid climate city

In previous chapters, discussion on thermal comfort, energy consumption, climatic design and atria have been provided. This chapter introduces Tehran (the capital of Iran) and places the information from the previous chapters in the context of the city, which has a semi-arid climate.

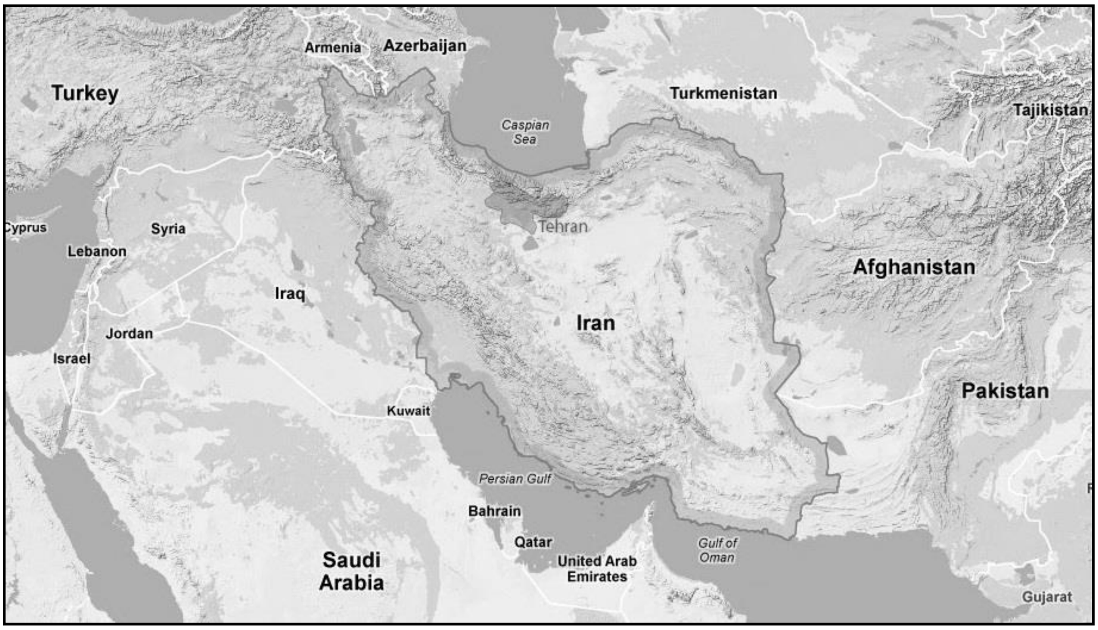


Figure 5. 1: Map of Iran and Tehran (GoogleMap)

Iran is the 18th largest country in the world (UNFPA, 2012), and is located in the Middle-East sharing borders with Turkey, Iraq, Afghanistan, Armenia, Turkmenistan, Azerbaijan, Pakistan and the waters of the Persian Gulf, Oman seas and Caspian Sea. Iran also stands on 1,648,195 km^2 of land, and in 2017 had a population of more than 81 million, (World Population Review, 2017a). Tehran is also known as the largest city in the Middle-East (Barati et al., 2010). Figure 5. 1 shows the location and scale of the city within Iran. It covers approximately 636 square kilometres of land and ranks today amongst the most populated cities in the world (Habibi & Hourcade, 2005).

Norouzitalab (2010) describes the history of the city, stating that it first began as a village. When the Mongols destroyed the city next to Tehran in the 13th Century, people began to move to the village and so Tehran started increasing in population to eventually become a city. Norouzitalab (2010) also states that, in the 17th Century a bazaar was added, walls were built around the city, and Safavid rulers settled in Tehran. Thereafter, the King of the Zand dynasty issued orders to build his palace in this region, which would thus have moved the capital to Tehran; however, he was dissuaded from this move before its completion. Nevertheless, in 1795, the king from the Qajar dynasty was crowned in Tehran and finally the city became the capital of Iran, as it has remained to this day (Norouzitalab, 2010).

5.1 Tehran's climate

Iran is a country with diverse weather conditions in different areas (Shokouhian et al., 2007). Haftlang (2003) describes Iran's climate as equating to the diversity found across a continent where, at the same time, snow can be found in the north and warmth in the south. Due to this difference, weather in Iran must be considered regionally (Keyhani, Ghasemi varnamkhasti, Khanali, & Abbaszadeh, 2010). Even though Iran's topographical complexity has resulted in climate diversity, the desert and steppe climates are the most dominant (Hastaie, 2000).

5.1.1 Climatic classification

There are different climatic classifications to consider, such as those provided by Koppen, Olgyay, Oliver, Riazee, Ganji, Tahbaz and Jalalian and Kasmaee. Koppen was known to be the first to classify world climate in 1900, and in 1936 made some modifications to his definition. His classification was based on air humidity, air temperature and vegetation type (Pourvahidi & Ozdeniz, 2013). A literature review by Pourvahidi and Ozdeniz (2013) on all the above classifications, found that the climatic regional divisions depended on different factors and that each of these factors could be studied at different levels, from micro to macro. Nevertheless, it is important not to complicate the divisions of climate if it is only studied for design purposes. For example, in a macroclimate the differences are more vivid, such as the difference between hot humid, temperate humid, hot dry and cold; however, each macroclimates can also consist of different microclimates.

Riazi and Hosseyni (2011) were the first Iranian researchers to study Iran's climatic classifications in 1977. They used the Olgyay (1992) method, considering data from 43 meteorological stations across the country. Their research was from a human comfort and building construction point of view and they concluded that, from Olgyay's research, Iran has nine different zones due to the five summer and six winter climates divisions.

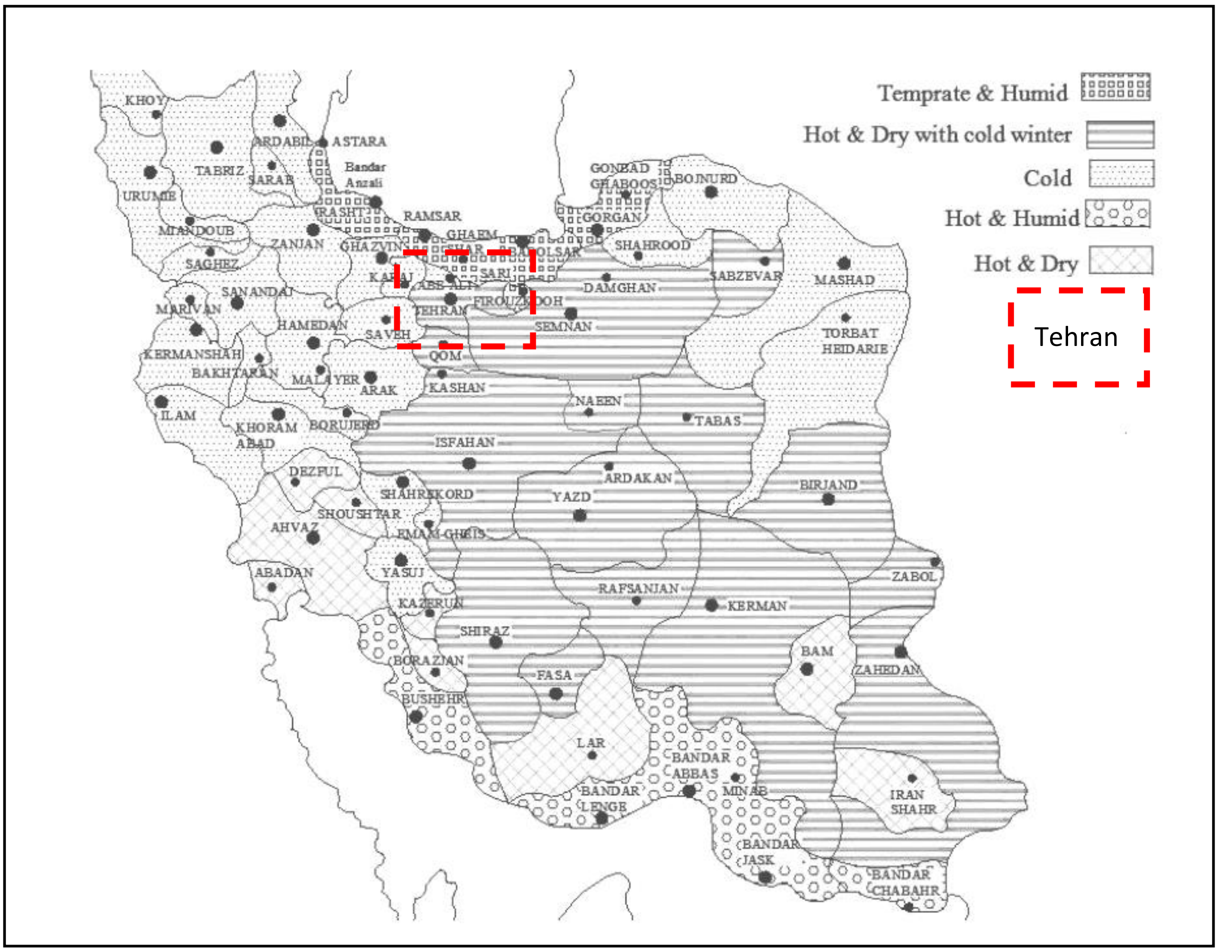


Figure 5. 2: Climate zones of Iran according to (Pourvahidi & Ozdeniz, 2013)

Pourvahidi and Ozdeniz (2013) also conducted analysis on climatic data from 68 meteorological stations in Iran. They applied international standards, studied the results for 12 months and produced many charts; from this, they concluded that there are five classification groups (Figure 5. 2). As validation, they also compared Iranian vernacular architecture in different regions of Iran and found that, in these five climatic regions, the vernacular architecture differed considerably. The five groups are: cool, temperate-humid, hot-humid, hot-dry with cold winters (known as semi-arid) and hot-dry climate. As such Tehran is categorised as hot-dry with a cold winter climate; this also agrees with Koppen’s world classification for Tehran’s climate explained as follow:

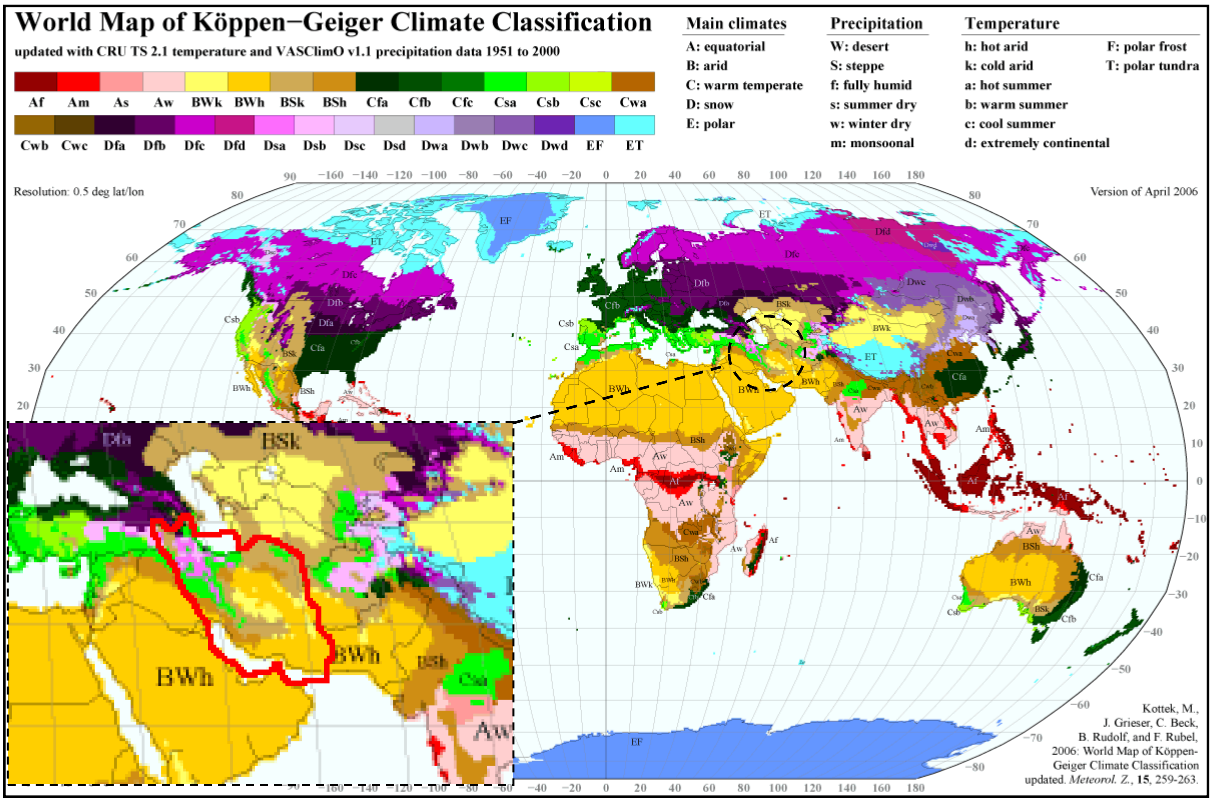


Figure 5. 3: Koppen’s world classification (Institute of Veterinary Public Health, 2017)

According to Koppen’s classification, Iran is divided into six different climates, namely warm, cold-desert, warm-semi-arid, cold-semi-arid, warm-Mediterranean and warm-continental. Haftlang (2003) claimed that, according to Koppen’s categorisations (Figure 5. 3), Iran mostly fits category B, whilst Tehran, is situated in the BS region, also known as the semi-arid or steppe climate zone. Koppen’s system defined microclimate category B as a dry climate, meaning that the amount of precipitation from rainfall or melted snow is less than the amount of evaporation (Haftlang, 2003). A dry climate is divided into two categories: the desert (BW), and semi-desert or steppe (BS) (Haftlang, 2003). The characteristics of Iran’s BS climate are stated by Haftlang (2003, p.19-20) below;

> ”…This climate separates the desert and humid climates and … covers approx. 500,000 sq.km area of Iran. Some of which is on the southern foothills of Alborz…This climate belongs to the foothills. From the point of view of annual average temperature, this climate can be divided into two categories:…areas where the average annual hot temperature above 18

degrees (BSh)… areas where the average annual hot temperature less than 18 degrees (BSk).”

Table 5. 1: Climate Criterion (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18\ ^{\circ}C$
k	Cold steppe /desert	$T_{ann} < +18\ ^{\circ}C$
a	Hot summer	$T_{max} \geq +22\ ^{\circ}C$
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10\ ^{\circ}C$
c	Cool summer and cold winter	not (b) and $T_{min} > -38\ ^{\circ}C$
d	extremely continental	like (c) but $T_{min} \leq -38\ ^{\circ}C$

As the annual average temperature of Tehran is less than 18°C (Table 5. 1), it is categorised as the BSk (semi-arid cold) region, with cold winters. This means that the climate is in the arid (B region’s main characteristic classification) + steppe (S precipitation classification) + cold (k Temperature classification) categories.

5.1.2 Climatic data

Tehran has a unique geographic location as its climate becomes warmer and drier towards the more southern reaches. Alborz Mountain is located in the north, (Figure 5. 4), where the climate is temperate in summer and cold with snow in winter; in contrast, the south of the city is near the desert, where summers are hot and winters are cold with scarce rainfall (Afshar, 2010).

Figure 5. 4: The region of Tehran region by Google Map

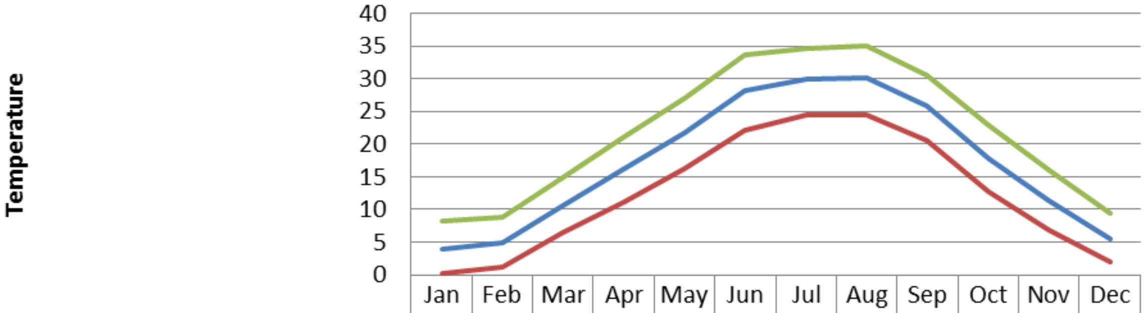
However, in order to study the temperatures of Tehran, the average temperatures of the whole city should be considered (Heidari, 2009). Table 5. 2 summarises Tehran’s weather temperature category in accordance with Heidari (2009) information on the city’s climate and ASHRAE’s 7 point scale (McIntyre, 1980); which is cold, cool, slightly cool, neutral, slightly warm, warm and hot.

Table 5. 2: Tehran’s climate based on ASHRAE’s 7-point scale

Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Cold			Cool			Slightly Cool	Neutral				Slightly warm	Warm	Hot		Warm	Slightly Warm	Neutral		Slightly cool			Cool	

Keyhani et al. (2010) also classify Tehran’s weather as being mild in spring, hot and dry in summer, pleasant in autumn, and cold in winter; this classification accords with those in Table 5. 2.

Table 5. 3: Tehran’s monthly temperatures (Climate Consultant 6 software)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tehran Average Dry Bulb Temp (C°)	3.88	4.97	10.66	16.29	21.74	28.25	29.87	30.07	25.89	17.78	11.41	5.58
Tehran average Low Dry Bulb Temp (C°)	0.28	1.2	6.37	11.17	16.23	22.15	24.48	24.52	20.47	12.79	6.82	1.9
Tehran Average High Dry Bulb Temp (C°)	8.16	8.77	14.87	21.2	26.99	33.58	34.63	34.97	30.53	22.93	16.14	9.4

Table 5. 3 represents the Energy Plus data file on Tehran’s monthly temperatures; moreover, the Iranian Metrological Organization (Khorasanizadeh, 2013) confirm these temperatures as the climate data of Tehran city.

Energy Plus (2014a, para.5) holds climate records covering the past 30 to 43 years in Tehran and the organisations “WeatherBank maintains hourly and daily historical data records from every National Weather Service reporting station … around the world.” Energy Plus uses climate data from Tehran’s Mehrabad Airport Station, which confirms that Tehran has an annual dry bulb temperature of 17.19 °C, which is similar to the mean temperature of 17.3 reported by the Tehran Municipality (2014) and the 17.2 reported by Haftlang (2003). Therefore, simulations that use Energy Plus as their climatic data are adopting a valid source of information; as such, Energy Plus’ weather data is used as the climatic source in the simulation program in chapters 8 and 9 of this thesis.

According to Table 5. 3, August has the highest average temperature and January the lowest. The months with the most comfortable temperatures are those around May, September and October (Table 5. 3 and Table 5. 4).

Table 5. 4: Tehran's weather data (Climate Consultant 6 software)

WEATHER DATA SUMMARY	LOCATION:	Tehran Mehrabad, -, IRN
	Latitude/Longitude:	35.41° North, 51.19° East, **Time Zone from Greenwich** 3
	Data Source:	ITMY 407540 WMO Station Number, **Elevation** 1190 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Dry Bulb Temperature (Avg Monthly)	3	4	10	16	21	28	29	30	25	17	11	5	degrees C
Dew Point Temperature (Avg Monthly)	-3	-3	0	0	3	2	6	6	4	2	0	-1	degrees C
Relative Humidity (Avg Monthly)	60	56	49	38	34	21	25	24	25	38	49	62	percent
Wind Direction (Monthly Mode)	270	270	280	280	270	270	290	180	180	280	0	290	degrees
Wind Speed (Avg Monthly)	2	2	3	4	3	3	2	1	2	3	2	1	m/s

Other data for Tehran's geographic characteristics, such as the wind speed direction and velocity range, humidity, dew point and dry bulb temperature can be seen in Table 5. 4. These information is illustrated as a Wind Wheel diagrams in Figure 5. 5 for cool season and in Figure 5. 6 for warm season. These are diagrams produced with Climate Consultant 6 software, which uses Energy Plus data in order to generate graphs and charts (more climate data in Appendix 2). In order to understand the Wind Wheel graph Climate Consultant Software (2014) provides a unique description below:

> "The Wind Wheel … displays for each wind direction the Wind Velocity and Frequency of Occurrence along with concurrent average Dry Bulb Temperature and Relative Humidity. The outer ring shows the percentage of hours when the wind comes from each direction. On the next ring the height and colour of the bars shows the average temperature of the wind coming from that direction (light blue is in the comfort zone, blue is cool or cold, and red is warm or hot). The next smaller ring shows average humidity (light green is comfortable, yellow is dry, and green is humid). The innermost circle shows the wind velocities that come from each direction; the tallest brown triangle is the maximum velocity for that period, medium brown is the average velocity, and the smallest light brown triangle is the minimum velocity. Hours when there is zero wind speed do not appear on this chart…Some weather stations report wind direction only within wide categories, which accounts for the white or empty wind direction zones on some charts…The Wind Wheel was developed by Rashed AlSaali as part of his PhD dissertation."

Figure 5. 5: Tehran's cool season climate characteristics (Climate Consultant 6 software)

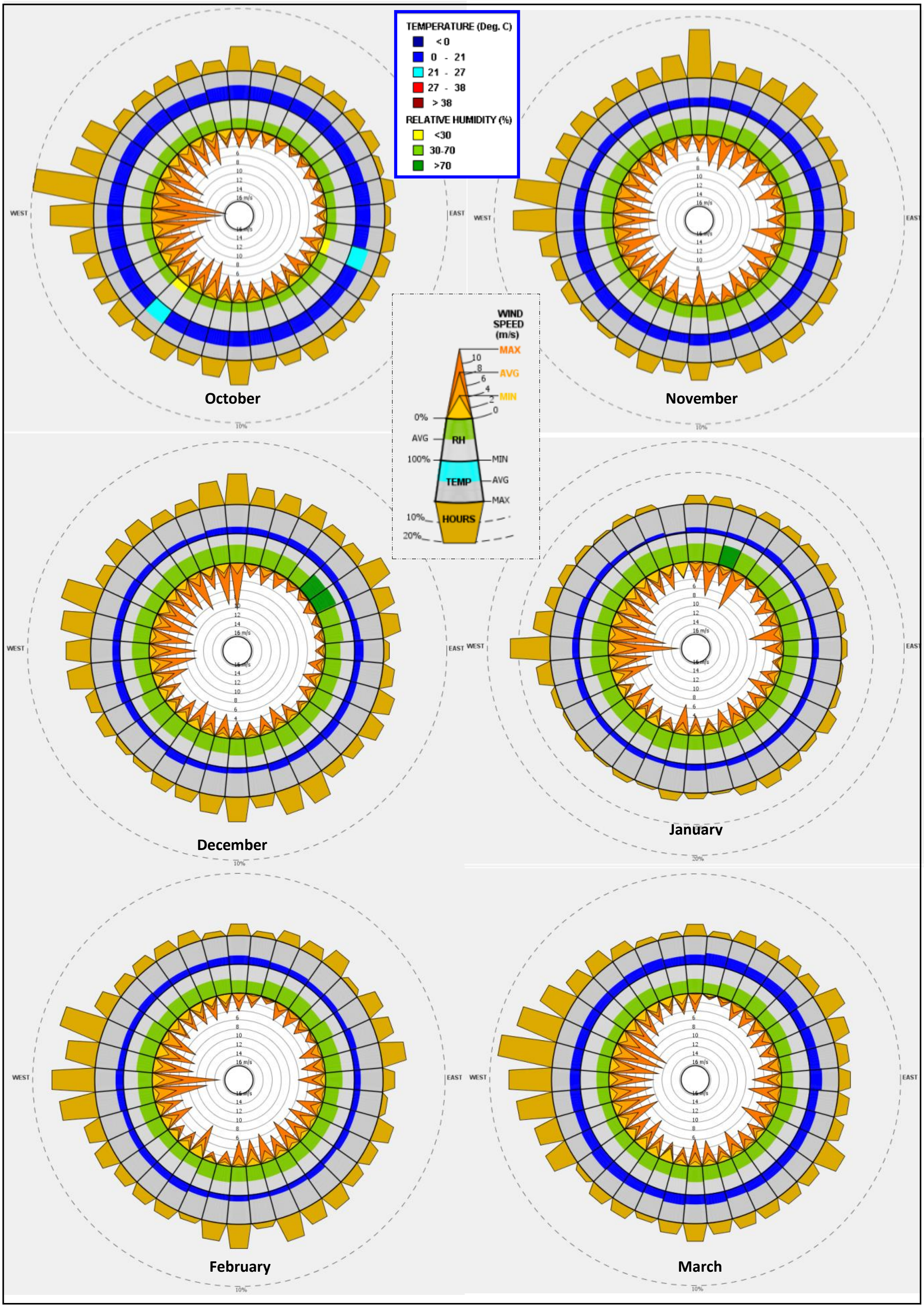
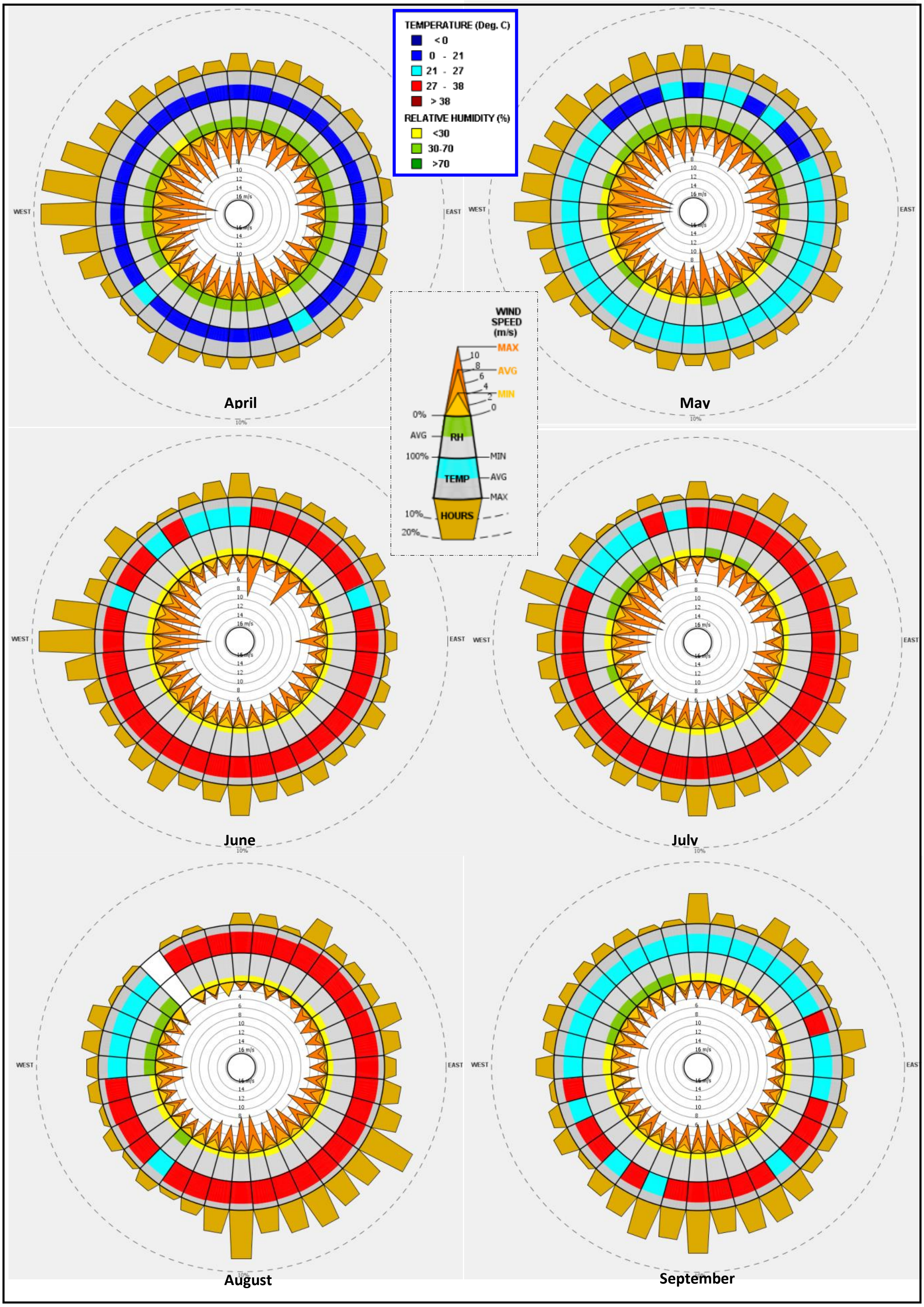


Figure 5. 6: Tehran's warm season climate characteristics (Climate Consultant 6 software)



Overall, Tehran is a city where buildings might need cooling in June, July and August during which the temperature is at its highest (where the red line is thickest in Figure 5. 6, and the highest average temperature is shown in Table 5. 4). Furthermore, buildings will require heating in December, January and February when temperatures are at their lowest (where the blue line is thinnest in Figure 5. 5 and the lowest average temperature is shown in Table 5. 4). It is possible that, in other months, there is also a need for support techniques to provide or maintain thermal comfort inside buildings.

Moreover, wind speeds vary from 1 to 4 metre per second (m/s) throughout the year but they are mostly in the direction range of west or north-west, except during August and September, when they are mostly from a southerly direction (see the inward spikes in Figure 5. 5 and Figure 5. 6 and the wind direction degree in Table 5. 4).

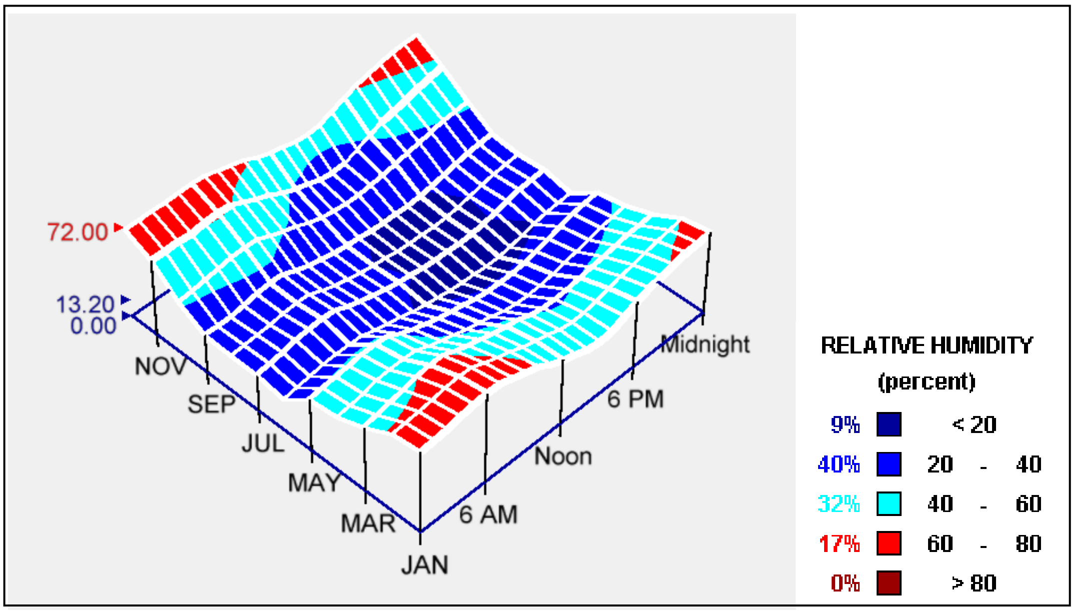


Figure 5. 7: Tehran Humidity level (climate consultant 6)

In terms of precipitation, Haftlang (2003, p.21) states that, "The rainfall humidity is also less and varying in this region like desert region…Tehran precipitation is 226mm… The rainy seasons are 5 months in Tehran. In Tehran maximum rainfall takes place during Nov-Dec and Dec- Jan.". Meanwhile, Mahmoodi, Zade, and Monam (2010) believe that the coldest and warmest months of the year are mid July-August and mid January-February, respectively. Furthermore, Keyhani et al. (2010) state that the coldest month is known to have a mean minimum temperature of -1°C and a mean maximum temperature of 8°C; whereas, the hottest month has a mean minimum temperature of 23°C, and a mean maximum temperature of 36°C. Thus, weather conditions can be harsh at times. Haftlang (2003, p.20) also states that "the temperature diversity during summer and winter and between day and night temperatures is high … which is due to the impact of sunrays during the dry summers and the cold central Asian winds during winters…"

In addition, humidity is at its lowest in summer and at its highest at winter; however it never exceeds more than 80% (Figure 5. **7**). As mentioned in chapter 2 if the operative temperature is in the comfort range then the humidity between 20% to 70% does not have an appreciable effect and temperature has main effect on the thermal comfort of occupants. Moreover, High humidity environments are those classified above 80% (Health and Saftey Executive, n.d.-b). It is stated by (Weather Spark, n.d., para.21) that "The perceived humidity level in Tehran, as measured by the percentage of time in which the humidity comfort level is [outside the comfort range and]…, does not vary significantly over the course of the year, [remains] … a virtually constant *0%* throughout.". This means that humidity is always inside the comfort range in Tehran.

The dew point temperature is also a measure of humidity and is the temperature where condensation first begins (Horstmeyer, 2008). Weather Spark (n.d.) states that below 18°C is classified as the comfort range for the dew point temperature, so if it rises above 18°C, humidity will potentially cause discomfort. On a monthly basis, the dew point temperature of Tehran, according to Table 5. 4 is in the average range of -3 to 6. As such Tehran's humidity falls within the comfort range throughout the year. Therefore, the thesis focuses on air temperature to calculate the thermal comfort of occupants. As such, it is important to know the temperature comfort zones in Tehran's semi-arid climate.

5.2 Tehran's Semi-arid Comfort zone

As explained in chapter 2, many researchers working in arid regions have challenged published international standards for indoor climates. This is due to the overcooling and discomfort caused for inhabitants (Tantasavasdi, Srebric, & Chen, 2001) and as a result the wasted energy consumption. Pitts and Saleh (2007) highlight the importance of providing a local thermal comfort range for each region. Their study shows that, in summer conditions in Britain if a cooling standard was to rise 3°C more than its setting, it can result in a 4.8% to

8.5% reduction in the cooling energy of an atrium. This is the reason why the concept of an Adaptive Comfort Standard (ACS) was introduced in ASHRAE Standard 55 (2013). The standard is based on local comfort surveys so it reflects people's preferences; this is important as buildings are made for people and what they feel should be the base measure for comfort levels (Barkkume, 2007).

Heidari (2009) also believes that a comfort temperature should be defined locally. For example, people living in cold climates might find a certain temperature too hot, whereas those living in hot and dry areas may find it comfortable. Knecht and Hart (2005) have summarised this as follows; "The more an indoor environment replicates the environment that humans evolve in, the exterior environment, the more comfortable people will find it". Furthermore, Heidari (2009) believes that people's actual comfort temperature range is larger (and thus different) from that which is measured under laboratory conditions. Therefore, a survey has to be conducted to understand Tehran's thermal comfort temperature range. Unfortunately, not many surveys have been carried out that examine the adaptive thermal comfort range of people in Tehran and further efforts by researchers are required. However, two studies are available which can provide sufficient information to draw useful conclusions.

Mahmoodi et al. (2010) have conducted research into the physiologically equivalent temperatures of people in Tehran to understand the relationship between how they perceive and how they feel different temperatures. However, their research has been based on an outside area in a specific location and not inside a building. They have also limited the parameters by restricting the sample population to men at the age of 35 walking at 0.5 metres per second with 0.9 Clo (Clo is used as a measure of clothes thermal insulation (Engineering ToolBox, n.d.)) in winter, 0.4 Clo in summer, and 0.6 Clo in spring and autumn. Table 5.6 displays their results compared with the thermal comfort temperature range of Middle Europeans (Lin, Matzarakis, & Hwang, 2010). Comparing the different comfort ranges in both regions highlights the importance of location as a substantial factor. As can be seen, there is a difference in what is referred to as cold by people in the semi-arid climate of Tehran compared with the perceptions of Western, Middle Europeans who generally experience a lower annual average temperature. Table 5. 5 shows, for example, the neutral temperature is 26°C-30°C for Tehran where as in Western/Middle European countries, 18°C-23°C is classified as neutral. For Tehran under 18°C is cool and above 34°C is warm, however in European countries, under 13°C is cool and above 29°C is warm. Therefore, based on the data in Table 5. 5, European people are more tolerant of cold climates, whereas people in the semi-arid climate of Tehran seem to be more tolerant of hot seasons.

Table 5. 5: Comparisons between physiologically equivalent temperature ranges

Thermal Sensation	Physiologically equivalent temperature range (°C) for western/ middle Europeans (Lin et al., 2010)	Physiologically equivalent temperature range (°C) for Tehran (Mahmoodi et al., 2010)
Very Cold	<4	<14
Cold	4-8	14-18
Cool	8-13	18-22
Slight Cool	13-18	22-26
Neutral	18-23	26-30
Slightly Warm	23.29	30-34
warm	29-35	34-38
Hot	35-41	38-42
Very Hot	>41	>42

Moreover, the comfort temperature may vary from one season to another even for people in the same district. This may be due to different styles of clothing (Heidari, 2009). For example, 19°C may be in the comfortable range for winter, whereas it may be too cold for summer. In addition, people tend to be more tolerant in warm or cold temperatures if they have control over their environment; for example, by opening windows or adjusting other openings in a dwelling. This might also explain why occupants in naturally ventilated buildings seem to have a wider range of thermal comfort, as demonstrated in the adaptive comfort standard (which will be explained later).

Even though research by Mahmoodi et al. (2010) was conducted on Tehran's climate, it did not focus on the thermal comfort range inside buildings with either gender. Therefore, the results were not sufficiently reliable to conclude an acceptable thermal comfort temperature range for the semi-arid climate of Tehran. However, Heidari (2009) conducted a survey in Tehran's buildings (377 questionnaires for warm and hot seasons, which included 12 company offices and 49 residential buildings, as well as 337 questionnaires for cool and warm seasons, which included 13 offices and 45 residential buildings). He states that the results show the average comfort temperatures in cool seasons ranging range from 18.2°C to 26.7°C and in warm weather from 22.8°C to 32.2°C. Heidari (2009) also claims that his results do not agree with the Iranian standards (Iranian standards which indicates a comfort range of 18°C to

22°C for cool season and 22°C to 25°C for warm season); however, they agree with the adaptive comfort standard in ASHRAE Standard 55 (2013).

Moreover, a year later Heidari (2010a) later provided a formula for the comfort temperature range of Iranian people, which was based on 15 cities in Iran and covered all the climates. It is similar to the Adaptive Comfort Model of ASHRAE Standard 55 (2013) (Figure 2.5). Formula 2 below shows how T_{comf} is calculated according to Heidari (2010a). In addition, Heidari (2009) indicated that the comfort range for 80% of the occupants is ±4°C of the Neutral temperature (T_{comf}). However, ASHRAE 55 recommends the range of ±3.5 of the neutral temperature for the comfort range of 80% of occupants and ±2.5 for 90% of occupants (Figure 2.6). Formula 1 shows how T_{comf} is calculated in ASHRAE standard 55. It is recommended that the thermally acceptable environment for 80% of people is appropriate in buildings known as thermally comfortable, meaning that less than 20% will be dissatisfied (ASHRAE Standard 55, 2013).

(Formula 1 by ASHRAE standard 55 for ACS):

$T_{comf} = 0.31T_{a.out} + 17.8$ $\quad 10 < T_{a,out} < 33$ C.

80% comfort= $T_{comf} \pm 3.5$

(Formula 2 by Heidari (2010)):

$T_{comf} = 0.30T_{a.out} + 17.8$ $\quad T_{comf}$ is the monthly average thermal comfort temperature

$T_{a,out}$ is the average outside monthly temperature

$10 < T_{a,out} < 33$ C

80% comfort= $T_{comf} \pm 4$

Based on Heidari (2010a) formula 2 of thermal comfort temperature, the neutral temperature ranging from 20.8°C to 27.7°C depending on the outside temperature (10°C to 33°C). In addition, if ±4°C is considered the range of comfort for 80% of people, then a neutral temperature of 20.8°C can be added or subtracted by four and therefore 16.8°C is the minimum temperature within the comfort range and 24. °C is the maximum in conditions when outside temperature is 10 °C. On the other hand, for the neutral temperature of 27.7°C, 23.7°C is the minimum temperature and 31.7°C is the maximum temperature within the comfort range in conditions when outside temperature is 33°C.

To summarise as discussed, Heidari has presented an annual comfort temperature range for Tehran occupants which is 18.2°C to 32.2°C. One year later he presented a formula for the population of Iran, including Tehran and other cities. Formula 2 indicates the annual comfort range of 16.8°C to 31.7°C. From the two results it can be concluded that Tehran definitely falls within the comfort range of 18.2°C to 31.7°C.

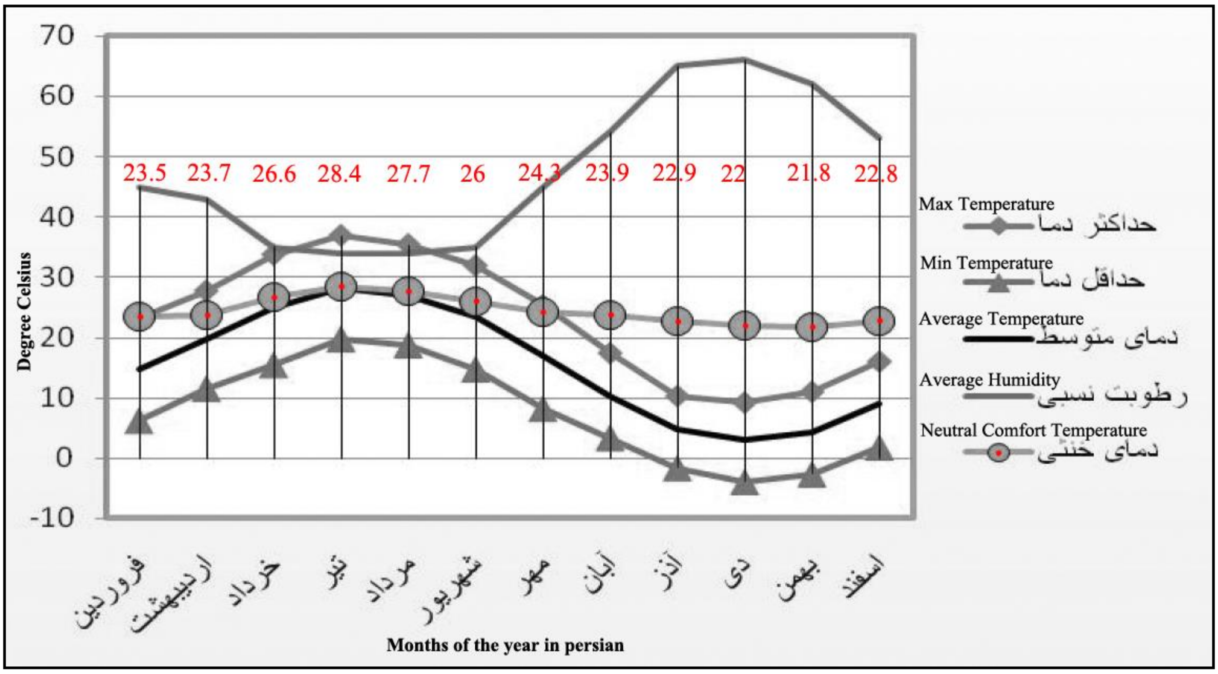


Figure 5. 8: A comparison of Tehran's monthly average temperature with the monthly neutral comfort temperature, according to statistics from the past 20 years (Heidari, 2009)

In addition, Figure 5. 8 shows the neutral temperatures in the city of Tehran in comparison with the average outside air temperature presented by Heidari (2009). Figure 5. 8 was originally presented with no digits for each month; however an attempt has been made to generate the specific numeric temperatures, which have been shown as circles on Figure 5. 8. As seen, the neutral temperatures are given in the Figure 5. 8 even when the average outside temperature is below 10°C and the lowest neutral temperature is 21.8°C. This means that, according to Heidari, for the neutral temperature of 21.8°C, the minimum comfort range for 80% of people is 17.8°C (almost 18°C) in the coldest month.

As seen in Figure 5. 8, the neutral temperatures have a range of almost six degrees throughout the year (Heidari, 2010a). Heidari (2009) claims that his annual neutral temperature can save more energy consumption for cooling buildings in summer compared to Iranian standards, where, 18°C to 25°C is the annual comfort temperature range according to Iranian standards and 16.8°C to 31.7°C is the annual comfort range according to Heidari. In his view, the new range would save at least 40% of cooling energy in summer and an overall of 25% of energy annually in Tehran's buildings.

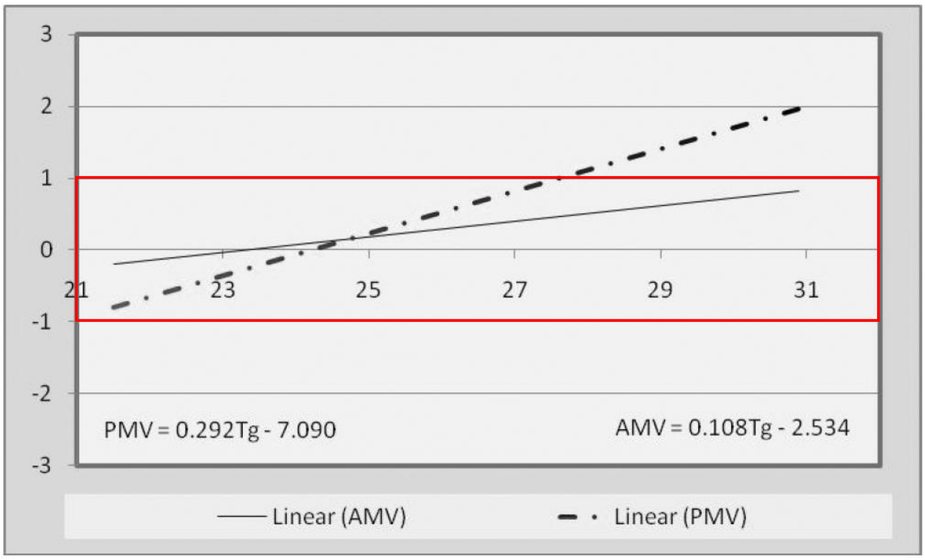


Figure 5. 9: Fanger's Predicted Mean Vote (PMV) formula (the base of ISO 7730) and Heidari's Actual Mean Vote (AMV) according to field studies in city of Tehran (Heidari, 2009)

Figure 5. 9 is presented by Heidari (2009) which compares the two formulas of Fanger and Heidari on the Predicted Mean Vote (PMV). As explained in section 2.3, the PMV that ranges between -1 to +1 is acceptable as 80% satisfaction of occupants' thermal comfort. According to Fanger's formula (shown below) the inside temperature of 31°C is close to the PMV of 2, which is not acceptable.

$PMV= 0.292T_g -7.09$

However, according to Heidari's PMV formula, which has been called the Actual Mean Vote (shown below), the temperature of 31°C is within the acceptable comfort range and is below the value 1.

AMV= 0.108 T_g -2.534

Since 1 is considered within the annual comfort range temperature, the AMV formula (for NV buildings only) rather than the PMV formula (for HVAC buildings only) presented by Fanger, is acceptable for Tehran. This, again, highlights the fact that HVAC used buildings have different comfort range than the buildings which make use of natural ventilation strategy.

To conclude, Heidari (2009) gives a reasonable understanding of the thermal comfort range of people in Tehran, which can help considerably in the design stages. He concludes it to be in the range of ± 4°C, from a neutral, or average, thermal comfort temperature. Therefore, Tehran's thermal comfort temperature range, depending on the month of the year, can be between 18.2°C to 31.7°C.

5.3 Tehran and the emergence of the high-rise

As a developing country, Iran has seen a significant rise in its population in the last few decades (Figure 5. 10) and high levels of urbanisation. As of the year 2017, the population of the country has been 81 million. Indeed, in a decade, the percentage of people in urban areas has risen from 64.5% to 71.4% and annual growth increased from 2.85% to 4.69% in 2011 (SCI, 2011).

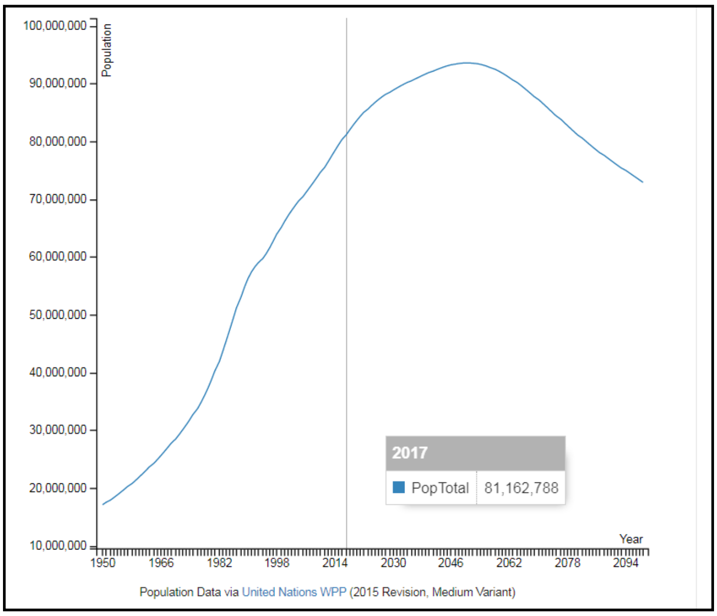


Figure 5. 10: Population of Iran (World Population Review, 2017a)

One of the most populated cities of Iran is Tehran (Barati et al., 2010) with almost 8.5 million reported as living in the area in 2015 (World Population Review, 2017b). Delfani, Karami, and Pasdarshahri (2010) also believe that Tehran today accommodates approximately 10% of the total number of people living in Iran. It is believed that Tehran is ranked the sixteenth most dense city worldwide, housing 13 individuals in every ten metres square. To put this into perspective, it is more than five times denser than New York City which inhabits 2.5 individuals in every 10 metres square of land (Aliabadi, 2013). Therefore, with such growth in population, it is inevitable that high-rise buildings will be built at a fast rate.

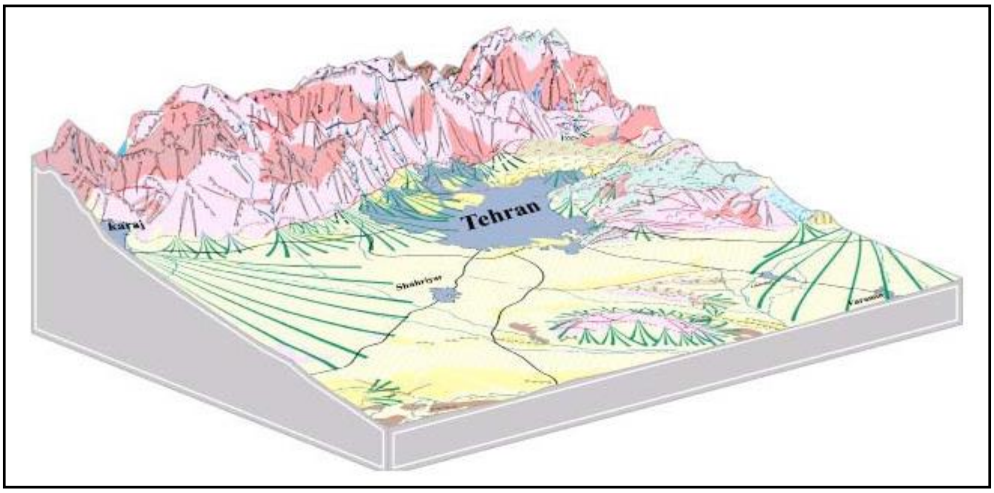


Figure 5. 11: Block diagram of the geomorphology within Tehran's limits; picture from the north and south of Tehran (Metropolis, 2017)

As for the location of the city, Tehran is situated at the geographic dimensions of longitude 51°29' E and latitude of 35°48' N, at an average elevation of 1549.1 metres above sea level (Khorasanizadeh & Mohammadi, 2013). Tehran is situated on a gentle north-south average slope of 0.026 (Malakooti, 2010) with Alborz mountain, which is mostly snow-capped, to its north and Iran's great central desert to its south (Figure 5. 11) (Malakooti, 2010).

Furthermore, Afshar (2010) believes that Tehran can be divided into three distinctive geographical zones; the mountain itself, the mountainside, and the desert. As these zones are situated from north to south, a unique cultural, social and natural environment develops from high to low class people, from cold to warm environments and these elements play a unique role in the character of the city. Strong competitors in business trade and modern construction with high rise luxury residential flats or offices are generally located in the north of Tehran. However, towards the south is the more traditional side of Tehran with museums and the grand bazaar. A short trip from north to the central to the south of Tehran highlights the cultural differences between these areas. Nevertheless, there is a threat to the original housing styles of Tehran, of which little still exists, and as such, there is little left of Tehran's old texture. Modern high-rise buildings are continually replacing the old houses at a rapid pace. These high-rise buildings have copied the culture of western high-rise buildings, and arguably created an identity conflict (Afshar, 2010; Norouzitalab, 2010; Zakerzadeh, 2009). Therefore, it is important to ensure that traditional inspirations for design and culture are also evident in the high-rise structure of Tehran to give them an identity that speaks of a specific place.

The significant emergence of high-rise buildings has been due to few factors. Firstly, in the 20^{th} Century, Tehran experienced a large migration of people from around the country. It is possible that the reason for this was because the city became the centre of financial, educational, cultural and commercial activities in Iran and therefore, created a strong attraction towards centralisation in the region (Hastaie, 2000; Malakooti, 2010). A few examples of centralising activities are described as follows:

Firstly, more than 40% of the nation's economic activities take place in the capital (Habibi & Hourcade, 2005). Tehran accommodates 25% of the country's total industry, consuming 20% of the country's energy (Tehran Municipality, 2014). It accommodates 45% of large industrial firms and 30% of Iran's public workforce (Noori, 2010). In addition, Tehran Municipality (2014) states that, being the largest business and industrial centre of Iran, 70% of all services have been centralised in this region.

Secondly, this significant centralisation of population and wealth has resulted in a shortage of land in the region (Madanipour, 2003b). To house as many people as possible, high rise buildings have presented a promising way forward and have helped to transform the location into a huge overgrown city (Zavoush, 1991). Finally, Tahbaz (2008) states that the fast growing population, the rise in land and building prices, and the changes in lifestyle have also resulted in the construction of densely laid out high-rise buildings.

Figure 5. 12: Ekbatan complex (Zolghadr, 2002)

R. Li (2007) explains the history of high-rise construction in Iran, stating that, in the mid 19th Century, Iran was exposed to modern techniques and ideas, and the state, the Pahlavi dynasty at the time, pushed the country towards an approach to modernisation that was inspired by the East. By the 1970s there was also an economic boom as well as new materials and methods of construction, which resulted in the development of high-rise buildings. This was also encouraged within the modernisation approach at the time, which included the removal of tax on any buildings over 10 storeys, and the granting of loans to convert old buildings into apartment blocks (K. T. Diba, 1980). Ekbatan Complex (Figure 5. 12) was amongst the first major example of high-rise construction in the city (Saadatfard, 2009) and its construction started around this time. In the 1980's, after the revolution, the private sector recognised the high-rise construction industry as a profitable business, and the construction of tall buildings continued (R. Li, 2007). However, at the same time there was a change of monarchy, as the country became the Islamic Republic of Iran and the city entered a confused urban and architectural stage (Afshar, 2010).

The pace of high-rise construction in Tehran has been fast due to the reasons mentioned above. However, in developed countries, the pace of high-rise construction has been slower as it started much earlier and therefore proceeded more gradually. This meant that developed countries had more time to address the problems experienced at the early stages, such as designing according to climate. Thus, the existing situation in the West is far less critical than the problems faced in developing countries, such as Iran (R. Li, 2007), meaning that Western buildings are built with better knowledge of designing according to climate. In contrast the fast pace of building tall in Tehran has given little opportunity for these considerations.

Farahi (2012) and Maleki (2011) claim that the practical problem of modern Iranian architecture is that it has embraced western designs without thinking about climate responsiveness and has failed to establish its own techniques and theories of high rise based on the success of past vernacular designs. In other words, despite the rich history of passive systems in Iran's vernacular architecture, modern Iranian designs lack the incorporation of passive techniques that motivated traditional designs in the past. This means that most construction in Iran, has not been successful in responding to climate design needs and nor do they give the impression of being born from their traditional design roots or their exclusive climatic place.

In the struggle to achieve climatic identity in the buildings of today (D. Diba, 2012), Some Iranian architects are starting to recognise, seek solutions and narrow the gap between old and new designs. There have been attempts by four architects to combine current technologies with traditional Iranian solutions, and they are; Nader Ardalan, Kamran Diba, Hossien Amanat and Hoshang Sheyhoon (D. Diba, 2012). However, the examples of their work do not cover tall buildings.

Khodabakhsh and Mofidi (2001) also emphasise that modern Iranian buildings are designed in contrast to climate conditions, despite having strong traditional climatic architectural design. For example, Moghaddam et al. (2011) states that, in Iran, the poor design of office blocks with highly glazed façades are becoming increasingly common. Not only do highly glazed façades increase the risk of overheating, but deep floor plans also require a large amount of electric lightings, which further increase heat gains. As result of neglecting the vernacular knowledge of buildings in the region, Khodabakhsh and Mofidi (2001) and Moghaddam et al. (2011) mention that HVAC systems have been used throughout most of the year to provide thermal comfort. However, Moghaddam et al. (2011) believe that, with good design, natural ventilation may be sufficient to ensure acceptable comfort levels in blocks

D. Diba (2012) encourages the recognition and integration of today's technological facilities with the motifs of traditional Iranian designs in order to revitalise high story buildings. It is important to understand that there is a design generation gap in Tehran, from the successful passive design buildings of the past to the non-climatic orientated design of the tall modern buildings of today. It is believed that natural cooling and heating systems are needed for multi-storey buildings (Maleki, 2011). This is because designing tall buildings according to climate, significantly helps with the problems of energy consumption, especially in Tehran.

There are also advantages in building tall that if designed according to climate it can be successful in lowering energy consumption:

> high rise building can house more people in a square metre of a land compared to low rise blocks (Sauerbruch et al., 2011). Furthermore, high rise compared to low-rise structures create less carbon footprint (Sauerbruch et al., 2011) and use less material for usable floor space, which Sobek (2011) believes is as important as reducing energy loads. Tall buildings also share natural energy between floors (Salib & Wood, 2013); for example, in cold seasons, the hot air rises towards the ceiling and helps the above floor with its heating loads (so less heating is needed).

However, if tall buildings are not designed according to climate, the results can mean the excessive energy consumption within these sectors.

5.3.1 Energy consumption in Iran

Since 2007 Iran has become one of the 12th most energy consuming countries in the world (Enerdata, 2017). Figure 5. 13 shows the percentage of energy rise over the years 2000 to 2016, and over the years 2015-2016. Iran's percentage of energy consumption rise is more than each of the European Union (almost 6 times) and Asia, America and Africa; it is also greater than the world overall statistics.

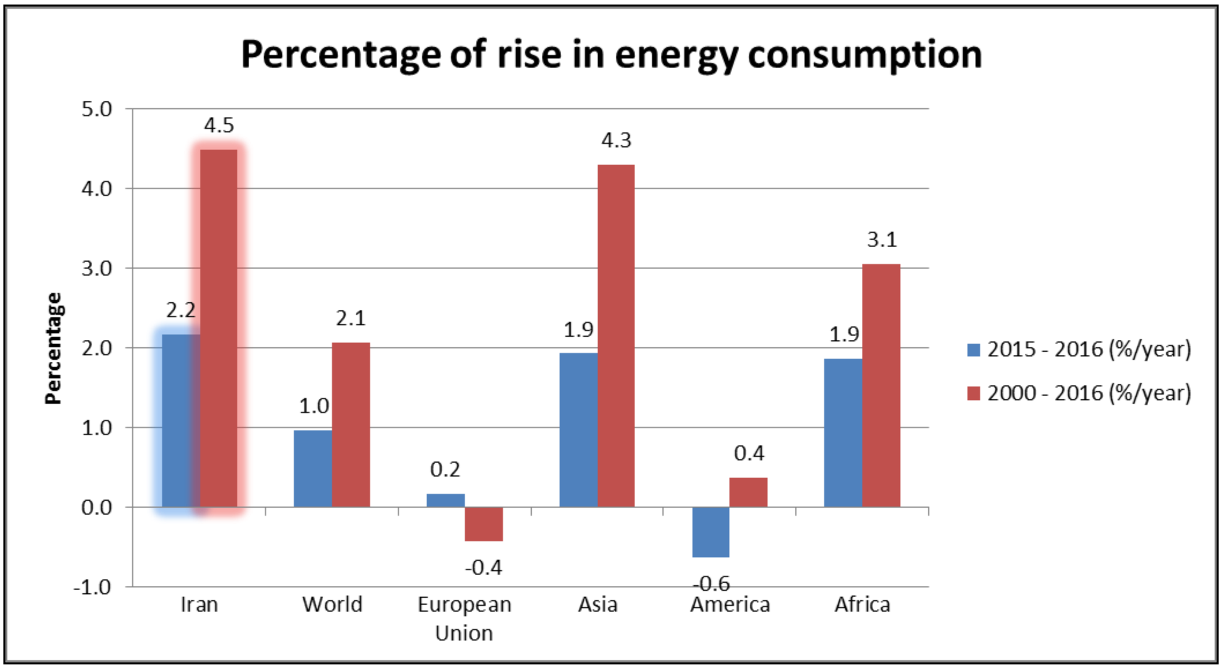


Figure 5. 13: Percentage of rise in energy consumption (Enerdata, 2017)

Figure 5. 14 compares Iran's energy consumption (as a developing country) from 1900 to 2016 with other areas around the world including those with developed countries. It is clear that the country's energy consumption rate is rising much faster than some other developed countries. Indeed the energy consumption in some developed countries, such as France, Italy, and the UK is starting to fall. However, Iran is one of the countries whose consumption has been rising fast in a comparatively short time (Enerdata, 2017). To further explain, Mazandarani, Mahlia, Chong, and Moghavvemi (2010) claims that, in 2008, electricity generation in Iran rose by 5% in only a year. One of the reasons for this is because the energy prices are low and the growth of urbanisation is fast (Asgar, 2014b), hence more energy is consumed.

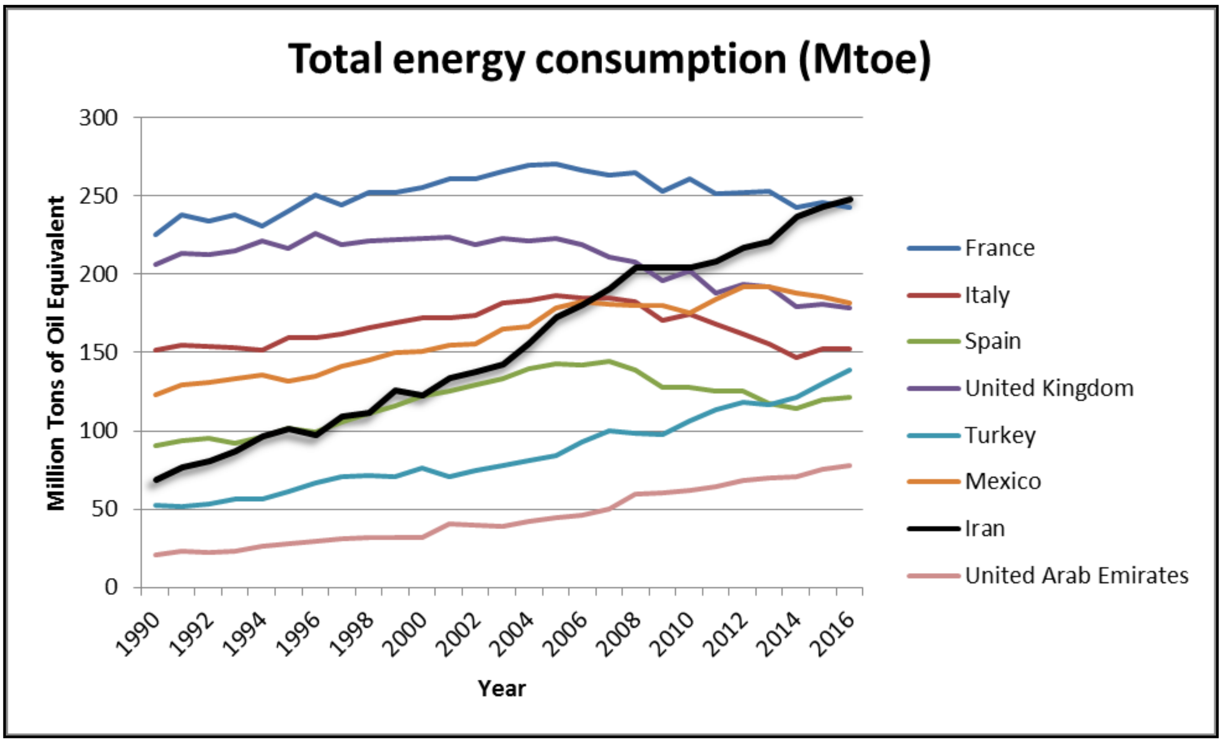


Figure 5. 14: Energy consumption of nations (Enerdata, 2017)

The building sector in Iran is the major energy consumption sectors (comprising almost 40% of the overall end users) (Iranian Ministry of Energy, 2011) (Figure 5. 15 shows the breakdown of consumption by sector). Moreover, the E.C.C (2010) claims that the energy consumption of the housing and commercial units in Iran have almost doubled in nearly a decade.

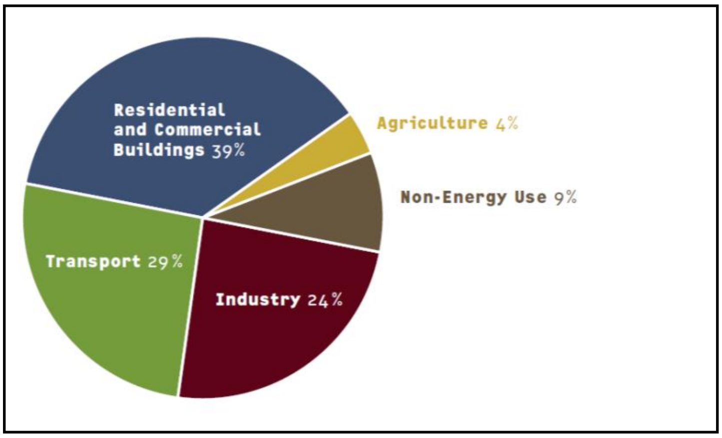


Figure 5. 15: Iran's energy consumption by sector in 2010, according to data issued by Iran's Ministry (Shahriari, Nasrollahi, Wehage, & Tarkashvand, 2013)

Shahriari et al. (2013) state that the annual energy consumption in the existing buildings of Iran is around 369 kwh/m2. Nevertheless, Table 5. 6 shows that more improvements are needed on the average energy consumption in buildings of Iran compared to some European countries (IFCO Iranain organization for Fuel Consumption Optimisation in the country, 2002).

Table 5. 6: Energy consumption of buildings (IFCO, 2002)

Country	Average energy consumption (kwh/m2)
Denmark	150
France	212.5
Germany	179.84
Greece	87.4
Netherland	207.5
Swiss	170
UK	220
Iran	369

Bagheri et al. (2013, p. 116) provide more detailed statistics, stating that:

> "… the approximate yearly primary energy consumption in residential buildings of Iran is about 450 kWh/m2, which is more than twice the indexes in many other countries [Karamnia, Amini et al.,2011; Pasdar, Pakdaman et al, 2011]…Among the various types of buildings according to the application type, offices buildings in Iran have noticeably high energy consumption indexes. Extensive research on more than 280 offices in Iran verify that the average yearly primary energy consumption index for these types of buildings in Iran is about 350 kWh/m2.
>
> Consideration of the function of these buildings (only 8–10 working hours a day) clarifies that the relative magnitude of the cited energy index (350 kWh/m2) is very high. Because most of the large office buildings in Iran are governmental or semi-governmental, energy management has not seriously been performed in them. In

addition, because the energy-costs do not affect the staff incomes in these buildings, they do not care about it."

In Iran, gas and electricity are the two most used energy sources in commercial and public service buildings. According to statistics from 2014 (shown in Figure 5. 16), electricity uses 29% and gas uses 54% of the overall energy used (gas is almost double the electricity usage). However, world statistics show the electricity usage to be almost double that of gas at 50% compared to 24% in the same year (Figure 5. 16).

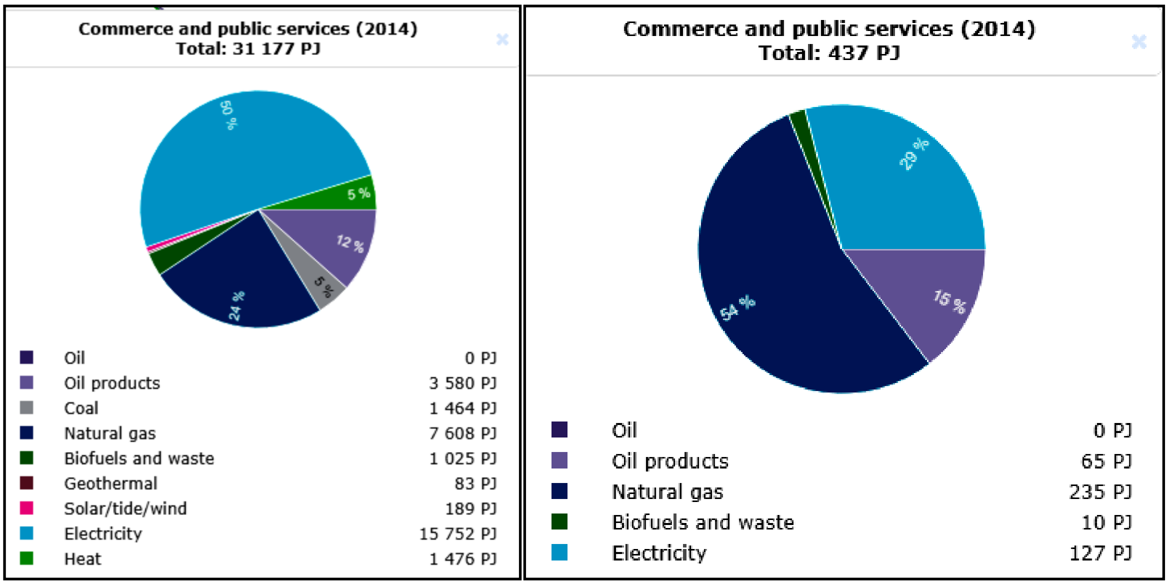


Figure 5. 16: Commercial and public sector energy sources in the year 2014 in the world on the left, and in Iran on the right (International Energy Agency, 2014)

Furthermore, Nasrollahi (2009) mentions that, from 1979 to 2005 (Figure 5. 17), there has been a decrease in petroleum or oil and an increase in gas and electricity use in the commercial and residential buildings of Tehran, and that overall, gas is the most used energy. For example, in 2004-2005, 26% petroleum and 73% gas and electricity were used.

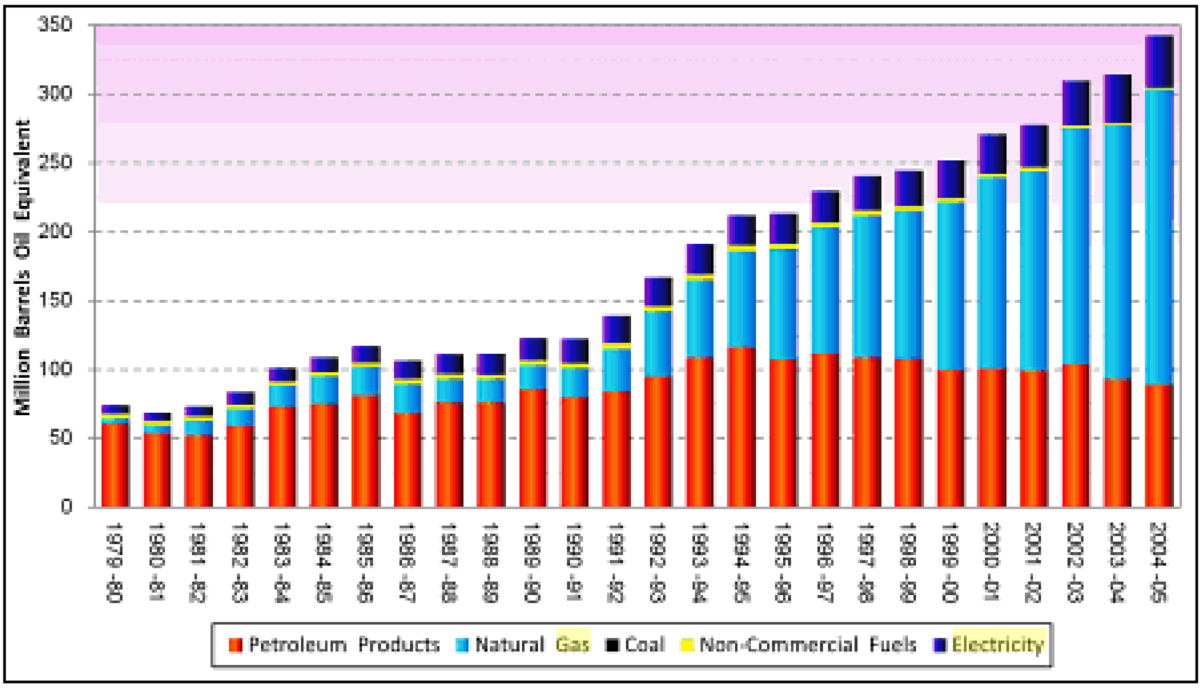


Figure 5. 17: Final consumption of residential and commercial by type of fuel (Nasrollahi, 2009)

Moreover, to generate electricity, (such as in 2013, for example) almost 67% of the primary fuel source is natural gas and 31% is oil (Figure 5. 18) (US energy Information Administration, 2015). Nasrollahi (2009) also claims that, more than 93% of the generated electricity in Iran is from gas and oil sources, which is highly inefficient; therefore, a reduction in consumption is needed. Moreover, it is not only electricity fuels that come from gas and oil, but (as seen in Figure 5. 18) 98% of Iran's total primary energy consumption is mostly from gas and oil (US energy Information Administration, 2015). As such, it is important to save these resources as much as possible because these types of fuel can expire and are not replaceable.

To summarise, in order to cool or heat buildings in Iran, two sources of electricity and gas are commonly used, and with gas also being the main primary energy source of electricity, it is clear that the consumption has to decrease because these sources are irreplaceable and they create CO2 emission which according to Paris Agreement (Department of Environment Islamic Republic of Iran, 2015) has to be decreased; hence, saving energy is of utmost importance.

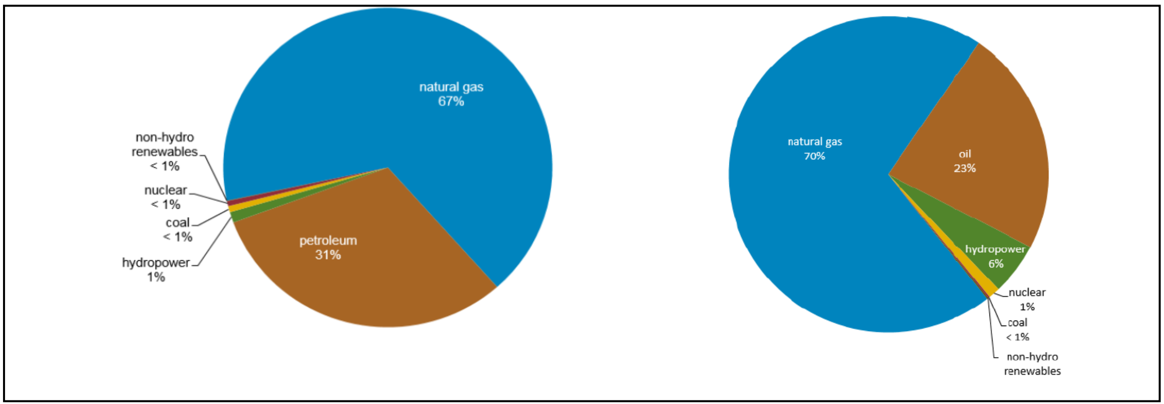


Figure 5. 18: Iran's total primary energy consumption by fuel in 2013 on the right, and Iran's electricity generation capacity by fuel in 2013 on the left (US energy Information Administration, 2015)

In terms of the public and office sectors in Tehran, these buildings use 25% of Tehran's electricity while only comprising 8.8% of the end use subscribers. The highest electricity consumption growth rate in Tehran is amongst office buildings, at 9% while the annual average growth rate is only 6% (Saboori, 2017). Out of the buildings, offices are having more percentage raise in gas and electricity consumption (19% rise) than residential (14% rise) (Figure 3.2). Therefore, it is important to improve energy consumption within office buildings; thus, this thesis explores the possibility of lowering the energy consumption of Tehran's office building sector via incorporating climatic design in offices.

5.3.2 Current building situation in Iran and the way forward

Over the past decade, there has been hardly any interest in constructing energy efficient buildings in Iran and one of the reasons is because of the subsidised and low energy costs in the country (Shahriari et al., 2013). However, if the energy costs were high, then buildings with low energy consumptions, although more expensive to build, would be worthwhile because they could return the investment through energy saving within an acceptable time-frame of the building life span.

The second reason for the lack of interest in energy efficiency is the economic downgrade of the Iranian currency value, which is influenced by high inflation in Iran (varying between 10% to 50% over the past decade (Economics, 2018)). The economic downturn of Iran reflects on the buildings to have a cheap design rather than a more elaborative design. Because as the currency is downgraded, people can no longer afford to buy the places they could previously, and therefore cheaper buildings become more favourable. Consequently building cheap reflects on the life span of the buildings, which are 25 to 30 years in Tehran whilst other countries have a 200 years building lifespan (NCRI, 2017) (Appendix 7). So buildings need to be renewed quickly due to their poor design.

The third reason for the lack of interest in energy efficiency is due to the lack of building regulation and its implementation concerning energy consumption in buildings. Even though a chapter dedicated to the improvement of energy efficiency in buildings has been incorporated into the Iranian National Building Code, energy management has not been seriously considered in many of the buildings of Iran (Bagheri et al., 2013).

Due to the above reasons, building designs have been poor. Nevertheless, since 2010 social interest in energy efficient buildings has improved considerably as some clients are taking an interest in low energy building design. This is because of the reduction of energy subsidies and rising prices of electricity, gas, petroleum and natural gas in an effort to limit the growth in demand (Shahriari et al., 2013; US energy Information Administration, 2015). The second phase of more subsidy reduction also started from 2014 (US energy Information Administration, 2015). Thus, the system is starting to change and this thesis contributes towards preparation for this new shift.

Nonetheless, there is still comparatively low interest in high cost renewable energy systems or materials, or in higher construction cost in general (such as building insulation, which increases the overall buildings cost) (Shahriari et al., 2013). However, Shahriari et al. (2013) believe that architectural energy saving methods through intelligent design seem more favourable than energy systems, materials or higher cost construction as it does not increase the building costs as much. They also state that there is great potential to create low energy buildings through design in Tehran’s climate, and claim that it would also be emission free, economically valuable and sometimes cost neutral. Therefore, this thesis also investigates the reduction of energy consumption through smart building design in Tehran’s climate. Never the less, more work is needed to raise the interest of architects and builders to design and build low energy consuming buildings.

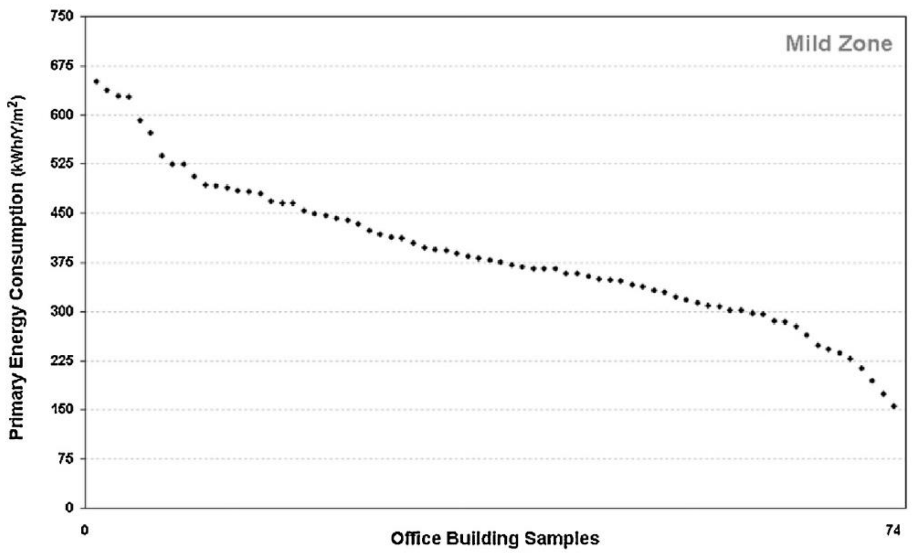


Figure 5. 19: Primary energy consumption for samples in the zones similar to Tehran's climate

Table 5. 7: Boundaries of grades in energy labels for office buildings in Iran- Tehran category is indicated by red line (I=primary energy consumption index (KWh/y/m2)

Boundaries of grades in energy label for office buildings in Iran (I = primary energy consumption index (kWh/Y/m²)).

Climatic zones	Grade A	Grade B	Grade C	Grade D	Grade E	Grade F	Grade G
Cold	$I<84$	$84 \leq I<168$	$168 \leq I<252$	$252 \leq I<336$	$336 \leq I<420$	$420 \leq I<504$	$504 \leq I<588$
Semi-arid	$I<75$	$75 \leq I<150$	$150 \leq I<225$	$225 \leq I<300$	$300 \leq I<375$	$375 \leq I<450$	$450 \leq I<525$
Hot and dry	$I<78$	$78 \leq I<156$	$156 \leq I<234$	$234 \leq I<312$	$312 \leq I<390$	$390 \leq I<468$	$468 \leq I<546$
Hot and wet	$I<82$	$82 \leq I<164$	$164 \leq I<246$	$246 \leq I<328$	$328 \leq I<410$	$410 \leq I<492$	$492 \leq I<574$

Bagheri et al. (2013) has also explored 74 offices both in Tehran and similar climates to Tehran. He states that the chart (Figure 5. 19) shows a wide range of energy consumption indexes, from 150 to 675 kwh/m2, but claims that this wide range was comprehensive for the target of his study, namely developing energy labels for office buildings within different climates in Iran. Bagheri (2013, p.122) states that, "This comprehensive covering on the energy indexes is a result of considering all the effective parameters for sampling, such as different HVAC system types, building sizes, usage types, operational characteristics", building structural types and so forth. He concludes that, in a similar climate to Tehran, 75 kwh/m2 is the upper limit for grade A office buildings, and 525 kwh/m2 is the upper limit for grade G buildings (Table 5. 7). In addition, Bagheri et al. (2013) claim that Tehran's office average energy usage is 350 kwh/m2.

5.3.3 Heating and cooling energy in Iran

Nasrollahi (2009) claims that no attention is generally paid to lowering the energy consumption of buildings through their design. As such, it is worth looking into the influence of design in lowering the energy consumption in buildings. Mahdavinejad and Abedi (2012) have divided the end use energy consumption of buildings into two groups: non-weather related (cooking, light, electricity equipment), and weather related (the heating and cooling of space). This thesis investigates the weather-related heating and cooling energy consumption of office buildings.

The largest energy end use in residential and non-residential sectors in the world is the consumption of HVAC systems (Lombard et al., 2008), and this is also the same in Iran. Delfani, Pasdarshahri, and Karami (2010) state that, in Iran, the rate of energy consumption, especially for electricity, has increased within the past two decades. This is due to the increasing number of high-rise buildings which rely on HVAC systems for the majority of the year (Shekarchian et al., 2011) where 61% of energy used in buildings is for heating and cooling (Figure 5. 20) (Riazi & Hosseyni, 2011)

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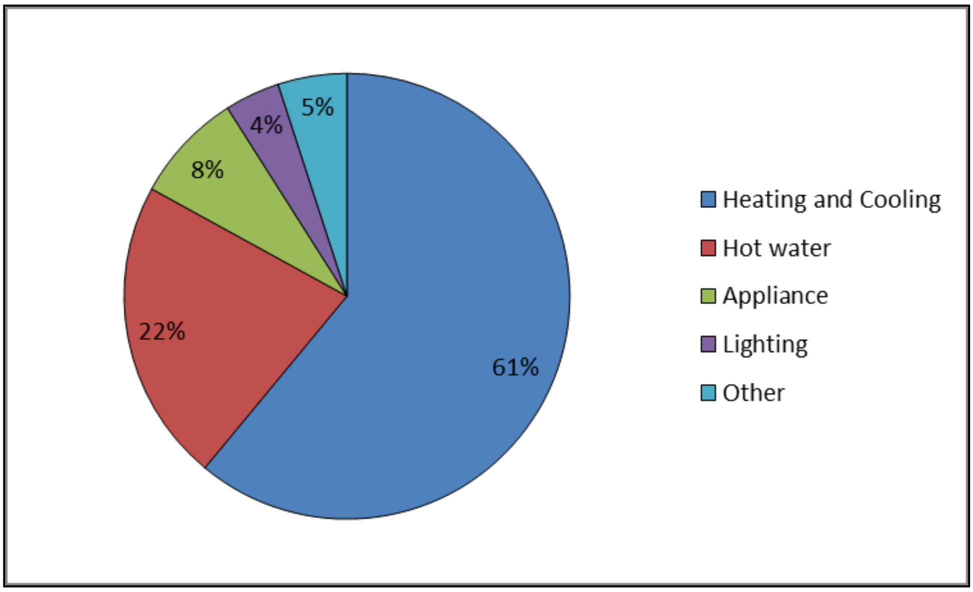


Figure 5. 20: Energy use in Buildings in Iran (Riazi & Hosseyni, 2011)

In Iran, building construction, household appliances, and heating and cooling systems are usually studied in relation to energy saving (Nasrollahi, 2009). In addition, a published report on buildings in Iran claims that 73% of gas energy is used for HVAC and that the energy is mostly used for heating with the peak months being January and Feburary (IFCO Iranain organization for Fuel Consumption Optimisation in the country, 2010). In addition, 50% of the electricity used in the office buildings of Tehran is consumed by heating and cooling systems (the other uses comprises 20% for light and 30% for electronic appliances) (Saboori, 2017).

One of the common heating systems in Iran is natural gas heaters (Hannani, Azimi, & Nikoofard, 2008), hence gas bills are usually for heating in offices. A reason behind the rise of gas consumption in residential, commercial and office buildings has been due to the intensity of cold days and the subsequent use of heating systems (Iran Deputy of Electricity and Energy Affairs, 2015). Also, in terms of cooling, for most office/administration buildings, central cooling systems (including chillers with air handling units) are used. These equipment for cooling use electricity as their source of energy. Therefore, electricity is used for most cooling systems in Iran (Nasrollahi, 2009). It is also suggested that, in using natural ventilation and natural sources of heat, the HVAC related energy consumption will be reduced in buildings (Centre for Climate and Energy Solutions, 2009). As such, it is important to design buildings appropriately with these considerations in mind.

5.4 Atria a potential strategy

Sozer et al. (2011) suggest that architects who design tall buildings must take advantage of the sun and wind and use them in a positive way just like vernacular architecture. Fathy (1986) states that traditional houses which have central courts and filigree windows have used these elements to create and maintain coolness without air conditioning, whilst also admitting light without glare. He believes that the same principles can be incorporated easily into high-rise buildings in similar climates, which means that atria can function as one element that, if used properly, might help to narrow the gap between old and new. The advantages and disadvantages of atria have been discussed in chapter 4 along with their flexibility and use in combination with other modern passive designs. Thus, atria, a design with traditional roots, might potentially be an advantage in the modern high-rise buildings of Tehran's semi-arid climate. But has atria been used in Tall buildings of Tehran? The answer is positive.

Atria are becoming popular within modern buildings in Iran's architectural designs of today. Therefore, it is important to ensure they are not poorly conceived, which can condemn a building to a long life of high energy consumption (Assadi et al., 2011). Unfortunately, the current motivation for incorporating them into design in Iran, and especially Tehran, is more likely as an architectural feature and not for the purpose of saving energy. Thus, they are not used to their full potential and as such, it has been suggested that research needs to be conducted on atria performances in this region (Assadi et al., 2011). Even though some designs have started to emerge that incorporate passive strategies in buildings, they have mostly never been built (Shahriari et al., 2013). Furthermore, not much research has been conducted into the design of buildings in Tehran and their incorporation of atria as successful climatic strategies. In addition, there are not many published works on successful examples of buildings with atria in this region. A few publications concerning semi-high-rise buildings with atria are mentioned in section 5.4.1, and three of them are based on offices. Another is a successful design of a high-rise residential building (so it has far fewer people and heat generated devices than an office).

As such, there is a strong need for more research in order to understand how offices with atria behave in the high rise buildings of Tehran and why they behave in the way they do. Also, it is important to establish whether they can truly be beneficial in terms of helping with the heating and cooling loads of offices and thus lead to a reduction in energy consumption from space conditioning. Moreover, other potential advantages should also be noted, such as improving the indoor air quality, providing natural light, improving occupants' social lives and encouraging a positive psychological effect on those using the building. Thus, this research investigates the effect of different atria configurations on the thermal comfort and energy loads of open plan high-rise office buildings in semi-arid climate.

5.5 Tehran's high-rise buildings with atria

As explained in previous sections, there is not much research available that analyses the behaviour of tall office buildings with atria in Tehran's semi-arid climate. A few examples of semi-high rise buildings with atria have been published, which are outlined below:

- A field study measurement was conducted on two semi-tall office blocks, namely the Pajoohesh-kade building (Figure 5. 21) and the Mino office block (Figure 5. 22), for a period of a year, from 2008 to 2009 (Medi, 2010). Pajoohesh-kade's cylindrically formed building has seven floors with a double glazed pyramid top skylight. In comparison, the Mino cubic form building has five floors with a flat roof and a double glazed skylight. The Mino building has five times more occupancy and computers than Pajoohesh-kade. The results showed that the Mino building considerably overheat, while Pajoohesh-kade overheats less. Both buildings have no sensible stack effect due to the lack of a roof opening, which causes overheating in warm seasons. However, they both behave favourably in terms of thermal conditions in cool seasons. Also the flat roof on the Mino building has been recognised as more appropriate for a semi-arid climate.

Medi (2010) also states that the adjacent rooms in these examples are not designed to receive daylight from the atria, despite this being one of their basic advantages, and that atria are usually surrounded by walkways that lead to office spaces. Thus, it is the walkways that tend to receive the light. This highlights the fact that these structures are not used to their full potential and instead are usually employed as a feature. Medi (2010) concludes that, by considering other systems, such as shades, exhaust vents on top floors, or adding thermal mass, the two atria could be improved.

As previously mentioned, the purpose of designing an atrium in Tehran is unfortunately to mostly serve as a corridor or for a large opening entrance, or for the purpose of lighting or to provide an architectural feature (Assadi et al., 2011). Hence in the two examples above, the atria glass roofs are not openable and this causes much discomfort in warm days.

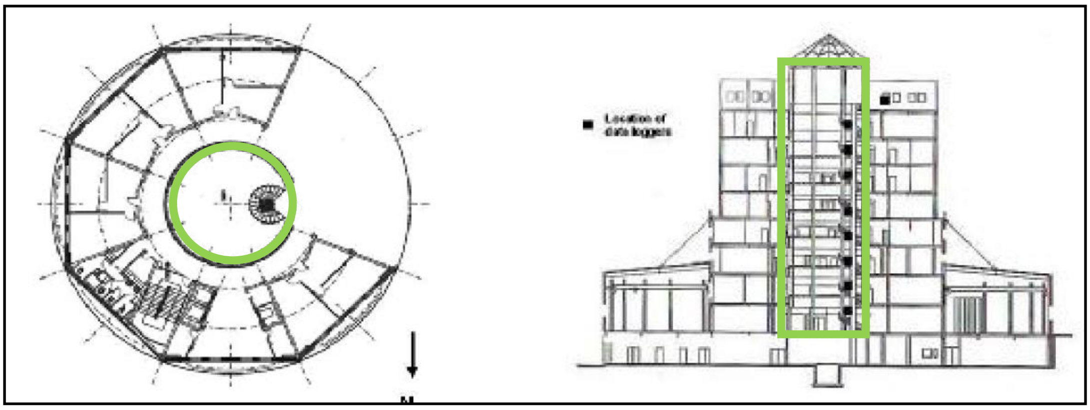


Figure 5. 21: Pajoohesh-kadeh office block with atria outlined in green

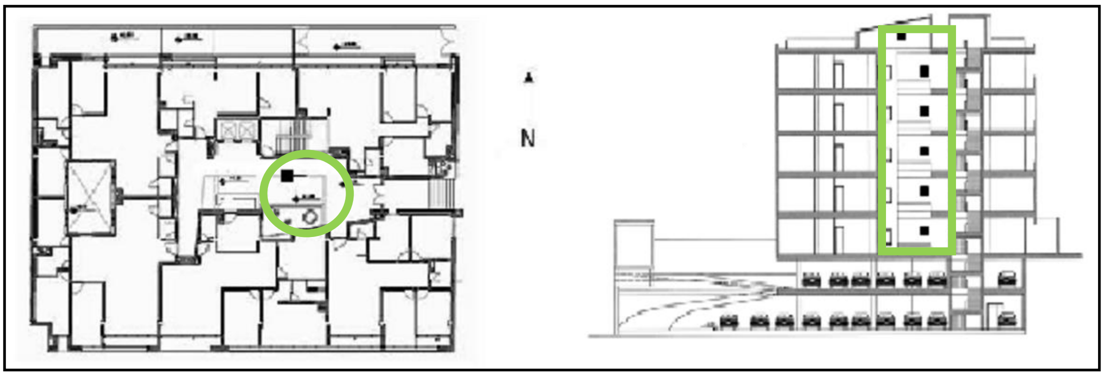


Figure 5. 22: Mino office block with atria outlined in green

- Another study has been conducted (in both warm and cool season) on a residential three-story model based in Tehran (Assadi et al., 2011). The research concludes that a fully naturally ventilated and heated residential building is not achievable by means of the stack effect and buoyancy flows in an atrium. However, it is believed that an atrium can decrease the heating load for building by up to 25%, which contributes towards less CO_2 production and fossil fuel consumption (Assadi et al., 2011).

- The Kaveh glass head office building (designed by Amirabbas Aboutalebi, with 6695 metres squared building area and 28850 metres squared floor space) was constructed in 2015. This building has referenced ancient architectural traditions (Figure 5. 23) (Lutyens, 2016) and has considered passive design (Reischer, 2016). This office block has nine floors with a long rectangular plan shape and an octagonal shaped atrium (Reischer, 2016). The atrium is orientated towards the south. However, this atrium is not an enclosed space with openable internal windows to offices. Instead, it is rather an open space all year round with no internal walls. It uses coloured glass, which is similar to the traditional designs in houses. Reischer (2016) adds that,

  > “The key elements [of this building] are the orientation of the house on the property [which is the]… exact East-West orientation, a curtain glass façade made of a low-E glass (double glaze), buffer zones for temperature storage / balancing and a natural air circulation… From this … atrium, warm air is also gained in winter for the other areas…

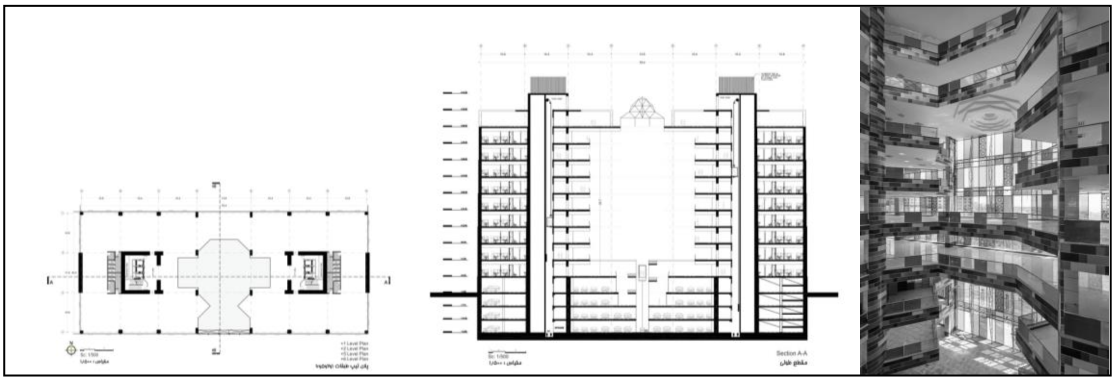


Figure 5. 23: plan and section (Reischer, 2016) and interior picture (Lutyens, 2016) of Kaveh glass head office

- Tahbaz (2008) investigated an existing semi-tall residential building in Tehran that has an atrium; however, this study was conducted in the warm season only. The case study building is aligned on the north-south axis (Figure 5. 24) and consists of a central open top atrium that sustains air movement inside the building and acts as an air pump (Figure 5. 24). The western and eastern parts of the building do not have any openings because, on the lower levels, they are attached to neighbours' walls and (for privacy) no openings have been provided on the top floors either. During the day, the breeze from the south is sucked into the rooms on the south façade. Since the building is open to outside air on the ground floor (the building is raised on pillars), the air also passes underneath the building and partially up the atrium hole. The airflow also passes through the south rooms, through the internal windows, into the atrium and up towards the roof (Figure 5. 24). This phenomenon, results in a vacuum effect that causes the air to speed up from the windward zone into the apartments. On the other hand, the leeward façade of the building, which happens to be on the north, experiences negative pressure, thus again creating suction which results in air passing through the other parts of the apartment. Tahbaz has calculated that, with acceptable air movement inside the building, thermal comfort can be achieved especially when the humidity levels are acceptable on the hottest days of Tehran. Although, in the case of extremely hot days, mechanical cooling systems are needed, and their use is reduced by the building's climatically sensitive design. Thus, Tahbaz claims that, in this case, the case study was successful for a warm season.

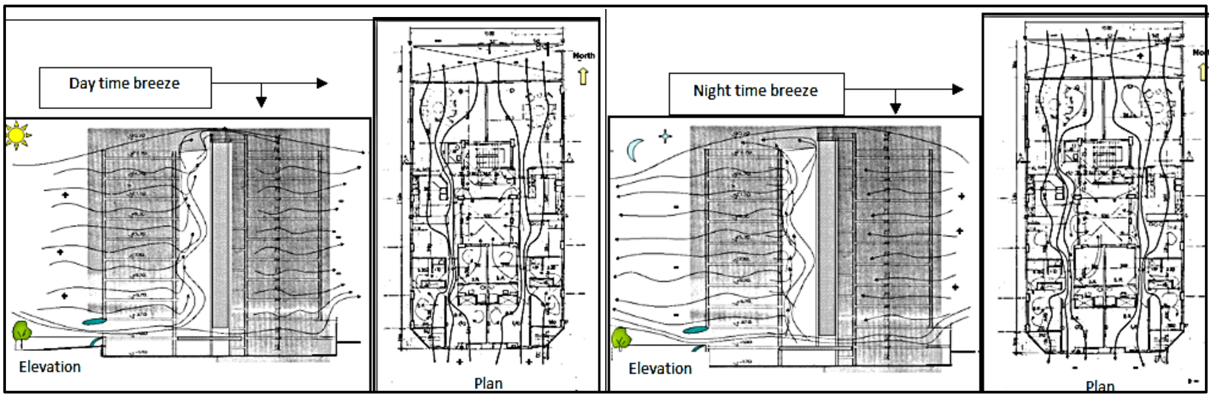


Figure 5. 24: Daytime breeze (towards the north mountains) and night-time breeze (from the north mountains) (Tahbaz, 2008)

Tahbaz (2008) believes that several elements affected the natural ventilation inside the building, and the points noted have been detailed below.

- In Tehran's semi-arid climate, it is important to have an open plan area with a minimum amount of walls on each floor. This point, along with the building's south-north alignment, helps with the wind tunnel effect and natural airflow from one side to the other (Figure 5. 24).
- The open space under the building has a significant role in ensuring natural ventilation. The area underneath the open space helps with the air suction from the bottom to the top, especially in warm days, in order to enhance the airflow inside the atrium as well as inside the building. The airflow underneath is cooler than the air in the core, which has absorbed heat from the surrounding walls. Hence cool air replaces the warmer air, which assists the airflow to the top, and creates a pressure difference between the core and interior of the rooms.
- Having these hollow spaces (an open atrium on the top and bottom) also increases the chance of air contact with the building and in cooling the mass.
- In conditions when wind is coming from east or west (since the building is closed from east and west), "the atrium is affected by the wind passing over the roof and the natural frequency of the wind causes alternate suction inside", which has a "great effect on revival the air movement inside the building than the continuum suction" (Tahbaz, 2008, p.9). Hence, this causes more natural ventilation than when a north-south wind is blowing.

These studies have either not been conducted on high-rise building or have not been used atria as a passive design element. Moreover, some did not study office type buildings or had not investigated results for a cool season. Hence, they are not effective examples for understanding how atria behave in semi-arid climates over the space of a year. Thus, further research is needed to understand weather this feature is beneficial for office buildings in Tehran and how reliable this design strategy is.

5.6 Summary of Chapter 5

This chapter highlights the fact that the effect of temperature on the energy load of buildings is considerable compared to other environmental factors such as air velocity and humidity in Tehran semi-arid climate. The chapter also explains in detail about the minimum comfort temperature in cold season to be 18.2°C and the maximum comfort temperature in warm season to be 31.7°C in Tehran.

Moreover, it explains on the history of high-rise buildings in Tehran and why the focus of the thesis has been on high-rise buildings. It also highlights the fact about why high-rise buildings had been poorly designed and later on explains why they are still no interest in energy efficient buildings in this country when it comes to constructing one (this has been looked into more detail in chapter 10 section 2).

Never the less, this chapter highlights the important fact of design gap in this region. It then proposes atria as a solution that potentially can help to address the gap. Information has also been provided regarding the necessity of using passive design because of high energy consumption in this region. It explains the importance to lower the energy consumption and especially the HVAC usage in high-rise offices of Tehran in detail and statistics have been provided to support the discussion. Moreover, current problem of buildings with atria in Tehran has been covered and few examples have been given as evidence.

CHAPTER 6: Methodology

A research methodology is defined as the effort to validate the rationale behind a particular research design and rationalise why it is suitable in solving the particular research problem (Bell & Waters, 2014).

The ways in which authors explain research methodology differs for scientific disciplines and social science. For this research, the well-known Research Onion diagram (Figure 6. 1) by Saunders, Lewis, and Thornhill (2012) is applied. This diagram separates the different levels of the research process; from the research philosophy and research approach in the outer layers to the research design (including research strategy, methodological choices, time horizon, and data collection method) in the inner layers.

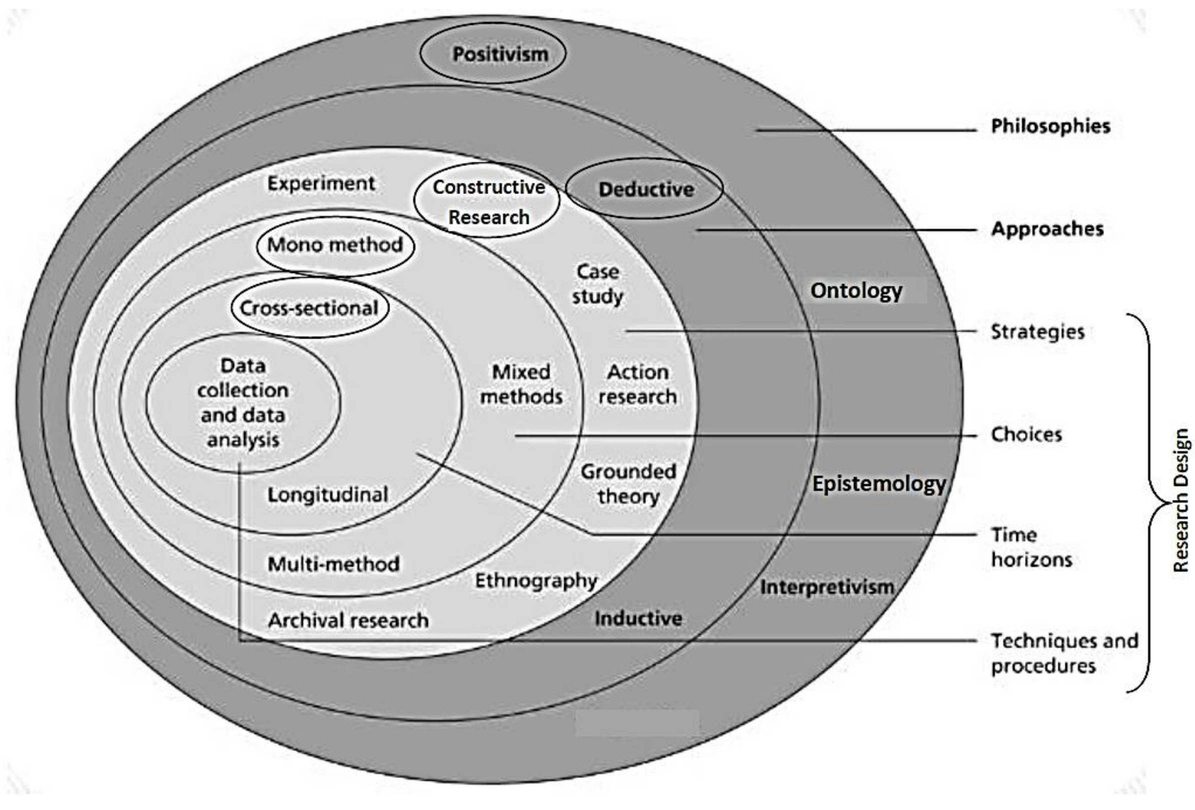


Figure 6. 1: Adopted Research Onion Diagram from Saunders et al. (2012)

6.1 Research Philosophy and Research Approach

A research philosophy concerns the researcher's assumptions about how the world operates, how acceptable knowledge is defined, and the role that values play (Collis & Hussey, 2013). The knowledge of philosophy helps the researcher to select a more appropriate research design. Collis and Hussey (2013) suggest three core approaches of research philosophy (which comprises the outer layer of the Research Onion):

1. **Ontology**: refers to the nature of reality and ontological questions include: what is out there to know? What is true? In order to provide valid information, two features of ontology are considered (Fellows & Liiu, 2015).

    - **Objectivism**: where reality can be recorded objectively and independently of the researcher and analysed structurally

    - **Subjectivism**: where reality is interpretative and dependant on the experience of the researcher

    This research has an objectivist approach because there is no need to check weather passive designs are successful (Figure 6. 2). This reality has been proven through vernacular architecture as well as by different successful modern examples throughout the world. However, it investigates how a particular passive design could contribute to lowering the energy loads in office buildings in a specific climatic region.

2. **Epistemology**: concerns with the nature of knowledge, validity, scope, source and limits of knowledge. Epistemological questions include: How we know what we know? A researcher can be a positivist or an interpretivist in this respect (Saunders et al., 2012):

    - **Positivism**: if the researcher is independent from what is being researched and believes that the truth is out there to be discovered then a positivist approach is adopted.

    - **Interpretivism**: if the researcher believes that the truth is developed based on social interaction then an interpretivist approach is adopted.

    This research uses a passive design, a technique that is already out there and has been known to contribute to sustainable designs in some climates. However, the techniques need to be observed in other regional climates in the world and information needs to be provided on how to optimise its performance in order to reduce energy loads in buildings. Moreover, the researcher is independent from the subject under research and there are no social interactions, hence the positivist approach has been adapted within this study (Figure 6. 2).

3. **Axiology**: concerns the judgment about value. There are two types of values :
    - **Value-laden statements**: where values are biased on someone's judgment
    - **Value-free statements**: where values are not influenced by anyone's judgment

   As the researcher has adopted a positivist stance, and the research provides results and discussions based on mathematical measurements, this study adopts a value-free approach (Figure 6. 2).

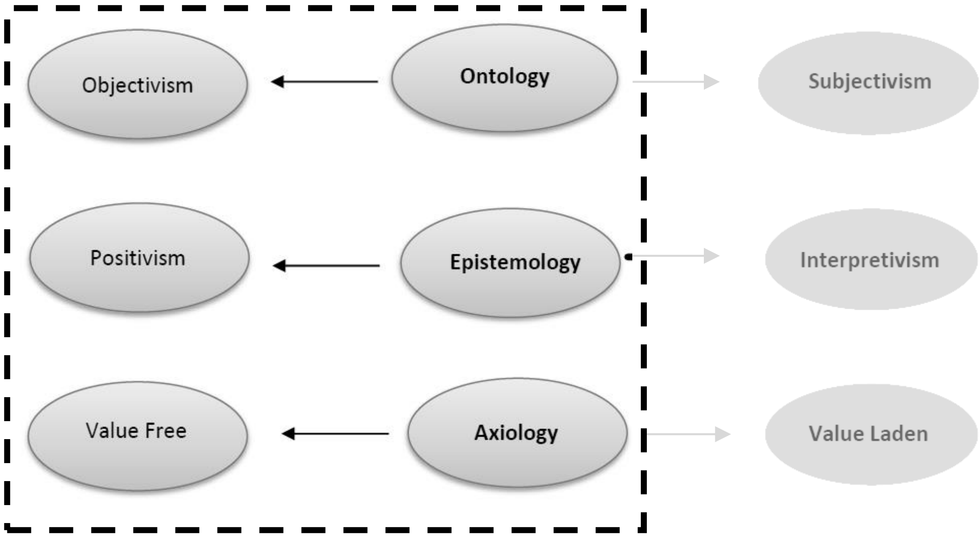


Figure 6. 2: Pylosophical stance of this research

The next layer in the research onion is the research approach. The research approach answers the question of how to acquire knowledge. Saunders et al. (2012) believes that there are three main research approaches in methodology: inductive, deductive and abductive.

1. **Inductive**: is a bottom up approach that travels from observation to theory, or from a 'specific observation' to a 'general conclusion' which may be true (Saunders et al., 2012). This means that, in order for the researcher to build a theory, observation is first conducted. The methods for data collection in this approach usually involve the

observation of a phenomenon, then searching for a pattern in the observations, and finally developing a generalisation or theory from the analysis of the patterns (Lodico, Spaulding, & Voegtle, 2010).

2. **Deductive**: is a top-down approach to knowing or a ‘general rule’ to a ‘specific conclusion’ which always is true (Saunders et al., 2012). In this approach, the researcher initially makes a prediction or a statement and then looks for evidence to approve or deny the statement or hypothesis (Bodart & Evrard, 2011). The method adopted to collect data is usually an experiment/s.

3. **Abductive**: is a ‘incomplete observation’ to a ‘best prediction’ approach which may be true. The research process starts with surprising facts and then chooses the best explanation among many alternatives. It can combine both cognitive and numerical reasoning (Saunders et al., 2012).

This research provides a hypothesis, as it believes that atria can be a potential passive design solution for lowering the energy loads in high-rise office buildings in the semi-arid climate of Tehran. Based on this hypothesis, data is then collected to validate or deny this statement and provide further insight into the subject. Therefore this thesis adopts a deductive approach.

6.2 Research Design

The inner layers of the Research onion are called the Research Design which includes: the ‘methodological choices’ (whether quantitative, qualitative or both), the ‘research strategy ‘and the ‘data collection method’. The data collection method’ is explained in section 6.3 where an in depth, step by step process is explained concerning the research strategy for this study.

In terms of the methodological choice, O'Leary (2014) explains that methodologies are somewhere in between or at either end of a spectrum of quantitative and qualitative methodologies. O'Leary (2014, p. 132) clarifies that, “Quantitative research … is often characterized as an objective positivist search for singular truths that relies on hypotheses, variables and statistics, is generally large scale, … Qualitative research, on the other hand, rejects positivist ‘rules’ and works at accepting multiple realities through the study of a small number of in depth cases…” Furthermore, Denscombe (2007) states that quantitative research tends to be associated with researcher detachment and a predetermined research design. This means that there is a definite sample or experimental procedure to be undertaken. In comparison, qualitative research is normally associated with a greater degree researcher involvement and usually with the emergence of a theory or design.

This research is based on a statistical comparison between different types of atria within different sets of building configurations. These are definite samples (prototypes) produced under the same circumstances without any personal attachment by the researcher to the project. Thus, this research tends more towards quantitative research.

In terms of research strategy (method), Saunders et al. (2012) defines a strategy as a plan and set of actions to achieve a goal, which are guided by the: research aim, objectives, approach and amount of time, access to potential participants, existing knowledge, and other data resources. This thesis is located in the field of the built environment where different strategies are introduced according to the research context, such as: Social Research, Architectural Research and Design Science Research (Crnkovic, 2010; Denscombe, 2007; Wang & Groat, 2002).

- Social Research strategies tend to adopt one of the following (Denscombe, 2007; Saunders et al., 2012): experiments, survey, case study, ethnography, Archival research, grounded theory, action research and mixed methods. A brief explanation of each is provided in Table 6. 1.

Table 6. 1 : Research Strategy Characteristics (Saunders et al., 2012)

Research Strategies	Characteristics
Experiment	• Suitable for laboratory research rather than the field
Survey	• Most frequently used to answer 'what', 'who', 'where', 'how much' and 'how many' questions • Used for exploratory and descriptive research
Case Study	• It is suitable for research which wishes to gain rich understanding of the research context and processes • Has considerable ability to generate answers to the question 'why', 'what', and 'how' • Not suitable for collection data for generalisation • Fits in with different research methods or techniques
Ethnography	• It is used to study groups • It requires a longer term of field work study

Action Research	• Provides in depth understanding to specific phenomena, [it is advices to be used]… in the education context
Grounded Theory	• Leads to developing a theory that explains social interactions and processes • Has been criticised widely due to its confusing process and time required to be completed • Collecting data processes might require visiting the field several times
Archival research	• This strategy makes use of administrative records and documents as the principal source of data • Allows research questions which focus upon past and changes over time to be answered
Mixed methods	• Allows answers to questions on what, how and why • Adopted to describe, explain and explore a phenomenon • Allows for diversity of views to aid interpretations • Allows for generalisation of the study or its relative importance • Allows for both qualitative and quantitative data to be employed in a single research • Allows combination of inductive and deductive approaches within a single research

This research does not investigate the social but rather the environmental aspects of a phenomenon, and the impact of an atrium and building configuration on office temperatures and energy consumption. Therefore, the social research strategy will not be adopted. As such survey, ethnography research, action research and grounded theory are not selected for this study. The research has a deductive approach so it is not using mixed methods (where inductive approach is also used). Moreover, records and documents are used as data collecting methods so this study does not use archive research. In addition, this research is not using a particular building or buildings that exist as a case study; instead, it looks into the most appropriate atria configuration for typical high rise office buildings in the specific climate of Tehran's. Thus, although Tehran climate is the focus of the study, case study research is not implemented as a specific case is not being investigated.

The most relevant of the above strategies is an experimental strategy, which is also part of Architectural Research and is explained when explaining architectural research later on. An experimental strategy is most suitable for a quantitative research choice and is undertaken in a highly controlled environment (Saunders et al., 2012). In experimental strategy, the experimenter simply manipulates one variable and looks for resultant changes in another. They look for a constant conjunction and if found, this constitutes a law (Robson, 1994). For the purpose for reaching the thesis objectives, the relationship between the unfixed parameters and the heating and cooling loads is investigated. Hence, the researcher has full control over the phenomenon studied and observes the effect that one independent variable has on another dependent variable. Therefore, this thesis adopts an experimental strategy.

- Architectural Research is another distinct strategy that Wang and Groat (2002) introduce. They state that it is important to distinguish the difference between researching a design process, which helps to inform the design process itself, and the design itself as research (Wang & Groat, 2002). A simple example of this would be the difference between the technique of sketching as research, and the research on a sketch. The seven strategies of Architectural Research, or design as research, are as follows: interpretive-historical research (design and history research), qualitative research (design and qualitative research), simulation and modelling research, experimental and quasi-experimental research, case study and combined strategy.

  This study aims to answer a key research question: Do atria *optimise* the comfort of office rooms in the semi-arid climate of Tehran? If so, which basic morphology could present the best solution over an annual timeframe? The research for this thesis is not considered to be historical or qualitative, nor based on argumentation; hence, historical research and qualitative research are of no interest in this thesis.

  This thesis uses modelling because a specific case study is not been investigated; however, modelling is employed as part of the research design technique and not as research itself. Hence, simulation and modelling as a type of research are not used in this thesis.

  Wang and Groat (2002) also introduce ‘case study’ as part of the architectural research category. This thesis does not aim to investigate a particular case study but instead explores the typical design of high-rise buildings and how to lower the energy loads using different configuration of atria design. It is thus necessary to create a prototype of these building typologies in order to investigate the impact of atria on the inside temperatures of high-rise office buildings in Tehran. In this thesis, an ‘experimental strategy’ within architectural research is not conducted on a real case scenario. However, models can be simulated and compared in an artificial world that are as near as possible to the real world. For this purpose Design science research is the most relevant research strategy that provides clear directions for this thesis.

- Design Science Research (DSR), sometimes known as Constructive Research (CR), is a fundamental research strategy for the engineering and sciences fields when considering concept formation, modelling and the use of artefacts (Crnkovic, 2010). Jarvinen (2004) suggests that, if the research question contains the verbs adjust, correct, introduce, extend, maintain, enhance, improve, change and build, then there might be a good chance that the study could be considered as Design Science Research.

  Constructive Research, or Design Science Research, could be defined as a research strategy that attempts to solve problems through the construction of artefacts (models, diagrams, plans, organisations) (Kasanen, Lukka, & Siitonen, 1993) by analysing the use and performance of such artefacts. It creates knowledge about how the problem can be solved, understood or explained to improve the systems designed (Crnkovic, 2010). Moreover, Jarvinen (2004) believes that an unsuccessful case should also be studied as it can similarly provide new knowledge.

  This thesis investigates different atria configuration to avoid excessive energy consumption by means of bioclimatic design strategies for providing thermal comfort temperature (a constructive solution). In order to do so artefacts are used to model different design geometries and the performance of artefacts are analysed individually and in relation to each other.

  Design Science Research, or Constructive Research, gives results that can have both practical and theoretical relevance. It is expected that the researcher will solve several knowledge problems concerning the feasibility, improvement and novelty of the issue under study (Henver, March, Park, & Ram, 2004). Thus, this research looks into *improving* the comfort of buildings through a *novel* approach of using atria in a semi-arid climate, which is *feasible* according to existing vernacular architecture.

Therefore, this thesis tends more towards applied Design Science Research as it can provide the means to answer the research questions more clearly. Thus it is necessary to clearly explain the characteristics of this strategy in more detail.

Within a Design Science Research strategy, a design exemplar (base prototype) is important. "A Design Exemplar is a general prescription which has to be translated to the specific problem at hand; in solving that problem, one has to design a specific variant of that design exemplar" (Van Aken, 2004, p. 227). This means that, in order to solve a problem, the design variations should be compared with an initial base design. This thesis will also use a base design to provide the basis of any subsequent comparisons. However, the base design first needs to be validated in order to be a true representative of real cases. This is further explained in section 7.3.

The outcomes of DSR usually include one of the following:

- **Artefacts** (Henver et al., 2004): which include concepts, models and methods.
- **Improvements** (Van Aken, 2004)
- **Technological rules** (Van Aken, 2004)

Since this thesis will be utilising Design Science Research, it is important to know the steps necessary within this strategy in order to manage the thesis accordingly. March and Smith (1995), and Henver et al. (2004) state that Design Science Research comprises two main activities, which are:

- **To build**: building is a process of constructing an artefact or an innovation for a specific purpose;
- **To evaluate**: this is a process of determining how well the artefact performs.

Nevertheless, there are a total of five steps within this strategy introduced by Vaishnavi and Kuechler (2017) which are:

- Awareness of a problem
- Suggestion
- Development
- Evaluation
- Conclusion

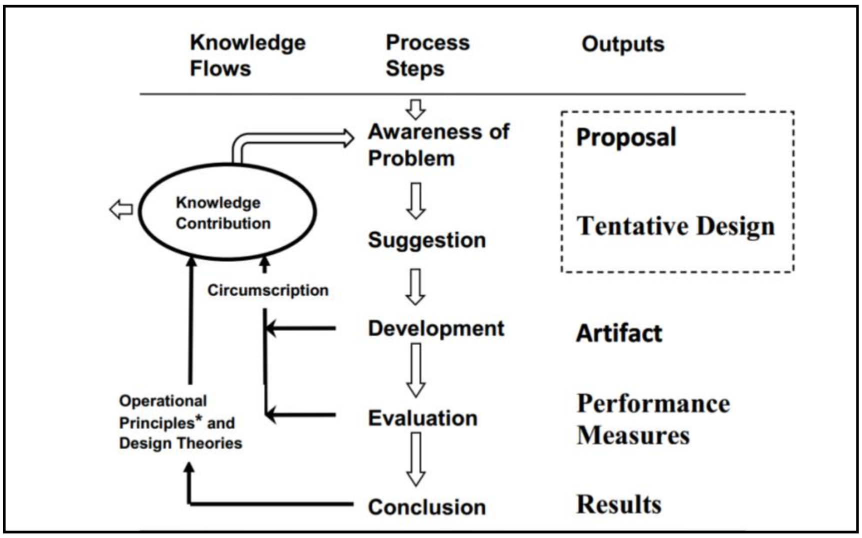


Figure 6. 3: Five steps of the Design Science Research process model (Vaishnavi & Kuechler, 2017)

As shown in Figure 6. 3, Design Science Research could be an iterative and not necessarily a linear process. Therefore, the suggestion and development phases (stages 2 and 3), which are the core element of a successful study (Kasanen et al., 1993), and the conclusion phase, could lead to a better understanding of the problem. This then leads to further design suggestions and developments, and this loop is illustrated in Figure 6. 3. Moreover, O'Leary (2014) believes that projects generally undertake one or more of the following, called "goal stages":

- Understanding a problem or an issue
- Finding workable solutions and working towards a solution
- Evaluating success and/or failure

In order to simplify the understanding used to inform the methodology in this thesis, it has been decided to combine both O'Leary's goal stages with the five process steps defined as Constructive Research by Vaishnavi and Kuechler (2017) (Figure 6. 3).

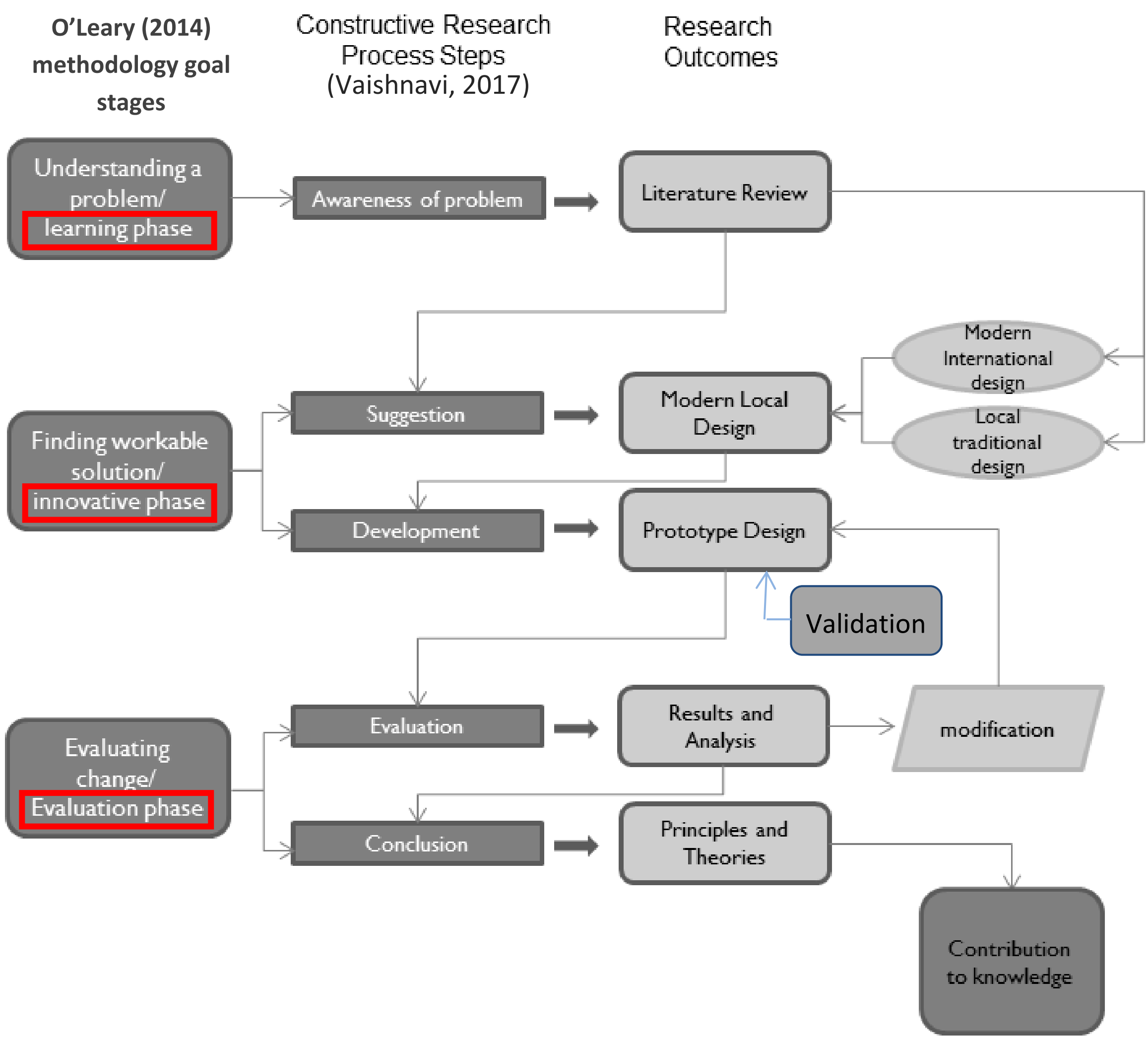


Figure 6. 4: Research methodology and stages of this thesis

Figure 6. 4 shows the combination of the two model stages. As illustrated in Figure 6. 4, the first column shows the goal stages and the second column shows its subdivision, called the constructive research steps; finally, the third column is the outcome of each step.

In order to undertake the defined stages, this research briefly explains the three main goal sets (shown in Figure 6. 4) as below and a more indepth explanation of each of the five steps derived from them are discribed in section 6.3.

- **Learning phase** (CR Process step 1): In this phase, the researcher reviews the literature in order to understand the gap in the field of study and develop their awarness of the problem. For this study, this included literature on: Tehran's highrise building problems, their energy consumption and acceptable local thermal comfort ranges, climatic design options including detailed research on atria (addressed in Chapters 2, 3, 4 and 5).

- **Innovation phase** (CR Process step 2+3): In this phase, the suggested solutions are carried out according to the literature review. Thereafter, in order to perform step 3, the prototypes are developed (Chapter 7). The prototypes are developed with attention to relevant building regulations and limitations, and the incorporation of knowledge from the literature. Therefore, the prototypes could be representative of real casestudy buildings. If the input data is correct and valid, and the simulation tools are selected and used correctly, the evaluation phase can begin and the output data should be reliable. For this study this means that prior to the completion of simulation process on the prototypes that incorporate atria, the base case (the prototype of a building with no atria) needs to be created and validated against the survey and empirical data (section 7.3). McHaney (1991, p. 95) defines validation technique as below:

  > "validation is the process of determining that the real world system being studied is accuratley representated by the simulation model. This process insures that the conceptual model is correct. It establishes an accaptable level of confidence that the conclusions drawn from running the simulation will give insight to the true operating charectristics of the system being modeled. The validation process should begin during the initial stage of a simulation project and continue until the end…Model validation can be best determined thorugh the analysis of the simulation output data. If the model output closly represents the expected values for the system's real world data, it is considered to be valid."

- **Evaluation phase** (CR Process step 4+5): In this phase, the simulation is conducted on the prototoypes and the results are evaluated and analysed (Chapters 8 and 9). Later, in Chapter 10, the conclusions are presented which ultimately state the ways in which new knowledge has been created for the wider fields of research and practice.

6.3 Thesis Steps adapted from Design Science Research

From the literature review, it was considered that providing heating and cooling by natural means could potentially help to overcome the disadvantages associated with mechanical devices. There has been no publication concerning passive design that optimises thermal comfort in high-rise buildings in Tehran's semi-arid climate. There have been however, a number of publications on traditional low-rise dwellings with successful examples of passive designs. Therefore, the passive designs within local vernacular architecture were studied as well as international examples of passive high-rise buildings (step 1 of the learning phase, namely the literature review stage). When comparing design techniques, it seemed that a few of the passive designs used in modern tall buildings had similarities with the passive design techniques of Iran's vernacular architecture. Atria are one such feature that appears to represent a potential passive strategy applicable to tall buildings to help meet occupants' thermal comfort needs (step 2 of the learning phase, namely the suggestions stage). The remainder of this chapter and the subsequent chapters will cover: the prototype design process (step 3, which is the innovation phase, named the development stage); results and analysis (step 4, which is the evaluation phase, named the evaluation); and finally, the conclusion (step 5 of the evaluation phase, named the conclusion), which will demonstrate the contribution to knowledge. The three phases of learning, innovation and evaluation are described in detail in the following sections.

6.3.1 Learning Phase: Literature Review

The learning phase and awareness of the problem is the first of three steps within Construction Research, which is covered extensively in the literature review. Wisker (2007) states that, with an ongoing literature review process, the researcher can remain in touch with relevant subject developments, and benefit from information disseminated by others in the field. It is useful to identify what others have done, and the in depth knowledge from other researchers help to distinguish the gap in knowledge (Murray & Hughes, 2008). In this case, the researcher could build on previous knowledge and take these a step further (Murray & Hughes, 2008). The literature review also helps to understand existing systems, methods and other technical approaches for a study, which helps when developing a research methodology.

This research has also benefited from the literature review. Chapters 2, 3, 4 and 5 cover different aspects of the issue under investigation through a review of the existing literature. The main sources have been books, e-books, journals, other PhD research, government websites, and other credible sources in the form of paper or electronic media. By summarising and critically analysing each source and grouping them into different themes, each chapter was formed and relevant knowledge was presented in a logical way. Below is a summarised description of how each chapter has contributed towards the preparation for the simulation stage. However, it is worth noting that, after the simulation and analysis, a comparison with the cited literature (in chapter 10) will help in securing a better understanding of the results.

Chapter 1 describes the introduction and a general summary of the research, whilst in Chapter 2, the characteristics of thermal comfort are detailed. Understanding thermal comfort and its parameters, gives an idea as to what is important and should be taken into consideration in the simulation process. Chapter 3 highlights problems concerning the energy consumption in buildings and the importance of using climatic design; it also introduces different passive design techniques and justifies the use of atria for the prototype design. Chapter 3 also lists the factors that are important in the climatic design of buildings and some of these are included in the prototype designs. Chapter 4 looks in more depth at atria design, its history and advantages and disadvantages, and introduces basic atria and functionality types. These basic atria types are later selected for use in the prototype design. The chapter also gives information about how atria perform, which later helps in understanding the reasons behind the results produced from the prototypes.

Chapter 5 covers all aspects introduced in Chapters 2 to 4 within the case study of Tehran; it explores the climate classification and thermal comfort temperature range in this city. Knowledge of Tehran's thermal comfort range helps in the critical analysis of the results. The Chapter then addresses the problem within this region, including the buildings and their energy consumption in general. It also covers an energy reality check on some existing office buildings within this regional climate. Chapter 7 covers the essential knowledge about prototype, its characteristics, how its formed, the software inputs, and a validation section on the base case scenario. Chapter 8 and 9 explain the results of the simulation conducted. Finally chapter 10 provides discussion on the results and then concludes the findings of the thesis.

6.3.2 Innovation Phase: Suggestions and Development

A Constructive Research methodology states its innovation process as the core element of knowledge creation (Bogdahn, 2012). This process consists of two stages, namely suggestion and development (Figure 6. 4).

6.3.2.1 Suggestions

In order to suggest a possible solution to a problem, thorough background knowledge is required. Thus an in-depth literature review helps in developing ideas, and is an essential part of research planning. Chapters 3 and 5 mostly cover the suggestions relevant to the innovation phase of the thesis:

> Examining the vernacular architecture of the region and exploring the passive technical designs that suit its semi-arid regional climate forms the basis of the recommendations of which technique to use as passive design in the porotypes. The passive technical designs in modern high-rise buildings have also been investigated; however, the examples were found in climates other than a semi-arid one. Finally, by comparing the vernacular passive techniques of the region with the modern passive techniques of other climates, a modern strategy that has the most similarities with vernacular passive strategies has been selected and recommended for high-rise office buildings within a semi-arid climate. An atrium is the recommended technique, which has similarities with the courtyard and solar chimneys/wind catchers of vernacular architecture.

The functionality of atria in a semi-arid climate and their impact on the adjacent offices in the high-rise buildings of Tehran have not been explored and neither have any publications mentioned the use of atria to provide thermal comfort via natural means in high-rise buildings. Hence, the main atria types in tall office buildings have been considered in order to run tests to analyse their performances in semi-arid region.

6.3.2.2 Development

Before explaining how to develop a model, it is important to understand what type of artefacts or models exist for the evaluation stage, and to determine the advantages of using a particular artefact. As previously mentioned, Constructive Research, or Design Science Research, can be defined as a methodology that tries to solve problems through the construction of artefacts (Kasanen et al., 1993). Artefacts are prototypes that can be used as tools to provide answer(s) to the research questions. It is of the utmost important to select the right type of model or prototype, whether physical or digital, and the right method to analyse and justify the prototype. Later sections will explain why this research has used virtual computer modelling and chosen Design-Builder Software to study the prototype.

In order to test proposed building designs, three options are generally available. The first option is to construct a full-scale model, the second is to build a scaled physical prototype of the building, whilst the final option is a virtual model. These are further explained in details as follow:

- **Full-scale models**: This involves the real measurement sizes of a model building constructed in real life, which is situated in the selected climate. Monitoring would then take place under various weather conditions in order to determine the building's performance. However, there are problems with this technique. Firstly, it is difficult to determine the effect of each element of the building on the results (Malama, 1997). Secondly, it is prohibitively expensive to build some of the models in this way. Maver and Petric (2003) believe that a full scale physical prototype might be applicable for small objects but that the production of a full size model is inappropriate if the object is of a very high capability value, such as the high-rise building in this research, and thus other methods should be used. As a result, a full-scale model would not be appropriate for the prototype development within this thesis.

- **Scale model**: This physical model can be used as a substitute for the full-scale model. They are cheaper than full scale models and are investigated under different conditions, usually in laboratories (Malama, 1997). The controlled laboratory conditions give the advantage of not only being cheaper than the full scale model but also provide controlled conditions where certain aspects of the building could be studied (Barrozi, Imbabi, Nobile, & Sousa, 1992). However, McLead (2001) believes that physical prototyping still has the disadvantage of being time consuming compared to some other modelling techniques, such as computer based models. This is because it requires manual tooling, assembly by skilled hands, delicate testing of the equipment, and time spent on interpreting the data. He explains that, when one prototype is tested, engineers often learn from it and have to revise the design; this means making another physical model for more accurate results and therefore repeating all the steps mentioned to further test the product. This process might take more than one attempt, especially if the revisions mean a number of design prototypes have to be made; this makes this option very time consuming. Even though rapid prototyping technology has helped with the construction of prototypes undergoing physical testing, the subsequent revisions are still very time consuming. Moreover, scaled versions cannot be a realistic representation of real cases as they cannot represent some parameters, such as occupancy, activities, and so forth (Malama, 1997). In terms of this research, time is a limited factor and, in order to address the temperature and energy load inside high-rise buildings, parameters, such as occupancy, clothing, activity and equipment heat production, would influence the internal temperature results and heating and cooling energy needed. Therefore, this method of prototype development and analysis will not be used in this research.

- **Computer-Based Digital Model**: In the late 1960's computer-based digital models started to emerge as a technology to complement modelling capabilities (Maver & Petric, 2003). Virtual models are based on computer simulations that use specialised software packages, hence the name computer-based model. Virtual prototypes, or models, are the "new generation of tools that enable [a] "predict and prevent" approach to design" (McLead, 2001, p. 16). In the fields of building science, urban planning and architecture, computer based models have advanced rapidly (Maver & Petric, 2003); indeed, they are also a very popular modelling method amongst researchers. With improvements in computer processing and the advantages that computer simulations offer, the use of this type of model has increased (Malama, 1997). In relation to other previously described methods, it also has the advantage of being cheaper, faster and more accurate as it can include occupancy and activity, which further highlights the reason why this type of prototype modelling is chosen for the thesis.

The advantages of using a simulation method and virtual prototyping are recognised by many researchers, who believe that they are of utmost importance in the design of climate sensitive and energy efficient buildings (Clarke, 2001; Ferrando, Delponte, Di Franco, Robert, & Guigou, 2014; Herkel, Pfafferott, & Jaschke, 2003; Maver & Petric, 2003; McLead, 2001; Wang & Groat, 2002). Some of these advantages are as follows:

- **Addressing difficult situations:** Virtual models in computer simulation is of use in situations where scaled models is difficult (Malama, 1997).

- **Widely used:** As previously mentioned, Maver and Petric (2003) state that the computer simulation of virtual prototypes is widely used in the field of building and in relation to environmental comfort. Therefore, this increases competition amongst software companies to provide the best simulation program, which in turn strengthens the accuracy and adaptability of computer simulation, making it a stronger modelling method.

- **Greater accessibility:** Accessing computer models and operating them is easy and practical for other members of the design team, whether they are located overseas or in the office (Maver & Petric, 2003). McLead (2001) also claims that using computer based simulation and virtual models help in reducing frustration amongst members of the design team.

- **Early Prediction:** Computer simulation can be used to predict the (thermal) performance of buildings at the sketch design stage (Clarke, 2001). An early prediction of results could inform future action or research in real world projects (Wang & Groat, 2002). This is important because, in identifying problems early in the production process, further problems can be avoided, for example, with additional costs (McLead, 2001).

- **Increased Speed:** Computer simulation allows a great number of possibilities to be tried in a short space of time (Malama, 1997). Lewis and Orav (1989) believe that the speed and capacity of simulation represents a key advantage in using computers, which has become increasingly important as a methodology. In some countries, there is a policy that, by 2020, all new buildings should be near zero energy, and so in order to be able to meet this deadline, there has been a strong shift towards digital prototyping (Ferrando et al., 2014). Usually adopted by engineers and designers, it is easier to rapidly test a hypothesis or design and conduct "what-if" solutions by using virtual modelling. This also helps in exploring any new features of a product (McLead, 2001). McLead (2001) also confirms that using virtual prototyping shortens the time needed to finish the design and helps to meet the critical time-to-market objectives.

- **Identify the effect of each element (or improving design insights):** Computer simulation can be used to identify the contribution of an element in the overall performance of the building (Malama, 1997). By using this method, insights are given in terms of the effect of design decisions on the performance of the model (Maver & Petric, 2003). This is because of the user's control over the virtual model (Wang & Groat, 2002). For example, by keeping all but one variable unchanged in a building, the effect of that altered variable on the performance of the building can be recorded

(Maver & Petric, 2003). This helps in understanding the behaviour of a context (Wang & Groat, 2002).

- **Widening the research for solutions and improving quality:** Using computer simulation to predict proposed design performance characteristics could help in widening the scope of the research in identifying appropriate solutions (Maver & Petric, 2003). In addition, McLead (2001) believes that, because of the opportunity to explore design alternatives more easily, the quality of designs could also be improved.

- **Verisimilitude of visualisation:** Computer simulation may be able to make graphical or realistic images for users, clients or other people who are engaged in the project. This helps in building a better understanding of the results, and thus enables better communication with the project developer or researcher (Maver & Petric, 2003).

- **Result accuracy:** Accurate computer-based models can help in assessing and evaluating new products designs as they give accurate results (McLead, 2001). Computer simulations can deliver accurate results if boundary conditions and input parameters are well defined (Herkel et al., 2003).

- **Cost saving:** There can be significant savings in the final cost production, and the profit margins can be maximised. This can be achieved by exploring different opportunities, design problems or product flaws at earlier stages of development through modelling in the virtual environment (McLead, 2001).

Never the less, there are also some disadvantages in using simulation programs that if the user is aware of them it can be addressed. The disadvantages are listed as follow (McHaney, 1991):

- As explained before simulation can provide speed in achiving results, however this is true if the developed model are simplified with reducing the details. However, simplifying the model may affect the models accuracy by eliminating key details (McHaney, 1991). Therefore, In order to make the most of the advantages presented by digital prototypes and computer simulations, users must master knowledge of the extended level of detail that the model should include for a particular simulation. Lewis and Orav (1989, p. 30) also adds that "…microscopic detail in a macroscopic model is seldom useful" and, "…the more detail in the simulation model, the more difficult to model the probabilistic aspects of the detail…". Thus, if a study is dealing with the bigger picture of a problem, then very small details may not have a considerable effect on the overall results, and the time spent on constructing or simulating the details would be wasted. Sometimes if a model is simpler it will produce acceptably similar results as a full detail development model (Di Paolo, Noble, & Bullock, 2000). Meanwhile, this will also have the advantage of shortening the simulation time and removing the complexity of a simulation. Hence, Lewis and Orav (1989) believe that simplifying models in a way that does not take away from the aim of the research is an art in itself. This research also tries to simplify its prototype as much and as reasonably as possible to take full advantage of the method used.

- Simulation is not an optimization tool. Answers to questions can be provided but these answers needs to be analysed as it may not be the optimum solusion.

- Since simulation relies on number generators to produce results, there is some uncertainty associated with the output that must be dealt with statistically thus validation is of importance. When an existing system is modeled, validation of the model is a statistical comparison between the result of the model and the data collected from the actual system. However, validating systems in the simulation programs that do not yet exist, can become a challenging task. comparison of the model with data from a similar system existing in nature helps to lend more confident that the model is valid. In this thesis, the base cases are the representative of models that already exist hence statistical comparisons is made between the results of base cases and the data in real life.

Moreover, examples of research using simulation software on virtual prototypes are as follows:

- Ji and Lomas (2009b) proposed an advanced natural ventilation system and predicted the likely thermal performance using DTS by evaluating and comparing four types of ventilation strategy.
- Aldawoud (2013) also compared four prototype atrium building models which presented the realistic characteristics of office buildings. This helped in comparing the

prototype characteristics in terms of height and glazing type and ratio on the energy consumption of the building.

- Moreover, Aldawoud and Clark (2008) compared closed top with open top atria and justified which had a more thermal comfortable performance in relationship to height.

In accordance with the above advantages of computer simulation, this research aims to use computer based modelling and simulation with simplified models as this technique has the potential to be accurate and produce reliable results in a limited time. It also has the advantage to help easily identify the effectiveness of each element in the models. Finally, the easy accessibility of the program and prototype, and the support of distant software professionals means it is the most appropriate modelling method for this study.

One type of simulation programs are the ‘Energy simulation’ programs. They are known to be mathematical systems that (Wang & Groat, 2002) which through such programs, designers can simulate energy consumption, and the cost of energy in existing buildings. They can also predict the thermal behaviour of buildings and establish the best thermal retrofit measurements to adapt in the building under analysis. This can include ventilation variables, inhabitants’ interior comfort, natural lighting needs, the HVAC system consumption, heating and cooling needs, indoor temperatures, and much more (Sousa, 2012). Since the aim of this research is to lower energy consumption in high-rise office buildings of semi-arid climate through the incorporation of atria, the thesis uses an ‘Energy simulation’ software to conduct the analysis.

The two most widely used simulation engines in building energy performance analysis is DOE-2 and Energy Plus, which both use long-time experience and knowledge; DOE-2 studies the whole building energy performance during design stage, however, experienced users can only use the engines few variable manipulations because the engine has limited interoperability (B. Li, 2017). On the other hand, Energy plus engine is suitable for all building life cycle phases. It also “… integrates heat and thermal mass balance in building system simulation to provide more accurate and reliable results.” (B. Li, 2017, p. 23). Drury, Hand, Kummert, and Griffith (2005) also mention that one of the best software tools for energy simulation is Energy Plus, whose development was sponsored by the United States of America’s Department of Energy in 1996. It provided a complete version that combined two other software, Blast and DOE-2, which were developed by the same department (Sousa, 2012). These systems had undergone extensive validation in their development and were support programs used by the United States of America’s Department of Energy (Energy

Efficiency & Reneable Energy, 2015a). It is important to note that Energy Plus does not have a visual interface and needs third party software, such as Simergy, Design Performance Viewer (DPV) and as Design Builder to allow users to view a conception of the building (Sousa, 2012). Taleghani et al. (2014) also mention that Energy Plus is a powerful element and states that the design principles that a third party software uses, provides the most detailed simulation with dynamic parameters. Hence, this thesis uses energy plus tool.

This thesis uses Design Builder as the selected DTS tool and as the virtual interface of energy plus in this research for modelling and evaluating different prototype designs. This is because softwares such as RIUSKA, eQUest, Building Design Adviser and ZEBO are user interface programs that use DOE-2 engine and according to previous literature this thesis takes advantage of energy plus engine. Moreover, software such as Simergy, which uses EnergyPlus engine, is only appropriate for early design stages and is incapable of modelling several buildings and also is limited to the United States in terms of location and Unit (Alchemy, 2017), which is not in favour of this thesis. In addition, DPV also using Energy Plus engine, has limitations and is incapable of simulating multiple buildings at the same time (B. Li, 2017).

Never the less, B. Li (2017, p. 25) believes that " Design Builder software, is the most comprehensive and easy to use interface for Energy Plus [compared to all the other interfaces]…Design Builder provides country or region specific templates for a wide range of parameters but enable customization of heating and cooling systems…Design Builder is adapted to all phases of the design process." The hourly weather data used are from the U.S. Department of Energy as the base of the simulations, however, it also accepts other weather data file inputs (Design Builder, 2015). Therefore this thesis has incorporated the EPW weather data file of Tehran and as an input file in the software. Mohammadpourkarbasi (2015) also agrees that Design Builder has proven to be the most inclusive interface to Energy Plus, which is the most advanced building simulator and that the software is able to model in detail the effect of building operation schedules, heat gain, and occupancy. It takes into account the solar heat gains through windows, the heat conduction and convection between zones, and the energy applied or extracted by mechanical systems (Chowdhury, Rasul, & Khan, 2008; Design Builder, 2015). Moreover, the definition options of occupancy and schedule in the software allows users to; create more precise prototypes; simulate and model building systems which are advanced; express components in distinctive detail; produce flexible results because of the capability to shift between zones; account for different seasonal environments; and produce results from sub-hourly to annually (Mustafaraj, Marini, Costa, & Keane, 2014). Last but not least, Taleghani et al. (2014) have used Design Builder in a project with an atrium, so it has already been tested with atria. They declare that Design Builder has been validated through procedures run by the Building Energy Simulation Test, known as BEST, which has been developed under the sponsorship of the International Energy Agency.

After determining the use of digital prototypes as the artefacts and the type of energy simulation package used, the next step is to develop the prototype design with its different configurations. As the research is investigating the effect of atria configuration on thermal comfort, it is important to know the parameters involved to develop the prototype; this is because some will be fixed parameters whilst others will not. Moreover, in order to produce valid prototype results, the base case (prototype without an atrium) is first validated to ensure it represents the real buildings in Tehran that have no atria via comparing their cooling and heating loads. Hence, the base case has to undergo an initial simulation via the computer thermal comfort simulation tool in order to determine the outcome results. The development stage of the prototype and the validation of the base case before evaluation, are all described in Chapter 7. Once the base case prototype is validated as representative of real buildings, the atria are incorporated into the design, and the main simulation and evaluation stage begins.

6.3.3 Evaluation phase (result, analysis and conclusion)

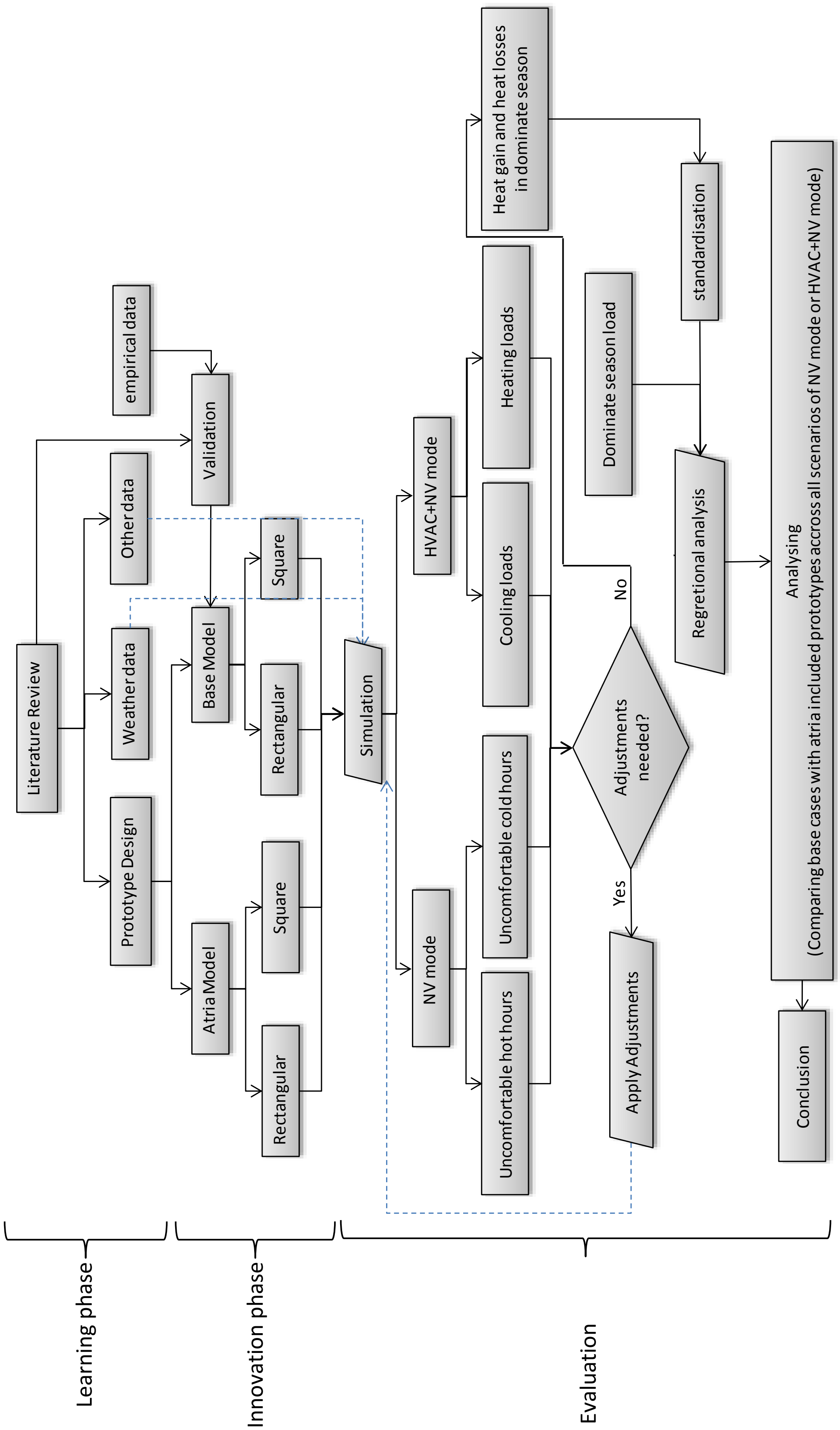
The evaluation is a crucial component of a research process (Henver et al., 2004; March & Smith, 1995). The goal of this thesis is to investigate the effect of different atria configurations on the thermal comfort and energy loads of open plan high-rise office buildings in semi-arid climate of Tehran. To evaluate a particular artefact, a type of model must be chosen; hence, the previous section describes and justifies why computer simulation and digital prototypes have been selected for this study. It is important to select the right simulation tool for reliable results. Hence, as explained this thesis uses Design Builder version 4. In this section the evaluation or simulation procedure is investigated and the analysis process and how the results are analysed in order to reach a conclusion is explained. Also a standardization technique and regression analysis is introduced as a method for correct judgments on the parameters which affect the final result outcomes.

Simulation software is used in order to answer the questions that can arise in the fields of physics, engineering, probability, statistics, and so on (Lewis & Orav, 1989). It is known that simulation can provide data to either develop or test a theory (Wang & Groat, 2002). In the simulation process, there are inputs as well as outputs. The inputs are usually the design hypothesis, whereas the "…outputs are the predictions of the operational behaviour and formal characteristics of the design under a particular set of content variables" (Maver & Petric, 2003, p. 643). When performing a simulation on a prototype, the following steps are covered: creation, measurement, evaluation and modification (Maver & Petric, 2003; Sousa, 2012). This means that the designer creates the design prototype, and the computer software calculates the performance and produces the performance measurements. Furthermore, the design team (or individual) evaluates the value and judges it against its aim and decides whether to modify and change the design in order to attain an acceptable outcome according to their parameters.

Figure 6. 5 illustrates the plan of evaluation for this thesis. The procedure generally consists of three different parts as explained in section 6.2 and illustrated in Figure 6. 4 in order to produce the thesis outcome. The major sections are: the learning phase (literature review), the innovation phase (prototype development), the evaluation phase (analysis of results and the conclusion).

Each prototype uses Tehran's weather climate data files, which are imported from Energy Plus. Energy Plus provides typical meteorological data for the year in Iran and, depending on the city, the records cover anything from a 30 to 43 year period. The files, which have been imported into Design Builder and provided via the Energy Plus website, have been created by Abdulsalam Ebrahimpour from the Building and Housing Research Center (BHRC) in Iran (Energy Efficiency & Reneable Energy, 2015b).

Figure 6. 5: Simulation plan of evaluation



This study involves varying minimum amount of elements that can be changed in the model while all other elements are constant. Therefore the change in results is due to the change of those elements (it will later be explained in this section that regression analysis will confirm the amount of impact of each element on the final results). Moreover, Figure 6. 5 shows that each prototype (rectangular and square plan shape) is simulated under two different modes; the NV mode and the HVAC+NV mode and at hourly output intervals throughout the year. This includes the base prototype design (no atria included) for rectangular and square plan shape buildings. Base cases are simulated and analysed to see if their energy consumption matches the statistics given. Once the base case models are validated, the atria are included in the models and the main simulation begins. The results are then examined and if there is an error, it is addressed. The results are then analysed and discussions are made using literature reviews and finally conclusions are derived.

One of the main results from the simulations stage is the ‘office hours of discomfort’ (hours outside the comfort range) during the cool and warm seasons for each model when natural ventilation is in place. The percentage of hours when offices are within the comfortable temperature range, as opposed to the overall office hours, is also calculated. The other main results are the heating and cooling loads in the cool and warm seasons for each model when HVAC, besides NV, is also included.

The next stage is to analyse the results; comparisons of the model results are divided into four sections:

A. Comparison of the discomfort hours in each model in NV mode in each of the rectangular and square plan prototypes

B. Comparison of the heating and cooling loads in each model in HVAC+NV mode in each of the rectangular and square plan prototypes

C. Comparison of the rectangular and square plan prototype results with each other

D. Comparison of the heat gains and losses in each model via standardisation technique and regression analysis in HVAC+NV mode in the cool season for both rectangular and square prototypes.

These stages are later on explained in more detail in section 7.2 and the actual analysis are in chapters 8, 9 and 10. In order to understand why the uncomfortable hours and energy loads increase or decrease from one prototype to another, secondary outputs are generated. These are the independent values which effect the main results (dependent values) of uncomfortable hours or energy loads. With performing analysis on the independent values it can be shown that which parameters are of significance for the energy performance optimisation in office buildings within Tehran semi-arid climate. Six parameters are introduced as the independent values (secondary outputs; see section 7.5 for their definition):

- Heat loss via external windows,
- Heat loss via internal windows (windows overlooking atria),
- Heat flow Via Glazing excluding transmitted short-wave solar radiation (glazing gain)
- Solar gain via external windows,
- Solar gain via internal windows
- Airflow rate (By conducting the regression analysis technique (Appendix 4) it is shown that this parameter can be ignored as its effect on results is not considerable)

These parameters are those that have changed in each model. All other outputs, such as heating from computer equipment or occupancy, have not been considered, as they do not significantly change throughout the simulation of all prototypes (Appendix 5).

However, to analyse which parameters of heat gains and losses has a significant contribution to the results and to analyse which contributes more a technique called regression analysis has been conducted. This technique is a "commonly used type of predictive analysis.

The overall idea of regression is to examine two things: (1) does a set of predictor variables do a good job in predicting an outcome (dependent) variable? (2) Which variables in particular are significant predictors of the outcome variable, and in what way do they (indicated by the magnitude and sign of the beta estimates) impact the outcome variable? These regression estimates are used to explain the relationship between one dependent variable and one or more independent variables. The simplest form of the regression equation with one dependent and one independent variable is defined by the formula $y = c + \beta.x$, where y = estimated dependent variable score, c = constant, β = regression coefficient, and x = score on the independent variable." (Statistics Solutions, 2013)

The regression analysis in this thesis is conducted in excel. The independent values of this thesis are the 6 parameters introduced and the dependent value is the energy load. By undertaking this analysis it can be shown that which parameters have more effect on the energy loads of the prototypes and by how much;

- To understand which parameters have significate effect a “P value” is generates. Any independent value which has a P-value below the value of 0.05 (the usual significance value) has a significant effect on the dependent value (Frost, 2017).

- To understand how much an independent parameter (amongst those which p value is below 0.05) has the most effect on the dependent parameter a “coefficient value” is generated. This value is used to form the formula (explained before by Statistics Solutions (2013)) which demonstrates the relation between the dependent and independent parameters.

Last but not least, the score of the independent values must undergo a standardization technique before the regression analysis takes place. “Standardization is the process of putting different variables on the same scale”(Frost, 2017, para.1). In regression analysis, to avoid misleading results it is best to standardize the independent variables. By standardizing, the scores of each parameter range between 0 and 1; for example, in the case of glazing gain, all the prototypes should have a digit between 0 and 1 as well as in the case of internal heat loss or internal heat gain. The formulas defined to create standardize scores are as follow:

Standardized score i = (Raw Score “RS”– min RS) / (max RS- min RS)

To explain this more clearly an example is shown in Figure 6. 6 where it shows the range of parameters before and after standardization (in SQ prototype HVAC+NV mode).

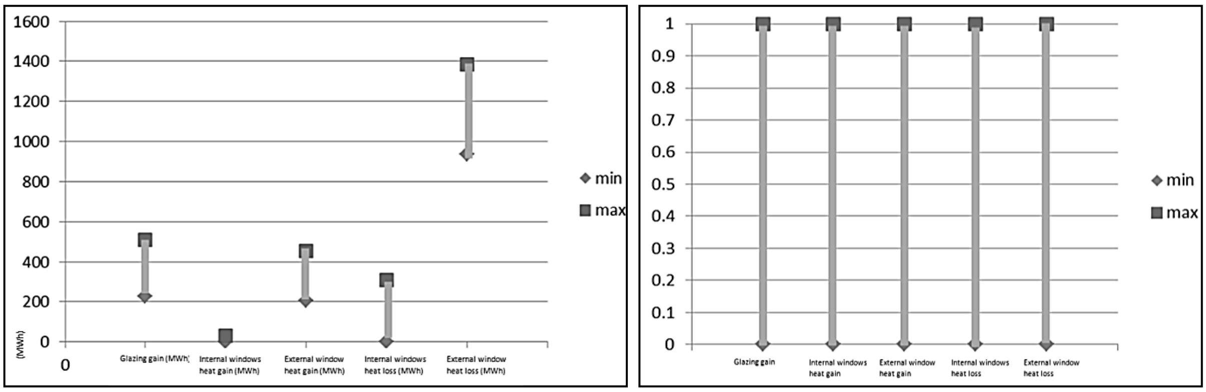


Figure 6. 6: graph before standardization (left) graph after standardization (right)

For example in the left graph of Figure 6. 6, in the heat loss via external window column, the difference between the maximum (1385.78 MWh) and the minimum (935.39 MWh) value is 450.39 MWh. However, after standardization the ranges of all parameters are between 0 and 1. The square prototype with 1 sided N atria, has an external window heat loss of 966.69 MWh which according to the standardised formula performed below, it has a standardise score of 0.07.

External window solar gain Standardized score for 1 sided N = (966.69-935.39)/ (1385.78-935.39) = 0.069

As explained, to understand which independent parameter has the most influence on the overall results (heating and cooling loads) of the buildings with atria a regression analysis is conducted in section 8.2 and section 9.2 of this thesis and explained in more detail, and a formula is generated between the variables to understand the relationship between the dependent and independent parameters.

6.4 Summary of Chapter 6

This chapter explains the reason of why this thesis has an objective, positivism and value-free philosophical stand. It also explains its deductive approach. Moreover, the research design is quantitative using a Design Science Research strategy with some similarities to experimental research. The DSR consists of three phases that this thesis also follows; the learning phase, which is covered by doing literature review; the motivation phase, which consists of a suggested solution and development of a prototype which is covered in chapters 5 and 7; and the evaluation phase which is covered in chapter 8 and 9 and the conclusion in chapter 10. The prototypes used are virtual prototypes that are built in the Design Builder simulation package. The reason of using virtual prototyping and DSR as the computer simulation program has also been explained. The plan of evaluation and analysis has also been described in detail and the dependent values and independent values produced by the software have been listed. Last but not least, the Standardisation technique as well as Regressional Analysis technique, which has been performed on the independent output values in order to highlight the impact of their independent parameter, has been explained.

CHAPTER 7: Development of Prototype and Scenarios

This chapter outlines both the information that helps to build the digital prototype and the results of a short simulation in order to validate the base case as a typical office building in Tehran before the main simulations take place in and the results are shared Chapters 8 and 9.

7.1 Simulation inputs

There are three ambient variables which have an important effect on the thermal comfort of occupants in buildings. Moosavi et al. (2014) states that these ambient variables are:

- Outside temperature
- Outside wind
- Solar radiation

These variables are also known to have much impact on the results of the prototype simulation described in future chapters.

Table 7. 1: Inputs of the simulation program

Input	
Design factors	**Environmental factors**
Building form	Occupancy density
Plan area	Office hours
Building height	Employees activity
Building orientation	Office light
Office external window glazing ratio	Employees clothing
Internal window glazing ratio	Equipment heat gain
Atrium area	Wind factor
Atrium external window glazing ratio	External window shad operation schedule
Atrium top glazing ratio	External window operational schedule
Type of atrium	Internal window operational schedule

Building material	Heating operational schedule
Building Orientation	Cooling operational schedule
Windows openable area	Atria Occupancy
Roof Shape	Atria top opening schedule

There are also two types of parameter that are used as inputs in the simulation program. The first are the parameters that help to form the prototype physics (design factors); these include the building plan and glazing ratio on the façade. The second type are not directly related to the design of the prototypes but influence the thermal comfort of the rooms (environmental factors); these include the occupancy schedule, clothing, airflow rates, and so forth (Table 7. 1). These factors are either fixed or considered variable. For example, Ji, Lomas, and Cook (2009) explore the variable of openings and calculate the overall heating and cooling loads in order to achieve the aim of an acceptable indoor thermal condition using dynamic thermal simulation and computer fluid dynamics. Moreover, Aldawoud (2013) evaluates the heating and cooling consumptions of four types of buildings with central atria elongated on east-west axis, which vary in the parameters of skylight glazing type, atrium height, skylight glazing ratio and climate. However the fix parameters are building area, atria area, operation schedule, fix internal temperature, construction, controls and occupancy. These models also do not exchange heat with outside and the building is connected to external environment only via atria skylight. Aldawoud and Clark (2008) evaluate the heating and cooling and overall annual energy consumptions of buildings with central square plan atria , which vary in the parameters of building glazing type, atrium height, building glazing ratio and compares them in open top or closed top atria in four climates. The fix parameters, however, are building area, operation schedule, fix internal temperature, airtightness, construction, air change rate and occupancy. Douvlou (2003) fixes the activity levels, clothing, and typical air velocity for a building prototype with atria. In order to evaluate the thermal comfort in the atrium, the study investigates a list of variables concerning building type, orientation, shading, glazing type, roof shape, ventilation and glazing ratio of the windows facing the atrium. He also claims that the most important factor to measure the thermal comfort is temperature. Finally, Moosavi et al. (2014) conducted a literature review on the parameters that can improve thermal performance and decrease the energy consumption in naturally ventilated spaces. They believe that these factors affect either the thermal or the ventilation performance in buildings. They further state that there is a lack of knowledge about how various design parameters influence atria thermal conditions, but according to their literature review they conclude that outlet opening sizes is the most influential parameter that affects thermal conditions inside buildings and the ventilation behaviour of atria which results in lowering energy loads. This thesis also investigates the most effective parameter in buildings which can cause less heating and cooling loads.

Section 7.1.1 to 7.1.8 explains the parameters which help to form the prototype physics. This is done via conducting more literature review to provide a rationale for each decision in terms of data inputs. Moreover, there are four variables (atria type, atria placement, building plan shape, and building orientation) which differ from one prototype to another and affect the heating and cooling loads and internal temperature of office spaces. The rest of the variables are fixed. The summary of input data for the design of the prototype (which the descriptions are provided in section 7.1.1. to 7.1.8) is shown in Table 7. 2.

Table 7. 2: design factors input data

Design factors	
Parameter	**Value**
Building form	Square and Rectangular
Plan area	500 m^2
Building height	12 story, each 3.5 m^2
Building orientation	North, East, South, West
Office external window glazing ratio	40%
Internal window glazing ratio	60%
Atrium plan area	150 m^2
Atrium external window glazing ratio	100%
Atrium top glazing ratio	100%
Type of atrium	1 sided, 2 sided, 3 sided, central and Linear
Building material	As in section 7.2.8
Building orientation	E-W axis or N-S axis
Window openable area	50%

Roof shape	Flat

7.1.1 Geometry of Forms

It is known that the shape of a building has an influence on its performance; for example, its height could influence the stack effect, and its shape could influence the wind induced ventilation in relation to the prevailing wind speed and direction (Moghaddam et al., 2011). Moreover, it is believed that the architectural shapes of high-rise structures start from the traditional extrusion of basic forms (Katodrytis, 2006) to the dynamic evolution of variations of computer generated complex forms (Wells, 2005). Basic forms in tall buildings are known to represent the different types of extrusion from a primary plan form, which are square, triangle and circle (Ching, 2007; Onyenobi, 2008). Onyenobi (2008) adds that other shapes, such as an elliptical floor plan, are generations of a circle (as rectangular is a generation of square) and that this approach of conceptualising and changing the width, length or height of a basic shape is widely used in high-rise, and especially in modern design approaches. Onyenobi (2008) also claims that a form could be transformed by subtracting a portion of its volume or, as Wells (2005) states, a multiple transformation of selected basic forms.

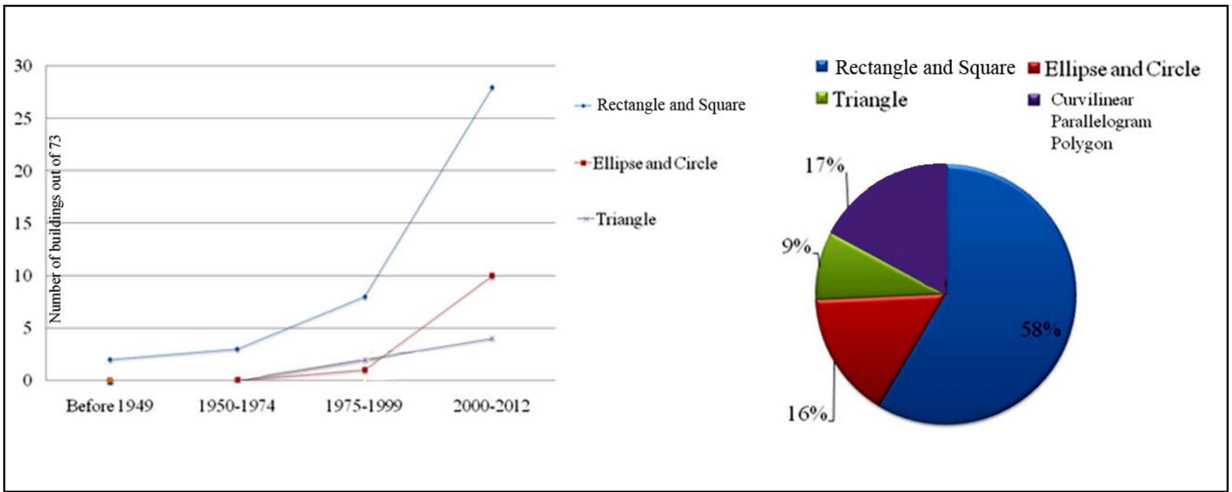


Figure 7. 1: comparison of the most used shape of 73 tallest buildings in the world (Alaghmandan, Bahrami, & Elnimeiri, 2014)

Amongst the basic plan shapes rectangular and square plan shape are known to be the most commonly used in most high rise buildings across the world (Figure 7. 1). In the case study of

Tehran, numerous rectangular building plan shapes have also performed the basic plan of traditional courtyard houses (Taleghani et al., 2014) (examples in Table 3.1 to Table 3.4 of Chapter 3), as well as modern high-rise buildings (Mahdavinejad, Ghaedi, Ghasempourabadi, & Ghaedi, 2012). Mahdavinejad et al. (2012) study Tehran's high-rise building shapes in detail and claim that most architects, use one of the five high rise building forms shown in Figure 7. 2, which are all generated from cubical shapes (rectangular or square plan). Pourvahidi and Ozdeniz (2013) also claim that, in the hot and dry regions of Iran with cold winters, cubic forms are popular. This thesis examines the square and rectangular plan shape buildings as these are the most commonly used configurations amongst high-rise buildings in semi-arid climate of Tehran as well as being popular across the world (Figure 7. 1).

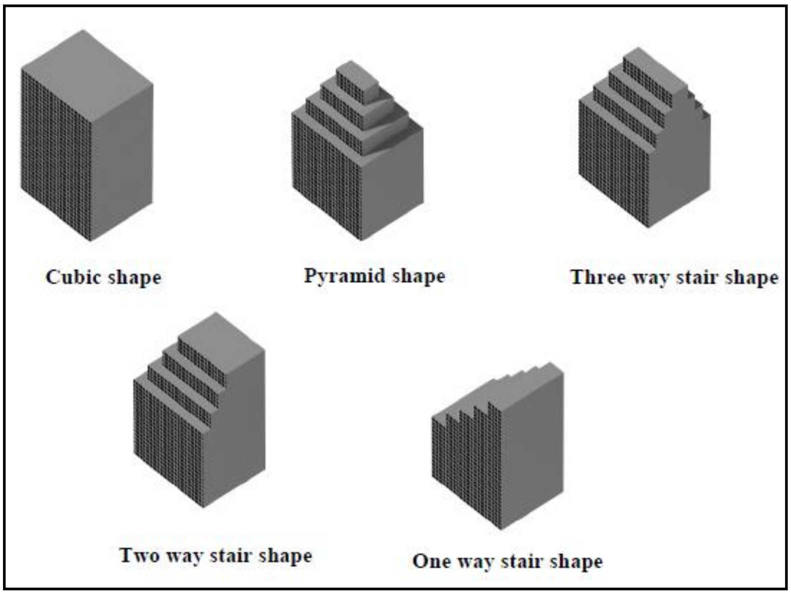


Figure 7. 2: Most used high-rise forms in Tehran, which also have 40% openings and windows in the façade (Mahdavinejad et al., 2012)

There are some literature regarding the performance of square and rectangular prototype plan shape buildings. In terms of energy consumption, Faizi, Noorani, Ghaedi, and Mahdavinejad (2011) conducted an analysis on square and rectangular plan shape buildings (with no atria) in Tehran and believes that rectangular plan shaped buildings can provide more solar gains than square as well as less energy loss depending on their orientation. Moreover, in terms of buildings that include a central atria, Aldawoud (2013) investigated four models of building which included atria. The models included a square plan shape building and other three models where rectangular plan shape buildings with three different width to length types. However, all the atria area and building area are fixed in all prototypes and all rectangular porotypes are orientated on the east-west axis. Aldawoud (2013) concluded that, amongst the four prototypes and in four climates (of hot-dry, hot humid, temperate and cold) those which have the biggest length to width ratio prove to be the most energy consuming. Thus for offices with central atria, it is more energy efficient to adopt a square shaped rather than a rectangular shaped plan.

In addition, Yeang (1948) states that, in cool and higher altitudes, a 1:1 ratio (square plan shape) performs more energy efficient compared to other ratios. He however, adds that in lower altitudes the elongated form (rectangular plan shape) is required. He also mentions that research shows that the optimum aspect ratio of buildings, and the preferred length to width ratio in an arid climate is a rectangular shape with 1:2 ratio. However, in tropical climates, the ratio of 1:3 is optimum.

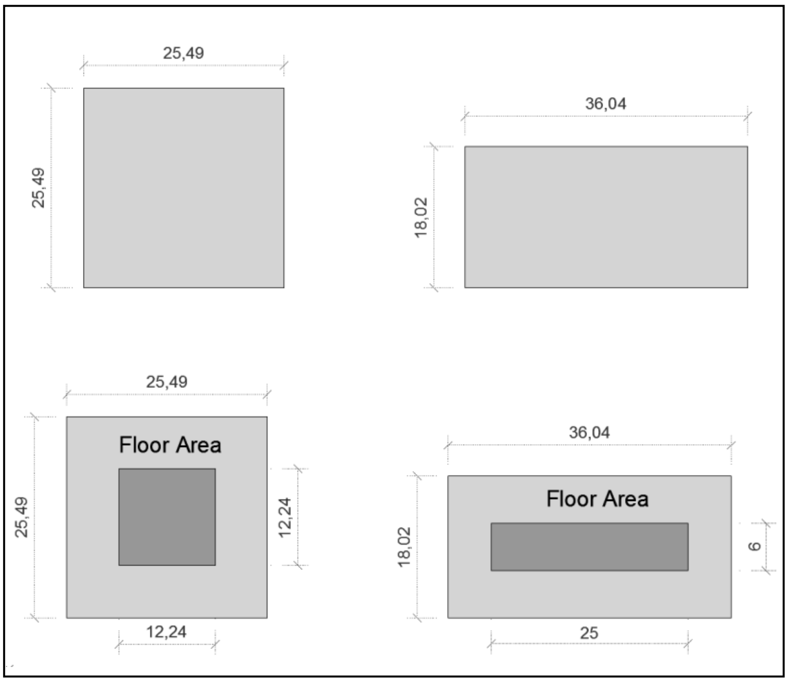


Figure 7. 3: Prototype plan and its dimensions

There are different views as to whether a square or rectangular form is more energy efficient in the semi-arid climate of Tehran. Since Tehran is a semi-arid climate with cold winters (not completely an arid climate nor completely a cold climate), thus, this study investigates both rectangular and square shaped plans of building forms to determine which is more efficient in terms of energy consumption and the achievement of thermal comfort. Based on Yeang (1948) findings buildings with ratios of 1:1 (square) and 2:1 (rectangular) length to width in their plans are further investigated in this research (Figure 7. 3).

7.1.2 Height

The height of a building with atria has an influence on its thermal performance (Aldawoud & Clark, 2008). The greater the height, the greater the temperature difference between the low and upper levels of the atrium. As explained in chapter 3, this causes the pressure gradient to generate effective buoyancy- driven ventilation and provide air flow. However Moosavi et al. (2014) and Chou, Liu, and Lin (2009) believe that, having tall atria does not necessarily mean an increase in air flow and ventilation rate as it also depends on the outlet valve. If the outlet valve is big enough and high, it would allow the warmer air to be released faster making way for cooler air. Moreover, the height of the atria roof is higher than the building roof because as Hegger, Fuchs, Stark, and Zeumer (2012, p. 201) indicate "…glazing atria can be employed for removing the exhaust air. Owing to the ensuing high air temperatures beneath the atria glazing (heat build-up), the atrium [glass roof] must be higher than the adjoining structure in order to reduce the thermal load on the top most floors." Hence this thesis has raised the atria height higher than the building roof.

Table 7. 3 shows some examples of office buildings (low-rise and high-rise, built or to be completed) in Tehran with the number of storeys height for each. The range of hight in the examples given are from 2 to 36. Never the less, in Tehran, tall buildings are classified as buildings above 12 storeys in height (TMPD, 2012). This thesis will use a 12-storey prototype as fixed parameter because of the threshold on the definition of tall in Tehran's regulations.

Table 7. 3: Examples of office buildings in Tehran (Orange font: to be built, Green font: competition and Black font: have been built)

hight	Name of building
2	commercial-office building in valiasr
2	Sharif univeristy of technology services complex (offices)
3	Commercial office abbas riah
3	Melli bank - tehran uni branch
4	PSP office building
5	sherkate meli palayesh va pakhshe aravardehaye nafti iran
5	Mehregan office building
5	pole roomi office building
5	Checker box office complex
6	Cheker box office complex
7	niyayesh office building
7	Narenjestan office building
7	Neshan office building
7	negine shargh complex
7	Narenjestan office building
7	Pole roomi office building
8	Asef offic ebuilding
9	Mayor office building N. 2 districk 3
10	Vozara office building
10	karafarin bank fereshte
11	tehran stock echange
12	tehran stock echange
12	nahid borj
12	edalat office block
13	Tele communication building
13	Tele communication office building
13	tehran stock echange
14	Shahkaram office building
14	shahkaram office
14	tehran stock echange
15	Sarmayeh centrral Bank
15	markazi central bank
15	almas office block
16	ebne batoote commercial, office building
16	Darabad office blcok
18	central railway office
18	Governorship office
18	Rahahan cebtral office
18	central offices of railway islamic republic of Iran
20	mellat central bank
20	melat central bank
20	Parsian commercial offcie buidling
20	pasargard bank headquarters
21	Morvarid office and commercial center
22	Central office of bank mellat
26	Milad tower
36	Velenjak Tower
	milad complex proposal
	ajoodaniyeh tower
Average hight: 12.36	

7.1.3 Building Orientation and Glazing Location

The orientation of buildings affect the indoor thermal climate in two ways; firstly, the orientation with regards to the sun (solar radiation from different orientations substantially affects the internal environment), and secondly, the orientation of the building with regards to the direction of the prevailing wind (Olgyay, 1992). However, the correct building orientation is something that can be learned from historic designs. As Galloway (2004, p. 6) describes, "our ancestors understood the orientation of their living areas…and how to distribute thermal energy to other living spaces" because they took advantage of the solar energy rays from the sun. Therefore, the orientation of vernacular structures could be inspiring to architects interested in passive climate control (Naciri, 2007). For example, Taleghani et al. (2014) states that a north-south courtyard direction in Iran has the shortest duration of solar radiation and is recommended in hot climates, whilst an east-west courtyard direction has the longest duration of solar radiation and is more favourable in colder regions. Moreover, in Tables 3.1 to 3.4 of Chapter 3, Soliemanipour (2015) shows that:

> The orientation of traditional buildings in a hot and dry climate is NW-SE with a central courtyard and a water feature. In hot and humid climates, the orientation is towards the wind from the sea with smaller central courtyards and covered deep verandas (street and corridors). In temperate humid the orientation towards south with plan proportion of 1 to 3 for (narrow plan for more cross ventilation in humid climate). Also in cold climates the building have rectangular plan with orientation towards the sun radiation and therefore the large windows are be placed in the southern front of the buildings.

Apart from the traditional buildings, research has also been conducted into the appropriate orientation of tall buildings and the appropriate glazing location. Faizi et al. (2011) conducted an analysis on tall buildings (with no atria) with square and rectangular plan shape and with different orientations in Tehran. He believes that the most to least translucent façades of rooms (in this thesis, it is the office's external window) are most energy efficient in the order of south, east, west and north sides in this order for Tehran as it receives the most solar radiation and the most day light access. So for more solar gains it is best to align the building on east-west axis for more south solar gains. However, for least energy loss it is best to have minimum façade on north where no sun penetrates (rectangular plan building aligned on N-S axis).

Moreover, BHRC (2007) and Faizi et al. (2011) state that, due to the low thermal resistance compared to other parts of outer surfaces, translucent layers should not be located on the undesirable and cold fronts of buildings (north façade). Iranian Regulations (BHRC, 2010) verify that the most to least energy efficient angles to have translucent facades are south, east and north. The north façade is the coldest facade because there is no heat gain on this angle in summer or in winter. However, the north façade windows could be of benefit in providing cool air on hot days. Also in summer sun angle is high on south facades so the sun cannot penetrate deep inside unlike in winter when the sun angle is low. Nevertheless, both Faizi et al. (2011) and Iranian Regulations (BHRC, 2010) agree that the south and then east are the best locations for the external windows of rooms for lowering energy consumption. Moreover, Khodabakhsh and Mofidi (2001) also say that the least amount of elevation should be targeted by solar radiation in arid (hot and dry) climates. Hence, large exposure of translucent facades towards sun is not favourable in arid climate.

Tahbaz (2008) also worked on a high-rise building with a rectangular plan shape in Tehran and on a north-south axis orientation, which was blocked on the east and west. Tahbaz concluded that the elongation of the building toward the south-north axis and open spaces (free plan) with minimal interior walls within the flats, helps the building to act as a wind tunnel for the local breeze, as there is no preventative element to terminate the air flow. However, Tahbaz did not check the east-west orientation with the north and south facades, which were blocked by neighbour buildings. Therefore, the conclusion is not complete in terms of best orientation.

Another example is the Kaveh Glass head office in Tehran which has a passive design. It is known that the key element of this building is its orientation on an exact east-west direction (Reischer, 2016).

Nevertheless, Iran’s regulations state that the buildings could utilise a fair amount of solar energy in winter if they are orientated towards the south; having more translucent layers on this façade helps to gain more of the sun’s radiant energy, which is especially beneficial during cold days and the shortest days (BHRC, 2010). Thus, in warm seasons it is generally most energy efficient to orientate building on a north-south axis and in cool seasons along the east-west axis. Therefore the orientation of north, east, west and south will be rechecked for the prototype designs in Tehran to determine the effect on energy consumption. In addition, the orientation of the façade on which the atrium is located is important as it has 100% glass façade. For example, Hastaie (2000) suggests that it is better not to construct an east-west linear atria because this orientation admits low angle sunlight in summer. Therefore, this thesis also investigates the effect of different atria placement and the building orientation on thermal comfort and energy load of a building.

7.1.4 Glazing Ratio

Annual heating, cooling and the total energy consumption as well as the daylight performance are considerably related to the glazing surface ratio of a building (Aldawoud & Clark, 2008). The importance of the right glazing ratio has been emphasised by Pan, Li, Huang, and Wu (2010). They have researched buildings with central atria and state that, in hot climates, a highly glazed building worsens the indoor thermal environment and causes the central atrium to overheat. This is due to the high altitude of the afternoon sun as well as the high temperatures that pour into the space from surrounding offices.

Ho (1996) suggested that different glazing ratios should be considered for different climates. He adds that, if the outside peak temperature of the hottest month is near 40°C then 20% glazing is advisable; whilst, if the peak is near 30°C, then 80% glazing should be acceptable. Furthermore, if the peak temperature is somewhere in between (near 35°C) then 50% glazing would be desirable. Tehran's mean maximum temperature is around 36°C (Keyhani et al., 2010); therefore, acording to Ho (1996), the glazing ratio should be a little less than 50%.

Moreover, the Iran Regulations (BHRC, 2007), Section 19 states that a 40% glazing ratio is the maximum allowed in high-rise buildings of arid climates of Iran. Mahdavinejad et al. (2012) also applied the regulation in its case study prototype. Thus, considering evidence from existing studies, it seems reasonable that a maximum 40% glazing for buildings in the semi-arid climate of Tehran is advisable. Therefore, this thesis will confirm the glazing ratio of the façade as 40% and thus, a fixed parameter.

7.1.5 Atrium Type

When buildings started to change in Tehran and inward looking courtyards were transformed into outward looking high-rise buildings (Madanipour, 2003a), other changes also occurred, such as the transition from closed interior plans to open plan buildings (Noori, 2010). Ji et al. (2009) state that non-domestic modern buildings are usually deep-plan and large. This thesis also uses open-plan prototypes with the consideration of atria which also provides light and fresh air to the deepest parts of the building. Moghaddam et al. (2011) state that, even though window openings on a façade help in providing natural ventilation to potentially provide thermal comfort, it is inadvisable to only rely on façade openings in larger buildings to achieve comfort (N. Khan, Y. B. Su, & S. Riffat, 2008). Therefore, incorporating atria could be an advantage. In terms of atria geometry Laouadi et al. (2003) state that if atria are designed in the correct shape and form, they could help with airflow inside buildings, removal of excessive heat gain, thermal comfort temperature in cool and warm seasons and to minimise thermal loads. Aldawoud (2013) also states that atria geometry is one of the most important factors from an energy efficiency perspective, because it can determine the overall energy performance of a building by having an impact on heating and cooling loads.

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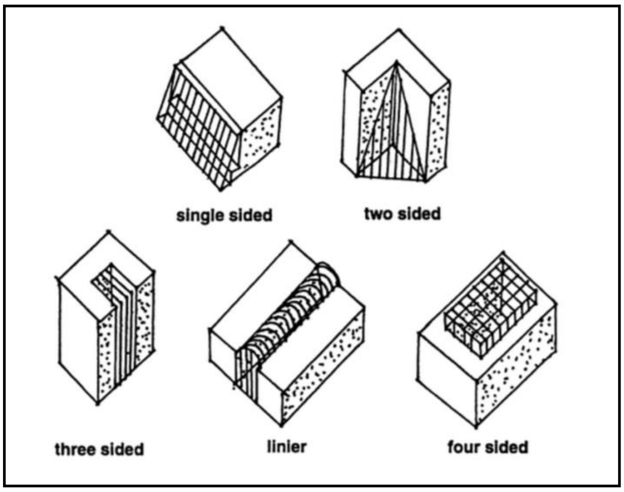


Figure 7. 4: Generic form of atrium building, the simpler types (Ahmad & Rasdi, 2000)

As mentioned in Chapter 4, and according to Saxon (1986), there are five main categories of atria forms. Thus, this research investigates all five categories of central, 1-sided, 2-sided, 3-sided and linear atria in square and rectangular plan shape buildings. There has been few studies on some atria type in buildings:

> In terms of the energy consumption of some building with atria and their performances, Aldawoud (2013) evaluates the heating and cooling consumptions of four types of buildings with central atria elongated on east-west axis, 1 square shape and three rectangular shape in different length to width ratios. He believes that narrow elongated central atria or atria with a higher ratio of length to width and positioned in the centre of the high rise building, generally perform better in terms of less energy consumption in hot-dry and hot-humid climates rather than in cold climates. However, compared to a square shape they are known to have poorer energy performances annually and thus considerably higher annual consumption rates in all

four climate regions of hot-dry, hot-humid, temperate and cold. Moreover, Gratia, Bruyere, and Deherde (2004) suggest the advantages of linear and central atria over other types explaining that buildings with central or linear atria have more adjacent spaces than buildings with other types of atria. Also, they have the advantage of allowing deeper-plan designs, as they allow light into the center of the deepest part of the building where natural light from building façades may not penetrate. Also as mentioned in chapter 5, an example of a naturally ventilated residential building in Tehran shows that a central atrium can help lower energy loads if they are also open from below (buildings raised on columns). In such a case, the open space at the ground floor level helps to cause a pumping effect, sustaining and increasing the air movement in the atria (the interior middle parts of the flats) that are not in direct contact with the natural outdoor winds (Tahbaz, 2008).

Last but not least, according to the Iranian National Building Codes, Section 19 (BHRC, 2010), the in-between spaces (or atria) provide more energy efficient buildings if they are positioned where the transformation of heat from the inside to outside in winter and from the outside to the inside in summer is minimised. This allows minimum external heat loss in offices in winter and minimum external heat gain in offices in summer.

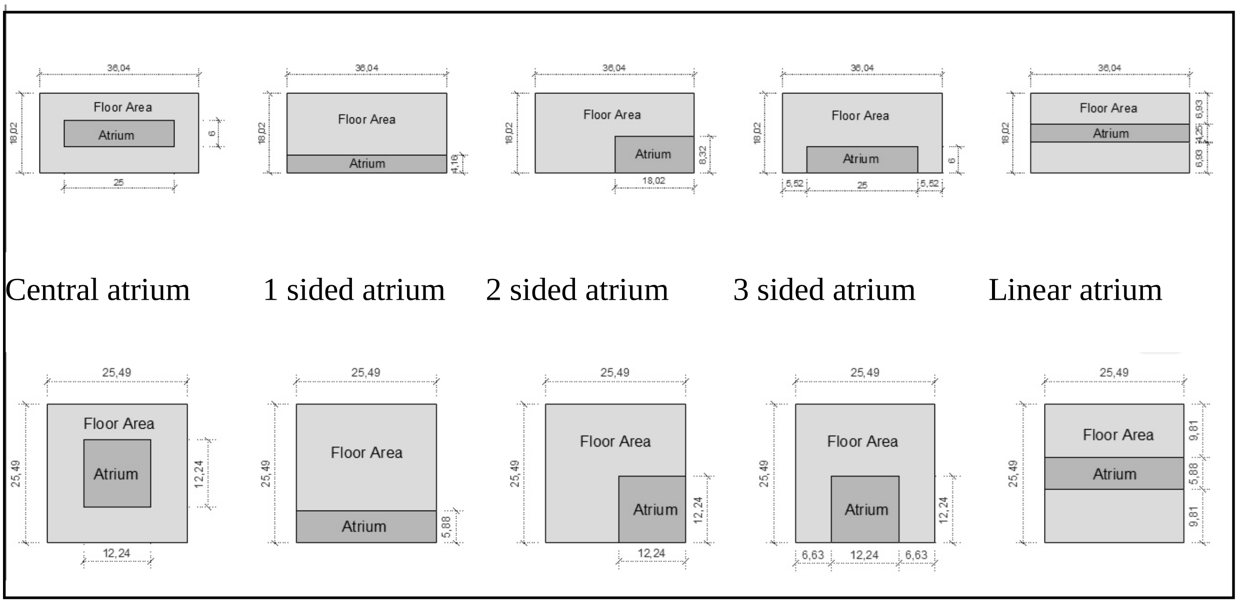


Figure 7. 5: prototype plan and different atria types with dimensions (with same fixed building and atria areas and within limitations and scope)

Not much information has been produced on all other types of atria in square and rectangular buildings of Tehran semi-arid climate (Figure 7. 5). Therefore the researcher needs to gather evidence on all basic types of atria in a semi-arid climate. Thus, to summarise, the prototype atria will focus on tall, open-plan buildings with the five atria options of linear, central, 1-sided, 2-sided or 3-sided (Figure 7. 5).

7.1.6 Atria Open vs Closed Top

Atria top openings have an important impact on the inside temperature. Sharples and Bensalem (2001) conclude that the large openings and strong suction forces in atria help with cooling loads and provide ventilation in high-rise buildings that are surrounded by other buildings. Chou et al. (2009) believe that the size and position of the stack opening, or roof opening, also has an effect on the internal thermal environment (apart from the effect on ventilation). However, they state that when the ambient temp is above 35 degrees Celsius, the efficiency of the stack effect is limited. Thus, the ambient temperature is also a factor to influence an efficient airflow and thus assist the cooling loads. Furthermore, in terms of the atrium outlet location, Hussain and Oosthuizen (2013) state that it should be at the highest point of the atria. Moreover, Moosavi et al. (2014) states that the opening state of the outlet (opened or closed) has great effect on air flow through atria as well as the internal temperature. Atria that are open at top reduce the annual cooling energy ratio of the adjacent spaces; however, they increase the annual heating energy ratio, especially in winter. Therefore, it is more energy efficient to close the top on very cold days. Laouadi et al. (2002) claim that, by having the atria roof closed in cold climates, 10% energy was saved. As such, the atria top would be open in the warm season and closed in the cool season. This approach was also considered by Taleghani et al. (2014) in their study on buildings in Iran’s arid climate.

7.1.7 Material

The materials used in the prototypes are the typical materials used in Iranian construction. The selection of envelope materials (external wall and window), however, have been incorporated with consideration of improving the building’s performance (Appendix 3). Thus the base case prototype is also the improved version of the typical building types in Tehran in terms of material. Hence, the base case results of energy consumption should be lower than typical office building in Tehran climate. This is discussed more in section 7.4 where the base case is validated.

7.1.8 Building Dimensions Defined by Iranian Regulations

Iranian building regulations are studied to justify the prototypes physical dimensions. Until 2014, no regulations had been published concerning tall building designs in Iran. However, in 2014, the Iranian National Building Regulations (BHRC, 2014) Section 4, added ‘Chapter 8’ which concerned tall buildings. This chapter in the regulation book is new and also the regulations concering tall buildings are an ongoing development process. Therefore, the references of some of the rules in this thesis have to be based on the reports provided by secondary sources alongside the general regulations. In these regulations, it is advised that considerations that are made for other types of buildings regarding building space, detail, etc, can also be applied to tall buildings. Below are some regulations that help in shaping the prototype model before simulation takes place.

- **Office occupied area:** According to Tehran’s Municipality and Planning Department (TMPD, 2012) for buildings above 12 storeys, a minimum area of land should be 2500 m^2 of which 20% (500 m^2) can be used to build the buildings. However, for the first two storey levels, 50% of the land could be used and for the third story and above, 20% can be used. For simplicity, in this thesis, the prototype plan uses equal amounts of space across all storeys; thus, 20% of the minimum land area will be considered for all levels at this point thus 500 m^2 is considered the occupied area of each office floor in all prototypes.
- **Atria Area**: For lands with an area of more than 200m^2, the central yard (atrium) should be at least 6% of the land area (BHRC, 2014). However, this has only been advised for residential buildings. As no other regulation has specifically been advised for office buildings (which in itself could probably be a statement of the unpopularity of atria in office blocks) this thesis will also consider 6% of the land as the atrium area. For tall buildings, a minimum of 2500 m^2 of land area is allowed; thus, 6% of 2500 is 150m^2. Therefore, this thesis considers the atria area to be 150 m^2 on each floor for all prototypes.
- **The floor to ceiling height:** For offices, the minimum height is 2.40 metres and if there are more than 20 people on a floor then the height should be no less than 3 metres (BHRC, 2014). for the purpose of this thesis, 3 metres of floor to ceiling height will be considered as occupancy is more than 20 people in a 500 m^2 floor.

- **Maximum distance for cross ventilation**: In order to secure cross-ventilation it is recommended that the depth of the offices are no more than 5 times the height of the floors and for single sided ventilation 2.5 times the height is the maximum allowance (GreatBuildings, 2015). In this thesis the height of rooms are 3 meters, therefore, the depth of prototype offices from one window to the opposite window should be no more than 15 m2 and for single sided no more than 7.5 meters. It will be checked that the prototypes of this thesis will follow this rule.
- **The minimum glazing area**: Based on the Iranian National Building Codes, Section 4 (BHRC, 2014) the window area of office blocks should be at least 1/8 of the plan area with at least half with the capability to open (an openable area on the façade as 1/16 of the plan area). In the prototype, 1/8 of the overall office and atria area for one storey (650 m^2) is 81 m^2. Thus, the minimum glazing area for the prototype is 81m; however, due to findings within the literature, the prototype window covers 40% of the façade, which is 120m^2 for one storey. This is more than the minimum number of 81 and as such it is acceptable. Also 50% of the external windows need to be openable in the simulation program whenever needed.

  Moreover, in offices with internal courtyards or atria, the façade overlooking these spaces should have at least 60% transparent glass with again at least half being openable. This has also been applied in the prototype, where internal windows cover 60% of the internal walls.

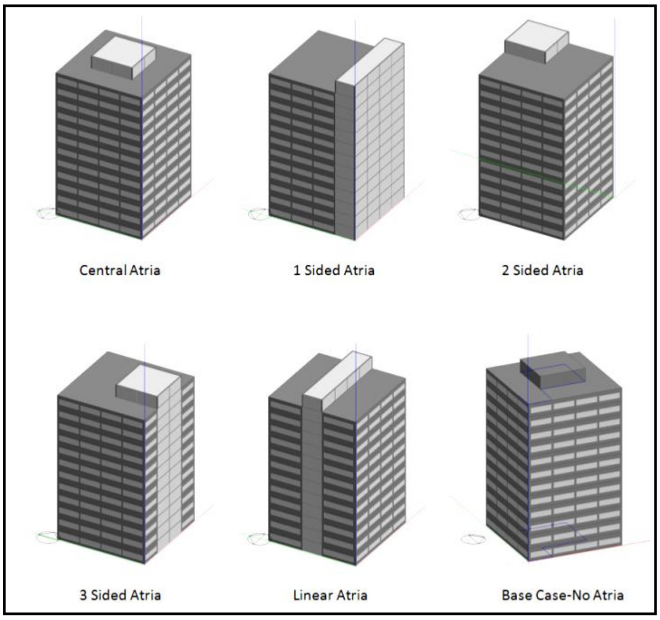


Figure 7. 6: Square prototype of different atria and base case

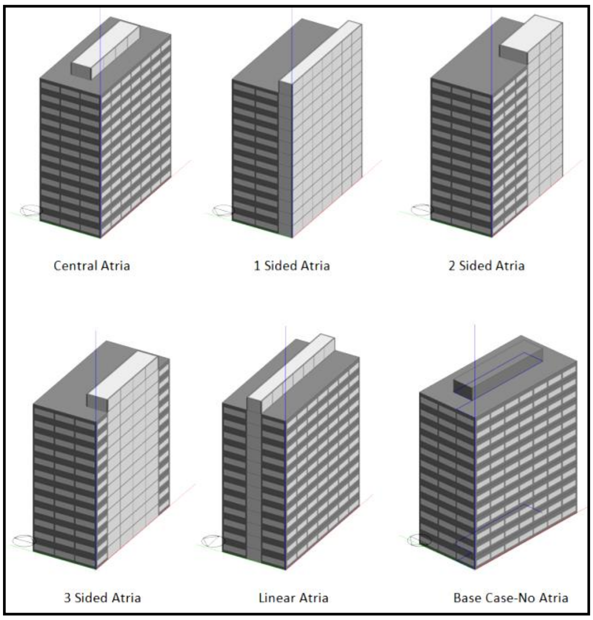


Figure 7. 7: Rectangular prototype of different atria and base case

All the inputs selected in section 7.2 are for designing the prototype. The prototype with the inputs are represented in Figure 7. 6 for square plan and Figure 7. 7 for rectangular plan office buildings. As mentioned, some of the input values in each of the prototypes are fixed, such as the 'base design factors'; however, some are dependent on the circumstances, such as some of the environmental factors outlined in Table 7. 1. For example, the scheduled time of office window opening depends on the interior temperature of the offices. The internal temperature itself is partially the indirect influence of atria type and orientation.

7.2 Modelling stages and analysis procedure

After the characteristics of the prototypes are introduced, the modelling stage in the simulation program takes place. However, before the explanations on how the modelling stages were conducted and how the results were analysed, it is important to acknowledge that:

- All the simulation results are produced in office hours, when the building is occupied, hence making the outputs more meaningful.
- The weather file used in this thesis provides the hourly weather data of Tehran.
- In Design Builder and in natural ventilation mode, the airflows are calculated from wind and stack pressures when carrying out simulation.
- The building context for which the simulation of the prototypes takes place is in an urban area.

The prototypes generated and used in the software which undergo the simulation procedure are shown in Figure 7. 8. The prototypes themselves differ in terms of plan shape, orientation, atria type, and placement (unfix parameter). Below explains the number of different prototypes in more detail:

> The porotypes cover the five selected atria types; central, 1-sided, 2-sided, 3-sided and linear. Building plan shapes are either square or rectangular as the reviewed literature identified that they are the most commonly used shapes in Tehran as well as ,statistically, the most commonly used plan shapes in the tallest buildings of the world. Therefore, two plan shapes for each of the five atria types totals ten prototypes, excluding the base case. The base case represents the typical office building blocks in Tehran, which do not have atrium (Figure 7. 6 and Figure 7. 7).
>
> Moreover, each of these prototypes is examined with an orientation towards all four main compass directions (Figure 7. 8). Thus, for the 1-sided atria example, it is orientated towards the four directions producing four different scenarios. However, some atria types (such as central in a square shape) only have one option and orientation and do not produce a new scenario. Thus, the 10 prototypes provide 35 scenarios of different orientations. In addition, orientation is also considered in base building case with no atria (in both square and rectangular plan shapes) which means the number of prototypes undergoing simulation stages is 38 (Figure 7. 8).
>
> In order to simply refer to a certain prototype, the researcher has given coded names to each 38 prototypes that has been designed in order to undergo simulation. These names also indicate what the prototype looks like (Figure 7. 8). The first part of the name is the type of atria for the office building, namely 1-sided, 2-sided, 3-sided, central and linear. The second part indicates where the atrium is situated. Thus, if the atrium is on the north of an office building and has a 1-sided atria, the name of the prototype is 1-sided-N. If the building has a linear atrium which has external atria façades towards the east and west, the building is called a linear-EW model. The third part of the name is used in the rectangular category and gives a sense of how the building is orientated. For example, if a building with an atrium located on the NE (2 sided-NE) is aligned horizontally on the east-west axis, then that prototype is called 2-sided (H)-NE model. Figure 7. 8 shows all the full names of all prototypes with their plan shape.

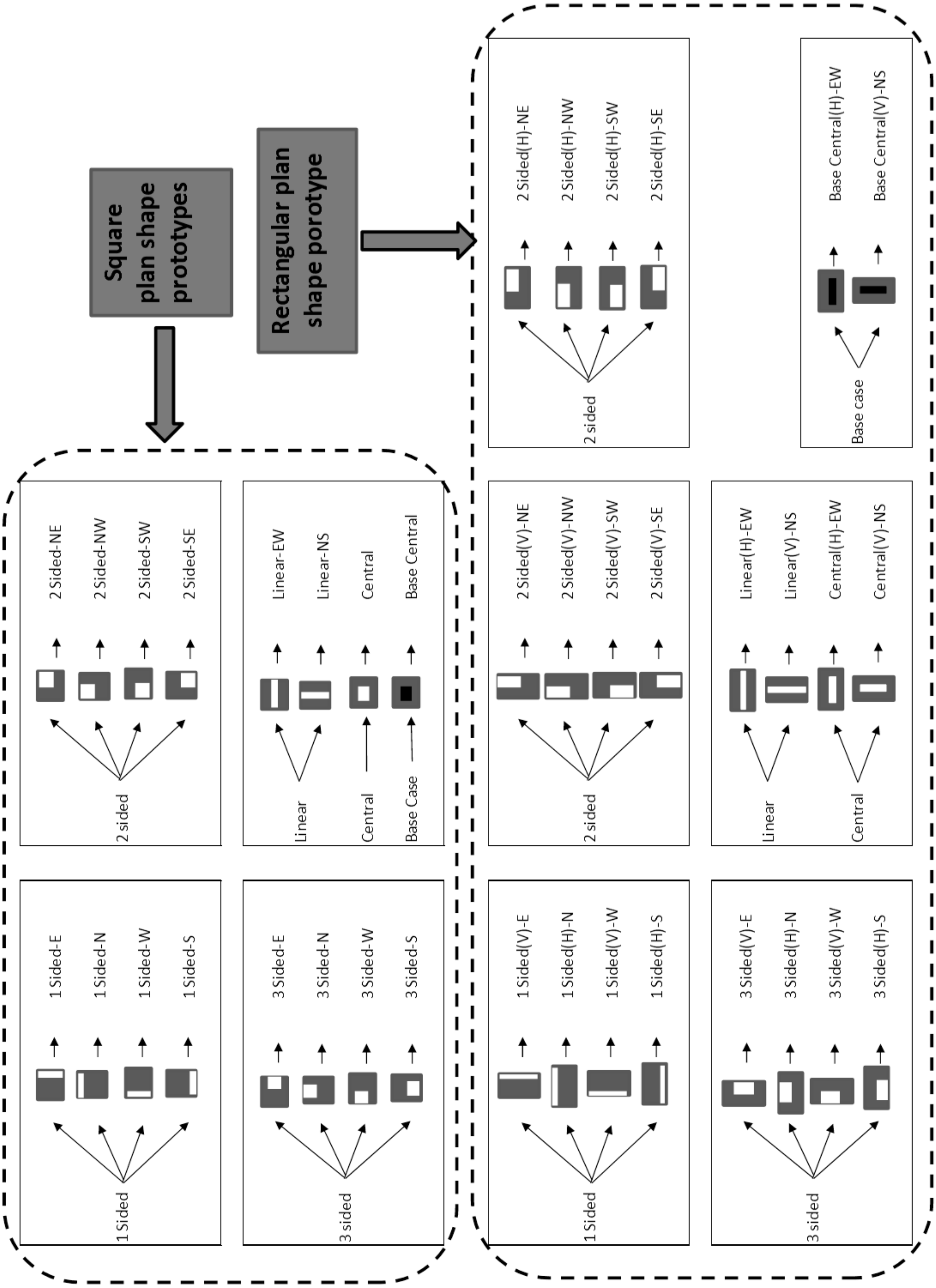


Figure 7. 8: all the plans of 38 prototypes used in simulation

As for the number of simulations, the simulation stage has four categories depending on the season and control mode (Figure 7. 9). In section 6.3.3 and as illustrated in Figure 6.5 the detail of the evaluation stage has been explained. There are two seasons; cool season (which covers October to March) and warm season (which covers April to September). Having two separate simulations rather than one annual simulation is important because some input data or operational schedules are different for each season. Thus the simulation could not be completed in one attempt. Also, in each season there are two different control modes; NV mode only and HVAC+NV mode which uses HVAC when NV is not enough to provide a thermal comfortable temperature. Therefore, each of these 38 models undergoes four set of simulations stages: ‘warm season NV mode’, ‘cool season NV mode’, ‘warm season HVAC+NV mode’, and ‘cool season HVAC+NV mode’. Therefore, 38 prototypes multiplied by four equals 152 simulations. As explained all simulation results are outputs for office hours only, when the building is occupied, and situated in an urban area replicating Tehran city. Each simulation performance takes one day to be completed with the computer facilities available to the researcher at the time of the research. Also in order to produce reliable results a considerable amount of simulation has been conducted to understand how the software works and to generate correct results.

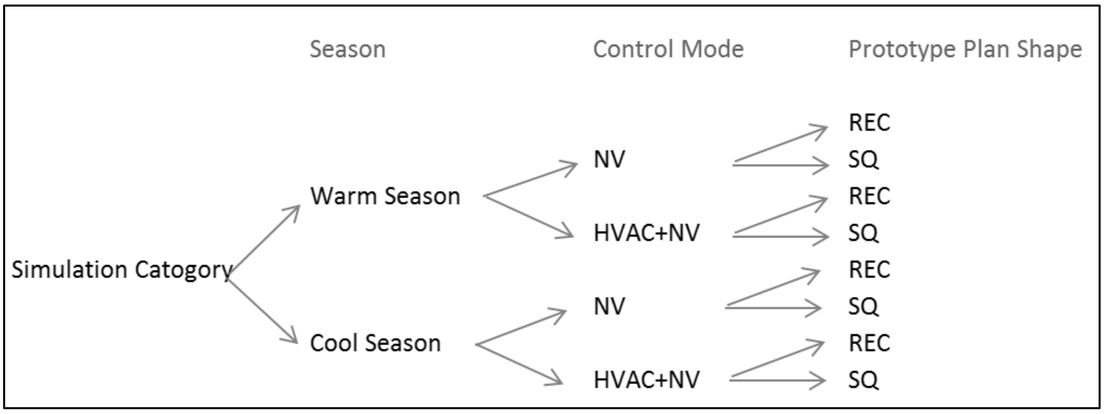


Figure 7. 9: Simulation Category

When the simulations are complete, there will be a comparative analysis of the various results that aims to identify the design characteristics that provides the least energy consumption in heating and cooling the office spaces, and provides most thermal comfort via natural means. The results of the prototypes with atria are also compared to the base case building with no atrium in the same simulation category. In other words, the base case acts as a benchmark and any prototype with more acceptable results than the benchmark could represent a potential design to consider in terms of lowering energy consumption for thermal comfort. Thus, the base case is a benchmark for assessing the designs with a more potential for lower energy consumption than the typical office buildings in Tehran.

7.3 Prototype (base case) validation

According to Law (2008), all simulation models need to be validated or any decisions made with the model may be erroneous. Montgomery (2012), Banks, Carson, Nelson, and Nicol (2009) and Law (2008) believe the following ideas are most common for developing a valid and credible model:

• Formulating the problem precisely: which have been addressed in this thesis.

• Interviewing appropriate subject matter experts if needed: not applicable to this thesis either as the base model is based on reality or it is not a matter of design opinion.

• Interacting with the decision-maker on a regular basis throughout the simulation project to ensure that the correct problem is being solved and to promote model credibility: not applicable to this thesis as there isn't an individual decision maker.

• Performing sensitivity analyses to determine important model factors: which has been addressed in this thesis)

• Comparing model and system results for an existing system (if any) – this is, in general, the most definitive validation technique available: This thesis validates the base model with example case studies which has been addressed in this section of the thesis. Others such as Fesharaki and X have used this validation method, modelling an existing building, in their prototypes to provide models with less energy consumption.

• Comparing model output data with the comparable output data for another model that is thought to be "valid": there isn't any other model, other than the base model which needs to be validated against reality

• Obtaining "representative" data for use in building and validating a model: This validation technique is also used in this thesis where existing statistical data is observed and compared against base model results, as it will be explained in this section.

As explained in the methodology section validating the base case prototype is of importance to make sure the simulation results of the base case are similar to typical office buildings of Tehran and that all simulations are valid. The porotypes with atria are in fact developed from the base case model which has no atria. Base case model represents the typical high rise office buildings. If the base case heating and cooling load value, generated by the simulation, replicates the value of heating and cooling loads of office buildings in Tehran, then it can be said that the base case is a true representation of an office building in Tehran. In that case the results of all prototypes, which have been developed from base case, can be valid also. The validation is performed in two sections.

One part of the validation is to compare if the overall heating and cooling load value of the base case replicates the overall heating and cooling load value of the typical office buildings in Tehran. This part of the validation can be done by looking into the base case energy result and the statistics in literature review already provided in chapter 5:

Based on 285 office examples in Iran covering all climates, the annual overall energy usage in offices on average is about 350 kwh/m2 (Bagheri et al., 2013) (74 of these examples are located in a similar climate to that of Tehran). As explained before 61% of the energy in buildings is used for HVAC (Riazi & Hosseyni, 2011). Thus, if the office energy consumption of 350 kwh/m2 is multiplied by 61%, then 213.5 kwh/m2 is the average cooling and heating energy in office buildings in Iran (including all climates). For the base cases, situated in Tehran climate the heating and cooling result generated from the simulation in average is 169.10 KWh/m^2 (Base-Central(V)-NS=192 kwh/m2, Base-Central(H)-EW=155.36 and square base case=159.79).

The value of 213.5 KWh/m^2 and the value of 169.10 KWh/m^2 are not very far apart, however, there is a difference between them. The difference in the results is because of the overall reasons mentioned below:

- The base cases in the program have been improved in terms of materials, shade, window percentage and window operational schedule.

- The base case is high-rise, however the statistics from offices includes all types of buildings.

- The temperate set-point for which the HVAC is active in the prototypes is different to the standards mentioned in the regulations which typical office buildings use. The comfort range in prototypes is more than that of Iranian regulation. Hence the amount of heating and cooling load value is less in the prototypes.

- Moreover, 61% is the statistic for HVAC percentage in Iranian buildings in general including office buildings but not specifically for offices.

- In addition, the statistics of energy consumption in the city of Tehran with semi-arid climate is not available; hence the statistic of office energy consumption (350 kwh/m2) in Iran, which covers different climate regions, has been used.

Moreover, the other part of the validation uses information only in Tehran climate rather than statistics of overall office buildings in Iran. As mentioned, statistics on heating and cooling load of offices in particular climate of Tehran is not available, hence, empirical data of existing office buildings situated in Tehran semi-arid climate has been investigated and compared with the base case:

A number of office buildings with electricity and gas bills have been studied. However, even though in Tehran each unit has a different electricity meter, the whole building usually shares the same gas meter and therefore, the gas bill is divided between units regardless of their usage percentage. For example, if a two-story building accommodates one office and one household on different floors, the office is responsible for half the gas bills even though its usage might be more or less. Thus, only offices that occupy a whole building can provide correct gas bill usage. Out of the nine office cases shown in Table 7. 4, five (cases A to E) are one office block and the other four remaining cases (cases F to I) are offices which are part of a multipurpose block. The data of cases where the whole building is one office block is acceptable in this study. As such, the gas bills have been shown only for five office case (Table 7. 5) and cases F to I are investigated no more. By looking into the electricity and gas usage it is apparent the electricity energy usage of the cases varies between 2 to 114 kwh/m2 (Table 7. 4), and the gas usage varies between 116 to 398 kwh/m2 (Table 7. 5) (sample bills are available in Appendix 1).

Table 7. 4: Annual electricity usage of some offices in Tehran

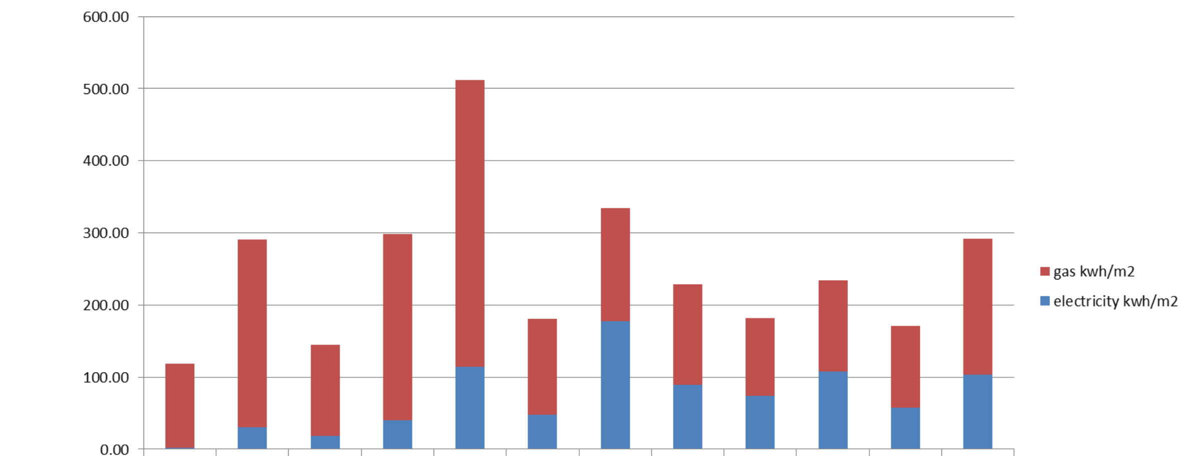
Electricity Usage in different cases	Case A (600 m2)	Case B (570 m2)	Case C (75 m2)	Case D (125 m2)	Case E (200 m2)	Case F (82 m2)	Case G (130 m2)	Case H (110 m2)	Case I (67 m2)
annual electricity usage (KWh)	1219.00	17341.00	1418.50	5033.00	22828.00	1362.00	4296.00	604.00	2061.00
annual usage per meter square	**2.03**	**30.42**	**18.91**	**40.26**	**114.14**	**16.61**	**33.05**	**5.49**	**30.76**

Table 7. 5: Annual gas usage of some offices in Tehran

Gas usage in different cases	Case A (600 m2)	Case B (570 m2)	Case C (75 m2)	Case D (125 m2)	Case E (200m2)
Annual gas usage (m3)	7057	14967	951	3246	10033
Annual usage (kWh/m2)	**116.68**	**260.48**	**125.79**	**257.60**	**398.11**

Moreover, Bagheri et al. (2013) has also explored 74 offices in Tehran and similar climates to Tehran with wide range of energy consumption from 150 to 675 kwh/m2 (Figure 5.20). However, he presents the detail gas and electricity usage for 5 cases of Tehran office buildings (cases J to N) and 2 case office buildings in similar climate to Tehran (cases O and P). These 7 cases have been added to the previous cases and all data are shown in Figure 7. 10.

Figure 7. 10: Overall gas and electricity usage of existing office buildings in Tehran



	Case A (600 m2)	Case B (570 m2)	Case C (75 m2)	Case D (125 m2)	Case E (200 m2)	Case J (1083 m2)	Case K (2400 m2)	Case L (4000 m2)	Case M (7000)	Case N (7200 m2)	Case O (8400)	Case P (9500 m2)
gas kwh/m2	116.68	260.48	125.79	257.60	398.11	133.00	157.30	139.10	108.00	126.70	112.50	188.10
electricity kwh/m2	2.03	30.42	18.91	40.26	114.14	47.90	177.20	89.70	74.30	107.40	58.00	103.60

The energy consumption of heat and gas is represented in kwh/m^2 in all cases of Figure 7. 10. Figure 7. 10 has a wide range of energy consumption from 119 to 512 kwh/m^2. Bagheri et al. (2013) study on energy consumption of 73 office cases in Tehran also shows a wide range from 150 to 675. The wide range of energy consumption per square meter amongst cases, as Bagheri et al. (2013) also stated, is due to the different circulation spaces, service spaces, building types, building sizes, building structures and building plans (open or cellular). Moreover, areas such as sanitary rooms, corridors, storage rooms and spaces that do not need heating or cooling, vary in each building. These spaces affect the value calculated for heating and cooling energy consumed per square meter. In addition, some buildings have been flats converted to offices and not specifically designed for office purposes. This can create a very different energy performance than the buildings purposely built as offices.

In terms of heating and cooling loads, section 5.3.1 mentions that 50% of electricity bills (in offices) and 73% of gas bills (in buildings in general) are due to HVAC. Therefore, this calculation is done on all 12 cases and the results are shown in Table 7. 6. The overall heating and cooling energy consumption in these offices are given in the final row (in red ink).

Table 7. 6: Heating and cooling energy consumption of 12 cases

annual energy (KWh/m2) in different cases	Case A (600 m2)	Case B (570 m2)	Case C (75 m2)	Case D (125 m2)	Case E (200 m2)	Case J (1083 m2)	Case K (2400 m2)	Case L (4000 m2)	Case M (7000)	Case N (7200 m2)	Case O (8400)	Case P (9500 m2)	Average
50% of electricity for heating and cooling in offices	1.02	15.21	9.46	20.13	57.07	23.95	88.60	44.85	37.15	53.70	29.00	51.80	**35.99**
73% of gas for heating and cooling in offices	85.17	190.15	91.82	188.05	290.62	97.09	114.83	101.54	78.84	92.49	82.13	137.31	**129.17**
heating and cooling energy (50% elect+ 73% gas)	**86.19**	**205.36**	**101.28**	**208.18**	**347.69**	**121.04**	**203.43**	**146.39**	**115.99**	**146.19**	**111.13**	**189.11**	**165.16**

In addition, the base cases heating and cooling loads generated by the simulation program is shown in Table 7. 7. The overall heating and cooling load is also in the final row (in red ink). Table 7. 7 also shows the average heating and cooling load of the three base case scenarios as well as the overall load according to statistics.

Table 7. 7: Heating and cooling energy consumption of base cases, their average and statistic value

annual energy (KWh/m2)	Base-Central(V)-NS	Base-Central(H)-EW	Square Base case	Average of base cases	statistics
Cooling load	13.08	12.71	13.22	13.00	
Heating load	179.05	142.66	146.58	156.10	
Heating and cooling load	192.14	155.36	159.80	169.10	213.50

Figure 7. 11: annual heating and cooling load of existing cases, the base cases and the statistic available

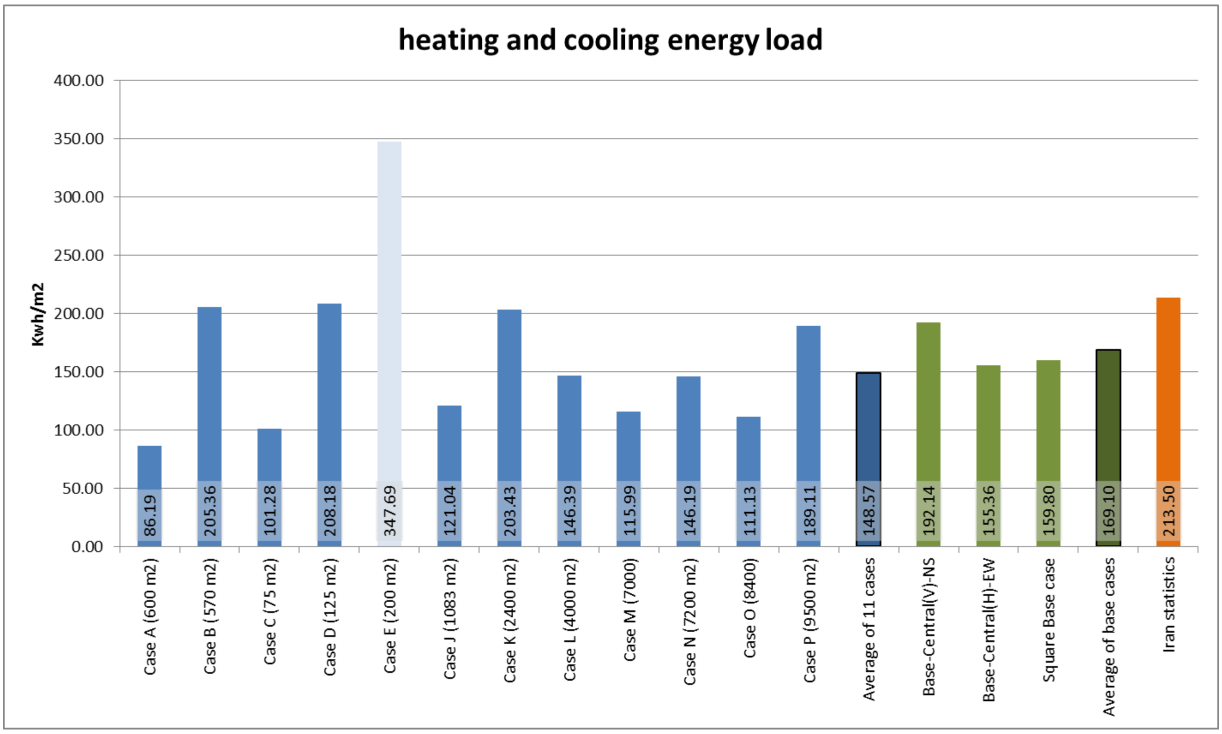


Figure 7. 11 illustrates the value of annual heating and cooling load per square meter in Table 7. 6 and Table 7. 7 (the values of the final row in red). Cases A to P (with exception of case E) represent typical office buildings but those of which that are a better practice in terms of lower energy consumption. The reason is that in the cases A to P (with exception of case E) the range of heating and cooling energy consumption is from 90 kwh/m^2 to 200 kwh/m^2 (average of 149 kwh/m^2 for 11 cases). However in Bagheri et al. (2013) 73 cases (Figure 5.21) the range of heating and cooling energy consumption (61% of the annual energy) is

from 90 kwh/m^2 to 400 kwh/m^2 (average of 213.5 kwh/m^2 for typical office building). So the selected cases (A to P) are representative of the better half (better practice in terms of lower energy consumption) of the typical office buildings in Tehran.

In addition, the base case prototypes, as mentioned before, are also the improved version of typical office buildings. Therefore with the value average of base cases (169 kwh/m^2) being near the value average of case A to P (149 kwh/m^2 with exception of case E), it can be concluded that the base cases are validated against the empirical data and can represent the better practice (in terms of lower energy consumption) of typical office buildings in Tehran. The interest of this study is to have the base cases generate less energy loads by incorporating atria as passive design element.

7.4 Definition of Some Terms in the simulation process

The terms below are used constantly in results and analysis chapters. Therefore it is important to explain them separately. The definitions of these terms are available in the Design Builder software help file.

Glazing gain: “The total heat flow to the zone from the glazing, frame and divisions for external glazing excluding transmitted short-wave solar radiation (which is counted for in ‘solar gains exterior windows’)”

External window heat gain: **“**(used to be called transmitted solar gains). Short-wave solar radiation transmission through all external windows. For a bare window, this transmitted radiation consists of solar radiation passing through glass and diffuse radiation from solar reflected from the outside window … For windows with a blind, this transmitted radiation consists of beam + diffuse short wave radiation that passes between the slats. The heating effect of solar radiation on opaque roofs and walls is accounted for in the roofs and walls fabric heat conduction data. Solar re-reflected back out of the external window and transmitted through internal windows is not subtracted.”

Internal window heat gain: “total beam + diffuse solar radiation transmission through interior windows. Requires the 3 full interior and exterior solar model option to be set.**”**

External window heat loss: Heat loss due to the exit "of the inside air through external windows, vents, doors, holes and cracks when using calculated natural ventilation option."

Internal win heat loss: heat loss to "other zones due to air exchange through open internal windows, doors, vents, holes and virtual partitions."

Cooling load: this means the sensible and latent loads added together. Heat that causes a change in temperature is called the sensible heat. The heat added to keep the air at a temperature is called the latent heat.

Heating load: energy supplied by local room heaters to maintain internal heating temperature

7.5 Summary of Chapter 7

This chapter explains the input parameters (such as building forms, orientation, glazing ratio, atria type and building dimensions) and their values (see table 7.2). It provides critical literature review on studies similar to this research. It further describes the model analysis stages being in 4 control modes; NV mode and HVAC+NV mode in either warm or cool season, with the number of models undergoing simulation to be 152. It also defines what base models are and how they are crucial for validating the results of the thesis. Last but not least, the validation procedure takes place in section 7.3 which assures the results of this thesis to be reliable.

CHAPTER 8: Square Prototype Results

The output of the square prototype have been generated via the Design Builder software program. The results of the simulation have been produced on hourly basis. The output concerns only the occupied office time. The simulation is done in two modes; the first is when the offices are naturally ventilated (as required) throughout the year without any assistance from mechanical systems. The second mode is when the building can take advantage of the HVAC and that is only when natural ventilation cannot provide a thermal comfort temperature on its own.

In the natural ventilation mode (section 8.1), one of the important outputs is the amount of hours that people in offices experience certain temperatures. The uncomfortable hours are the amount of hours outside the 23-31 range in warm season and 18-26 in cool season. These have been manually calculated for each 12 storeys of a prototype and added to each other to form the uncomfortable hours of each model. The reason for doing this manually is because the comfort temperature range in Tehran is different to that provided by the standard used in the Design Builder software. The amount of uncomfortable hours in warm season and cool season give the understanding that an atrium alone cannot provide thermal comfort temperature in offices throughout a year. By comparing the uncomfortable hours between prototypes, it is clear which typologies have fewer uncomfortable hours.

In the HVAC plus natural ventilation (HVAC+NV) mode (section 8.2), which is the second mode used in the simulation program, one of the most important outputs are the heating and cooling loads. These loads are calculated both in warm and cool seasons and cover a whole year. The more the heating and cooling loads there are in a prototype, the more energy is consumed to warm and cool the offices (and more HVAC is used), thus the less energy efficient the prototype will be and the more attention is required to design them according to climate.

In order to understand why some prototypes have greater annual energy loads and more annual uncomfortable hours (section 8.2), more outputs are generated. Some of these outputs have almost the same value in all the models, such as heat gain via light, occupancy and equipment (Appendix 5). However, some differ from one prototype to another. The outputs where their values differ in different models are glazing gain, external window heat gain, internal window heat gain, external window heat loss, and internal window heat loss. The meaning of each term has been defined in Chapter 7, section7.5.

8.1 Calculated uncomfortable hours in NV mode

This section investigates the thermal performance of prototypes using natural ventilation throughout the year. When natural ventilation takes place, cooler outside air ventilates through the windows and into the warm indoor offices. Figure 8.1 shows the uncomfortable hot hours in the base case (the prototype with no atria) alongside all the other prototypes with atria.

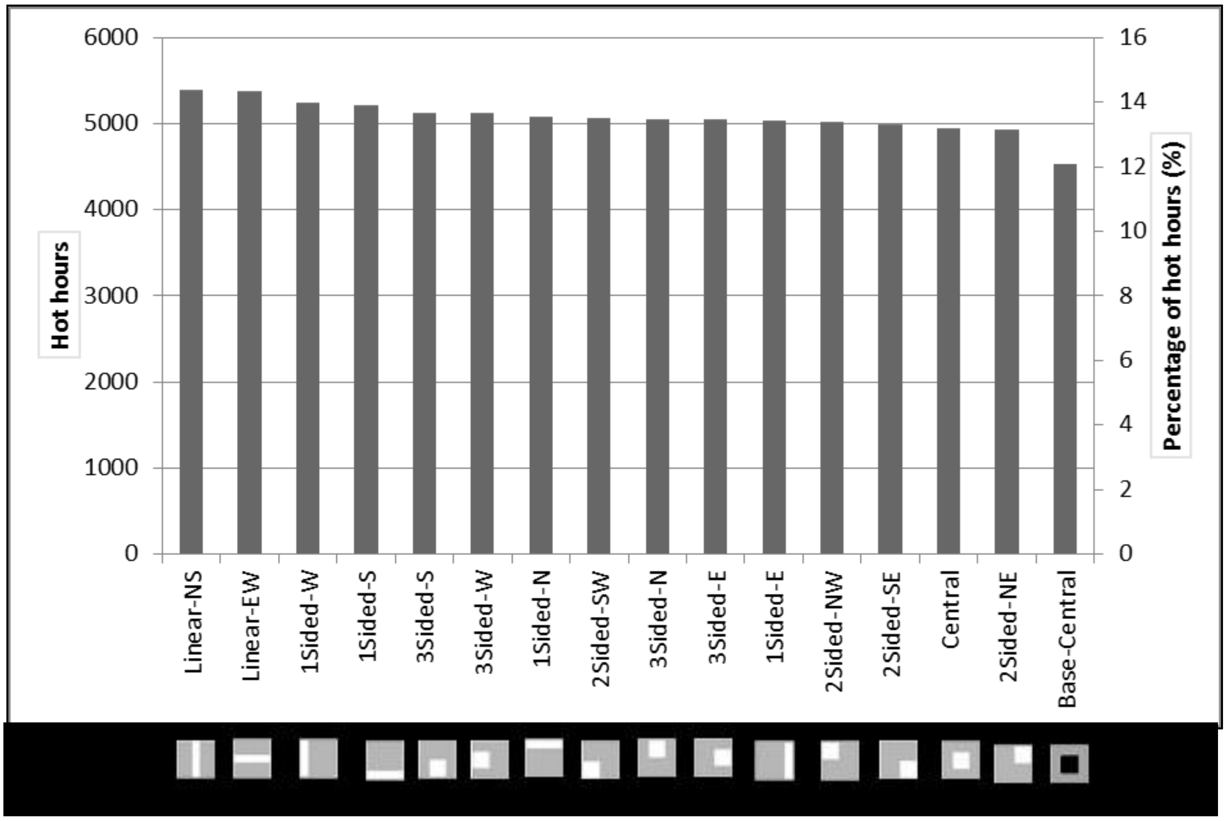


Figure 8.1: Annual hot hours and percentage of annual hot hours in offices using only NV mode (in descending order)

In the prototypes with atria, the glazing top roof of the atria opens during the six months that are classified as the warm season to assist with the airflow and removal of heat. Figure 8.1 shows that, in a warm season, naturally ventilated offices with a linear type atrium have the largest number of uncomfortable hot hours. Moreover, offices with a Central and 2-sided NE atrium have the least number of hot hours. For buildings with 2-sided NE and Central atria, the atrium is located on the cool side (namely the north where there is no direct sunlight, and the East which sees early morning sun, which is not hot). Hot air escapes through the cooler atria, is released at the top and thus results in fewer hot hours. On the other hand, an atrium which is exposed to the warm sides (south or west) have a lower temperature difference between the offices and the atria with low hot air flow; this results in a greater number of annual hot hours. Therefore, the results show that in NV mode, if buildings were to be designed only according to warm season then a building with no atrium provides cooler offices, and the buildings with a linear type atrium (followed by 1-sided W and 1-sided S) are amongst the warmest offices.

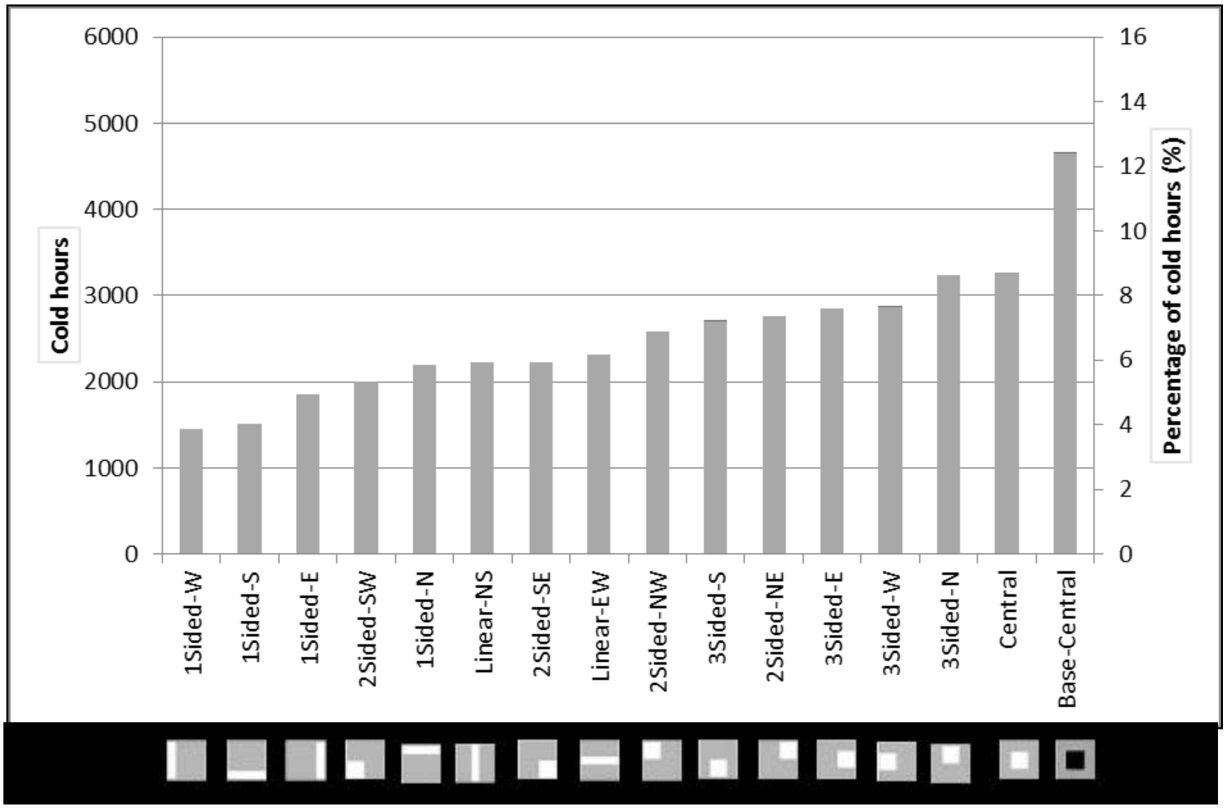


Figure 8.2: Annual cold hours and percentage of annual cold hours in offices of NV mode (in ascending order)

Moreover, to assist with the preservation of heat and minimisation of heat loss and according to previous literature the glazing rooftop of the atria closes during the six months classified as the cool season. Figure 8.2 shows that, in a cool season, amongst the prototype with atria, naturally ventilated offices with a central atrium have the largest number of uncomfortable cold hours. However, offices with 1-sided W and 1-sided S atria, followed by 1-sided E, have the least uncomfortable cold hours and are warmer. Meanwhile, the base case, which has no atrium, has the largest number of cold hours amongst all the models. Therefore, naturally ventilated buildings with no atria are not worth considering for the cool season.

A comparison amongst the prototypes (excluding the base case) is made in the warm and cool seasons. Depending on the placement of atria, the hot hours in offices of different prototypes, varies between 4924 and 5392 (Figure 8.1). Again, depending on the placement of atria, the cold hours in offices of different prototypes, varies between 1451 and 3270 (Figure 8.2). The results from the comparison show that:

1. The uncomfortable hours in a warm season are much higher than the uncomfortable hours in a cool season. This means that occupants in offices in all the prototypes experience more hot hours than cold hours in a year.

2. The difference of uncomfortable hours between prototypes in warm season is lower (468 hours, which is 1.24 % difference excluding the base) than in cool season (1819 hours, which is 4.9 % difference excluding the base). This means that the prototypes act very similarly in a warm season but very differently in a cool season.

In terms of atria placement during a warm season offices with atria located on the cool side (north and east) have fewer hot hours compared to offices with atria located on the south and west side. The sun penetration on atria located on the north and east is less compared to the ones located on south and west, therefore, the temperature differences between offices and atria located on north and east are greater causing office hot air to escape more through a cooler atrium. Thus, in NV mode, the more an atrium is exposed to sun, in this case from a westerly and southerly direction, the warmer the offices are in the warm season.

However, this rule does not apply in the cool season. Because there is strong cold wind coming from NW direction which impacts where the offices can be located to have less cold hours. So it’s a balance of having the offices on warm side (south and west) in cool season and having the closed atria on the windward side (north and west). The more the façade exposure of offices to west and north (the direction of prevailing cold wind in cool season) the more cold hours there are. So it is best for the atria to be placed in these directions because the atrium top is closed in the cool season and airflow is not encouraged from offices to atria and atria can act as an insulation gap. Also offices can benefit from the low south sun angle in cool season. Never the less, by comparing the prototypes in warm and cool seasons it can be seen that the offices of 1-sided-W and 1-sided-S models are amongst those with the most hot hours in a warm season and also have least cold hours in a cool season.

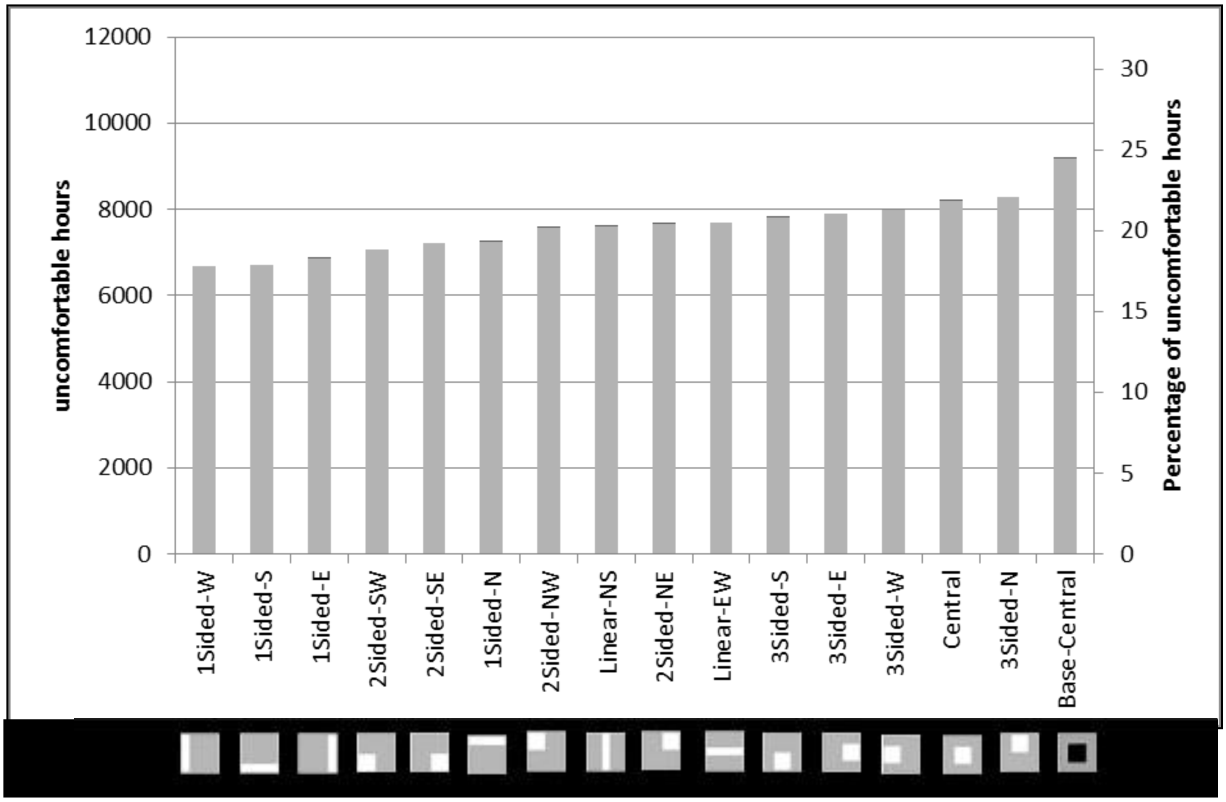


Figure 8.3: Annual uncomfortable hours and percentage of annual uncomfortable hours in offices in NV mode (in ascending order)

Although the performance of buildings with no atria are better in terms of fewer uncomfortable hours in warm season; it is the opposite situation in cool season where the building with no atrium has the most uncomfortable cold hours. Thus, the annual graph (Figure 8.3) is generated to demonstrate the annual number of uncomfortable hours to help better understand the prototype performances over a year.

Figure 8.3 shows that offices of 1-sided W model have the least annual amount of uncomfortable hours, whilst the offices of base case have the greatest amount of uncomfortable hours. The differences in annual uncomfortable hours between the highest value and lowest value case in NV mode is 2507.5 hours or 6.67%. Thus, incorporating an atrium helps with lowering the number of uncomfortable hours throughout the year.

Moreover, the order of offices from least to most annual uncomfortable hours is very similar to the order of offices from least to most cold hours. Hence, designing with particular attention to the cool season is important. The reason for this similarity is due to the fact that the prototypes act very similarly in warm season but not in cool season. Thus, when the cold hours are added to the hot hours to generate the annual uncomfortable hours, the results are similar to those in cool. However, this is only in terms of uncomfortable hours. The building load that contributes to energy use should also be calculated to reach a final conclusion.

8.2 Calculated Cooling and Heating load in HVAC+NV mode

This section investigates the annual cooling and heating loads of buildings using NV with help of HVAC to reach thermal comfort for the typical office hours. Because, after natural ventilation occurs, the temperature might not fall to the degree needed (the degree which is in the thermal comfort range; 18°C to 26°C in cool season and 23°C to 31°C in warm season). In this case, the HVAC mode is triggered to help the offices to reach a comfortable thermal temperature. If offices are above 31°C in warm season, and below 18°C in cool season, the HVAC system is used to provide thermal comfort. Using NV as much as possible and HVAC only when needed reduces the energy loads and as a result energy consumptions is decreased.

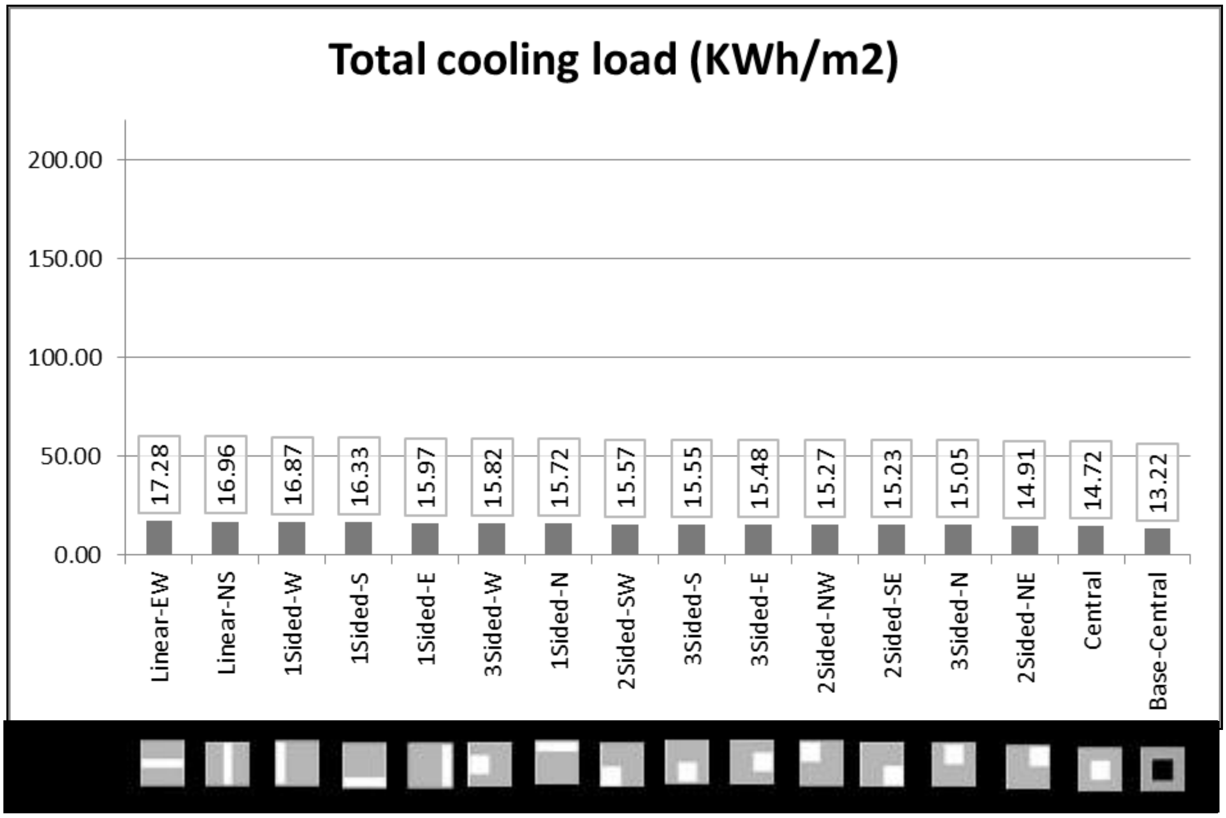


Figure 8.4: Cooling load in offices in HVAC+NV mode (in descending order)

As mentioned before, to assist with the airflow and removal of heat, the glazing rooftop of the atria opens during the six months classified as the warm season. Figure 8.4 shows that, in warm seasons, the offices with a linear atrium, followed by 1-sided W and 1-sided S have the most cooling loads. They also have the most uncomfortable hot hours in a naturally ventilated office building (Figure 8.1); hence, a greater cooling load is needed to provide thermal comfort. Also, amongst the models (base case excluded), offices with central and 2-sided NE atria have the lowest cooling loads (Figure 8.4). Again, this complements the fact that they also have the fewest hot hours when offices are naturally ventilated (Figure 8.1); hence less energy is used to provide a comfortable thermal temperature (Figure 8.4). Nevertheless, the base case presents the lowest office cooling load in a warm season (Figure 8.4) as it also has the least amount of hot hours in the NV mode (Figure 8.1). The conclusion is derived that if buildings were only to be designed according to the warm season, then buildings with no atria would be the most energy efficient in HVAC+NV mode. The same conclusion has been drawn if buildings are in the NV mode in terms of minimal heat loads.

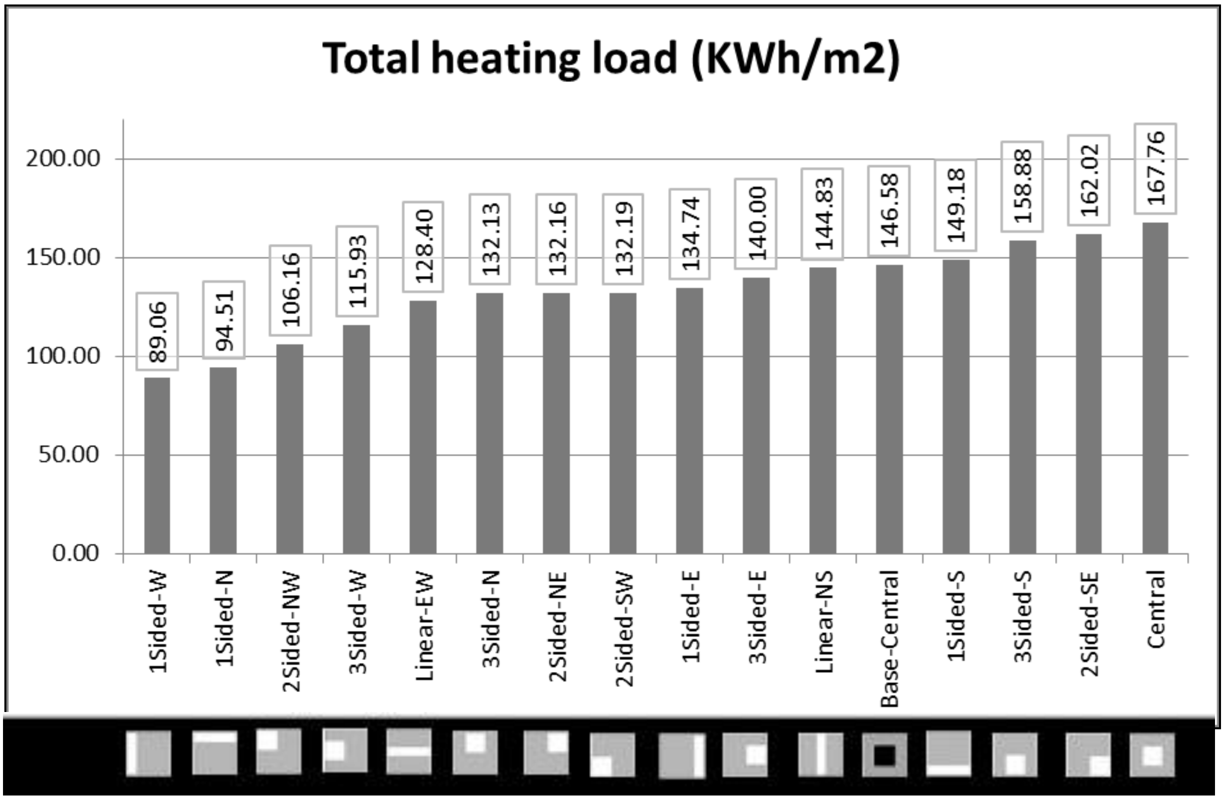


Figure 8.5: Heating load in offices in HVAC+NV mode (in ascending order)

As previously mentioned, the glazing rooftop of the atria closes during the six months classified as the cool season to assist with the preservation of heat and less heat loss.

Figure 8.5 shows that, in the cool season, the offices with a central atrium have the greatest heating load in a HVAC+NV mode. As offices with a central atrium also have the highest number of cold hours (Figure 8.2), this results in the highest heating loads. Moreover, the model with a central atrium has the maximum area of external office windows (Appendix 8), and thus the amount of heat loss is amongst the highest values compared to other prototypes. This section will later explain that, in a cool season, the parameter of heat loss via an external window has the most effect on the heating load results compared to other heat gain and heat loss parameters.

In contrast, offices of the 1-sided W followed by 1 sided N model produce the lowest heating load in the cool season (Figure 8.2). They are amongst the models with lowest number of cold hours in NV mode (Figure 8.2).

The base model, however, is amongst the models that have the highest heat load. Few prototypes, such as the offices with central, 2-sided-SE, 3-sided-S and 1-sided-S atria generate greater heating loads than the base model. This confirms that, if atria are not designed correctly, they can add more energy consumption to a building.

Figure 8.5 results are important and have a substantial impact on the annual results of heating and cooling loads, which will be discussed later. Since the results in Figure 8.5 are important, the reasons why some prototypes are more energy efficient than others are further analysed later in this section.

A comparison amongst the prototypes with atria (excluding base case) is made in the warm and cool season. The cooling load in offices of different prototypes, depending on the atria placement, varies between 14.72 to 17.28 KWh/m^2 per year (Figure 8.4). Depending on the placement of the atria, the heating loads in offices of different prototypes vary between 89.06 to 167.76 KWh/m^{2}per year (Figure 8.5). The results in comparison show that:

1. The heating loads in the cool season are much higher than cooling loads in the warm season. This means that, in order to provide a thermal comfort temperature, more energy is used in a cool season compared to a warm season.

2. The range difference of heating loads between prototypes in a cool season are higher (78.7 KWh/m^2 per year) than the cooling loads in a warm season (2.56 KWh/m^2 per year). This again conforms that the prototypes act very similarly in a warm season but very differently in a cool season.

These differences are illustrated on a monthly basis in Figure 8.9 for the prototypes that have the least and most heating and cooling loads. An important conclusion, however, is derived when comparing the uncomfortable hours with the prototype loads. This important conclusion is that the dominant season to design for is the cool season in Tehran. The following points explain the reason behind this statement:

1. Even though the uncomfortable hot hours are significantly greater than the uncomfortable cold hours (almost double) in each prototype, the cooling loads are far fewer than the heating loads (comparing Figure 8.1 with Figure 8.4 and also comparing Figure 8.2 with Figure 8.5).

2. In Iran the energy consumed to provide heat via HVAC is greater than the energy consumed to provide cool air via HVAC.

3. Since prototypes in the warm season perform similarly, it is important to emphasise the design of buildings in the cool season within Tehran's semi-arid climate. (Comparing Figure 8.1 and Figure 8.4 in a warm season with Figure 8.2 and Figure 8.5 in a cool season). This is where the differences in the prototype performances also lie. Hence, it is important when designing to pay particular attention to the design of buildings in the cool season of Tehran's semi-arid climate.

Since the cool season is dominant, it is important to know what causes some prototypes to have a lower heating load and what causes others to have a greater heating load. In other words, it is important to know which independent parameter(s) have a considerable effect on the heating load results and by how much. The independent parameters that have been investigated are those where their value differs from one prototype to another. Therefore, the results of heat gain via electronic equipment, light and occupancy have not been examined as their values are similar in each of the models. The five independent parameters that differ from one model to another which affect the heat load are: glazing gain, external window heat gain, internal window heat gain, external window heat loss, and internal window heat loss (sample of detailed outputs are in Appendix 5). Each of these terms was explained at the end of chapter 7. These values have been generated through the Design Builder software program. The regression analysis is needed to determine the effect of independent variables on the depend variable of heating load. However, as explained before a standardisation technique must be conducted first. As such these technique (explained in chapter 6) is demonstrated as followed in the cases of square prototypes with atria:

A standardisation technique has been manually conducted on all the five parameters to adjust the value ranges from zero to one. It helps to ensure that the results are in a state that can be comparable from one parameter to another. Table 8. 1 shows the independent values of each model (excluding base cases) before standardisation as well as the dependent value of heating load.

Table 8. 1: parameter values before standardisation

Square /cool season	Heat gain via glazing (MWh)	solar gain via external window (MWh)	Heat loss via external windows (MWh)	solar gain via internal window (MWh)	Heat loss via internal windows (MWh)	Zone heating load (MWh)
1Sided-N	376.45	346.89	966.69	12.77	112.51	508.13
1Sided-S	511.12	453.61	1349.58	21.82	310.65	834.55
1Sided-E	429.41	389.05	1232.17	16.53	199.47	749.93
1Sided-W	428.89	389.01	935.39	16.43	207.42	486.95
2Sided-NW	352.34	325.17	993.81	9.73	94.87	561.32
2Sided-NE	352.22	325.16	1168.69	9.77	101.3	715.13
2Sided-SW	415.75	375.2	1200.48	13.62	192.43	727.31
2Sided-SE	415.84	375.17	1385.78	13.66	200.52	891.68
3Sided-N	311.22	290.22	1135.33	9.73	36.26	689.69
3Sided-S	379.21	340.62	1305.43	15.44	105.61	856.69
3Sided-E	335.97	308.74	1192.49	11.88	68.9	747.65
3Sided-W	335.83	308.68	1057.83	11.81	69.99	611.79
Linear-NS	349.43	315.55	1219.58	32.08	125.37	774.89
Linear-EW	345.5	312.44	1131.5	30.72	90.86	689.84
Central	299.08	273.48	1331.31	9.31	43.39	876.74
Base-Central	228.66	205.53	1194.24	0	0	795.11

However after performing the standardisation formula on the five independent parameters, the values change to what is shown in Table 8. 2.

Table 8. 2: Independent parameter values after standardisation

Square /cool season	standardizing glazing gain	standardizing solar gain via external win	standardizing heat loss via external win	standardizing solar gain via internal win	standardizing heat loss internal win
1Sided-N	0.36	0.41	0.07	0.15	0.28
1Sided-S	1.00	1.00	0.92	0.55	1.00
1Sided-E	0.61	0.64	0.66	0.32	0.59
1Sided-W	0.61	0.64	0.00	0.31	0.62
2Sided-NW	0.25	0.29	0.13	0.02	0.21
2Sided-NE	0.25	0.29	0.52	0.02	0.24
2Sided-SW	0.55	0.56	0.59	0.19	0.57
2Sided-SE	0.55	0.56	1.00	0.19	0.60
3Sided-N	0.06	0.09	0.44	0.02	0.00
3Sided-S	0.38	0.37	0.82	0.27	0.25
3Sided-E	0.17	0.20	0.57	0.11	0.12
3Sided-W	0.17	0.20	0.27	0.11	0.12
Linear-NS	0.24	0.23	0.63	1.00	0.32
Linear-EW	0.22	0.22	0.44	0.94	0.20
Central	0.00	0.00	0.88	0.00	0.03

With these standardised values the regression analysis can be conducted in excel. The generated P values and coefficients are presented in Table 8. 3.

Table 8. 3: Initial P value and coefficients of independent parameters

	Coefficients	*P-value*
Intercept	530.0543964	0.00270×10^{-8}
standardizing glazing gain	420.2414036	0.181199235
standardizing solar gain via external win	-444.5551436	0.161197982
standardizing heat loss via external win	403.6498705	0.01839×10^{-8}
standardizing solar gain via internal win	0.300783253	0.981450937
standardizing heat loss internal win	-35.49996623	0.503353422

As it can be seen in Table 8. 3 the P-value of the standardised values of glazing gain, internal window heat loss, internal window solar gain and external window solar gain are above the value of 0.05. This means that these parameters do not have significant effect on heating loads. As such only the parameter of heat loss via external window has a significant effect on the heating load results. Therefore the regression analysis is once again conducted without the other five parameters to generate the correct coefficient.

Table 8. 4: Correct P value and coefficients of the independent parameter

code		*Coefficients*	*P-value*
	Intercept	499.3247084	0.00259×10^{-13}
A	standardizing heat loss via external win	407.206671	0.00215×10^{-8}

Table 8. 4 shows the correct co-efficient value of ‘external window heat loss (parameter A in the formula) to be 407.2 and the formula of the heating load (parameter y) is:

y=407.2xA+499.32.

The positive values of coefficient means that the more value of that parameter the more the heating load there is. So the more the heat loss via external window the more the heating loads which is logical. The scatter plot of the standardise value and the linear formula that it follows is shown in Figure 8. 6.

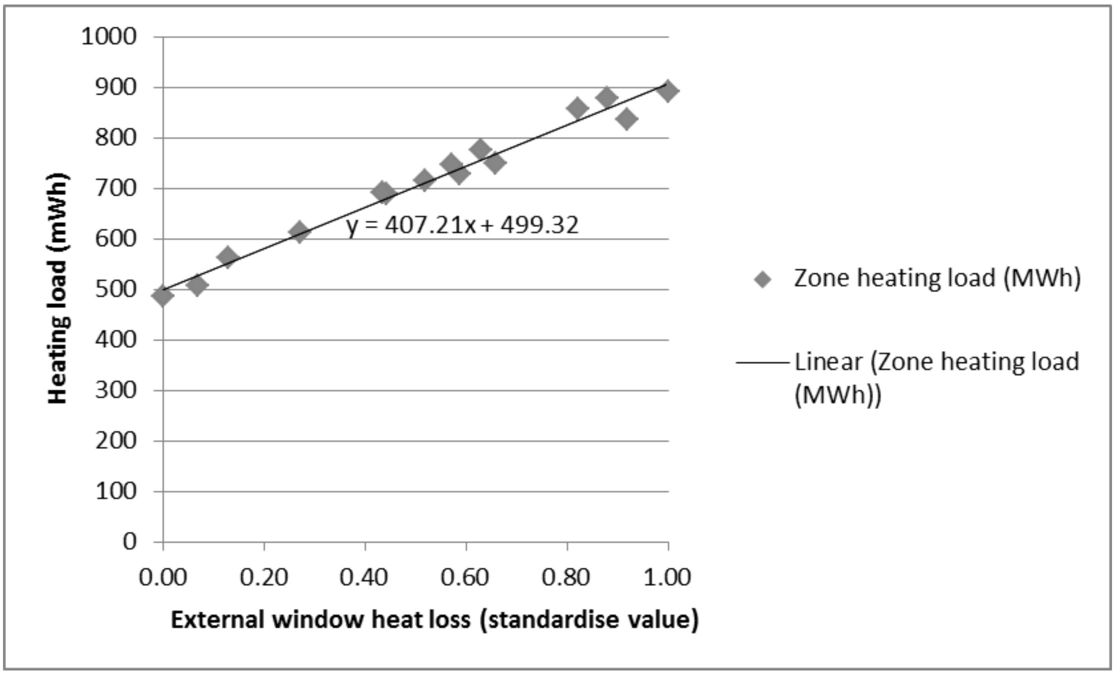


Figure 8. 6: The scatter plot of the standardise value of external window heat loss

In order to understand why some configurations have more external window heat loss than others, the parameter of the external office window areas (Table 8.5) is notable. When comparing the heat load graph (Figure 8.5) with the office's external window area (Table 8.5), a combination graph can be provided. However, to produce this combination graph it is easier to use the 'atria's external window area' (Table 8.6) instead of the 'offices external window'. Since the façade area is the same on all four sides, the atria's external window area is equal to the value of the façade minus the 'office external window area'. Thus, the greater the external window of the atrium on one side, the less the external window area of the offices on the same side. This means that the atria's external window areas are really the complimentary value of the offices' external window area. As such it makes no difference in working with Table 8.6 instead of Table 8.5. However, Table 8.6 has the advantage of helping the graph look less complicated and simpler. This is because more orientations simply do not have external atrium windows and the value area would be zero. Having more zero values simplifies the combination graph making it more understandable.

Table 8.5: External window area of offices, from least to most heat load

External office win area	North	East	South	West
1Sided-W	329.448	428.232	329.448	0
1Sided-N	0	329.448	428.232	329.448
2Sided-NW	222.6	428.232	428.232	222.6
3Sided-W	428.232	428.232	428.232	222.6
Linear-EW	428.232	329.448	428.232	329.448
3Sided-N	222.6	428.232	428.232	428.232
2Sided-NE	222.6	222.6	428.232	428.232
2Sided-SW	428.232	428.232	222.6	222.6
1Sided-E	329.448	0	329.448	428.232
3Sided-E	428.232	222.6	428.232	428.232
Linear-NS	329.448	428.232	329.448	428.232
Base-Central	428.232	428.232	428.232	428.232
1Sided-S	428.232	329.448	0	329.448
3Sided-S	428.232	428.232	222.6	428.232
2Sided-SE	428.232	222.6	222.6	428.232
Central	428.232	428.232	428.232	428.232

Table 8.6: External window atrium area from least to most heat load

External atria win area- in order of heat load least to most	North	East	South	West
1Sided-W	246.96	0	246.96	1070.58
1Sided-N	1070.58	246.96	0	246.96
2Sided-NW	514.08	0	0	514.08
3Sided-W	0	0	0	514.08
Linear-EW	0	246.96	0	246.96
3Sided-N	514.08	0	0	0
2Sided-SW	0	0	514.08	514.08
2Sided-NE	514.08	514.08	0	0
1Sided-E	246.96	1070.58	246.96	0
3Sided-E	0	514.08	0	0
Linear-NS	246.96	0	246.96	0
Base-Central	0	0	0	0
1Sided-S	0	246.96	1070.58	246.96
3Sided-S	0	0	514.08	0
2Sided-SE	0	514.08	514.08	0
Central	0	0	0	0

Thus, by combining Figure 8.5 with Table 8.6, Figure 8.7 is generated. In Figure 8.8, each colour represents the orientation of the atrium's external windows (namely, the direction they are facing). The bar size of each colour is the value of the external atrium window area in the direction of the coded colour. So, for example, the 3-sided-W case has only a purple bar which means the glazing façade of the atrium is towards west. In this case the purple bar total is over 500 m2 which is the west atrium glazing façade area. The graph is also in the least to most heat load order from top to bottom. Thus, the models on the top of the graph are warmer and have lower heat loads than those below.

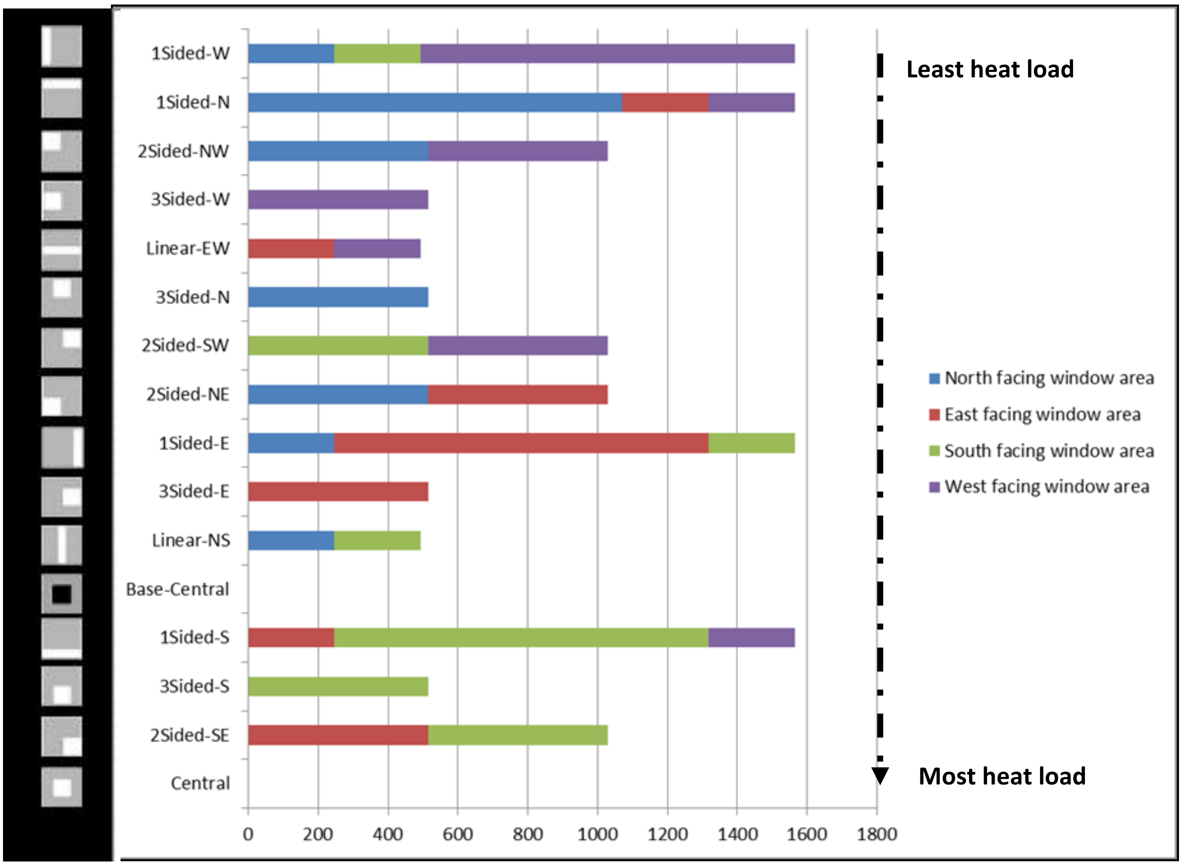


Figure 8.7: External window position and area value in m^2 (from least to most heat load from top to bottom)

In Figure 8.7, the amount of north and west (purple and blue) coloured bars are mostly seen at the top of the graph amongst the models with lowest heat loads, and the south and east (green and red) coloured bars are mostly seen towards the bottom of the graph amongst the models with the greatest heat loads. This means that lower heat loads and less energy are consumed to reach thermal comfort when more external windows of an atrium face towards the west and north (where the office's external windows are more exposed to the south and east). Furthermore, when more external atrium windows face the south and east (where the office's external windows are more exposed to the north and west) greater heat loads are required and more energy is consumed in reaching thermal comfort. The reason for this is due to two factors:

1. The office exposure to the morning and afternoon sun (east and south): During office hours and in a cool season, the sun's rays (at a low angle in the cool season) penetrate deep inside the offices help to warm the rooms from the early office hours through to the afternoon. Even though the west sun

penetration is warm, its effective time on the offices is not much because the office hours are limited. So in comparison, external office windows will benefit from the longer lasting effect of an east and south sun rather than a west sun, which has a shorter time frame to affect the building for its office hours. As a result, less external window heat loss occurs in offices exposed to east and south orientations.

2. The prevailing wind: the prevailing wind in the cool season comes mostly from the north-west and west, as shown in Figure 5.6. If the external atrium windows face mostly towards south and east then offices mostly face the north and west, which are the facades with less exposure to the sun rays in office hours and the most exposure to the prevailing wind. Therefore, with the offices facing north and west (and atrium facing south and east) more office external window heat loss and less heat gain occurs in the rooms, which ultimately results in greater heat loads. In a cool season the top of the atrium is closed. Therefore, having the atrium orientated in the direction of the cold wind is beneficial as it can act as an insulation gap and shield the offices from the cold west and northwest wind. Thus the lower the heat loss from external window offices on the north and west, the more the south and west solar gains can be effective.

The above two reasons explain why 1-sided W, 1-sided N and 2 sided NW have the lowest heating loads (Figure 8.5) and the least 'external window heat loss' (Table 8. 1). It also explains why the Central, 2-sided SE and 3-sided S have the greatest value in both parameters. In the case of the central atrium, even though the offices are exposed to south and east, the atrium does not block any heat loss from the north and west. Moreover, as the core of the building is usually the warmest part, having an atrium in the centre also takes away that advantage.

The results from the cool season, being the dominant season, suggest that the buildings with atria can perform more energy efficient than the base case, which has no atrium. However, the annual graph (Figure 8. 8) is presented with the total heating and cooling loads to help better understand the overall results.

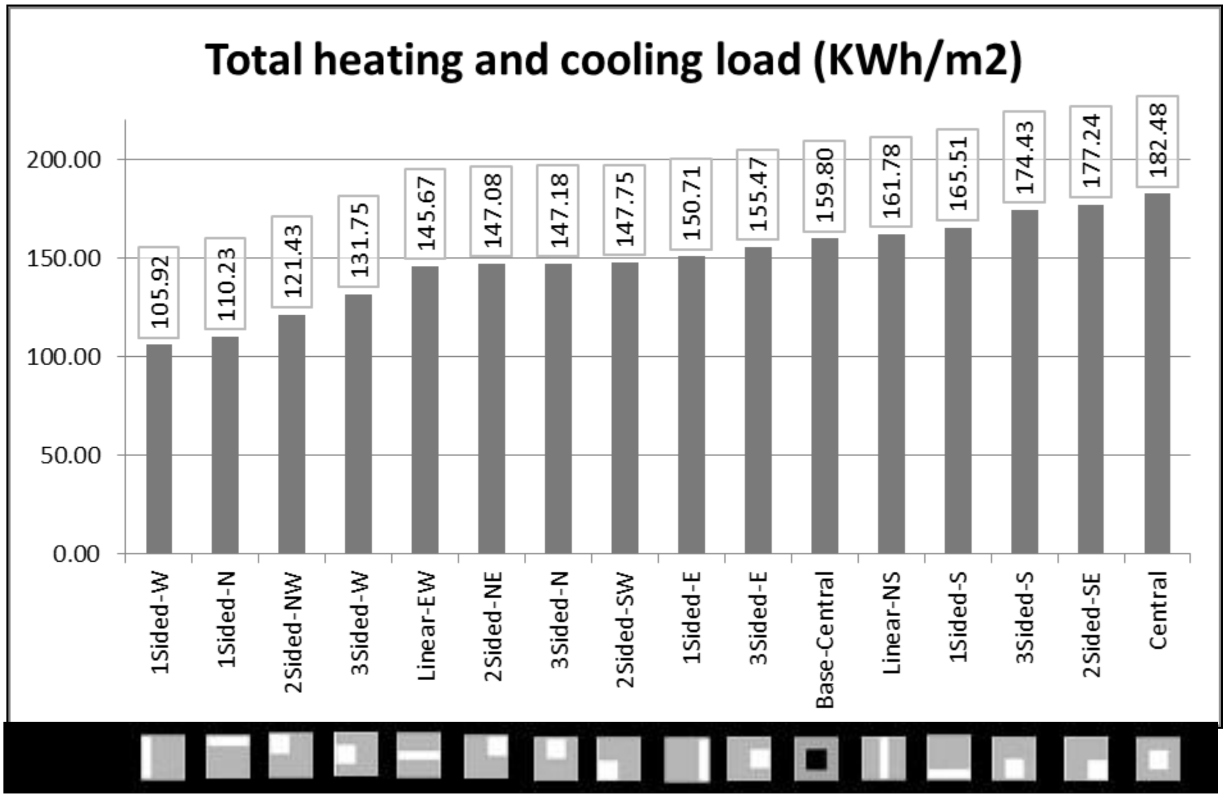


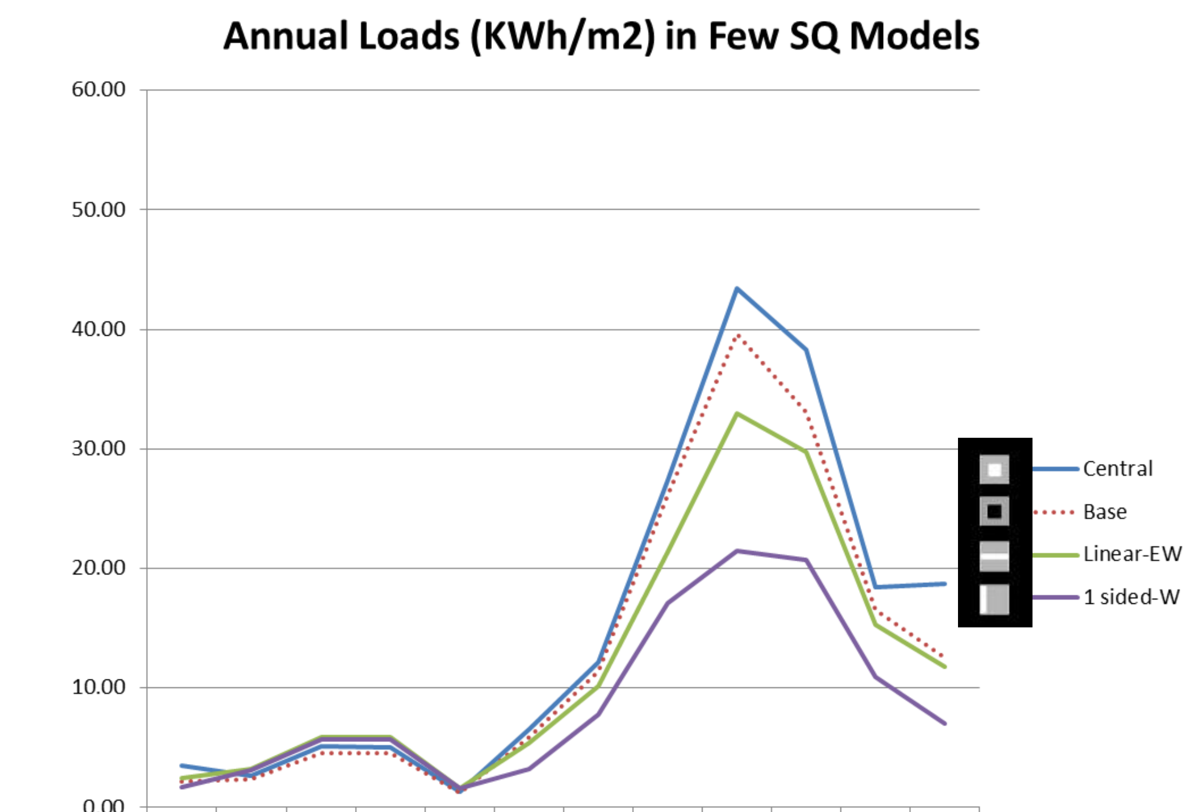
Figure 8. 8: Annual heating and cooling loads in offices in HVAC+NV mode (in ascending order)

The overall values of the annual loads for all models are presented in Figure 8. 8. The offices of the 1-sided W case have the lowest heating and cooling loads overall; they also have the lowest annual uncomfortable hours when only NV is on (Figure 8.3). Also, the offices of the central atrium have the greatest heating and cooling loads overall; they also are amongst the models with most uncomfortable hours. The load difference between the offices of the central model and the offices of the 1-sided W model is 76.66 KWh/m^2.year.

The base case prototype does not have the highest overall heating and cooling loads. This highlights the fact that, if atria are not designed well, it can generate greater loads and more energy consumption compared to a building with no atrium. However, if designed correctly, the incorporation of an atrium can mean lower cooling and heating loads and greater energy savings than buildings with no atria. Moreover, there are more similarities between the annual load graph (Figure 8. 8) and the heating load graph (Figure 8.5) than the cooling load (Figure 8.4). This again indicates that the cool season is the dominant season.

From all the prototypes, four key models have been selected in order to present their annual results in a clearer way (Figure 8.9). These models are: firstly, those whose offices have the most and least heating loads in the cool season (1-sided-W and Central) and secondly, the most and least cooling loads in the warm season (Linear-EW and Central). Thirdly, the models with the most and least annual heating and cooling loads have been selected (again, 1-sided-W and Central) along with the base case.

As mentioned before, the months April to September, which are classified as the warm season, have the atrium top open to help with exsessive heat loss or natural ventilation. Whereas, the months October to March, which are classified as the cool season, have the atrium roof closed for less internal heat loss. Since the models represented are the most and least energy consumed cases in each season, it means that the rest of the models fall between the maximum and minimum values illustrated in the graph (Figure 8.9). This graph presents the conclusions discussed before, in a clear, simple format and with critical models showing heating and cooling loads on a monthly basis.



	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Central	3.52	2.66	5.09	5.04	1.35	6.56	12.14	27.32	43.40	38.33	18.38	18.71
Base	2.12	2.36	4.57	4.51	1.23	5.86	11.34	26.12	39.61	33.09	16.50	12.48
Linear-EW	2.43	3.17	5.86	5.84	1.60	5.41	10.18	21.36	33.00	29.77	15.26	11.79
1 sided-W	1.70	3.07	5.68	5.68	1.60	3.22	7.81	17.05	21.44	20.72	10.95	7.00

Figure 8.9: Square monthly loads in few critical models (central: most heating load, linear E-W: most cooling load, 1-sided west: least heating loads and base case: least cooling load)

As can be seen in Figure 8.9, in a warm season, the models are almost similar in terms of their heat load (lines near eachother); however, there is a substantial difference in a cool season (lines apart from eachother). This means that it is the cool season which distinguishes the performance of the prototypes over a year. Also, the heating load values in the cool season are greater overall than the cooling load values in the warm season. As such, in order to reach thermal comfort with less energy consumption Figure 8.9 again represents why the cool season is the dominant season for designing buildings.

In Figure 8.9, the offices of the base model result are represented by the dotted line on the graph. Offices of the base model have the lowest load in a warm season. However, since there is not much difference between the models in a warm season and the values are low compared to the cool season, it is the cool season that is important. In a cool season the basecase offices are amongst the high values. As previously mentioned, they also have the greatest number of annual uncomfortable hours. Thus, it is more energy efficient to include an appropriately designed atrium overall as it can help to limit cooling and heating loads in a semi-arid climate.

8.3 Summary of Chapter 8 results

Table 8. 7 summarises which prototypes have the least and most uncomfortable hours and loads in warm and cool season. The descriptions of each have been covered in previous sections. However, this section covers the summary for the results of offices in square models in following bullet points:

Table 8. 7: Summary of cases with lowest and highest values in all categories

Summary	**NV mode** **Warm season**	**NV mode** **Cold season**	**HVAC+NV mode** **Warm season**	**HVAC+NV mode** **Cold season**
Uncomfortable hours	*Most:* Linear-NS Least: Base case	*Most: base case* Least: 1sided-W		
	Annually Most: Base case Least: 1 sided-W			
Heating or cooling load			Most: Linear-EW Least:Base case	*Most: Central* Least: 1 sided-W
			Annually Most: Central Leas: 1 sided-W	

- **Warm season**: In the warm season the least energy consumption for cooling (in HVAC+NV mode) amongst the office models with atria is the central case. It also is amongst the lowest number of uncomfortable hot hours (in NV mode). In the prototype with central atrium heat loss is maximised as atrium is placed in the centre of the building and not on cold facades of west (in office hours) or north to act an insulation gap for minimise heat loss. Central atrium also is not, placed on the south façade to generate green-house effect. These type of atria, help to suck out the heat from the core of the building via its open top. Thus in warm season central atrium is a good option for offices compared to other types of atria. But Tehran has a semi-arid steppe climate and its cool season needs consideration also.

  Moreover, in warm season the linear model is not an efficient choice as the cooling loads are the highest (in HVAC+NV mode) and they have a high number of uncomfortable hot hours (in NV mode). The 1-sided models are also not a good option in a warm season as they also have high cooling loads (in HVAC+NV mode) (Figure

8.4) and are amongst the models with most hot hours (in NV mode) (Figure 8.1). However, when comparing the offices of base model with the offices of all the models with atria, the offices of base are the coolest. They also have the lowest cooling loads and the lowest number of uncomfortable hot hours. Therefore, it is more energy efficient not to have any atrium in a warm season of a semi-arid climate.

- **Cool season**: In a cool season, the offices of the base model, followed by the Central model have the highest number of uncomfortable cold hours (in NV mode). They are also amongst the models with highest office heat loads (the Central model has the greatest heat load). In cool season it is more energy efficient for closed top atria, which can act as an insulation gap, to be places on cold facades so that offices can gain direct sun penetration from warmer facades (east and south) and therefore, heat loss is minimized through cold façades (north and west in office hours). Among the warmest office models in a cool season are the 1-sided W and 1-sided N, which have the lowest number of uncomfortable cool hours (in NV mode) and the lowest heating loads (in HVAC+NV mode). However, the decision should be made on which model has the lowest heating and cooling loads annually and thus consumes less energy in providing a thermal comfort temperature.

- **Dominant season**: The value of the heating loads is much greater than the value of the cooling loads (in HVAC+NV mode), despite the fact that the cold hours are far fewer than the hot hours (in NV mode). Moreover, the difference between the least and most heating loads in the model types is 78.7 KWh/m^2; however, for the cooling loads it is much less at around 4.06 KWh/m^2. In addition, more energy is consumed to heat a space by 1 degree than to cool it by the same amount. Thus, for the above reasons, the cool season is the dominant season to design for.

- **Overall most energy efficient prototype**: Compared to all models, the offices of the 1-sided W model are the warmest in a cool season and are suggested to have the lowest annual heating and cooling loads. The 1-sided N model is the second option with low overall annual heating and cooling loads. However, the Central model does not represent a good option as it is the coolest, whilst the linear model is not a good option either as it is not the warmest in the dominant cool season. Thus, 1-sided W followed by 1-sided N are the two top most energy efficient options for square designs.

- **Atria placement:** Also, in terms of the orientation and placement of the atrium, in the warm season, weather in NV or HVAC+NV mode, there is not much difference between the models. However in the dominant cool season, the differences in the models are more apparent. It is important to place the external office window where there is least heat loss. This approach also affects the atrium placement (with the closed top in cool season); it is arguably more energy effienct for the atrium to be placed where the most amount of external window heat loss occurs for office buildings. Since the dominant factor is the cool season, the more the atria blocks the west and north-west winds, the warmer the offices are and the lower the heating and cooling loads (Figure 8. 10). As such, less energy is consumed in providing thermal comfort. Also, the external window gain is more from the east with the morning sun, and from the south for the afternoon sun, in office hours. By the time the sun is in the west, the office hours almost comes to an end so the effective time is less.

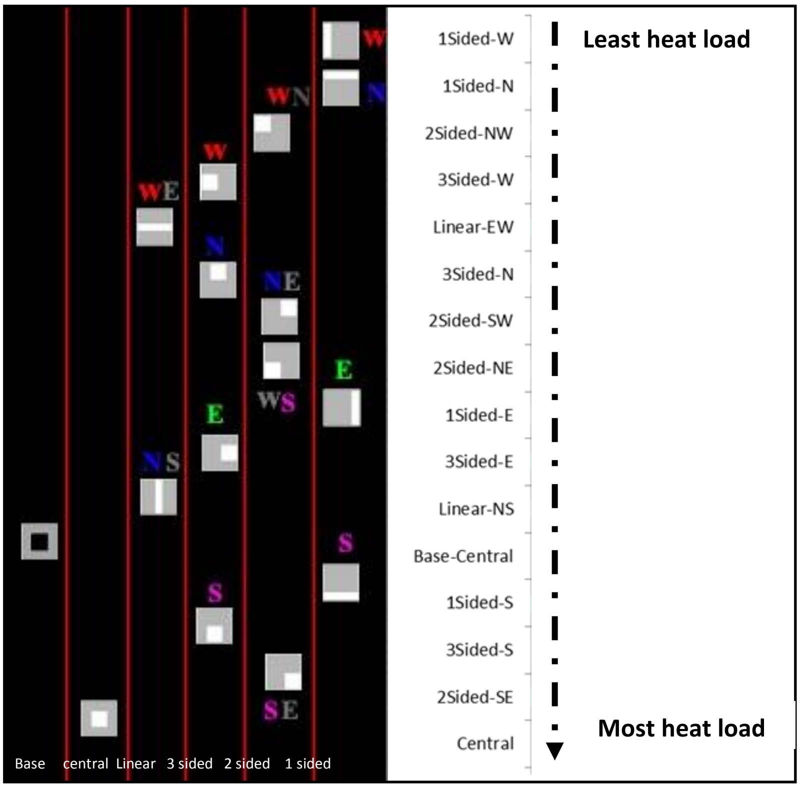


Figure 8. 10: order of prototypes from least to most heating load from top to bottom with indication of atria placement

CHAPTER 9: Rectangular Prototype Results

The outputs of the rectangular prototype have been generated via the Design Builder software program. The output concerns only the occupied office time. The simulation is conducted in two modes. The first mode is when the offices are naturally ventilated, when needed, throughout the year without the aids of any mechanical systems. The second mode is when the building also uses HVAC which is only used when natural ventilation cannot provide thermal comfort temperature on its own.

In the natural ventilation mode (section 9.1), one of the important outputs is the amount of hours that people in offices experience certain temperatures. The uncomfortable hours which are the amount of hours outside the 23-31 range in warm season and the 18-26 range in cool season have been manually calculated for each of the 12 storeys of a prototype and added to each other to form the uncomfortable hours for each model. The reason for doing this manually is because the comfort temperature range in Tehran is different to that provided by the standard used in Design Builder software. The amount of uncomfortable hours in a warm and cool season provides an understanding that atrium alone cannot provide thermal comfort temperatures constantly in offices throughout a year. By comparing the uncomfortable hours between prototypes, it is clear which typologies have fewer uncomfortable hours.

In the HVAC plus natural ventilation (HVAC+NV) mode (section 9.2), which is the second mode used in the simulation program, one of the most important outputs are the heating and cooling loads. These loads are calculated both in warm and cool season and cover a whole year. The greater the heating and cooling loads for a prototype, the more energy is consumed to warm and cool the offices (more HVAC is used) thus the less energy efficient the prototype will be and the more attention is required to design them according to climate.

In order to understand why some prototypes have more annual energy loads and more annual uncomfortable hours compared to others (section 9.2), more outputs are generated. Some of these outputs have almost the same value in all the models, such as heat gain via light, occupancy and equipment (Appendix 5). However, some of them differ from one prototype to another. The outputs in which their values differ across models are: glazing gain, external window heat gain, internal window heat gain, external window heat loss, and internal window heat loss. The meaning of each term has been defined in Chapter 7, section 7.5.

9.1 Calculated Uncomfortable hours in NV mode

This section investigates the thermal performance of prototypes using natural ventilation throughout the year. When neutral ventilation takes place, cooler outside air ventilates through the windows and into the warm indoor offices. Figure 9.1 shows uncomfortable hot hours in the base case (the prototype with no atria) along with the all the other prototypes with atria.

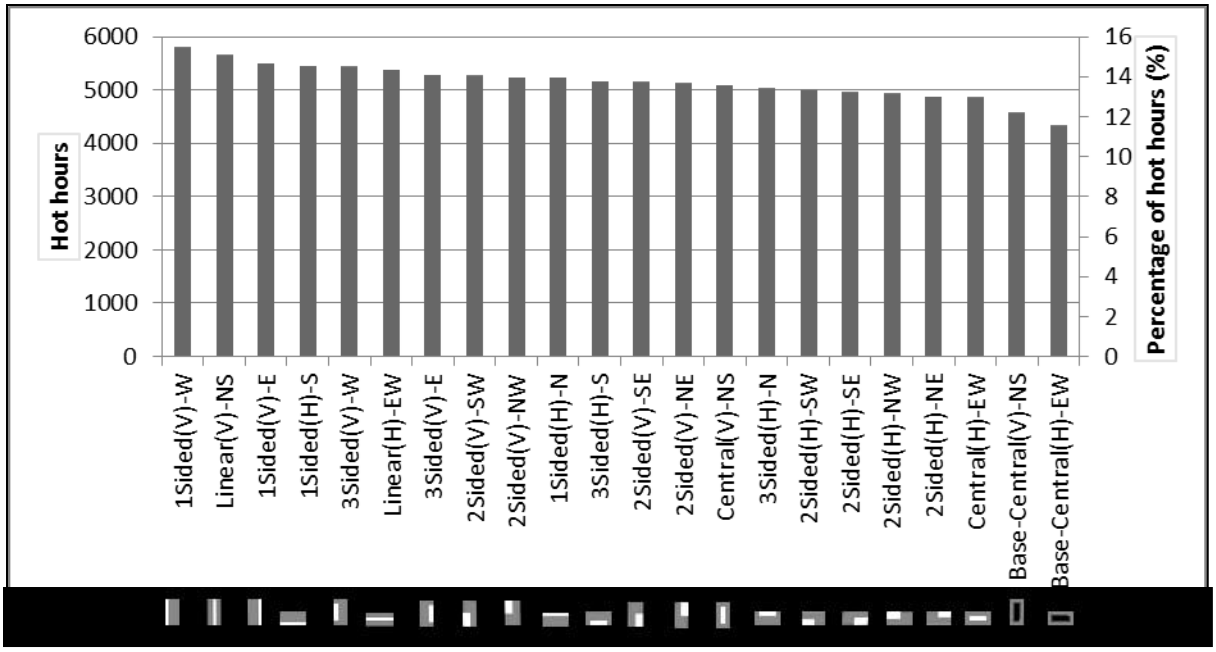


Figure 9.1: Annual hot hours and percentage of annual hot hours in rectangular plan offices in NV mode (in descending order)

In the prototypes with atria, the glazing rooftop of the atria opens during the six months that are classified as the warm season to assist with the airflow and the removal of heat. Figure 9.1 shows that, in warm seasons, naturally ventilated offices with 1-sided (V)-W atrium, aligned on the NS axis, have the most uncomfortable hot hours. For the buildings with Central (H)-EW atrium, and 2 sided (H)-NE, that are both aligned on the EW axis, the atria are located on the cool side (namely the north where there is no direct sunlight, and the east which sees early morning sun, which is not hot). Hot air, escapes through cooler atria and is released at the top resulting in fewer hot hours. On the other hand, atria that are exposed to the warm sides (south or west) have less temperature differences between the offices and the atria, with a low hot air flow from office to atria that results in a greater number of annual hot hours.

Thus, in NV mode the results show that, if buildings were designed only according to the warm season then a building with no atrium aligned on an east-west axis provides cooler offices, and the offices with a 1-sided W atrium are the warmest.

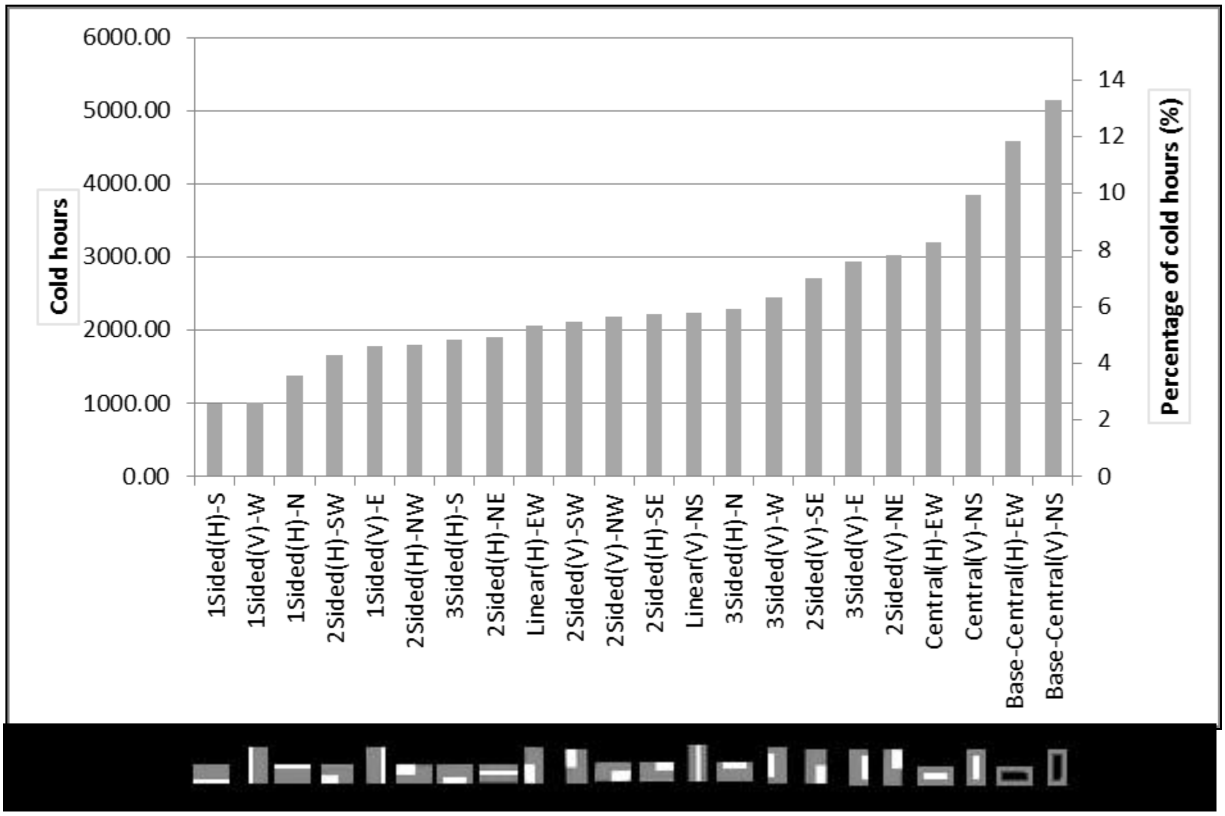


Figure 9.2: Annual cold hours and percentage of annual cold hours in rectangular plan offices in NV mode (in ascending order)

Moreover, the glazing rooftop of the atria closes during the six months classified as the cool season to assist with the preservation of heat and less heat loss. Figure 9.2 shows that, in thecool season, amongst the prototype with atria, naturally ventilated offices with Central atria aligned on the NS and EW axes have the most uncomfortable cold hours. However, the offices with 1-sided (H)-S and 1-sided (V)-W atria have the least cold hours and are warmer. Meanwhile, the base cases with no atria, whether the building is aligned on the NS or EW axis, have the largest number of cold hours amongst all the models. Therefore, it is not worth considering naturally ventilated buildings with no atria in the cool season as almost all offices with a 1-sided atrium have fewer cold hours.

A comparison amongst the prototypes (excluding the base cases) is made in the warm and cool seasons. The hot hours in offices of different prototypes, depending on the placement of atria, varies between 4867 to 5804 (Figure 9.1). The cold hours in offices of different prototypes, depending on the placement of atria, varies between 975 to 3744 (Figure 9.2). The results in the comparison show that:

1. The uncomfortable hours in a warm season are much higher than the uncomfortable hours in a cool season. This means that occupants in offices in all the prototypes experience more hot hours than cold hours in a year.

2. The difference in uncomfortable hours between prototypes in a warm season is lower (937 hours, which is 2.49% difference excluding base) than in a cool season (2769 hours, which is 7.37% difference excluding base). This means that the prototypes act very similarly in a warm season but very differently in a cool season.

In terms of the atria placement, during the warm season offices with atria located on the cool side (north and east) have fewer hot hours compared to offices with atria located on south and west side. The sun penetration into atria located on the north and east is less compared to those located on south and west, therefore, the temperature difference between offices and atria located on north and east is greater, which causes office hot air to escape better through a cooler atrium. So in NV mode, the more an atrium is exposed to sun, in this case the westerly and southerly direction, the warmer the offices are in the warm season.

However, this rule does not apply in the cool season. Because there is strong cold wind coming from NW direction which impacts where the offices can be located to have less cold hours. So it’s a balance of having the offices on warm side (south and west) in cool season and having the closed atria on the windward side (north and west). The more the façade exposure of offices to west and north (the direction of prevailing cold wind in cool season) the more the cold hours there are. So it is best for the atria to be placed in these directions because the atrium top is closed in the cool season and airflow is not encouraged from offices to atria and atria can act as an insulation gap. Also offices can benefit from the low south sun angle in cool season. Nevertheless, by comparing the prototypes across warm and cool seasons it can be seen that offices of 1-sided(V)-W and 1-sided(H)-S models are amongst the offices with the most hot hours in the warm season and least cold hours in the cool season.

Moreover, in terms of the building orientation, the horizontal orientations of the models usually contribute to fewer hot hours in the warm season and fewer cold hours in the cool season. The vertical orientation of models usually contributes to more hot hours in the warm season and more cold hours in the cool season. This is because, in the warm season, the angle of the afternoon sun on the south is high, which means that the sun does not penetrate deep into the buildings on the south façade. Furthermore, the angle of the evening sun on the west and east is low, which helps the sun penetrate deeply into the offices. Meanwhile, buildings on the vertical orientation (on south-north axis) have a bigger area on the east and west façade and a small area on the south. Therefore, they have more hot hours in the warm season.

On the other hand, in the cool season, the angle of the afternoon sun on the south is low, unlike in the warm season, which means that the sun penetrates deeply into the buildings on the south façade. Buildings on the horizontal orientation (on an east-west axis), have a greater area on the south façade and a smaller area on the east and west. Therefore, they have fewer cold hours than the vertically orientated buildings.

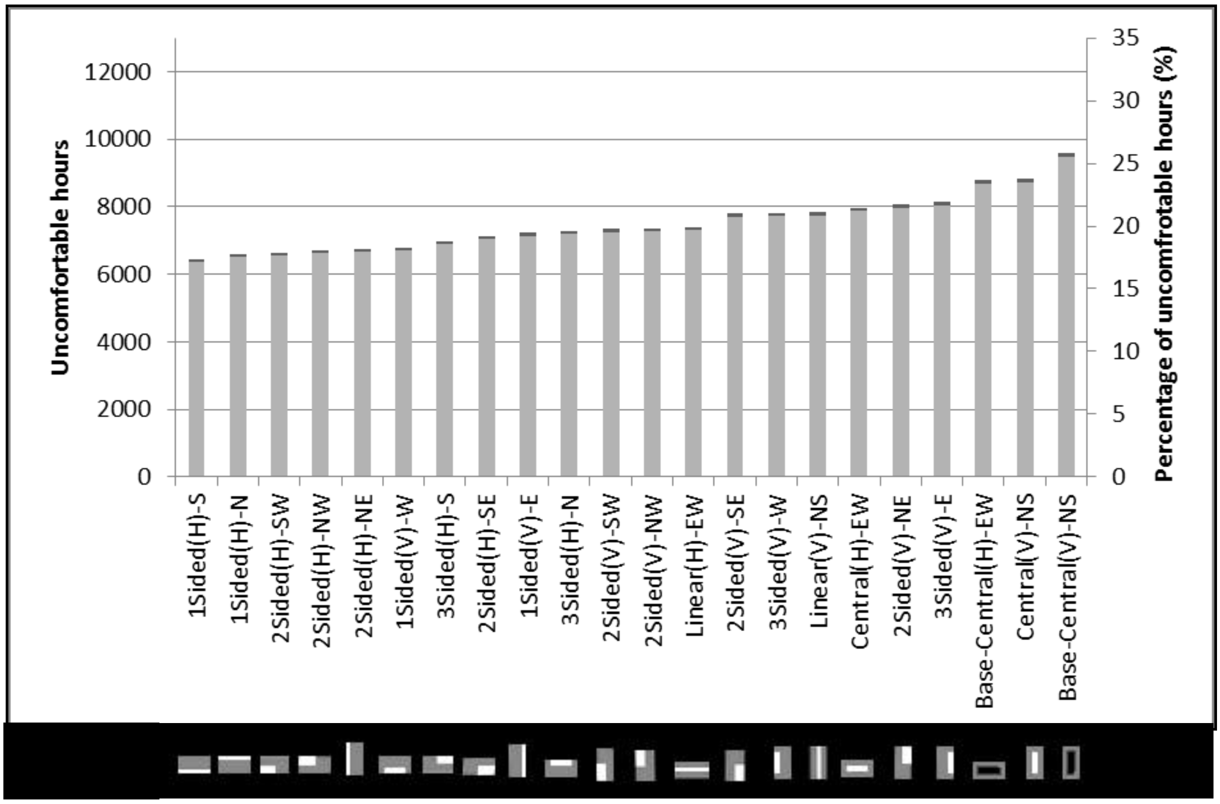


Figure 9.3: Annual uncomfortable hours and percentage of annual uncomfortable hours in offices in NV mode (in ascending order)

Although the performance of buildings with no atria are better in terms of fewer uncomfortable hours in warm season; it is the opposite situation in cool season where the building with no atrium has the most uncomfortable cold hours. Thus, the annual graph (Figure 9.3) is generated to demonstrate the annual number of uncomfortable hours to help better understand the prototype performances over a year.

The results of the uncomfortable hours from the warm and cool seasons are added together and presented in Figure 9.3 as the annual uncomfortable hour graph; this amalgamated visual representation helps to better understand the overall prototype behaviours during the year.

Figure 9.3 shows that offices of the 1-sided (H)-S model have the least amount of uncomfortable hours annually, whilst the offices of the base case (V)-NS model have the greatest amount of uncomfortable hours. The differences in the annual uncomfortable hours between the highest and lowest value case (namely, 1-sided (H)-S and base-(V)-NS respectively) in NV mode is 3150 hours or 8.38%. Thus, incorporating an atrium helps with lowering the number of uncomfortable hours throughout the year.

Moreover, the order of offices from the least to most annual uncomfortable hours is very similar to the order of offices from the least to most cold hours. Hence, designing with attention to the cool season is important. The reason for this similarity is due to the fact that the prototypes act very similarly in the warm season but very differently in the cool season. Thus, when the cold hours are added to the hot hours to generate the annual uncomfortable hours, the difference in the results is similar to that for the cold hours. However, this is in terms of the uncomfortable hours. The building load, which contributes to energy use, should also be calculated to reach a final conclusion.

9.2 Calculated Cooling and Heating load in HVAC+NV mode

This section investigates the cooling and heating loads of buildings using NV throughout the year with help of HVAC to reach thermal comfort for the typical office hours. Because, after natural ventilation occurs, the temperature might not fall to the degree needed (the degree that is in the thermal comfort range; which is 18°C to 26°C in cool season, and 23°C to 31°C in warm season).In this case, the HVAC mode is triggered to help offices to reach a comfortable thermal temperature. If the offices are above 31°C in the warm season, and below 18°C in the cool season, the HVAC system is used to provide thermal comfort. Using NV as much as possible and HVAC only when needed reduces the energy loads and as a result the energy consumption decreases.

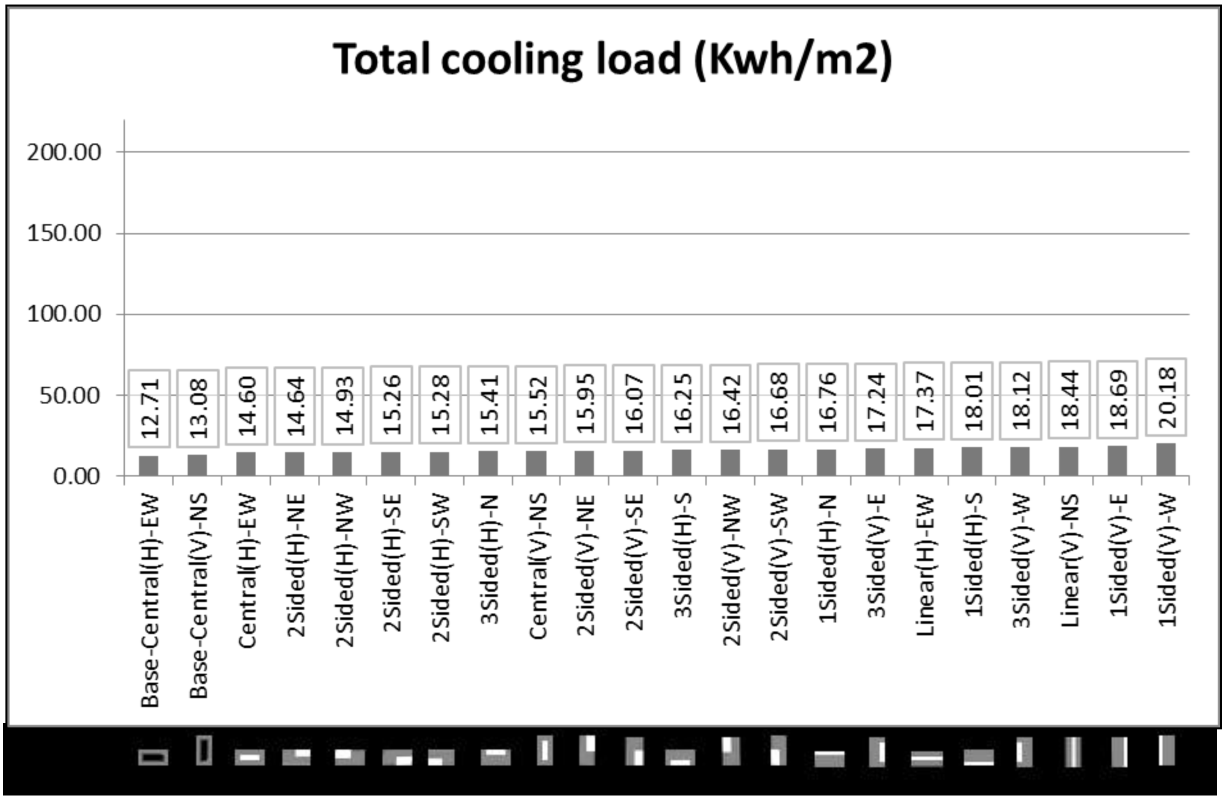


Figure 9.4: Cooling load in offices in warm season HVAC+NV mode (in ascending order)

As mentioned before, the glazing rooftop of the atria opens during the six months classified as the warm season, to assist with the airflow and removal of heat. Figure 9.4 shows that, in warm season the offices of the 1-sided-(V)-W model have the greatest cooling load. It also has the most uncomfortable hot hours in a naturally ventilated office building (Figure 9.1); hence, a greater cooling load is required to provide thermal comfort. Also, amongst the models (base case excluded), offices with a central (H)-EW atrium aligned on the EW axis, have the lowest cooling load (Figure 9.4). Again this complements the fact that they also have the fewest hot hours when offices are naturally ventilated (Figure 9.1); hence less energy is used to provide thermal comfort (Figure 9.4). Nevertheless, the base case (H)-EW has the lowest office cooling load in the warm season (Figure 9.4) as it also has the lowest hot hours in NV mode (Figure 9.1). The conclusion is derived that if buildings were only to be designed according to the warm season, then, in terms of minimum heat loads building aligned on the east-west axis and with no atria would be the more energy efficient option in HVAC+NV mode.

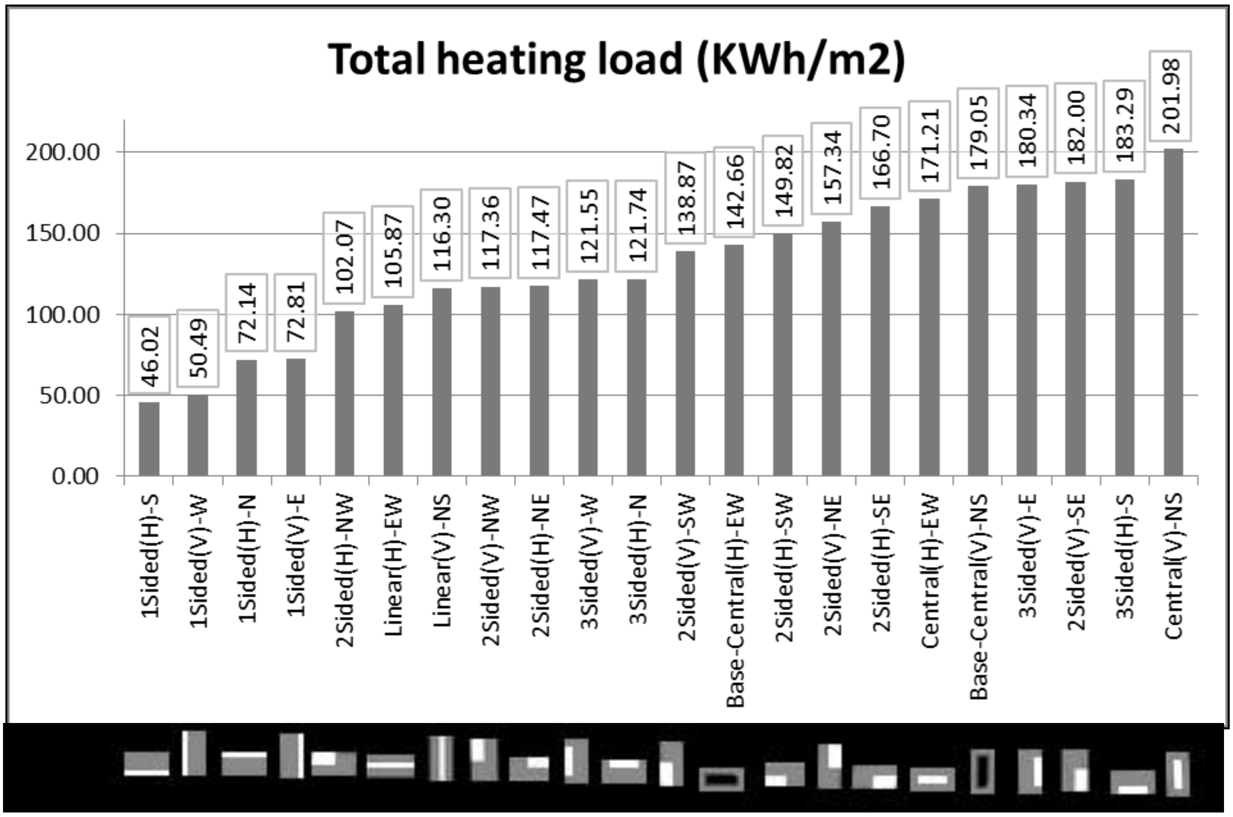


Figure 9.5: Heating load in offices in the cool season in HVAC+NV mode (in ascending order)

As mentioned before, the glazing rooftop of the atria closes during the six months classified as cool season to assist with the preservation of heat and ensure less heat loss. Figure 9.5 shows that, in the cool season, offices with a Central (V)-NS atrium have the greatest heating load in HVAC+NV mode. Offices with Central (V)-NS atrium also have the highest number of cold hours. Moreover, the model with a Central (V)-NS atrium has the maximum area of external office windows, and thus the amount of heat loss is amongst the highest compared to other prototypes. It will be later explained in this section that the parameter of heat loss via external windows has the greatest effect on the heating load results compared to other heat gain and loss parameters in a cool season.

On the other hand, offices of the 1-sided (H)-S followed by the 1-sided (H)-W model produce the lowest heating loads in the cool season. They are amongst the models with lowest number of cold hours in NV mode (Figure 9.2).

The base case models, however, are amongst the models with high heat load. Few prototypes, such as the offices with central(H)-NS, 3-sided(V)-E, 2-sided(V)-SE and 3-sided (H)-S atria generate greater heating loads than both of the base models (horizontally or vertically orientated). This confirms that, if atria are not designed correctly, they can add more energy consumption to a building.

The results in Figure 9.5 are important and have a substantial impact on the annual results of heating and cooling loads, which will be discussed later. Since the results in Figure 9.5 are important, the reasons why some prototypes more energy efficient than others are further analysed later in this section.

A comparison amongst the prototypes with atria (excluding the base cases) is made in the warm and cool season. The cooling load in offices of different prototypes, depending on the placement of atria, varies between 14.60 to 20.18 KWh/m^2.year (Figure 9.4). Depending on the atria placement, the heating load in offices of different prototypes varies between 46.02 to 201.98 KWh/m^2 per year (Figure 9.5). The results in comparison show that:

1. The heating loads in the cool season are much higher than cooling loads in the warm season. This means that, in order to provide thermal comfort temperature, more energy is used in a cool season compared to a warm season.
2. The difference in heating loads between prototypes in a cool season is higher (155.96 KWh/m2 per year) than the cooling load in warm season (5.58 KWh/m2 per year).This again confirms that the prototypes act very similarly in a warm season but very differently in a cool season.

These differences are illustrated on a monthly basis in Figure 9.9 showing the prototypes with the least and most heating and cooling loads. An important conclusion, however, is derived when comparing the uncomfortable hours with the prototype loads. This important conclusion is that the cool season is the dominant season to design for in Tehran. The following points explain the reason behind this important statement:

4. Even though the uncomfortable hot hours are significantly greater than the uncomfortable cold hours (almost double) in each prototype, the cooling loads are far fewer than the heating loads (comparing Figure 9.1with Figure 9.4 and comparing Figure 9.2 with Figure 9.5).
5. In Iran, the energy consumed to provide heat via HVAC is greater than the energy consumed to provide cool air via HVAC.

6. Since prototypes in the warm season perform similarly, it is important to emphasise the design of buildings on the cool season within Tehran's semi-arid climate. (Comparing Figure 9.1 and Figure 9.4 in warm season with Figure 9.2 and Figure 9.5 in cool season). This is where the differences in the prototype performances also lie. Hence, it is important to emphasise the buildings design in the cool season of Tehran's semi-arid climate.

Since the cool season is dominant, it is important to know what causes some prototypes to have lower heating loads whilst others have a greater heating load. In other words, it is important to know which independent parameter(s) have a considerable effect on the heating load results and by how much. The independent parameters that have been investigated are those whose values differ from one prototype to another. So the results for the heat gain via electronic equipment, light and occupancy have not been examined as their values are similar in each of the models. The five independent parameters that differ from one model to another and affects the heat load are glazing gain, external window heat gain, internal window heat gain, external window heat loss, and internal window heat loss. Each of these terms has been explained at the end of chapter 7. These values have been generated through the Design Builder software program (sample of the detail outputs are in Appendix 5). The regression analysis is needed to determine the effect of independent variables on depend variable of heating load. However, as explained before a standardisation technique must be conducted first. As such these technique (explained in chapter 6) is demonstrated below in the cases of restangular prototypes with atria:

> A standardisation technique has been manually conducted on all the five parameters to adjust the value ranges from zero to one. It helps to ensure that the results are in a state that can be comparable from one parameter to another. Table 9. 1 shows the independent values of each model (excluding base cases) before standardisation as well as the dependent value of heating load.

Table 9. 1: parameter values before standardisation

Rec/cool season HVAC+NV mode	Heat gain via glazing (MWh)	solar gain via external window (MWh)	Heat loss via external windows (MWh)	solar gain via internal window (MWh)	heat loss via internal windows (MWh)	Zone heating load (MWh)
1Sided(H)-N	370.35	375.48	837.91	19.56	45.43	379.5
1Sided(H)-S	512.61	525.77	782.71	37.53	14.31	227.91
1Sided(V)-E	401.22	415.68	857.99	26.42	31.98	377.7
1Sided(V)-W	403.54	416.19	729.5	26.21	16.62	261.08
2Sided(H)-NW	375.58	343.14	994.35	10.4	85.07	540.01
2Sided(H)-NE	375.49	343.13	1092.61	10.43	88.23	630.26
2Sided(H)-SW	471.38	418.18	1352.31	16.63	256.74	835.28
2Sided(H)-SE	471.56	418.24	1455.94	16.66	258.97	931.11
2Sided(V)-NW	373.97	343.09	1085.25	11.53	100.67	625.84
2Sided(V)-NE	374.02	343.15	1328.5	11.6	118.77	851
2Sided(V)-SW	417.45	377.05	1242.79	14.32	177.3	754.68
2Sided(V)-SE	420	380	1500	10	200	1000
3Sided(H)-N	361.12	333.38	1099.04	13.27	78.71	640.53
3Sided(H)-S	500	440	1560	30	300	1020
3Sided(V)-E	390	360	1480	20	160	992.16
3Sided(V)-W	389.48	355.5	1110.84	17.47	145.51	653.11
Linear(V)-NS	334.88	311.28	1078	38.67	23.34	593.69
Linear(H)-EW	354.7	325.51	1051.04	38.22	20.21	552.76
Central(V)-NS	310	280	1550	10	40	1060
Central(H)-EW	331.51	298.42	1380.92	12.17	52.24	901.15

However after performing the standardisation formula on the five independent parameters, the values change to what is shown in Table 9. 2.

Table 9. 2: Independent parameter values after standardisation

REC /winter (NV+HVAC mode)	standardizing glazing gain	standardizing solar gain via external win	standardizing heat loss via external win	standardizing solar gain via internal win	standardizing heat loss internal win
1Sided(H)-N	0.30	0.39	0.13	0.33	0.11
1Sided(H)-S	1.00	1.00	0.06	0.96	0.00
1Sided(V)-E	0.45	0.55	0.15	0.57	0.06
1Sided(V)-W	0.46	0.55	0.00	0.57	0.01
2Sided(H)-NW	0.32	0.26	0.32	0.01	0.25
2Sided(H)-NE	0.32	0.26	0.44	0.01	0.26
2Sided(H)-SW	0.80	0.56	0.75	0.23	0.85
2Sided(H)-SE	0.80	0.56	0.87	0.23	0.86
2Sided(V)-NW	0.32	0.26	0.43	0.05	0.30
2Sided(V)-NE	0.32	0.26	0.72	0.06	0.37
2Sided(V)-SW	0.53	0.39	0.62	0.15	0.57

2Sided(V)-SE	0.54	0.41	0.93	0.00	0.65
3Sided(H)-N	0.25	0.22	0.44	0.11	0.23
3Sided(H)-S	0.94	0.65	1.00	0.70	1.00
3Sided(V)-E	0.39	0.33	0.90	0.35	0.51
3Sided(V)-W	0.39	0.31	0.46	0.26	0.46
Linear(V)-NS	0.12	0.13	0.42	1.00	0.03
Linear(H)-EW	0.22	0.19	0.39	0.98	0.02
Central(V)-NS	0.00	0.00	0.99	0.00	0.09
Central(H)-EW	0.11	0.07	0.78	0.08	0.13

Table 9. 3: Initial P value and coefficients of independent parameters

	Coefficients	*P-value*
Intercept	317.0432259	0.00520×10^{-15}
standardizing glazing gain	-183.9337422	0.000264896
standardizing solar gain via external win	69.38658477	0.088260868
standardizing heat loss via external win	748.9054937	0.000008×10^{-15}
standardizing solar gain via internal win	-25.10314678	0.000273665
standardizing heat loss internal win	92.80171811	0.000163974

With these standardised values the regression analysis can be conducted in excel. The generated P values and coefficients are presented in Table 9. 3. As it can be seen in Table 9. 3 the P-value of the standardised value of external window solar gain is above the value of 0.05. This means that this parameter does not have significant effect on heating loads. As such the other four parameters have a significant effect on the heating load results. Therefore the regression analysis is once again conducted without the insignificant parameters to generate the correct coefficient.

Table 9. 4: Correct P value and coefficients of the independent parameter

Code		*Coefficients*	*P-value*
	Intercept	322.7841767	0.0069×10^{-17}
A	standardizing heat loss via external win	743.8856162	0.0076×10^{-19}
B	standardizing glazing gain	-116.4152695	0.00842×10^{-6}
C	standardizing heat loss internal win	75.08519219	0.000010581
D	standardizing solar gain via internal win	-26.80879314	0.000207789

Table 9. 4 shows the correct coefficient value of ‘external window heat loss (parameter A in the formula) is 743.88 which is the highest. This means that this parameter has the most effect on heating loads. After the parameter of external window heat loss the parameter of ‘Heat gain via glazing’ (parameter B) has the most effect with the second largest coefficient value of -116.4. as such ‘heat loss via internal window’ (parameter C) which the coefficient value of 75.08 and ‘solar gain via internal windows’ (parameter D) coefficient value of -26.80 are the third and fourth most effective parameter on the heating load results . Hence, the formula of the heating load (parameter y) is:

$$y= 743.88xA-116.41xB+75.08xC-26.8xD+322.78$$

The positive values of coefficients means that the more value of that parameter the more the heating load there is. For example the more the heat loss via external window the more the heating loads. On the contrary the negative value of coefficients means that the more the value of that parameter the less the heating loads. For example the more the heat gain via internal windows the less the heat loads, which is logical. Moreover, the coefficient value of external window heat loss is significantly more than the others hence it can be said that this parameter is the dominate parameter which affects the results more.

In order to understand why some configurations have more external window heat loss than others, the parameter of the external office window areas (Table 9.5) is notable. When comparing the heat load graph (Figure 9.5) with the office’s external window area (Table 9.5), a combination graph can be developed. However, to produce this combination graph, it is easier to use the ‘atria’s external window area’ (Table 9.6) instead of the ‘offices external window’. Since the façade area is the same on all 4 sides (if we look into buildings on E-W axis separately from those aligned on N-S axis), the atria’s external window area is the value of the façade minus the ‘office external window area’. Thus, the greater the atrium external window on one side, the less the external offices window area on the same side. This means that the atrium’s external window area is really the complimentary value of the office external window area. As such, it doesn’t make a difference to work with Table 9.6 instead Table 9.5. However, Table 8.6 has the advantage of making the graph look simpler. This is because more orientations simply do not have external atrium windows and thus the value area would be zero. Having more zero values simplifies the combination graph making it more understandable.

Table 9.5: External window area of offices, from least to greatest heat load from top to bottom

Office external window area	North	East	South	West
1Sided(H)-S	605.47	232.85	0.00	232.85
1Sided(V)-W	232.85	605.47	232.85	0.00
1Sided(H)-N	0.00	232.85	605.47	232.85
1Sided(V)-E	232.85	0.00	232.85	605.47
2Sided(H)-NW	302.73	302.74	605.47	162.96
Linear(H)-EW	605.47	232.85	605.47	232.85
Linear(V)-NS	232.85	605.47	232.85	605.47
2Sided(V)-NW	162.96	605.47	302.74	302.73
2Sided(H)-NE	302.73	162.96	605.47	302.74
3Sided(V)-W	302.74	605.47	302.74	185.47
3Sided(H)-N	185.47	302.74	605.47	302.74
2Sided(V)-SW	302.74	605.47	162.96	302.73
BASE(H)-EW	605.47	302.74	605.47	302.74
2Sided(H)-SW	605.47	302.74	302.73	162.96
2Sided(V)-NE	162.96	302.73	302.74	605.47
2Sided(H)-SE	605.47	162.96	302.73	302.74
Central(H)-EW	605.47	302.74	605.47	302.74
BASE(V)-NS	302.74	605.47	302.74	605.47
3Sided(V)-E	302.74	185.47	302.74	605.47
2Sided(V)-SE	302.74	302.73	162.96	605.47
3Sided(H)-S	605.47	302.74	185.47	302.74
Central(V)-NS	302.74	605.47	302.74	605.47

Table 9.6: External window atrium area from least to greatest heat load from top to bottom

Atria external window area	North	East	South	West
1Sided(H)-S	0	174.72	1513.68	174.72
1Sided(V)-W	174.72	0	174.72	1513.68
1Sided(H)-N	1513.68	174.72	0	174.72
1Sided(V)-E	174.72	1513.68	174.72	0
2Sided(H)-NW	756.84	0	0	349.44
Linear(H)-EW	0	174.72	0	174.72
Linear(V)-NS	174.72	0	174.72	0
2Sided(V)-NW	349.44	0	0	756.84
2Sided(H)-NE	756.84	349.44	0	0
3Sided(V)-W	0	0	0	1050
3Sided(H)-N	1050	0	0	0
2Sided(V)-SW	0	0	349.44	756.84
BASE(H)-EW	0	0	0	0
2Sided(H)-SW	0	0	756.84	349.44
2Sided(V)-NE	349.44	756.84	0	0
2Sided(H)-SE	0	349.44	756.84	0
Central(H)-EW	0	0	0	0
BASE(V)-NS	0	0	0	0
3Sided(V)-E	0	1050	0	0
2Sided(V)-SE	0	756.84	349.44	0
3Sided(H)-S	0	0	1050	0
Central(V)-NS	0	0	0	0

However, in the case of the rectangular prototype, Table 9.6 is separated into two groups: The ones aligned on the east-west axis, namely horizontal buildings (Table 9.7), and the ones aligned on north-south axis, namely the vertical buildings (Table 9.8). This is because the horizontal buildings should be compared within themselves, as well as with the vertical buildings, and is conducted to make the comparison of the façade areas reliable. For example, it would not be correct to compare the south façade area of a horizontal building with the south façade area of a vertical building as one is greater than the other. The comparison to justify the reason behind the optimum location of atria in terms of helping with the heating loads is only feasible when the façade areas stay the same and only the location of atria changes.

Table 9.7: External window atrium area from least to greatest heat load from top to bottom (in buildings aligned on east-west axis)

Atria external window area	North	East	South	West
1Sided(H)-S	0	174.72	1513.68	174.72
1Sided(H)-N	1513.68	174.72	0	174.72
2Sided(H)-NW	756.84	0	0	349.44
Linear(H)-EW	0	174.72	0	174.72
2Sided(H)-NE	756.84	349.44	0	0
3Sided(H)-N	1050	0	0	0
Base (H)-EW	0	0	0	0
2Sided(H)-SW	0	0	756.84	349.44
2Sided(H)-SE	0	349.44	756.84	0
Central(H)-EW	0	0	0	0
3Sided(H)-S	0	0	1050	0

Table 9.8: External window atrium area from least to greatest heat load from top to bottom (in buildings aligned on north-south axis)

Atria external window area	North	East	South	West
1Sided(V)-W	174.72	0	174.72	1513.68
1Sided(V)-E	174.72	1513.68	174.72	0
Linear(V)-NS	174.72	0	174.72	0
2Sided(V)-NW	349.44	0	0	756.84
3Sided(V)-W	0	0	0	1050
2Sided(V)-SW	0	0	349.44	756.84
2Sided(V)-NE	349.44	756.84	0	0
Base (V)-NS	0	0	0	0
3Sided(V)-E	0	1050	0	0
2Sided(V)-SE	0	756.84	349.44	0
Central(V)-NS	0	0	0	0

Therefore, by combining Table 9.7 with the horizental models in Figure 9.5, Figure 9.6 is generated. Also, by combining Table 9.8 with Figure 9.5, Figure 9.7 is generated. In Figure 9.6 and Figure 9.7 each colour code represents the orientation of the atrium's external windows. The bar size of each colour is the value of the external atrium window area in the orientation of the coded colour. For example the 3-sided(H)-S case has only a green bar, which means the atrium's glazing façade is towards the south. The amount of the green bar is over 1000 m^2, which is the amount of the south atrium's glazing façade area. The graphs also are in the order of heat load, from least to most and from top to bottom. Thus, the models at the top of the graph are warmer and have lower heat loads than those below.

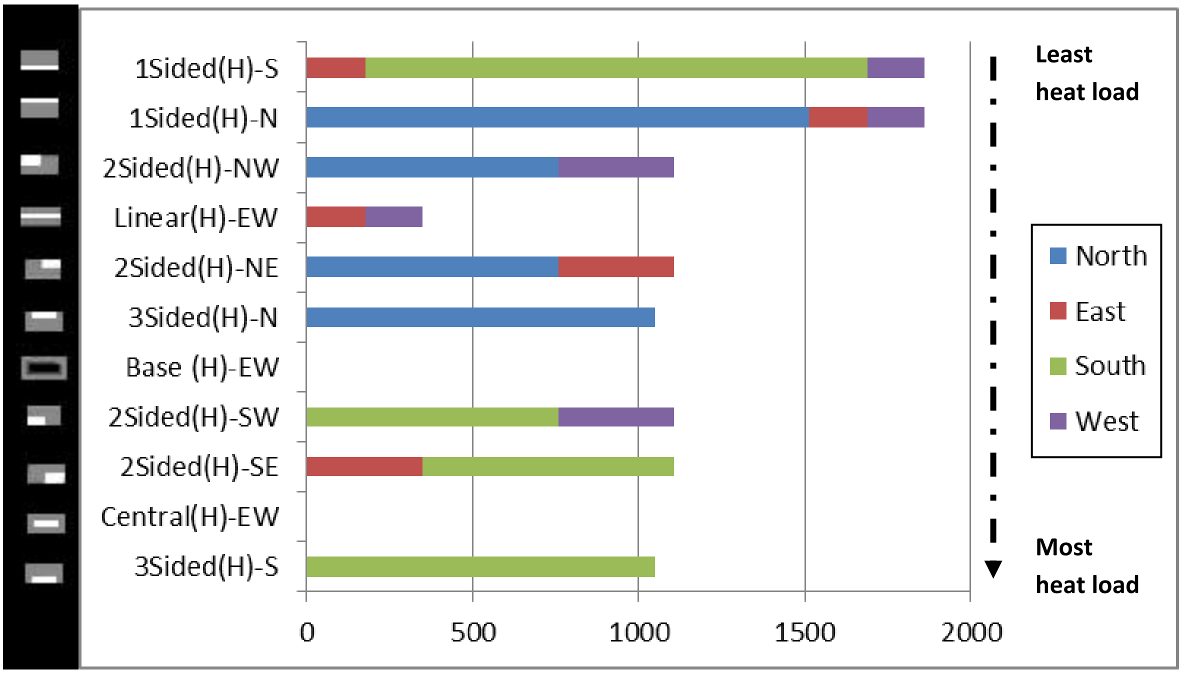


Figure 9.6: External window position and area value in m^2 (from least to most heat load) in horizontal buildings

Buildings aligned on the east-west axis have their longer façade towards the north and south. In Figure 9.6, with the exception of the 1-sided (H)-S model, the amount of north (blue) coloured bars are mostly seen at the top of the graph where the models with lowest heat loads are seen, and south (green) coloured bars are mostly seen towards the bottom of the graph where the models with greatest heat loads noted. Lower heat loads and less energy are consumed in reaching thermal comfort when more external windows of an atrium face towards the north (office external windows are more exposed to the south). Furthermore, when more external atrium windows face the south (office external windows more exposed to the north), greater heat loads and a higher energy consumption are required to achieve thermal comfort.

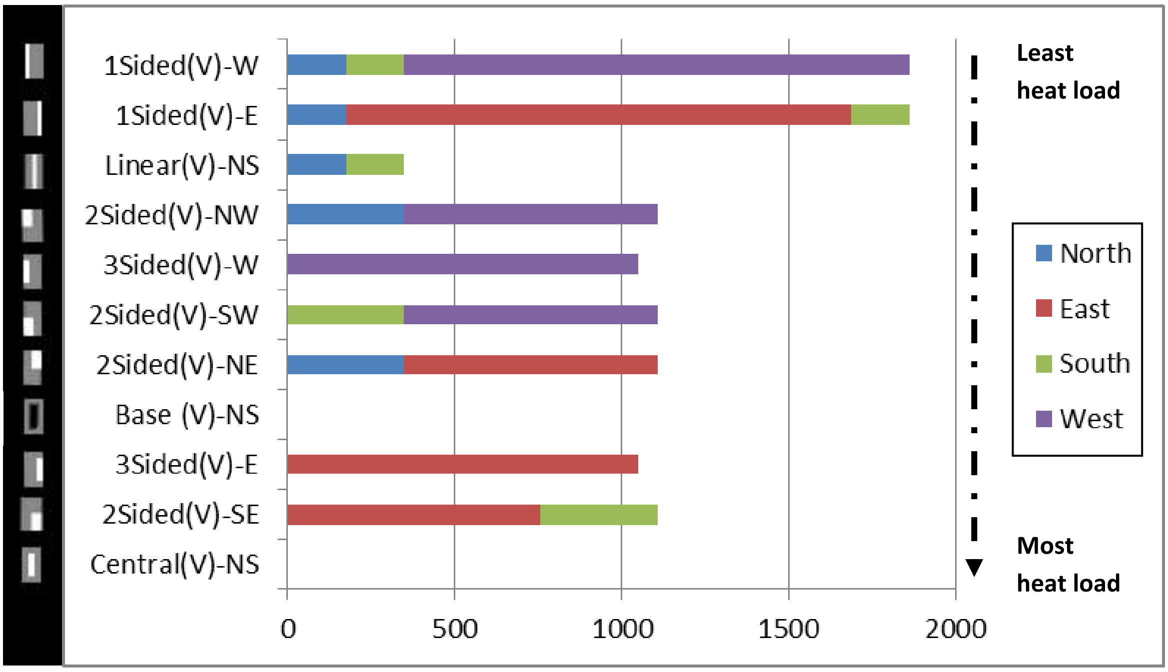


Figure 9.7: External window position and area value in m^2 (from least to greatest heat load) in vertical buildings

Also, buildings aligned on the north-south axis have their longer façade towards the east and west. In Figure 9.7, with the exception of the 1-sided (V)-W, the amount of west (Purple coloured) bars are mostly seen at the top of the graph amongst the models with the lowest heat loads. The east (red coloured) bars are mostly seen towards the bottom of the graph where the models amongst the greatest heat loads. Furthermore, when more external windows of an atrium face towards the west (and more office external windows are exposed to the east) lower heat loads are required and less energy is consumed to achieve thermal comfort. Moreover, when more external atrium windows face the east (more office external windows are exposed to the west) greater heat loads and more energy is consumed to achieve thermal comfort.

Overall, Figure 9.6 and Figure 9.7 show that when more external windows of an atrium face towards the west and north (and more office external windows are exposed to the south and east) lower heat loads are required. The reason for this is due to two factors:

1. **The office exposure to the morning and afternoon sun** (east and south): During office hours and in the cool season, the sun's rays are at a low angle in the cool season and penetrate deep inside the offices. This helps to warm the rooms from the early office hours through to the afternoon. Even though the westerly sun penetration is warm, it has very limited effect on occupants, as the hours of office use are limited. In comparison, external office windows benefit more from the longer lasting effect of sun from the east and south rather than the west, which has a shorter time frame to affect the building in office hours. As a result, less external window heat loss occurs in offices exposed to an orientation to the east and south.

2. **The prevailing wind**: The prevailing wind in the cool season is mostly from the north-west and west, as shown in Figure 5.6. Therefore, it can be concluded that, if the external atrium windows mostly face towards the south and east, this results in more office windows facing the cold north and west winds. As such, when offices are colder, a greater heating load is required. Thus, for the dominant cool season having the atrium to be orientated in the direction of the prevailing wind, acting as an insulation gap (when the top of the atrium is closed in the cool season) and shielding the offices from the cold west and north-west wind helps with less energy loads in the building. The less heat loss in the external window offices from the north and west, the more the south and west solar gains can be effective.

The above two reasons explain why 1-sided(V)-W and 1-sided(H)-N have very low heating loads (Figure 9.5) and very low 'external window heat loss' (**Error! Reference source not found.**). However, 1-sided(H)-S and 1-sided(V)-E also have a very low heat load and external window heat loss, which the reason for this will be explained separately.

The above two reasons also explain why 3 sided(H)-S, central (V)-NS and 2 sided (V)-SE have the greatest value in both parameters. In case of the central atrium, even though the offices are exposed to the south and east, the atrium is not blocking any heat loss from the north and west. Moreover, as the core of buildings are usually the warmest, having an atrium in the centre takes that advantage away from the offices.

Finally, the two models previously mentioned as exceptions (offices of the 1-sided(V)-E and the 1-sided (H)-S) have low heat load values due to the impact of three influences: atrium depth, the amount of hours that the atrium is exposed to the sun, and the office depth.

- Atria depth: When atria are long and thin (and thus have a shallow depth) they can heat up faster; for example, for the 1-sided(H)S model, the atrium becomes warm quicker than in other models (Appendix 11, first bullet point). This is because the atrium is long and thin and is the minimum depth of atrium in this configuration. The same is true for the 1-sided-E model, where the atrium warms up faster compared to most models because of its shallow depth (Appendix 11, second bullet point).

- The amount of atrium exposure to sun: When more atria is exposed to the sun and for longer hours, it holds the heat better (green-house effect) and results in a lower heat load. Again, in the 1-sided(H)S case, the atrium not only becomes warm quicker, because of less atrium depth, it also stays warm for longer. This is because, with the help of the glass façades on the east and west, the sun is able to penetrate inside for longer, from the morning to the evening. The same is true for the 1-sided(V)E model, where the atrium warms up quickly because of its shallow depth, and the morning and afternoon sun is allowed inside the building from the east and south façades to create a greenhouse effect from the early office hours.

- Office Depth: the greater the office depth, the less effective the atrium heat. All 1-sided atria have a minimum office depth; hence, the warmth from the atria is exposed to the majority of its office area. This is another reason why all office models with 1-sided atria have the lowest heating loads compared to other prototypes.

Furthermore, out of the three effective ambient variables mentioned in section 7.1 (outside temperature, outside wind and solar radiation), solar radiation has a significant effect on the offices of the 1-sided (H)-S and 1-sided (V)-E models. Due to the points mentioned previously, it causes a greenhouse effect in the atrium. As a result, any heat gain from the atrium to the offices occurs during the day, which overcomes the effect of office heat loss on the windward side of the offices. Hence, these models have a low heat load despite the fact that the offices are exposed on the north and west. However, amongst the other prototypes, where the offices and atria have a greater depth and the atria are less exposed to the sun, wind has the most effect amongst the ambient variables. In this respect, the external window heat loss parameter becomes more important. Hence, buildings with more external window heat loss have greater heating loads.

Nevertheless, with the three points explained earlier, some questions arise which are as follows:

1. *Why is there a noticeable difference between the heat load of the rectangular 1-sided (H)-S (37.98 KWh/m^2) and the 3-sided (H)-S (170 KWh/m^2) prototypes as both have large atria glazing on the south?* The atrium of the 3-sided(H)-S model does not have the same exposure to the sun as the 1-sided(H)-S. The atrium of the 1-sided(H)-S model has façades on the east, west and south, and the 3-sided(H)-S model has façades only on the south. This means that the 1-sided(H)-S atrium is exposed to sun all day round. The sun in the morning starts to heat the atrium, which becomes a solar engine throughout the day as the sun does not allow the atrium to cool. On the other hand, the 3-sided(H)S model is less exposed to the sun; namely, half of the day and half of the afternoon. This is because, until noon, the atrium of the 3-sided(H)S model is cold as it is blocked on the east. Although it starts to heat up at noon, it cannot heat up enough as the west is blocked again when the sun moves towards the west. Thus, the atrium of the 3-sided(H)S model does not have the same heat density as the 1-sided(H)S model (see Appendix 11). Therefore, external window heat loss is the dominant factor in the 3-sided(H)S model but not in the 1-sided(H)S model where solar gains are more effective.

2. *When comparing the square and rectangular models, why are the offices of the 1-sided-E and 1 sided –S (square configuration) not amongst the lowest heat loads, like their equivalent rectangular configurations?* One of the reasons for this is because of the office depth of these models. For the same office area, the office depth is greater for the square than the rectangular configuration. Thus a greater depth of office, means less atria impact on the offices. Thus, the atrium warmth penetrates less in the offices of square configurations compared to rectangular models, which have less depth to their office.

Another reason is the difference of the atria depth between the rectangular and square models; for the same area, the square atrium is much deeper and its atrium has a smaller glazing area on the south or east than its rectangular configuration (Table 9. 9). Thus, atria on the south and east in the rectangular model heats up more and faster than in the square model.

Moreover, it can be said that the square 1-sided-S model has almost the same effect as the rectangular 3-sided(H)S model. This is because the atrium glazing area on the south and the atria depth are similar between the square configuration and the rectangular configuration (Table 9. 9). Due to the same reasons, it can also be said that the square 1-sided-E configuration has a similar effect to the rectangular 3-sided-(V)E configuration (Table 9. 9). This is more vivid when looking into the placement of these prototypes in Figure 8.5 and Figure 9.5. These two Figures show prototypes in the order of the least to the most heat loads. The placement of the 1-sided-S and 1-sided-E in the square models (Figure 8.5) are amongst those with the greatest heating loads, which is similar to the placement of 3-sided(H)S and 3-sided(V)E in the rectangular models (Figure 9.5).

Table 9. 9: South façade area and depth of atria in four types of models

	Atria glazing area on the south	South atria depth	Atria glazing area on the east	East atria depth
Square 1sided-S	1070.58 m2	5.88 m2		
Rectangular 3sided(H)-S	1050 m2	6 m2		
Square 1sided E			1070.58 m2	5.88 m2
Rectangular 3sided(V)-E			1050 m2	6 m2

Overall, it can be concluded that, in the cool season and amongst all heat gain and heat loss parameters, the 'external window heat loss' has a more significant effect on the restangular models. This means that, out of three effective ambient variables (outside temperature, outside wind and solar radiation), the wind has the most effect on the prototypes, affecting the amount of external window heat loss. Thus, it is more energy efficient to shield from the wind by placing the atrium on the west or north. In Figure

8.8, where the prototypes are ordered from the least to the most heat loads from the top to the bottom of the graph, this rule is also illustrated. The same can be said for rectangular models (Figure 9.6 and Figure 9.7), with the exception of the 1-sided(H)S and the 1-sided(V)-E. For these models the effect of solar radiation is more significant. This is due to the fact that the office and atrium depth are shallower and therefore the sun exposure to the atrium is greater compared to all other prototypes.

Overall, according to all the results from the cool season, being the dominant season, it can be suggested that the buildings with atria can perform more energy efficient than the base case. However, the annual graph (Figure 9.8) is presented with the total heating and cooling loads to help better understand the overall results.

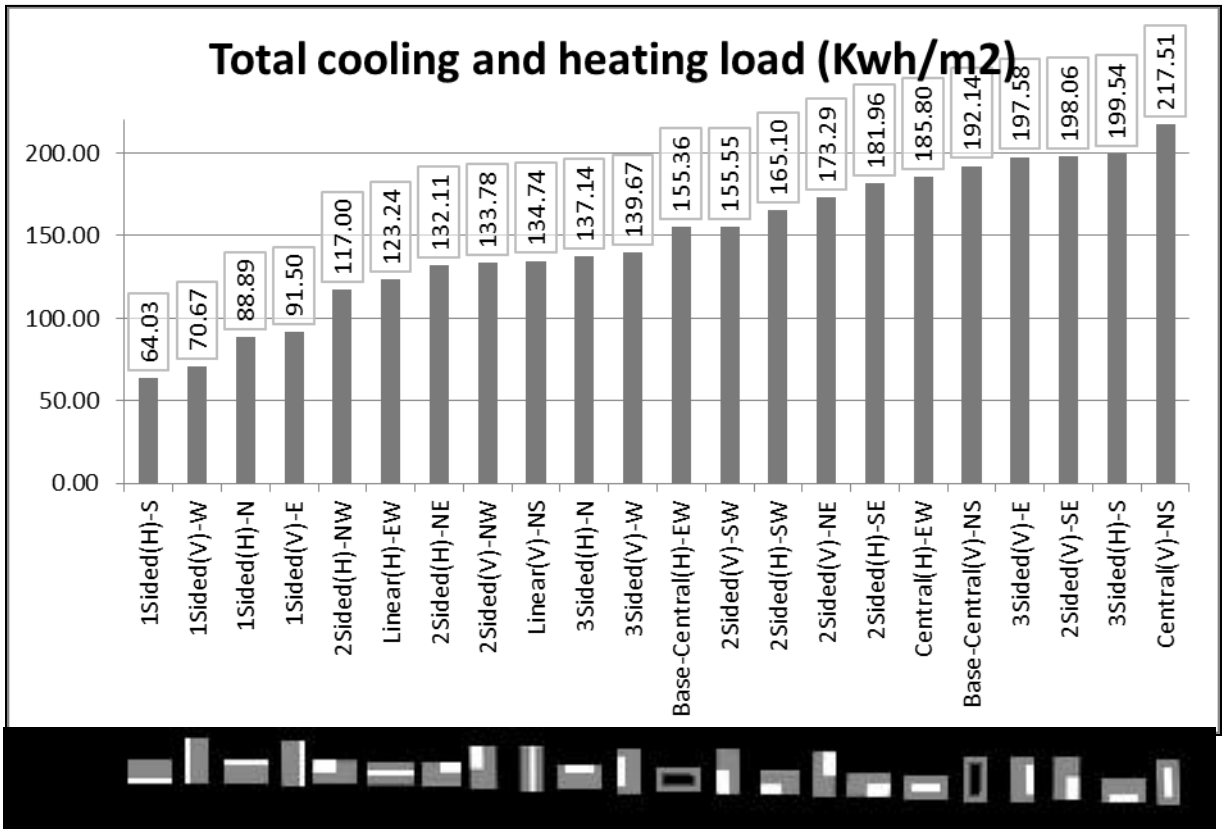


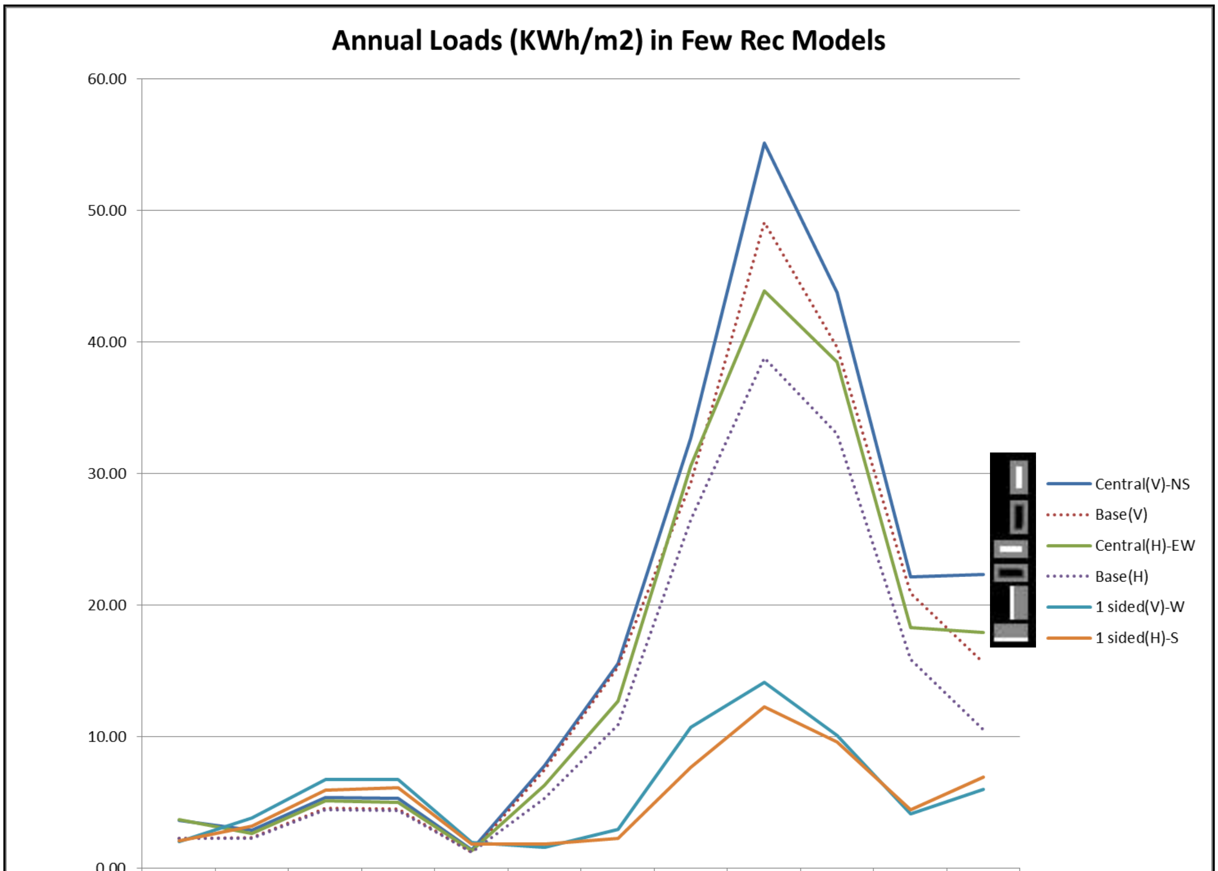
Figure 9.8: Annual heating and cooling loads in offices in HVAC+NV mode (in ascending order)

The overall values of the annual loads for all models are presented in Figure 9.8. The offices of 1-sided(H)-S case have the lowest heating and cooling loads overall, they also have the lowest annual uncomfortable hours when only NV is utilised (Figure 9.3). Also, the offices of the central(V)-NS atrium have the greatest heating and cooling loads overall, they also are amongst the models with most uncomfortable hours (Figure 9.3). The load difference between the offices of the 1-sided(H)-S model and the offices of the central(V)-NS model is 153.48 KWh/m^2.year.

The base case prototypes are not the case with highest overall heating and cooling loads. This highlights the fact that, if atria are not designed well, they can generate more loads and energy consumption compared to a building with no atrium. However, if designed correctly, the incorporation of an atrium can mean lower cooling and heating loads and greater energy savings than buildings with no atria. Moreover, there are more similarities between the annual load graph (Figure 9.8) and the heating load graph (Figure 9.5) than the cooling load (Figure 9.4). This again indicates that the cool season is the dominant season.

From all the prototypes, six key models have been selected to further analyse their annual results (Figure 9.9). These models are: firstly, those whose offices have the most and least heating loads in the cool season (1-sided(H)-S and Central(V)-NS) and secondly, the most and least cooling loads in the warm season (1-sided(V)-W and Central(H)-EW). Thirdly, the models with the most and least annual heating and cooling loads have been selected (again, 1-sided(H)-S and central(V)-NS) along with the base cases.

As mentioned before, between April to September, which are classified as the warm season, buildings would have their atrium tops open to help with excessive heat loss or natural ventilation. Whereas, between October to March, which are classified as the cool season, buildings will have their atria roof closed for less internal heat loss. Since the models represented are the most and least energy consumed cases in each season, the rest of the models fall in between the maximum and minimum values illustrated in the graph (Figure 9.9). This graph presents the conclusions previously discussed, in a clear, simple format and with the critical models showing their heating and cooling loads on a monthly basis.



	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Central(V)-NS	3.62	2.85	5.34	5.31	1.41	7.81	15.54	32.71	55.15	43.77	22.14	22.32
Base(V)	2.25	2.32	4.54	4.51	1.21	7.48	15.33	29.29	49.09	39.62	20.92	15.64
Central(H)-EW	3.66	2.63	5.08	4.99	1.35	6.29	12.69	30.59	43.87	38.47	18.28	17.90
Base(H)	2.24	2.24	4.43	4.36	1.17	5.30	10.90	26.48	38.80	33.04	15.88	10.53
1 sided(V)-W	2.01	3.79	6.71	6.72	1.97	1.59	2.96	10.72	14.09	10.07	4.12	5.99
1 sided(H)-S	2.08	3.16	5.90	6.12	1.84	1.85	2.28	7.69	12.26	9.59	4.44	6.90

Figure 9.9: Rectangular monthly loads for six critical models (Central (V)-NS: most heating load, 1 sided (V)-W: most cooling load, 1 sided (H)-W: least heating loads and central (H)-EW: least cooling load and both base cases)

As can be seen in Figure 9.9, in the warm season, the models are similar in terms of their heat loads (lines near each other); however, there is a substantial difference in the cool season (lines apart from eachother). This means that the cool season distinguishes between the prototype performances over a year. Also, the heating load values in the cool season are greater overall than the cooling load values in the warm season. As such, Figure 9.9 represents why the cool season is dominant season for design to reach thermal comfort through a lower energy consumption.

In Figure 9.9 the offices of the base models results are represented by the dotted line on the graph. Offices of the base models have the lowest loads in a warm season. However, since there is not much difference between all the models in the warm season and the values are low compared to the cool season, it is the cool season that is important. In the cool season, the offices of the base cases produce amongst the highest values in the cool season. As previously mentioned, they also have the greatest number of uncomfortable hours annually. Thus, it is important to include an appropriately designed atrium overall as it can help to bring down cooling and heating loads in a semi-arid climate.

9.3 Summary of Chapter 9 results

Table 9.10 summarises which prototypes have the least and most uncomfortable hours and loads in warm and cool season. The descriptions of each have been covered in previous sections. However, this section covers the summary for the results of offices in rectangular models in following bullet points:

Table 9.10: Summary of cases with lowest and highest values in all categories

<table>
<tr><th>Summary</th><th>NV Model
Warm season</th><th>NV mode
Cold season</th><th>HVAC+NV mode
Warm season</th><th>HVAC+NV mode
Cold season</th></tr>
<tr><td rowspan="3">Uncomfortable hours</td><td>Most: 1 sided(V)-W
Least: Base case (H)</td><td>Most: Base case (V)
Least: 1sided (H)-S</td><td colspan="2" rowspan="3"></td></tr>
<tr><td colspan="2">Annually</td></tr>
<tr><td colspan="2">Most: Base case (V)
Least: 1 sided (H)-S</td></tr>
<tr><td rowspan="3">Heating or cooling load</td><td colspan="2" rowspan="3"></td><td>Most: 1 sided (V)-W
Least: Base case (H)</td><td>Most: Central (V)-NS
Least: 1 sieded (H)-S</td></tr>
<tr><td colspan="2">Annually</td></tr>
<tr><td colspan="2">Most: Central (V)-NS
Least: 1 sided (H)-S</td></tr>
</table>

- **Warm season**: In the warm season the least energy consumption for cooling (in HVAC+NV mode) amongst the office models with atria is the alognated E-W building with cnetral atria (central(H)-EW). It also is amongst the prototypes with the lowest number of uncomfortable hot hours (in NV mode). In the prototype with central atrium aligned on E-W axis, heat loss is maximised as atrium is placed in the centre of the building. These type of atria, help to suck out the heat from the core of the building via its open top. Thus in warm season central(H)-EW is a good option for offices compared to other types of atria. But Tehran has a semi-arid steppe climate and its cool season needs consideration also.

  Moreover, in warm season the 1 sided model, 1-sided(V)-W and 1-sided(V)-E models, are not efficient choices as the cooling loads are the highest (in HVAC+NV mode) and they have a high number of uncomfortable hot hours (in NV mode). The linear models are also not a good option in a warm season as they also have high cooling loads (in HVAC+NV mode) and are amongst the models with most hot hours (in NV mode). However, when comparing the offices of the base models with the offices of all the models with atria, the offices of the base models are the coolest with the lowest number of uncomfortable hot hours. Both base cases, also have the lowest cooling loads. Therefore, it is more energy efficient not to have any atrium in a warm season of a semi-arid climate with the building orientated on an east-west axis.

- **Cool season**: In the cool season, the offices of the base models followed by central models have the highest number of uncomfortable cold hours (in NV mode). They are also amongst the models with the highest office heat loads (Central (V)-NS has the greatest heat load). The 1-sided(H)-S and 1-sided(V)-W are among the warmest office models in a cool season, and have the lowest number of uncomfortable cool hours (in NV mode) and the lowest heating loads (in HVAC+NV mode). Never the less, all offices with 1-sided atria tend to have the lowest heating loads (in HVAC+NV mode) and the lowest cold hours (in NV mode) including 1 sided(H)-S and 1 sided(V)-E. The reason is because of the three charectrictics that 1 sided atria have; lower office depth, lower atrium depth and the most exposure of the atrium to the sun; more exposure of the atrium to the sun is provided when an office and atrium depth are low. However, the decision should be made on which model has the lowest heating and cooling loads annually and thus consumes less energy in providing a thermal comfort temperature.

- **Dominant season**: The value of the heating loads is much greater than the value of the cooling loads (in HVAC+NV mode), despite the fact that the cold hours are far fewer than the hot hours (in NV mode). Moreover, the difference between the least and most heating loads in the model types is 155.96 KWh/m^2; however, for cooling loads it is far less at around 5.58 KWh/m^2. In addition, more energy is consumed to heat a space by 1 degree than to cool it by the same amount. Thus, for the above reasons, the cool season is the dominant season for design.

- **Overall most energy efficient prototype**: Compared to all models, the 1 sided models perform more energy efficient than others. The offices of the 1-sided(H)-S model are the warmest in a cool season and are suggested to have the lowest annual heating and cooling loads. The 1-sided(V)-W model is the second option with low overall annual heating and cooling loads. However, Central(V)-NS model does not represent a good option as it is the coolest. Thus, the 1-sided (H)-S model followed by 1-sided(V)-W model are the two top most energy efficient options for rectangular designs.

- **Atria placement**: In terms of the orientation and placement of the atrium, in the warm season (whether in NV or HVAC+NV mode) the difference between the models are not significant and overall the models on the horizental axis are cooler. However, in the dominant cool season, the differences in the models are more apparent. It is important to place the external office window where there is the least heat loss. This approach also affects the atrium placement (with a closed top in the cool season); it is arguably more energy efficient for the atrium to be placed where the most amount of external window heat loss occurs for office buildings. Since the dominant factor is the cool season, the more the atria blocks the west and north-west winds, the warmer the offices are and the lower the heating and cooling loads (Figure 9. 10). As such, less energy is consumed in providing thermal comfort. Also, in office hours, the external window gain is more from the east with the morning sun, and from the south for the afternoon sun. By the time the sun is in the west, the office hours are almost coming to an end so there is less effective time available

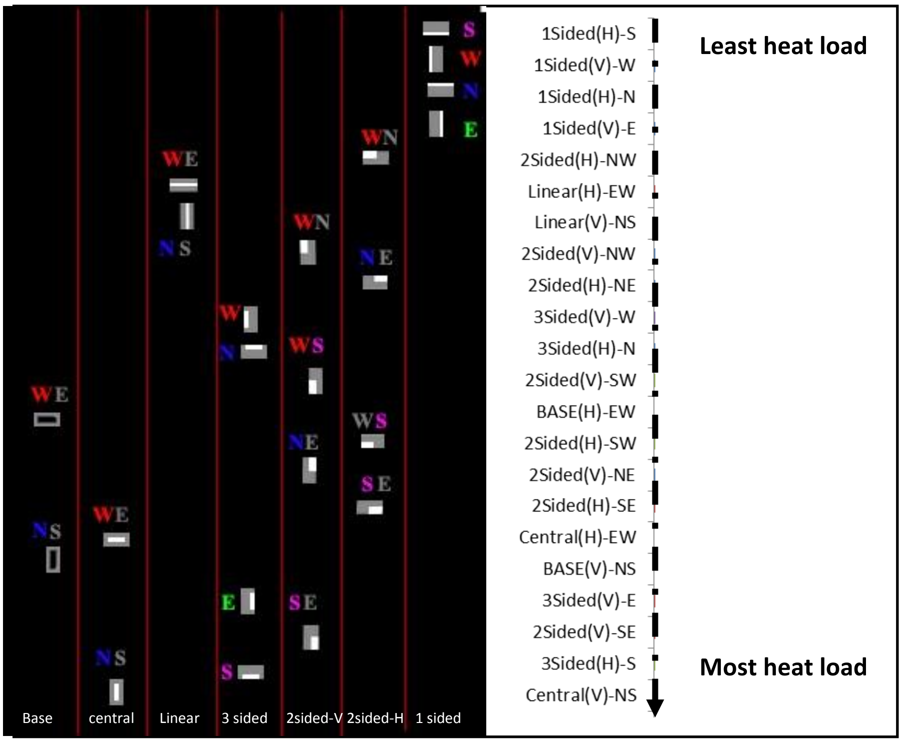


Figure 9. 10: order of prototypes from least to most heating load from top to bottom with indication of atria placement

CHAPTER 10: Discussion and Conclusion

10.1 Comparison of the rectangular and square plan prototypes

Chapter 8 and 9 covered the results and analysis of the square and rectangular prototype separately, however, a comparison between the overall results of rectangular and square prototypes is addressed in this section.

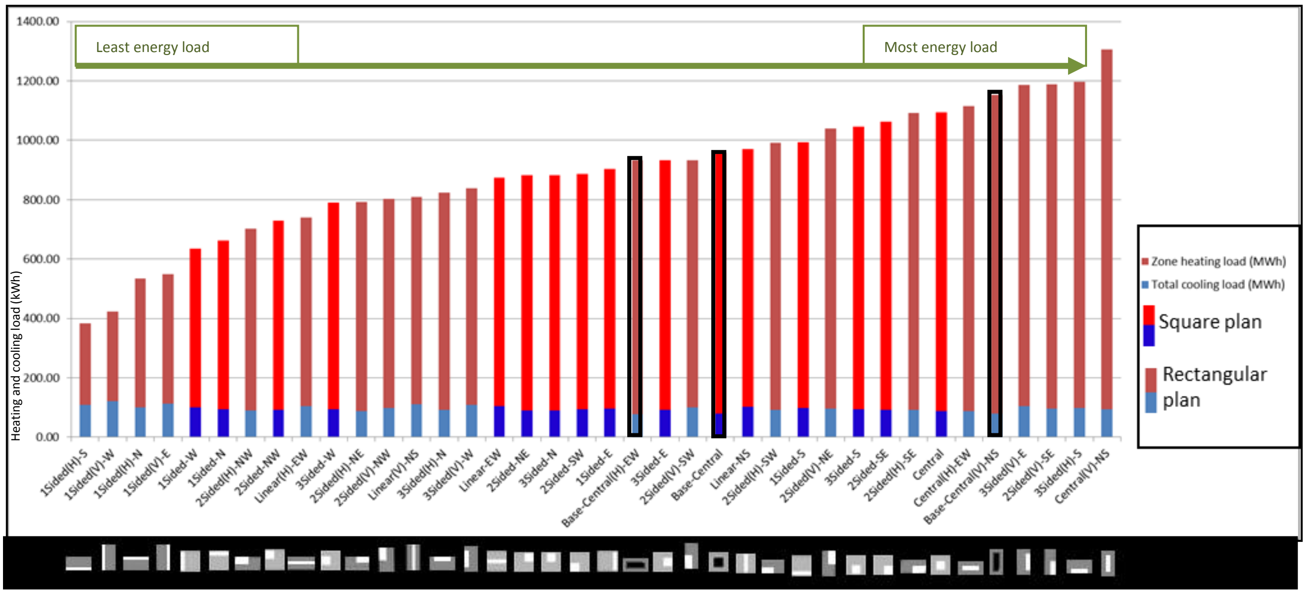
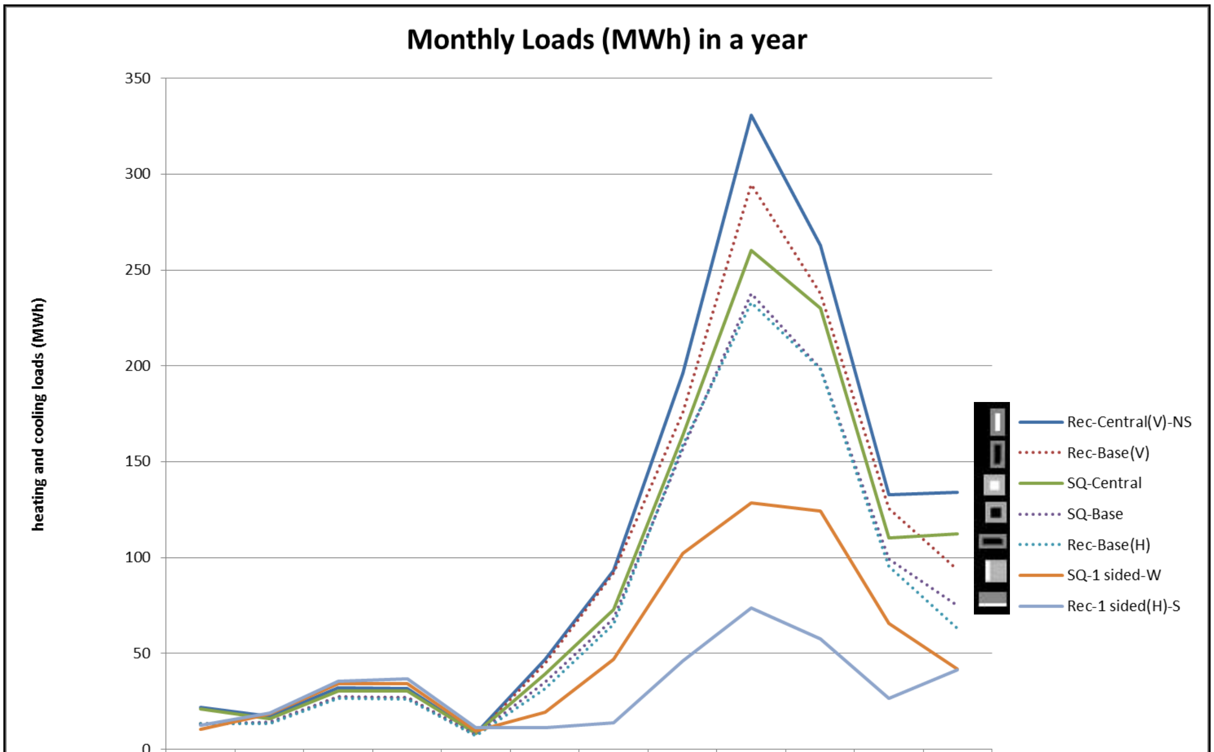


Figure 10. 1: Overall heating and cooling loads in KWh (heating load in red, cooling load in blue)

Figure 10. 1 shows all the models (including the three base cases) with their heating loads in red and their cooling loads in blue. The rectangular models are in the darker colours whilst the square models are in the vibrant colours. This graph also is ordered from the lowest to the greatest annual energy load, from left to right. Figure 10. 1 shows that, over a year, the heating loads are much greater than the cooling loads for both the square and rectangular models. Furthermore, the blue cooling load spectrum shows a greater similarity across all prototypes compared with the red heating load spectrum. It also shows that the first six models with the lowest annual energy loads are the 1-sided model types. Moreover, the six greatest energy loads are for: Sq-Central, Sq-3-sided-S, and sq-2-sided-SE in the square prototype, and likewise rec-central(H)-EW, rec-3-sided(H)-S, and rec-2-sided(V)-SE in the rectangular prototype. So comparing the lowest and highest energy loads in square model

with those in rectangular model shows the same atria placement in square and rectangular models result in similar energy loads.



	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Rec-Central(V)-NS	21.7	17.1	32.06	31.83	8.44	46.87	93.25	196.26	330.92	262.63	132.85	133.89
Rec-Base(V)	13.5	13.89	27.25	27.03	7.23	44.85	91.95	175.73	294.54	237.74	125.53	93.82
SQ-Central	21.1	15.97	30.51	30.21	8.08	39.34	72.82	163.93	260.38	230	110.28	112.27
SQ-Base	12.73	14.14	27.42	27.06	7.37	35.17	68.05	156.73	237.64	198.54	98.99	74.89
Rec-Base(H)	13.46	13.45	26.59	26.16	7	31.79	65.38	158.85	232.81	198.22	95.26	63.17
SQ-1 sided-W	10.2	18.43	34.05	34.09	9.61	19.3	46.87	102.29	128.62	124.32	65.71	41.98
Rec-1 sided(H)-S	12.48	18.94	35.4	36.73	11.04	11.1	13.67	46.13	73.57	57.55	26.64	41.37

Figure 10. 2: Monthly loads in base prototypes as well as the most and least energy consumed prototypes

In Figure 10. 2, the base case prototypes and models with greatest and least annual loads in each rectangular and square model are selected from Figure 10. 1. These have been separately illustrated with their monthly loads throughout a year. Figure 10. 2 shows in more detail that the cool season loads (October –March) for both rectangular and square models are greater than those in the warm season (April- September). Also, it clearly shows that both rectangular and square models have a wider variation of results in the cool season and more similar results in the warm season, as the lines in the graph for the warm season meet. The base cases of both the rectangular and square models tend to be amongst the lowest energy consuming prototypes in the warm season but amongst the greatest energy consuming prototypes in the cool season. This means that it is more energy efficient not to have atria in the warm season but to have atria in the cool season. However, the cool season is the dominant consideration for building design in Tehran; thus, buildings in the area can reduce their energy load and energy consumption by including atria as a passive design feature. However, in the cool season, all models (both square and rectangular) with central atria had the highest heating loads (higher than the base case). Conversely, the sq-1-sided-W and rec-1-sided-S are the lowest energy consuming models with the lowest heating loads in the cool season.

Research on atria type, building shape, atria placement and the orientation of buildings was addressed within the literature review; these findings are compared to the results of this study:

- **Atria type**: Aldawoud (2013) believes that rectangular (as opposed to square) buildings, with central atria are the most energy consuming. However, his research was only on rectangular building orientated on the east-west axis. Never the less, his conclusion is also supported by the results from this thesis. In addition, Aldawoud (2013) states that in rectangular buildings with central atria and aligned on east-west axis, the energy load is lower for the warm than the cool season. Aldawoud (2013) also believes that these types of building have a more energy efficient performance in hot-dry or hot-humid climates than in temperate or cold climates. In this thesis, Rec-central-EW also has a lower energy load for the warm season than the cool season. However, since the cool season is dominant in Tehran, these types of atria are not favourable.

  However, for buildings with no atria in a warm season in Tehran's climate, Faizi et al. (2011) claims that rectangular prototypes consume less energy than square. The results in this study support this statement as they show that both base case-(H)-EW (12.71 kwh/m2) and base case-(V)-NS (13.08 kwh/m2) have a lower energy load in the warm season than the square base case (13.22 kWh/m2).

- **Building shape:** Aldawoud (2013) claims that, between the four prototypes with central atria (three rectangular plan and one square plan), those with the greatest length to width ratios, have poorer energy performances. As such, they have considerably higher annual consumption rates across the following four climates: hot-dry, hot humid, temperate and cold. Thus, for offices with central atria, it is more energy efficient to have a square rather than a rectangular shaped plan. Aldawoud (2013) states that, compared to a square shape, rectangular shaped buildings with central atria perform more energy efficient in a warm season than in a cool season, although annually rectangular form buildings with central atria perform the least energy efficient than the square shape. This thesis also confirms that offices of rectangular plan buildings with central atria have higher annual loads compared to offices with square plan buildings with central atria (Figure 10. 1).

- **Atria placement:** BHRC (2010) argues that atria, or in-between spaces, are more energy officiant for the building to be positioned where the transformation of heat from inside to outside in a cool season is minimized. BHRC (2007) also states that, due to their lower thermal resistance in comparison to other outer surfaces, translucent layers (or external office windows in this case) should not be located on the undesirable, cold fronts of buildings. In addition, Iranian Regulations (BHRC, 2010) clearly state that the most to least energy efficient angles for translucent layers in buildings are south, east and north. The results of this thesis indicate that, generally, atria are more energy efficient for buildings to be positioned on the north and west, which maintain cooler façades during office hours. However, if an atrium is shallow in depth with maximum exposure to the sun, and the offices also have a shallow depth, then the greenhouse effect within an atrium can help significantly in lowering heating loads.

- **Orientation of translucent façades**: Moghaddam et al. (2011) states that a key consideration for ventilation is the outlet openings (such as size and location). Thus, translucent external façades are important impacts on energy loads. Faizi et al. (2011) states that, the N-S orientation in rectangular plan buildings provide minimum shading in a warm season and the elongated southern façades in E-W oreintated rectangular building attract more effective solar radiation in a cool season. Moreover, Taleghani et al. (2014) has worked on orientation of traditional buildings with courtyard and states that the N-S courtyard direction in Iran has the shortest duration of solar radiation and is recommended in hot climates. Meanwhile, the east-west courtyard direction has the longest duration of solar radiation and is more favourable in colder regions. Since the cool season is dominant when considering design in Tehran, it can be concluded that an E-W orientation is more energy efficient. In addition, Soleymanpour et al. (2015) agrees that in cold climates large windows should be orientated towards the south. Likewise, Abdullah and Wang (2012) believes that buildings orientated towards the south in the northern hemisphere (and the north in the southern hemisphere), allow for maximum sunshine in winter and provide protection from peak heat in summer (through the high sun angles on the south side). Also

Iran's regulations (BHRC, 2010) state that buildings could utilise a fair amount of solar energy in winter if they are orientated towards the south. Including more translucent layers on a south façade helps to maximise more of the sun's radiant energy, which is especially beneficial during cold days (BHRC, 2010). Hence, it is more energy efficient to have a larger amount of office windows on the south. This means, for the rectangular prototypes, developing buildings on an E-W axis. Finally, (Reischer, 2016) states that the orientation in Kaveh Glass head office in Tehran which is design with attention to climate, is one of the key element of the design. This building is known to be orientated on an exact east-west direction. The results of this thesis agree with the literature demonstrating that it is more energy efficient to have offices with translucent façades facing the south in Tehran's climate.

Overall, as Sozer et al. (2011) and Moosavi et al. (2014) state, architects must take advantage of sun and wind because as Moosavi et al. (2014) believes, solar radiation, outdoor temperatures, and wind direction and speed are three ambient variables that have a direct effect on buildings. Sozer et al. (2011) and Moosavi et al. (2014) findings are supported by this research as all three affected the simulated design results. Section 10.3 summarises the overall conclusions in a more comprehensive way. Thus, the results of this dissertation can help architects to design atria buildings according to the climate region of Tehran.

10.2 Importance of the pricing policy on the design of energy efficient buildings

This thesis has investigated atria as a passive design element in lowering the energy load and as a result energy consumption in typical office buildings in Tehran. However, the energy cost saving in these prototypes can also explain the impact that Iranian policy has on building climate designs. In order to do so, the costs of the energy per square meter (as of the year 2017) should first be determined.

- **Gas price:** In Tehran, the cost of gas in office buildings is 1500 Iranian Riyals (£0.032 British pound) per m3 (Afkarnews, 2017). Each meter cube is almost equal to 9.92 KWh/m^2. Therefore for each kwh/m2, the gas price is 151.2 Iranian Riyals (£0.003). The cost of gas for both the warm and cool seasons remains the same.

- **Electricity price:** The electricity price in Tehran depends on the amount of electricity used on a monthly bases (Moradi, 2017) (Table 10. 1). The price can vary between 1801 Iranian Riyals (under 100 Kwh) to 2946 (above 600 Kwh) Iranian Riyals (Moradi, 2017). All the examples in this section have used more than 600 kwh, thus the price of electricity is 2946 Iranian Riyals (£ 0.06).

Table 10. 1: Price of electricity usage in Iran

Electricity usage	Price per unite (Iranian Riyal)
Up to 100 kwh	1801
100 to 200 kwh	1882
200 to 300 kwh	1965
300 to 400 kwh	2046
400 to 500 kwh	2291
500 to 600 kwh	2619
Above 600 kwh	2946

For comparison purpose, the value of the building costs in Iran are converted to British pounds instead of Iranian Riyals. Since the energy prices in Iran are subsidised, to enable a better understanding of the relationship between price and energy usage, apart from Iranian energy prices, UK energy prices are also applied to the cases (Table 10. 2).

The subsidised energy prices in Iran compared to the energy prices in the UK, are very different, and this is shown in Table 10. 2. The price of gas in the UK is almost 13 times the cost in Iran, while the price of electricity in the UK is twice as much as in Iran. The huge difference in gas price is because the Iranian government provides considerable subsidies to gas prices.

Table 10. 2: Gas and electricity prices in Iran and UK

Energy	IRAN energy prices per kWh/m2	UK energy prices per kWh/m2
Gas	£ 0.003 (151.2 Riyal)	£ 0.04
Electricity	£ 0.06 (2946 Riyal)	£ 0.13

In order to calculate the heating and cooling costs of a typical office building in Tehran, empirical data is collected. Separate statistics on the heating and cooling loads of office buildings in Tehran were not available; hence, empirical data has been gathered by collecting the gas and electricity bills of a number of office buildings based in the semi-arid climate of Tehran. For a typical office building in Tehran, the gas (used for heating) usage is 129.17 kwh/m2 and the electricity (used for cooling) usage is 35.99 kwh/m2 (see ‘average’ column in Table 7.6) in a year. This means that, based on Iranian energy prices, the heating cost is £0.38/m2 annually and the cooling cost is £2.15/m2 annually, with the overall total being £2.5/m2 for both heating and cooling annually (Table 10. 3). Below are the calculations showing the heating and cooling costs based on Iranian energy prices:

129.17 x 0.003= 0.38 pound per meter square

35.99 x 0.06 = 2.15 pound per meter square

However, if UK energy costs are applied to the typical office building in Iran, the price is considerably higher: the heating cost is £5.16/m2 and the cooling cost is £4.67/m2. This makes the overall total £9.83/m2 (Table 10. 3). Below are the calculations showing the heating and cooling costs based on UK energy prices:

129.17x 0.04= 5.16 pound per meter square

35.99 x 0.13 = 4.67 pound per meter square

Table 10. 3: Heating and cooling energy and costs for typical office buildings and designed prototypes

		building in Iran with Iran energy price				building in Iran with uk energy price		
	Energy	Energy Usage (kwh/m2.y)	Price of unit for 1 kwh/m2 in Iran (£)	Price of gas & electiricty energy usage in Iran (£) per m2 annually	Overall cost for heating and cooling in Iran (£) per m2 annually	*Price of unit for 1 kwh/m2 in UK (£)*	*Price of gas & electiricty energy usage in UK (£) per m2 annually*	*Overall cost for heating and cooling in UK (£) per m2 annually*
Iran typical office building(better practice)	Heating (gas)	129.17	0.003	0.38	***£2.50***	*0.04*	*5.16*	***£9.83***
	Cooling (electricity)	35.99	0.06	2.15		*0.13*	*4.67*	
Average of three base cases	Heating (gas)	156.09	0.003	0.46	***£1.04***	*0.04*	*6.24*	***£7.92***
	Cooling (electricity)	13	0.06	0.77		*0.13*	*1.68*	

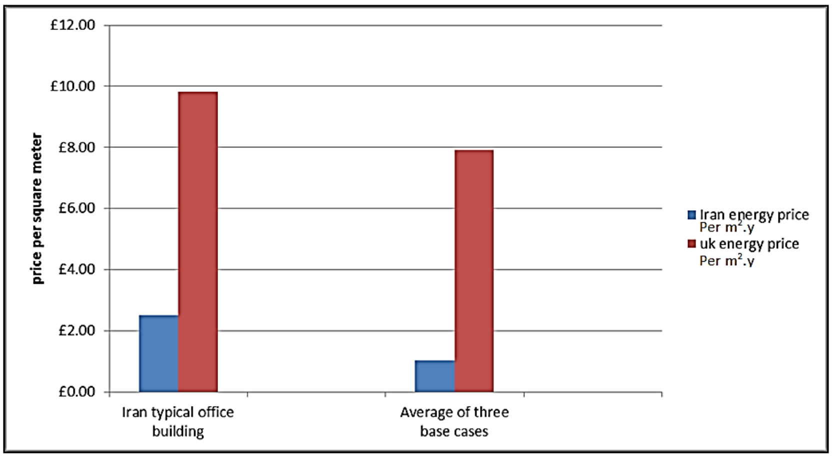


Figure 10. 3: Comparison of the heating and cooling costs with Iranian and UK energy prices

The same calculations were conducted on the square and rectangular plans of the base case prototypes (which are the improved versions of a typical office building). These are shown in Table 10. 4. For example, in Iran, the overall heating and cooling cost of the rectangular base case aligned on the north south axis (rec-base case (V)-NS) is £1.31 per m^2 annually. However, if the UK energy cost is applied, it would be £8.86 per m^2 annually. Thus, the overall costs of the prototypes in Iran with subsidised energy prices are far less than if the buildings had UK energy prices. Developed from the data in Table 10. 4, the average annual loads and costs of the three base cases are shown in Table 10. 3. In this Table, the annual heating and cooling load is 156.09 kwh/m^2.y, with the price of £0.46 per m^2 annually (or £6.24 per m^2 annually if UK energy prices are applied). Also, the average cooling load is 9.67 kwh/m^2.y, with the price of £0.58 per m^2 annually (£1.68 per m^2 annually if UK energy prices are applied).

Table 10. 4: Heating and cooling energy and costs in the three base case prototypes

Prototype cases	Energy	building in Iran with Iran energy price				building in Iran with uk energy price		
		Energy Usage (kwh/m2.y)	Price of unit for 1 kwh/m2 in Iran (£)	Price of gas & electricty energy usage in Iran (£) per m2 annually	Overall cost for heating and cooling in Iran (£) per m2 annually	Price of unit for 1 kwh/m2 in UK (£)	Price of each energy usage in UK (£) per m2 annually	Overall cost for heating and cooling in UK (£) per m2 annually
Square Basecase	Heating (gas)	146.58	0.003	0.43	£1.22	*0.04*	*5.86*	*£7.57*
	Cooling (electricity)	13.22	0.06	0.79		*0.13*	*1.71*	
Rec-Basecase(H)-EW	Heating (gas)	142.66	0.003	0.42	£1.18	*0.04*	*5.7*	*£7.35*
	Cooling (electricity)	12.71	0.06	0.76		*0.13*	*1.65*	
REC Basecase(V)-NS	Heating (gas)	179.05	0.003	0.53	£1.31	*0.04*	*7.16*	*£8.86*
	Cooling (electricity)	13.08	0.06	0.78		*0.13*	*1.7*	

Table 10. 3 summarises the data for typical office buildings in Iran and the average values of base cases and Figure 10. 3 illustrates these values, which are highlighted in red. A difference is noted when comparing the heating and cooling usage of the base case and a typical office building in Iran. The gas usage of the base case is almost within the same range as the gas usage of a typical office building. However, the electricity usage of the base case (which has a higher unit cost) is almost half the usage of a typical office building in Tehran. This is because the Heidari (2009) comfort range has been applied to the base case, meaning that cooling is turned on when temperatures reach above 31°C. However, in typical Tehran office buildings, and in accordance with regulations, cooling is usually switched on when temperatures reach above 25°C. This is a 6-degree difference in the set point for the warm season. However, in the cool season, the heating set point between the two standards does not vary as much (only a degree difference). There is not, therefore, as great a difference in the heating load of the base case and typical office buildings as there is in the cooling load. According to Heidari (2009), the 6°C difference between the standards in the warm season saves a minimum of 40% in cooling energy. Hence, the electricity of the base case is almost half that of a typical office building.

In understanding the differences, it can be seen that the base case costs are similar to a typical office building in Iran. These are based on Iranian energy prices and UK energy prices. In terms of the similar HVAC costs, this again validates that the base case is representative of a typical office building in Iran.

Finally, the cost of all the square plan prototypes are also calculated and represented in Table 10. 5 and illustrated in Figure 10. 4. Also, the cost of all the rectangular plan prototypes are calculated and represented in in Table 10. 6 and illustrated in Figure 10. 5. Where the atria prototypes' energy costs are lower than the base case, they are highlighted in red (shown in the last row of Table 10. 5 and Table 10. 6). These are the designs with potentially lower loads and lower costs compared to a typical office building in Tehran.

Table 10. 5: Heating and cooling energy and cost in square prototypes in a year

SQ		1Sided-N	Base-Central	2Sided-NW	1Sided-W	2Sided-NE	3Sided-W	3Sided-N	2Sided-SW	3Sided-E	1Sided-E	Central	2Sided-SE	3Sided-S	Linear-EW	1Sided-S	Linear-NS
Energy Usage (kwh/m2)	Annual cooling load	15.71	13.22	15.27	16.84	14.91	15.82	15.05	15.56	15.48	15.97	14.72	15.22	15.54	17.28	16.30	16.96
	annual heating load	94.51	146.58	106.16	89.06	132.16	115.93	132.13	132.19	140.00	134.74	167.76	162.02	158.88	128.40	149.18	144.83
Protoypes in Iran with Iran energy price	Cooling Cost/m2.y	0.94	0.79	0.92	1.01	0.89	0.95	0.90	0.93	0.93	0.96	0.88	0.91	0.93	1.04	0.98	1.02
	Heating Cost/m2.y	0.28	0.44	0.32	0.27	0.40	0.35	0.40	0.40	0.42	0.40	0.50	0.49	0.48	0.39	0.45	0.43
	Overall heating and cooling cost/m2.y	1.23	1.23	1.23	1.28	1.29	1.30	1.30	1.33	1.35	1.36	1.39	1.40	1.41	1.42	1.43	1.45
	Annual overall heating and cooling cost of the whole building	7358.01	7397.55	7406.22	7665.39	7746.54	7781.91	7796.28	7979.16	8091.51	8173.89	8318.88	8396.07	8455.44	8530.17	8552.58	8710.65
	annual cost difference of protoype and base case	-39.54	0.00	8.67	267.84	348.99	384.36	398.73	581.61	693.96	776.34	921.33	998.52	1057.89	1132.62	1155.03	1313.10
	annual percentage of saving cost	**0.53**															
Protoypes in Iran with uk energy price	Cooling Cost/m2.y	2.04	1.72	1.98	2.19	1.94	2.06	1.96	2.02	2.01	2.08	1.91	1.98	2.02	2.25	2.12	2.20
	Heating Cost/m2.y	3.78	5.86	4.25	3.56	5.29	4.64	5.29	5.29	5.60	5.39	6.71	6.48	6.36	5.14	5.97	5.79
	Overall heating and cooling cost/m2.y	5.82	7.58	6.23	5.75	7.22	6.69	7.24	7.31	7.61	7.47	8.62	8.46	8.38	7.38	8.09	8.00
	Annual overall heating and cooling cost of the whole building	34939.20	45489.60	37384.30	34508.40	43349.00	40162.40	43449.40	43857.70	45670.60	44792.50	51744.00	50756.50	50255.00	44290.10	48515.10	47982.90
	Annual cost difference of protoype and base case	-10550.40	0.00	-8105.30	-10981.20	-2140.60	-5327.20	-2040.20	-1631.90	181.00	-697.10	6254.40	5266.90	4765.40	-1199.50	3025.50	2493.30
	Annual percentage of saving cost	**23.19**	**0.00**	**17.82**	**24.14**	**4.71**	**11.71**	**4.48**	**3.59**		**1.53**				**2.64**		

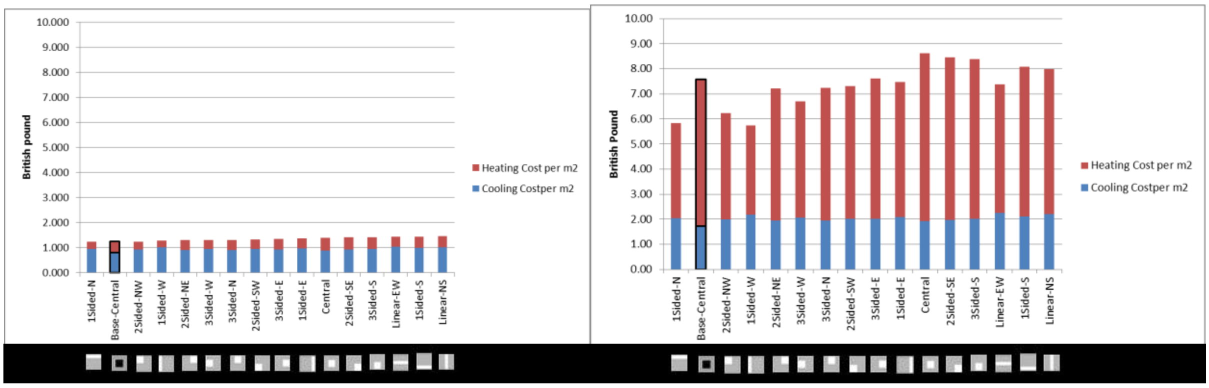


Figure 10. 4: Left SQ prototype with Iranian energy prices, right: SQ prototype with UK energy prices

Table 10. 6: Heating and cooling energy and costs in rectangular prototypes

REC		1Sided(H)-N	1Sided(H)-S	1Sided(V)-E	1Sided(V)-W	2Sided(H)-NW	2Sided(H)-NE	2Sided(H)-SW	2Sided(H)-SE	2Sided(V)-NW	2Sided(V)-NE	2Sided(V)-SW	2Sided(V)-SE	3Sided(H)-N	3Sided(H)-S	3Sided(V)-E	3Sided(V)-W	Linear(V)-NS	Linear(H)-EW	Central(V)-NS	Central(H)-EW	Base-Central(V)-NS	Base-Central(H)-EW
Energy Usage (kwh/m2)	Annual cooling load	16.76	17.88	18.68	20.22	14.93	14.64	15.27	15.26	16.41	15.95	16.67	16.07	15.41	16.25	17.24	18.11	18.45	17.37	15.52	14.60	13.08	12.71
	annual heating load	72.14	46.02	72.81	50.49	102.07	117.47	149.82	166.70	117.36	157.34	138.87	182.00	121.74	183.29	180.34	121.55	116.30	105.87	201.98	171.21	179.05	142.66
Protoypes in Iran with Iran energy price	Cooling Cost/m2.y	1.01	1.07	1.12	1.21	0.90	0.88	0.92	0.92	0.98	0.96	1.00	0.96	0.92	0.97	1.03	1.09	1.11	1.04	0.93	0.88	0.78	0.76
	Heating Cost/m2.y	0.22	0.14	0.22	0.15	0.31	0.35	0.45	0.50	0.35	0.47	0.42	0.55	0.37	0.55	0.54	0.36	0.35	0.32	0.61	0.51	0.54	0.43
	Overall heating and cooling cost/m2.y	1.22	1.21	1.34	1.36	1.20	1.23	1.37	1.42	1.34	1.43	1.42	1.51	1.29	1.52	1.58	1.45	1.46	1.36	1.54	1.39	1.32	1.19
	Annual overall heating and cooling cost of the whole building	7333.23	7263.90	8033.52	8187.39	7210.29	7385.37	8193.27	8492.62	8020.62	8572.32	8499.57	9059.91	7737.03	9148.08	9451.86	8706.93	8734.20	8159.40	9223.50	8335.89	7932.36	7141.65
	annual cost difference of protoype and base case	191.58	122.25	891.87	1045.74	68.64	243.72	1051.62	1350.97	878.97	1430.67	1357.92	1918.26	595.38	2006.43	2310.21	1565.28	1592.55	1017.75	2081.85	1194.24	790.71	0.00
	annual percentage of saving cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Protoypes in Iran with uk energy price	Cooling Cost/m2.y	2.18	2.32	2.43	2.63	1.94	1.90	1.98	1.98	2.13	2.07	2.17	2.09	2.00	2.11	2.24	2.35	2.40	2.26	2.02	1.90	1.70	1.65
	Heating Cost/m2.y	2.89	1.84	2.91	2.02	4.08	4.70	5.99	6.67	4.69	6.29	5.55	7.28	4.87	7.33	7.21	4.86	4.65	4.23	8.08	6.85	7.16	5.71
	Overall heating and cooling cost/m2.y	5.06	4.16	5.34	4.65	6.02	6.60	7.98	8.65	6.83	8.37	7.72	9.37	6.87	9.44	9.45	7.22	7.05	6.49	10.10	8.75	8.86	7.36
	Annual overall heating and cooling cost of the whole building	30387.80	24987.80	32040.10	27887.50	36138.70	39612.10	47866.24	51907.77	40966.70	50198.70	46327.60	56210.80	41232.30	56662.80	56726.70	43296.90	42300.40	38957.90	60582.90	52473.30	53176.50	44147.90
	Annual cost difference of protoype and base case	-13760.10	-19160.10	-12107.80	-16260.40	-8009.20	-4535.80	3718.34	7759.87	-3181.20	6050.80	2179.70	12062.90	-2915.60	12514.90	12578.80	-851.00	-1847.50	-5190.00	16435.00	8325.40	9028.60	0.00
	Annual percentage of saving cost	**31.17**	**43.40**	**27.43**	**36.83**	**18.14**	**10.27**			**7.21**				**6.60**			**1.93**	**4.18**	**11.76**				

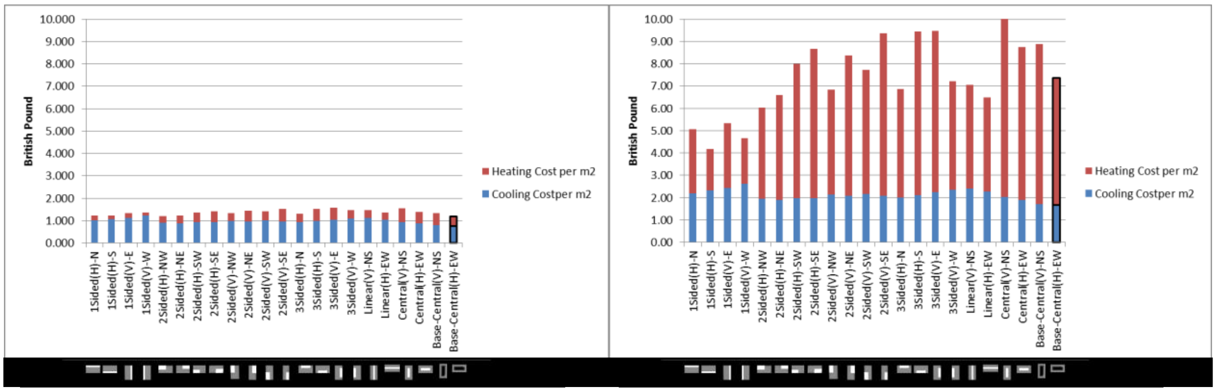


Figure 10. 5: left REC prototype with Iranian energy prices, right :REC prototype with UK energy prices

As energy costs are low in Iran, only the 1-sided-N has a lower price in the square plan prototypes than the base case. However, it is only 0.5% lower which is not significant. In comparison, no rectangular building prototype has a lower cost than the base case.

Nevertheless, if these prototypes use UK energy prices instead the cost results vary considerably. By looking into the last row of both Table 10. 5 and Table 10. 6, the prototypes with a significant reduction in their heating and cooling energy costs are apparent. In the square prototype, 1-sided-W, 1-sided-N, 2-sided-NW, and 3-sided-W have more than a 10% saving compared to the base case. These prototypes show the most to least energy savings in comparison to the base, ranging from 24% to 11%. This is also the same order for the top four least to most annual heating and cooling loads for the square prototype. Of the rectangular models, the prototype with the most energy savings is 1-sided (H)-S with a 43% saving compared to the base case. This is followed by: 1-sided-W, 1-sided-N, 1-sided-E, 2-sided-NW, linear-EW and 2-sided-(H)-NE. These have, respectively, the most to least energy savings, which are greater than 10% compared to the base. This is also the exact order of the top seven least to most annual heating and cooling loads.

Hence, it can be concluded that, with current situation, even though the energy load is lower amongst some of the prototypes with atria, the energy costs are not significantly reduced. This is because the heating loads are much higher than the cooling loads in a typical Tehran office building. This was true for the base cases and all designed prototypes. In other words, heating loads have a greater share of the annual energy loads than the cooling loads; therefore, designs should aim to minimise heating loads. Gas is the major energy source for heating, and electricity the major energy source for cooling. However, gas prices are very cheap in Iran due to subsidies; gas is 1/20th of the electricity price in Iran (in UK gas is almost 1/3rd of electricity price). In Iran, the overall cost of heating typical office buildings, is far less than for cooling. Thus, people are encouraged to spend more on heating instead of making adjustments to building designs to reduce the need for additional (non passive) heating. Nevertheless, the Iranian government could address this by ratifying a correct energy efficient policy in buildings in order to save energy and promote energy efficient buildings.

10.3 Research summary

With a population density of 12,896 persons per square kilometre (Population of 2017, 2017), Tehran is one of the most populated cities in the world where the pace of high-rise building construction is increasing. However, most of the high-rise structures are poorly designed and do not take into account the specificity of Tehran's climatic conditions (Farahi, 2012; Khodabakhsh & Mofidi, 2001; Maleki, 2011). The three main reasons for this are: subsidised energy that keeps energy costs low; the downgrade of the Iranian currency which means that customers prefer to buy cheaper buildings, and the lack of building regulation and enforcement of legislation to promote the consideration of energy consumption. A result of not considering climate in design means that Tehran's buildings have high-energy consumption rates (369 kwh/m2 as the average annual energy consumption). However, Iran's traditional architecture demonstrates successful models of sustainable practice that make the most of natural energy sources.

This thesis examined the possibility of applying these principles of vernacular architecture to the design of Tehran's tall buildings in order to, as D. Diba (2012) states, address the design generation gap between vernacular and modern buildings. One successful traditional design feature from the region is the courtyard. As a modern passive design technique, atria have been inspired by courtyard. According to Hashemi et al. (2010), the use of openings on the inside (such as courtyards and gardens) helps to minimise heating and cooling loads. The same principle has been applied to the open spaces of atria within a building. According to Moosavi et al. (2014), atria can present a potential solution to passively lower energy loads. Aldawoud (2013) also states that well-designed atria could reduce the demand to condition spaces artificially. It is concluded that, with considerable advantages, carefully designed atria could provide potential energy savings in tall buildings.

The focus of this thesis was on office buildings (high-rise) as they are amongst the most energy consuming buildings in Iran using an average of 350 kwh/m2 (Bagheri et al., 2013)**.** In Tehran, 70% of all services are centralized (Tehran Municipality, 2014). Moreover, in Iran 61% of a building's energy is used for HVAC (Riazi & Hosseyni, 2011), which contrasts significantly with the 33% used worldwide (Salib & Wood, 2013). Because of the poor design of buildings, HVAC has been used throughout most of the year to provide thermal comfort (Khodabakhsh & Mofidi, 2001; Moghaddam et al., 2011). Also, offices consume a greater percentage of gas and electircity compared with residential buildings (International Energy Agency, 2015) (Figure 3.2). Through the careful use of atria in tall building design, this thesis aimed to minimize the energy used by HVAC in offices, in providing thermal comfort. Atria as discussed are inspired by courtyards, and are a successful passive design feature of vernacular architecture. They are known as climate modifiers (Moosavi et al., 2014) that can help with heating and cooling loads, and according to Göçer et al. (2006), should be included in buildings of Middle-East warm countries. However, not many publications address the successful implementation of buildings with atria in Iran. This is because, in this region, they are not designed with the purpose of energy saving but rather as an architecture feature (Assadi et al., 2011). Also, the architectural designs developed that consider their local climate tend not to be built (Shahriari et al., 2013). Therefore, there is limited research on the use of atria in Tehran's semi-arid climate and no guidelines regarding their optimum use. It was suggested that research needs to be conducted on the performance of atria in this region and that the natural heating and cooling systems in multi-storey buildings should be renewed (Maleki, 2011).

Thermal comfort is one of the most important parameters when designing buildings (Douvlou, 2003). The thesis critically reviewed acceptable levels of thermal comfort in Tehran and explained that, since Tehran does not experience extreme humidity, the research would focus on air temperature to investigate occupant comfort. Tehran's semi-arid climate has westerly prevailing wind in the cool seasons and a southerly prevailing wind in the warm seasons. As such, the thermal comfort temperature range in large spaces is almost 18 to 26 degrees Celsius in the cool season, and 24 to 31 degrees Celsius in the warm season (Heidari, 2009, 2010a). Heidari (2009) believes that, compared to Iranian standards, this comfort range saves 40% in cooling and 25% in energy overall.

In order to calculate the energy consumption in achieving thermal comfort in offices with atria, typical Tehran office blocks were designed as prototypes for the simulation program. Typical Tehran buildings are mostly cubical with either square or rectangular plan buildings; thus, the prototypes used these two configurations. Prototypes without an atrium were also simulated and called base cases. The energy load of the base cases were compared against empirical data that were collected from existing office buildings in Tehran to ensure the prototypes were in the same value range. The prototypes were then developed from the base case, and five types of atrium were introduced as the basic shapes, which were incorporated in the prototype designs (Figure 7.4 in chapter 7). The rectangular and square base cases were used as reference points, or benchmarks, for the other prototypes with atria; as such, the prototype results were compared with the benchmarks. The prototypes with lower results than the benchmarks were considered to have lower energy consumption. From these results and analysis, the final conclusions were derived.

This thesis adopted a Design Science Research methodology and followed its steps. The rationale for using a computer simulation program (Design Builder) and a digital rather than a scale model was also explained in chapter 6. This rationale included the time required for the simulation as well as the elements that could not have otherwise been easily included, namely: the occupancy, activity, clothing and equipment heat production.

The simulation of the rectangular and square model was investigated in the two modes of NV and HVAC+NV during both the warm and cool seasons. Apart from the simulations that were conducted as pilot studies, 152 simulations were developed and the results produced were based on hourly output intervals throughout a full year. One of the main results from the simulations was the "office hours of discomfort" (the hours outside the air temperature comfort range) during the cool and warm seasons for each model. This was when only natural ventilation was in place. The percentage of hours in the comfort range, as opposed to the overall office hours, was also calculated. The other main results were the heating and cooling loads in the cool and warm seasons for each model when HVAC, as well as NV, was also included. Secondary outputs were also generated which were used to help analyse the reasons behind the final conclusions.

Six parameters were introduced as secondary outputs, whose values changed throughout the different prototypes and modes. These parameters were: the heat loss via external windows; the heat loss via internal windows (windows overlooking atria); the heat gain via glazing; the solar gains via external windows; the solar gains via internal windows, and the airflow rate. However, by performing regression analysis, some of these parameters proved to be insignificant in the energy load results.

The comparison of the model results were divided into four sections:

A. A comparison of the discomfort hours in each model in NV mode in each of the rectangular and square plan prototypes

B. A comparison of the heating and cooling loads in each model in HVAC+NV mode in each of the rectangular and square plan prototypes

C. A final comparison of the rectangular and square plan prototype results in all modes over a year.

D. A comparison of the heat gains and losses in each model via the standardisation techniques and regression analysis in HVAC+NV modes in the cool season for both rectangular and square prototypes

Points A, B and D were addressed in Chapters 8 and 9 and point C in Section 10.1. Section 10.2 also briefly covers the effect of the cost on climatic design in Tehran. The further sections are the summary of the overall conclusions derived from the results, limitations and conclusions, recommendations and suggestions for future studies.

10.4 Conclusions of findings

- **Atria prototype performances in warm and cool seasons (rectangular and square prototypes):** It was noted that both the rectangular and square prototypes behaved similarly in warm season but differently in cool season. Figure 10. 6 shows that, in NV mode, the rectangular and square prototypes had a very similar number of uncomfortable hot hours in a warm season. Thus in Figure 10. 1, the cooling load value of all the prototypes was similar. However, in a cool season, the number of uncomfortable cold hours was not as similar amongst the prototypes (Figure 10. 6). As a result, the heating loads were also very different between the prototypes, as shown in Figure 10. 1. Thus, in terms of their energy load and number of uncomfortable hours the difference between the prototypes was greater in a cool season, but similar in a warm seasons. This pattern of the energy load is clearly shown in Figure 10. 2.

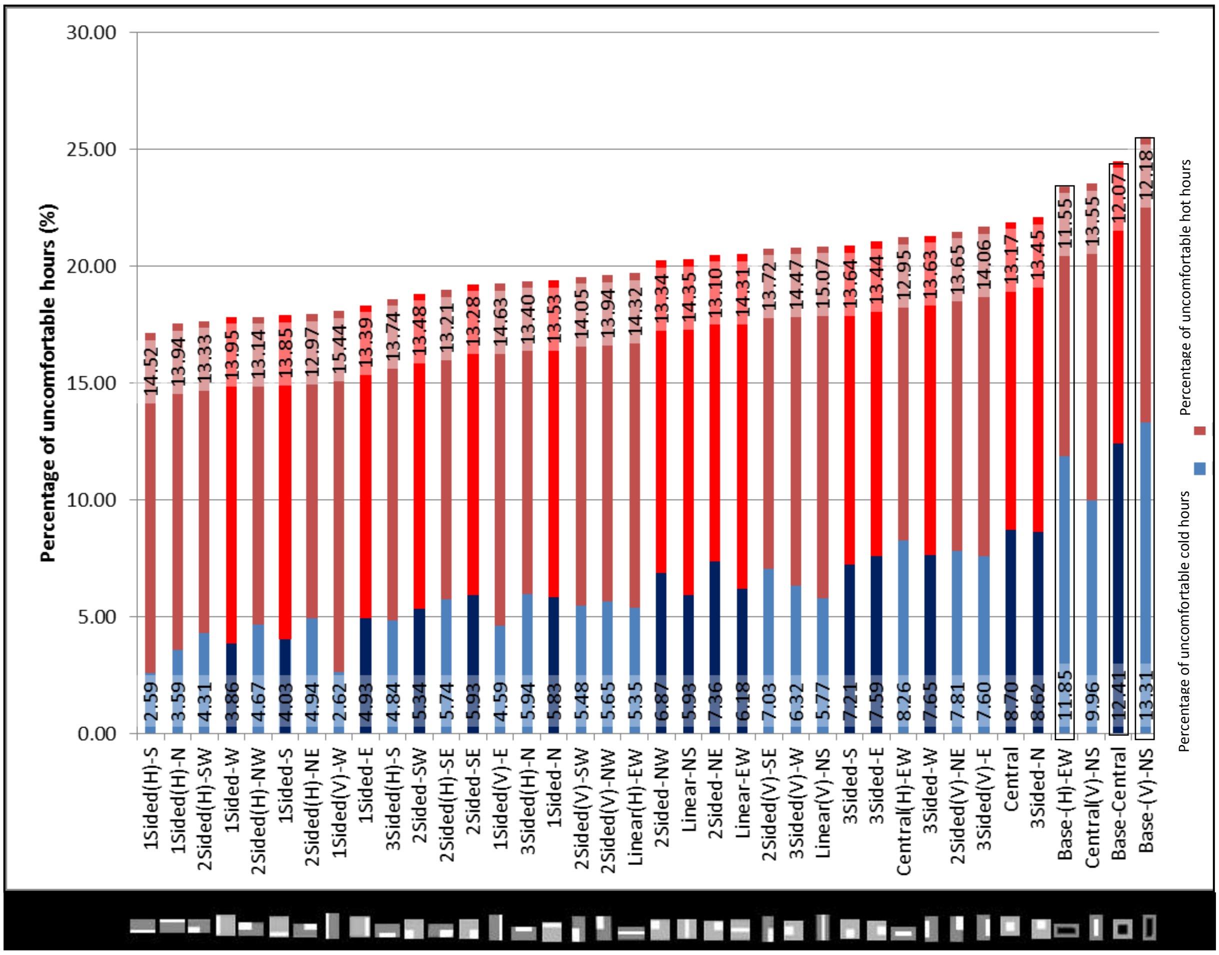


Figure 10. 6: Rectangular and Square prototypes percentage of uncomfortable hours (in ascending order)

- **Relationship between the uncomfortable hours and energy loads in the warm and cool seasons (rectangular and square prototypes)**: Across all prototypes, the heating loads were much greater in the cool season, than the cooling loads in the warm season (Figure 10. 1). For example, the Rec-base-(V) was the most energy consuming prototype (Figure 10. 2), where the heating load was more than 19 times the cooling load over the peak months. In comparison, the Rec-1-sided(H)S was the lowest energy consuming prototype (Figure 10. 2), where the heating load was only twice the cooling load over the peak months; thus, the overall energy load remained high. However, according to Figure 10. 6 the number of uncomfortable hours was much lower for a cool season than a warm season. This means that a small amount of cold hours needs a large amount of energy to heat up the offices in a cool season, whereas a large number of hot hours demand far less energy to cool down the offices in a warm season.

- **The dominant season (rectangular and square prototypes)**: There are several indications that affirm that the cool season is dominant in Tehran and thus most important to design for. Even though the uncomfortable hot hours are greater in number than the uncomfortable cold hours, the cooling loads are lower than the heating loads. Therefore, the energy consumed in providing thermally comfortable temperatures in a warm season is actually less than in a cool season. Moreover, the order of the prototypes from least to most uncomfortable hours in a year is similar to the order of the prototypes for the cool season (from least to most cold hours). The results of annual uncomfortable hours (Figure 8.3 in square prototype and Figure 9.3 in rectangular prototype) and uncomfortable cold hours (Figure 8.2 in square prototype and Figure 9.2 in rectangular prototype) are shown in chapters 8 and 9. The same pattern is seen between the annual energy loads (Figure 8.9 in square prototype and Figure 9.9 in rectangular prototype) and the heating loads (Figure 8.5 in square prototype and Figure 9.5 in rectangular prototype). This indicates that, even though the annual results are comprised of both the warm and cool seasons, the effect of the cool season is reflected more in the annual uncomfortable hour and energy load graphs.

- **The dominant factor in a cool season (rectangular and square prototypes):** The dominant factor that most affects the heating load results is the “external window heat loss”. Thus, considering the external window area and its placement is important when designing buildings as the greater the heat loss via the external office windows, the greater the potential heating load.

- **Rectangular VS square prototypes building performance:** The low energy-consuming prototypes (Figure 10.1) and the prototypes with low number of uncomfortable hours (Figure 10. 6) are amongst the rectangular models rather than the square. This is because the rectangular model has less depth in its offices and atria, and thus has the potential to heat up quickly. Shallower offices help the heat to penetrate more, and, if it comes into contact with the sun, a narrower atrium can act more effectively as a greenhouse compared to one with more depth. As a direct result of more heat gain, less energy is consumed in providing thermal comfort. Faizi et al. (2011) also agree that, in Tehran, rectangular plan buildings have a lower energy load than square plan buildings.

- **The building orientation (rectangular prototypes):** The results of this research show that, for the semi-arid climate of Tehran, the most translucent façades on the rectangular prototype are most energy efficient for the building to be positioned on the south followed by the east. Positioning the translucent facades (external office windows) on the south followed by east in rectangular buildings helps with lowering the heating loads in a cool season (Explanation would be made in later bullet points as to why in the 1 sided type atrium the prototypes with 1-sided-S and 1-sided-E atria, which have their external office windows on the north and west façade also have low heating loads in their offices). Even though the number of hot hours is greater than the number of cold hours, most of the energy load occurs in the cool season in order to warm up the building. Thus, in Tehran, it is preferable to have the most translucent façades on the south and east for their direct heat gains. This is because the east façade receives the morning sun while the south receives the afternoon sun, and they both contribute towards heating the building over office hours. This orientation is also effective in a warm season when the angle of the sun is high on the south façade. This contrasts with the cool season when the east and west sun angle is low. Hence in the warm season, heat cannot penetrate deeply into the buildings from the south façade.

- **Atrium or no atrium (base cases):** even though buildings with no atrium are beneficial in a warm season, the overall annual results demonstrate that having an atrium is beneficial in Tehran. This is because the cool season is dominant and has a significant effect on the annual outcome. Thus, if atria are designed correctly they are beneficial in lowering the energy loads and in providing thermal comfort. However, it would be wrong to state that the inclusion of atria would always lead to a reduction in energy load and energy consumption. In some cases, buildings with atria perform worse than the base cases where no atrium is included. For example, the prototypes with offices overlooking a central atria consumed a high amount of energy over both the cool season and annually when compared to their base cases (Figure 10. 1).

- **Atria placement (square and rectangular prototypes):** The results of the simulation exercise show that the location of an atrium needs careful consideration. The analysis in Chapters 8 and 9 show that it is generally more energy efficient not to include any of the five types of atrium if designing for the warm season in Tehran's climate. However, as the cool season is dominant, atria in this season contribute considerably to lowering heating loads. As such, the atrium's placement is important.

  In the cool season, it is more energy efficient for the atrium to be located on the west and/or north to minimise any heat loss from the coldest façades. The location of an atrium on the north and/or west reduces the external window area on these façades and, as a result, the external window heat loss (Figure 8.11 and Figure 9.12). A closed atrium on the north and west acts as an insulation space for office buildings. Meanwhile, offices gain direct heat from the south and east as they have more exposure to the morning and afternoon sun, and become the warm façades during office hours.

- **The characteristics of 1-sided protoypes with south and east atria (rectangular and square plan models):** Despite the finding that, in a cool season, it is more energy efficient to have atria on the north or west to block wind and minimise heat loss (in both square and rectangular prototype), the 1-sided atrium (H)S and the 1-sided atrium(V)E in the rectangular prototype demanded far less heating than most other rectangular prorotypes (unlike what happened in square prototype). This is because of the three characteristics of these two models; firstly, they have narrow depth atria; secondly, there is greater exposure of the atria to the sun, which creates more greenhouse effect,; finally they have narrow depth offices which allows for more heat penetration. Furthermore:

  1. The greater the greenhouse effect created in the atria, the more they can assist with heating loads in a cool season. This can be achieved through long, thin atria glass façades which expose a large area of the atrium to the sun. It helps the atria to heat up faster and hence assists with the office heating loads. In contrast, if the atria is shorter and deeper, its greenhouse effect is not as great; hence, for the same square meter, the 1-sided-S and 1-sided-E square configurations do not produce the same

energy load results as the rectangular models. Thus, the atria on the south and east façades of the square buildings are greater heating load models.

2. For the same office area, the square prototypes have deeper offices than the rectangular models and the impact of the atria, in terms of lowering heating loads, on deeper offices is less significant. This is because the warmth of the atria cannot cover as great an area as a rectagular shape with less office depth. In these cases, minimising the translucent surfaces on cool façade, blocking the wind, and avoiding external window heat loss becames more important. Thus, help in lowering heating loads can be accessed from less external office window heat loss, where atria act as an insulation wall on a cold façade to block the impact of wind on office temperatures. Alternatively, it can be accessed from greater heat gains, which can occur through the exposure of atria with long thin façades.

- **The amount of savings through using atria (square and rectangular prototypes):** Figure 10. 7 and Figure 10. 8 shows the percentange reduction of energy loads in all square and rectangular prototypes with atria compared to the base cases (base cases represent a typical office buildings in Tehran and has been validated in chapter 7). After simulation, the square protytpes with the lowest heating and cooling loads showed a reduction of 33.71% in energy loads (Figure 10. 7). In the rectangular models, the prototypes with the lowest heating and cooling loads showed a reduction of 58.79% in energy (Figure 10. 8). Assadi et al. (2011) has claimed that atria has helped the heating loads to decrease 25% in a 3 story residential building in Tehran. This thesis also confirms a considerable amount of saving energy loads in a year. Hence, it can be concluded that, if atria are designed and used properly in accordance with their climate, they can be beneficial in lowering energy load and energy consumption. This is particularly the case for high-rise office buildings in Tehran, if the designs are based on rectangular configurations

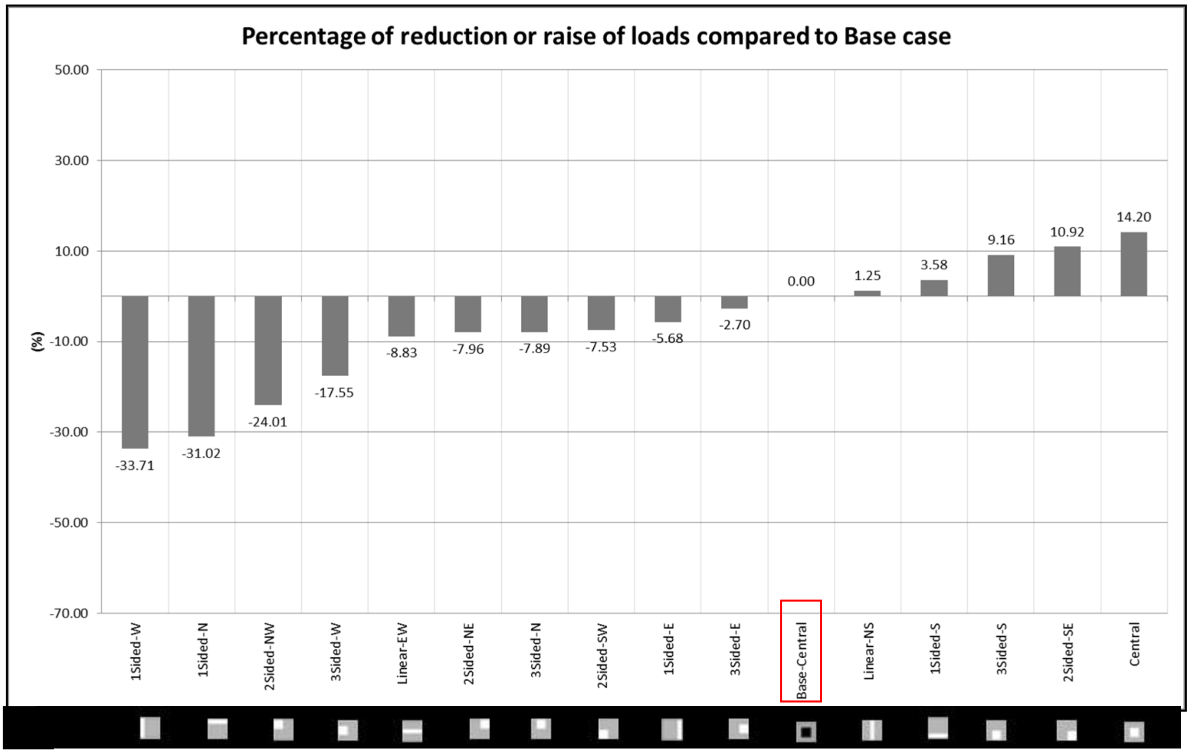


Figure 10. 7: Percentage reduction or raise in energy loads compared to the base case-central in square prototypes

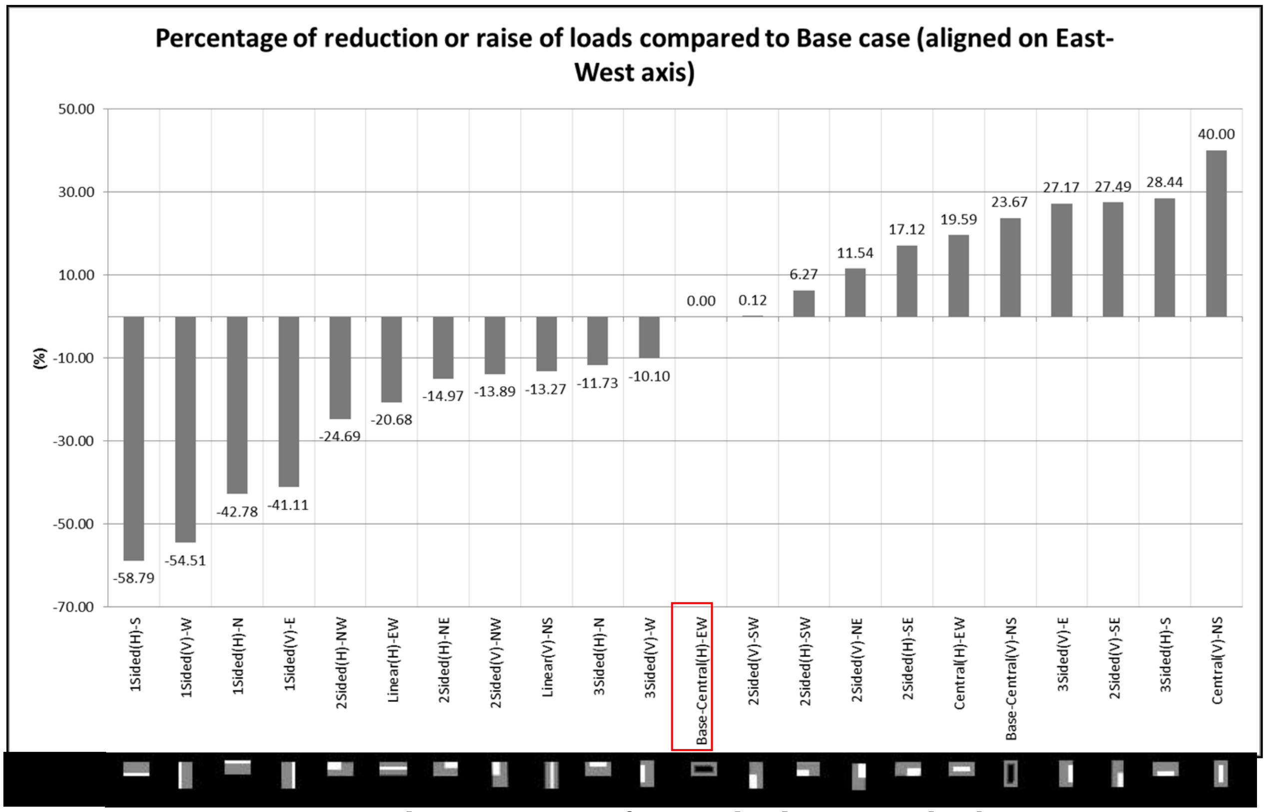


Figure 10. 8: Percentage reduction or raise of energy loads compared to base case-central(V)-NS in rectangular porotypes

10.5 Building design recommendation based on the results

Design guidelines for the semi-arid climate of Tehran are derived from the final results. The design guidelines stemmed from the results and the researches are as follows:

- Using atrium in high-rise open plan office buildings can be beneficial in Tehran in terms of lowering annual heating and cooling loads.
- A rectangular configuration has the potential to save more in heating and cooling energy than a square configuration
- In terms of their annual energy loads, buildings orientated towards the east-west axis are potentially more efficient than north-south orientation.
- The cool season is the dominant season to design for in Tehran.
- The external window heat loss from offices is the most important parameters that affect the heating loads in the dominant cool season.
- The atrium location is more energy efficient when located on the west or north façade, with external office windows exposed to east and south façade (assuming the atria top is closed in the cool season)
- The atria depth, office depth and atria exposure to the sun are parameters that have a significant effect on the annual energy loads (the shallower the depth of office and atria, the greater the exposure of the atria to heat, and the more energy efficient the building should be).
- The low energy cost of gas, the main heating source in buildings, has discouraged clients from designing buildings that make best use of passive solar gains in cool seasons; the dominate season of excessive energy use in Tehran’s office buildings. Therefore, it is advised that the government has to enforce an appropriate energy efficiency policy.
- The government should also modify the building codes for standard sustainable building practice for office buildings in Iran.
- Promote a positive change in office buildings could be done by using the opinions of commented inventors, engaging owners and occupants of such buildings.

10.6 Research contribution to knowledge

Sobek (2011) claims that the next generation of building designers need to ensure a better natural light supply, better fresh air supply and the reuse of energy conservation in order to cool or heat air and passive designs are the promising way forward to create sustainable buildings with less energy consumption. This thesis provides new insights and evidence of the element of atria design as a passive design element that can help to provide more comfort levels, supply better fresh air, potentially provide a better natural light supply, and act as conservers of heat and cold air. In addition, the knowledge developed in this thesis would further support the importance of local knowledge and environmental context in the sustainable design of contemporary buildings. The Head of Iran Energy Efficiency Organization (IEEO-SABA) also declared that the country has the potential to achieve zero energy buildings by 2030 (ISNA, 2015). Hence, this research could contribute towards the aim of achieving zero energy buildings for 2030 through developing sustainable design practices to office buildings design.

There has been very little research done on buildings with atria in Tehran region. One of the reasons for the unconstrained use of energy in the building sector is the subsidised energy prices. The low cost of energy led to the disregard of sustainable design practices. The thesis acknowledges the fact that the low energy cost of gas, the main heating source in buildings, has discouraged clients from designing buildings that make best use of passive solar gains in cool seasons; the dominate season of excessive energy use in Tehran's office buildings. This research could persuade the government to enforce an appropriate energy efficiency policy.

Most of the existing research on atria buildings are on low-rise, whilst very little has been conducted on high-rise construction. This thesis extends the knowledge of atria passive design in high-rise buildings. The thesis addresses a gap in knowledge of atria energy performance in tall buildings in semi-arid climate. The thesis also provides information on the impact of different configurations of atria buildings (rectangular (2:1 ratio) and square porotype) on heating and cooling loads.

Moosavi et al. (2014) believe that there is a lack of knowledge about the influences of design parameters on the thermal conditions of buildings with atria. This research examined the impact of atria on the overall building performance (particularly in the dominate season of energy consumption in semi-arid climate of Tehran). The thesis identifies that the parameter that most affects the thermal comfort within a tall office building in semi-arid climate of

Tehran is the amount of heat loss via external windows of offices. Therefore, the external window positions and exposure to sun is of most importance to energy efficiency and thermal comfort in this region.

Last but not least, this dissertation has provided a set of unique and original results regarding the effect of different atria configurations on the thermal comfort and energy loads of open plan high-rise office buildings in the semi-arid climate of Tehran. The recommendations could help government to further develop the regulation in the light of the proposed guidelines of design tall office building in the semi-arid region of Tehran. Information provided in this thesis could also help architects to design more energy efficient atria buildings. The results will provide bases for future research in atria design and energy efficiency in office buildings and other typologies.

10.7 Limitations

Even though this thesis has achieved its aim and objectives, some limitations exist.

- There has been limited empirical data available in Tehran office buildings which meant that a complete set of information on buildings was either not available or access was limited (i.e. the exact square meter of offices in some cases).
- The software on the computer performed slowly and, including the trial and error simulation, the overall simulation period took more time than initially anticipated. If the software had been faster, the researcher could have conducted more simulations regarding other aspects (for example, other configurations).
- Air flow was the only other aspect that changed between the prototypes; however, this was not investigated because it was outside the scope and time of this thesis. However, a regression analysis (appendix 4) did confirm the relative insignificance of this parameter on the heating loads.
- Even though in Tehran each unit has a different electricity meter, the whole building usually shares the same gas meter and therefore the gas bill is divided between units regardless of their usage percentage. Thus, in the empirical data gathered, only offices that occupy a whole building can provide correct gas bill usage. Hence only these type of offices could be selected as cases to collect empirical data.

- The percentage of gas used for heating offices was not available but the percentage of gas used for heating buildings in general was available. Hence this percentage (73%) was used to calculate the heating loads for the cases (the cases for which the empirical data was collected).

10.8 Direction for further research

This thesis examined different configurations of atria buildings and their impact on thermal comfort and energy loads in semi-arid climate of Tehran. Further research can be conducted on other configurations such aerodynamic buildings which are also favourable in skyscrapers. Moreover, this thesis focuses on semi-arid climate region. There is a scope to extend this research to other climatic regions. Moreover, other techniques combined with atria can be investigated in order to enhance the thermal comfort of buildings such as segmentation of atria spaces or using double skin façades to lower the energy consumption in buildings. Further research could also be done on identifying the facilitators of the barriers to design/technology transfer with industry, university and government partners internationally and produce a feasible report for investors identifying the most commercially viable atria solutions for determined market with a roadmap for implementations. Also additional research can be conducted on encouraging all levels of government to take the lead in innovative atria design/ construction, by implementing a scheme of incentives for construction of such buildings. In addition it is important to advance the evidence-base policy and practice through a user-centred approach to office building post-occupancy evaluation and effective understanding of feedback.

Efficient use of energy and resources is one of the topical subjects and sustainable architecture is the leading idea in designing contemporary buildings. Vernacular architecture gives historical clues, evident by human experiences, to enhance our understanding for future cities. It is hoped that this and future researches would help to provide living and working spaces which are more sustainable, more energy efficient and less damaging to the human environment.

Appendices

Appendix 1: Example bills of the cases

This is an example gas bill for case B that shows the gas usage for almost two months in cubic meter.

نام مشترك : خانم خديجه شيخ حسيني	شهر : تهران	تعداد واحد : ١
نشاني : * * *	كد حوزه : ٠٠٥	گروه : B
شماره اشتراك : ٠٠٣١٠٨٩٤١٣٤٥ - ٠٣٠٣٠١٠٥٦٦٨٤٩٠٩	سريال كنتور : ٠٠٠٠٠٢٧٠٧٦	ظرفيت : ١٠
كد آدرس : ٥٢١٣٠٥٨٦٠٠٠٠	شماره پرونده : ٥٦٦٨٤٩	نوع مصرف : تجاري

تاريخ قرائت پيشين	تاريخ قرائت فعلي	رقم شمارش گر پيشين	رقم شمارشگر فعلي	كاركرد شمارشگر	مصرف استاندارد
٩٤ / ٠٦ / ٢٣	٩٤ / ٠٨ / ٠٤	٨٤,٧٣١	٨٦,١٦٦	١,٤٣٥	١,٤٤٥
بهاي گاز مصرفي	آبونمان	عوارض	بيمه	بدهي متفرقه	مانده بدهي
٢,١٦٠,٢٧٥	٦١,٩٣٠	١٩٩,٩٩٨	٠	٠	٠
مانده صورتحساب قبلي	تعداد بدهي	شماره سري	مانده مبلغ هزار ريال	كسر مبلغ هزار ريال	عوارض گازرساني به روستا
٠	٠	١٤٥	٧٥	٣٠٥	٢١٦,٠٢٧

مبلغ قابل پرداخت	مهلت پرداخت	شناسه پرداخت	شناسه قبض
٢,٦٣٨,٠٠٠	٩٤ / ٠٩ / ٢٩	٠٠٠٠٢٦٣٨١٤٥٢٨	٠١٠٨٩٤١٣٠٦٢٣٤

This is an example electricity bill for case B which shows the electricity usage for two months in kWh. It also shows the electricity usage for the previous year.

چاپ قبض اينترنتي کاربر: تاریخ: ۱۳۹۵/۰۵/۲۳ شماره صندوق پستی وزیر نیرو : ۰۲۱-۸۸۶۴۴۸۵۰ کاربر: تاریخ : ۱۳۹۵/۰۵/۲۳

مشترک محترم: شکراله سمیعی خلجابادی
نشانی : م ونک خ ونک خ خدامی بعدازآرارات
کد پستی : . پلاک : ۴
پرونده : ۶۵۰۷۳۱/۰ رمز رایانه : ۰۳۹۲۵۵۹/۵
شناسایی : ۲/۱۲/۳۲۰۲۰/۲۶/۶۶۰۰۰ تعداد خانوار :
عنوان و کد تعرفه : ۲-۵(سایرمصارف) نوع فعالیت : .
بدنه کنتور : ۱۰۴۰۶۴۱۲ فاز/آمپر: ۱۰/۳
تاریخ نصب : ۵۲/۰۷/۰۳ ارقام/ضریب کنتور : ۱/۵
تاریخ انقضاء پروانه: ۹۹/۹۹/۹۹ نحوه قرائت کنتور: مامور۰۰
صدور صورتحساب : ۹۳/۰۲/۰۷ مراجعه بندی : .
منطقه برق : منطقه برق بیهقی
آدرس منطقه : خ کاندی خ نوزدهم پلاک۲۶
تلفن واحد حوادث :
پاسخگویی صورتحساب: ۸۸۷۷۶۴۳۴

شناسه قبض	شناسه پرداخت

دوره-متوسط	۱	۲	۳	۴	۵	۶
سال گذشته					۴۶۲۵	۴۴۸۱
سال جاری	۳۹۴۸	۴۱۲۷	۴۷۴۱	۴۵۹۶	۳۸۲۰	۳۹۲۳

شرح	تاریخ	میان باری	اوج بار	کم باری	دوره
قرائت کنونی	۹۲/۱۱/۰۵	۹۴۶۷۰	۰	۰	۹۲-۶
قرائت پیشین	۹۲/۰۹/۱۳	۹۱۲۷۰	۰	۰	
مصرف (kWh)		۳۴۰۰	۰	۰	

مصرف کل کنتور (kWh): ۳۴۰۰
متوسط مصرف ۳۰روز : ۱۹۶۱/۵۴ تعداد روز: ۵۲

تعداد روز آخرین تغییرات: ۵۲ مصرف آخرین تغییرات: ۳۴۰۰

پله های مصرف	نرخ	مصرف	مبلغ ۳۰ روزه	فرمول محاسبه و مبلغ
تا مصرف ۱۰۰	۱۳۶۴	۱۰۰	۱۳۶۴۰۰	۵۳۴۵۰۰
تا ۲۰۰ مازاد بر ۱۰۰	۱۴۲۶	۱۰۰	۱۴۲۶۰۰	
تا ۳۰۰ مازاد بر ۲۰۰	۱۴۸۸	۱۰۰	۱۴۸۸۰۰	
تا ۴۰۰ مازاد بر ۳۰۰	۱۵۵۰	۱۰۰	۱۵۵۰۰۰	
تا ۵۰۰ مازاد بر ۴۰۰	۱۷۲۶	۱۰۰	۱۷۲۶۰۰	
تا ۶۰۰ مازاد بر ۵۰۰	۱۹۸۴	۱۰۰	۱۹۸۴۰۰	
مازاد بر ۶۰۰	۲۲۳۲	۱۳۶۱/۵۴	۳۰۳۸۹۵۳	

بهای انرژی با نرخ متوسط ۱۸۶۰ ریال محاسبه شده است
هزینه مصرف اوج بار = ریال۴۹۶ x میزان مصرف در اوج بار
تخفیف مصرف کم باری = ریال۴۲۸ x میزان مصرف در کم باری
تعداد روز قبل از سال۹۰: ۰ مصرف قبل از سال۹۰: ۰
مبلغ قبل از سال ۹۰ (ریال): ۰

عنوان	مبلغ (ریال)
مبلغ مصرف	۴۸۶۴۶۱
مبلغ قبل از آخرین تغییرات	۴۷۰۷۶۹۱
بهای برق دوره	۵۱۹۴۱۵۲
مالیات ارزش افزوده	۲۱۱۶۴۹
عوارض برق	۱۰۳۰۰۰
بستانکاری	۵۵۰۷۴۴۲
کسر هزار ریال	۵۶۹

مبلغ قابل پرداخت: ۱۰۰۰۰۰ ریال
مهلت پرداخت: ۹۳/۰۳/۲۲

شناسایی : ۲/۱۲/۳۲۰۲۰/۲۶/۶۶۰۰۰
پرونده: ۶۵۰۷۳۱/۰

رمز رایانه	دوره	سال
۰۳۹۲۵۵۹/۵	۰۶	۹۲

شناسه قبض

شناسه پرداخت

واریز به حساب سپهر
محل پرداخت:
۴ مبلغ قابل پرداخت: ۱۰۰۰۰۰ ریال
یکصد هزار ریال

Appendix 2: Tehran energy plus climate data

This file shows which climatic data has been considered in generating the results of the thesis prototypes in the Design Builder software.

Climate Consultant 6.0 BETA (Build 3, Nov 18, 2014)

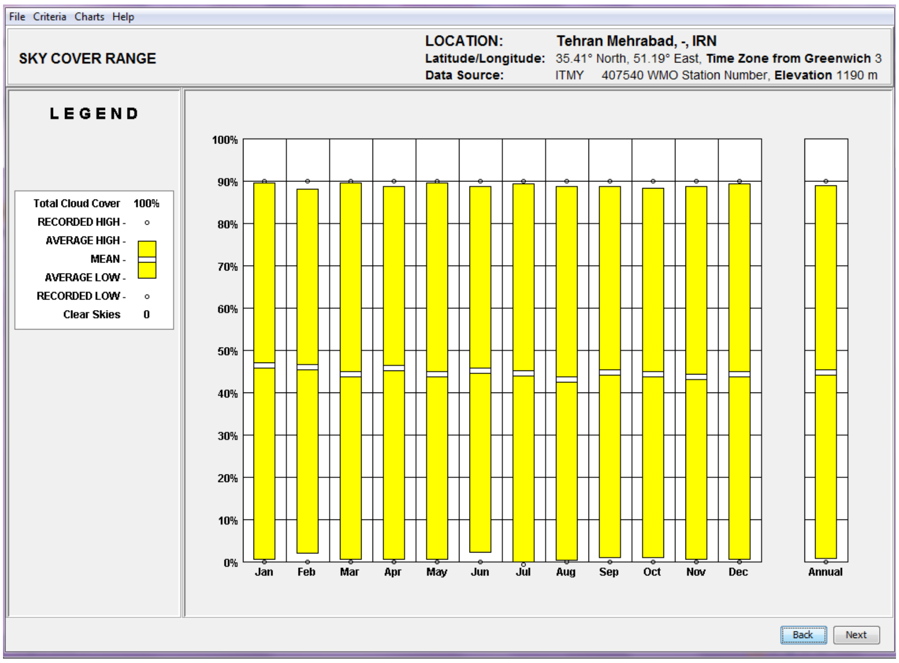
File Criteria Charts Help

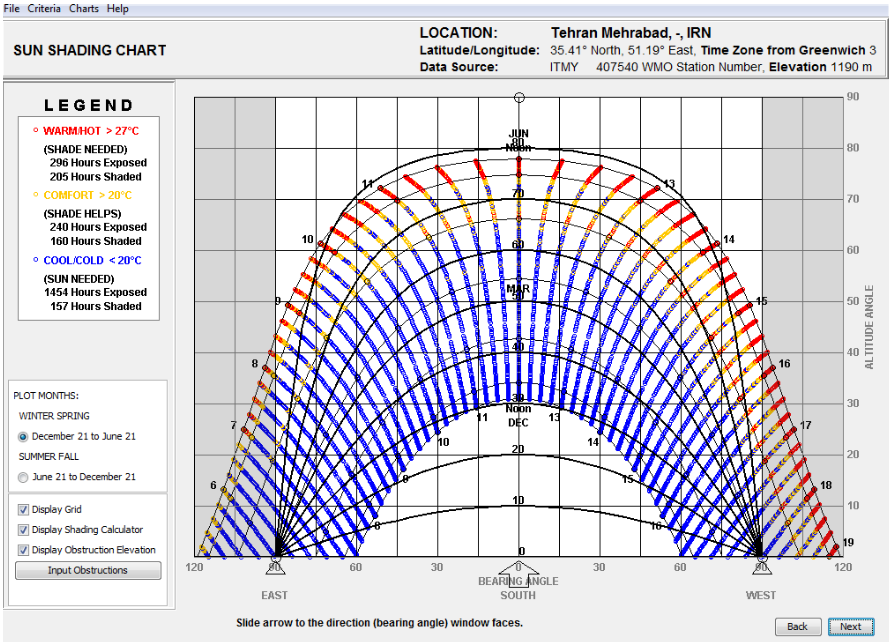
WEATHER DATA SUMMARY

LOCATION: **Tehran Mehrabad, -, IRN**
Latitude/Longitude: 35.41° North, 51.19° East, **Time Zone from Greenwich** 3
Data Source: ITMY 407540 WMO Station Number, **Elevation** 1190 m

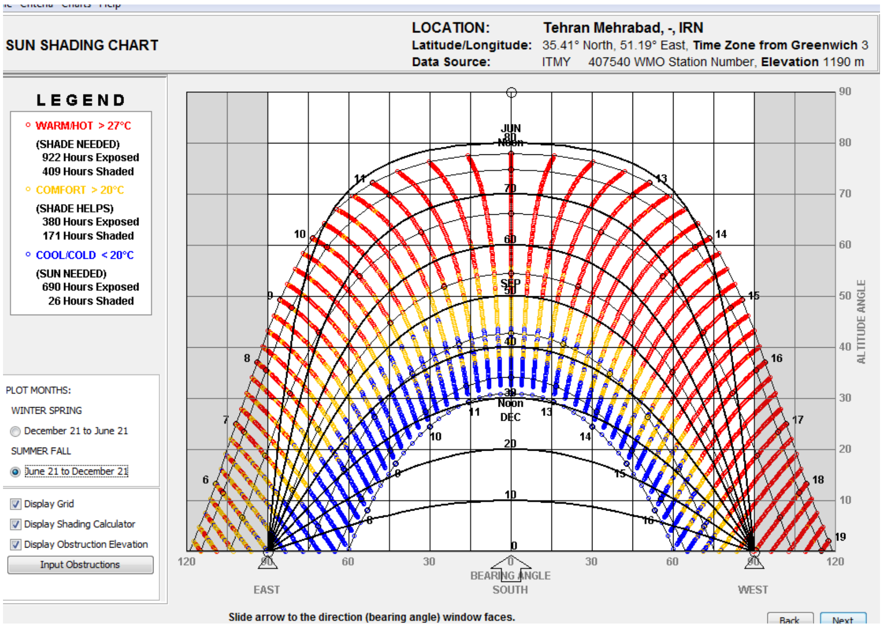
MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	308	391	465	500	571	609	565	588	557	449	390	291	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	310	354	352	286	406	501	383	498	554	447	535	299	Wh/sq.m
Diffuse Radiation (Avg Hourly)	182	214	257	312	289	265	301	254	216	211	153	170	Wh/sq.m
Global Horiz Radiation (Max Hourly)	557	713	852	894	1012	1069	995	1042	1001	819	710	503	Wh/sq.m
Direct Normal Radiation (Max Hourly)	437	523	522	413	565	670	516	689	775	637	750	437	Wh/sq.m
Diffuse Radiation (Max Hourly)	312	369	452	540	479	417	497	406	344	361	249	271	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	3057	4170	5504	6475	7948	8741	7985	7827	6807	4975	3954	2814	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	3074	3765	4163	3704	5641	7199	5415	6622	6777	4935	5413	2885	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1809	2281	3050	4042	4028	3802	4250	3385	2651	2346	1553	1642	Wh/sq.m
Global Horiz Illumination (Avg Hourly)													lux
Direct Normal Illumination (Avg Hourly)													lux
Dry Bulb Temperature (Avg Monthly)	3	4	10	16	21	28	29	30	25	17	11	5	degrees C
Dew Point Temperature (Avg Monthly)	-3	-3	0	0	3	2	6	6	4	2	0	-1	degrees C
Relative Humidity (Avg Monthly)	60	56	49	38	34	21	25	24	25	38	49	62	percent
Wind Direction (Monthly Mode)	270	270	280	280	270	270	290	180	180	280	0	290	degrees
Wind Speed (Avg Monthly)	2	2	3	4	3	3	2	1	2	3	2	1	m/s
Ground Temperature (Avg Monthly of 3 Depths)	9	8	8	10	15	20	23	25	24	22	17	13	degrees C

Back Next

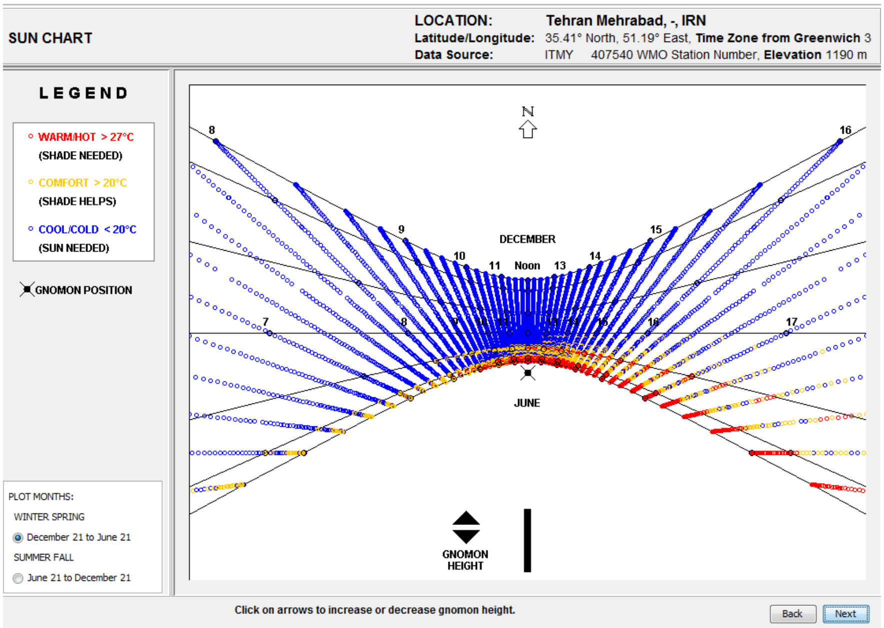




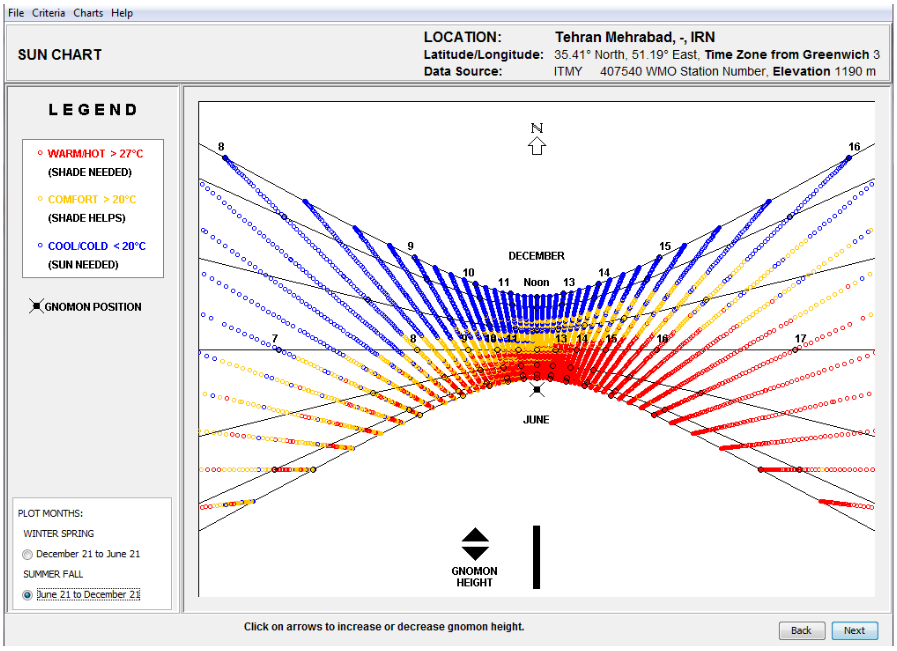
File Criteria Charts Help
SUN SHADING CHART
LOCATION: Tehran Mehrabad, -, IRN
Latitude/Longitude: 35.41° North, 51.19° East, Time Zone from Greenwich 3
Data Source: ITMY 407540 WMO Station Number, Elevation 1190 m
LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
296 Hours Exposed
205 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
240 Hours Exposed
160 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
1454 Hours Exposed
157 Hours Shaded
PLOT MONTHS:
WINTER SPRING
December 21 to June 21
SUMMER FALL
June 21 to December 21
Display Grid
Display Shading Calculator
Display Obstruction Elevation
Input Obstructions
ALTITUDE ANGLE
BEARING ANGLE
EAST
SOUTH
WEST
Slide arrow to the direction (bearing angle) window faces.
Back
Next



SUN SHADING CHART
LOCATION: Tehran Mehrabad, -, IRN
Latitude/Longitude: 35.41° North, 51.19° East, Time Zone from Greenwich 3
Data Source: ITMY 407540 WMO Station Number, Elevation 1190 m
LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
922 Hours Exposed
409 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
380 Hours Exposed
171 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
690 Hours Exposed
26 Hours Shaded
PLOT MONTHS:
WINTER SPRING
December 21 to June 21
SUMMER FALL
June 21 to December 21
Display Grid
Display Shading Calculator
Display Obstruction Elevation
Input Obstructions
ALTITUDE ANGLE
BEARING ANGLE
EAST
SOUTH
WEST
Slide arrow to the direction (bearing angle) window faces.
Back
Next



SUN CHART
LOCATION: Tehran Mehrabad, -, IRN
Latitude/Longitude: 35.41° North, 51.19° East, Time Zone from Greenwich 3
Data Source: ITMY 407540 WMO Station Number, Elevation 1190 m
LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
COMFORT > 20°C
(SHADE HELPS)
COOL/COLD < 20°C
(SUN NEEDED)
GNOMON POSITION
PLOT MONTHS:
WINTER SPRING
December 21 to June 21
SUMMER FALL
June 21 to December 21
N
DECEMBER
JUNE
GNOMON HEIGHT
Click on arrows to increase or decrease gnomon height.
Back
Next



File Criteria Charts Help
SUN CHART
LOCATION: Tehran Mehrabad, -, IRN
Latitude/Longitude: 35.41° North, 51.19° East, Time Zone from Greenwich 3
Data Source: ITMY 407540 WMO Station Number, Elevation 1190 m
LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
COMFORT > 20°C
(SHADE HELPS)
COOL/COLD < 20°C
(SUN NEEDED)
GNOMON POSITION
PLOT MONTHS:
WINTER SPRING
December 21 to June 21
SUMMER FALL
June 21 to December 21
N
DECEMBER
JUNE
GNOMON HEIGHT
Click on arrows to increase or decrease gnomon height.
Back
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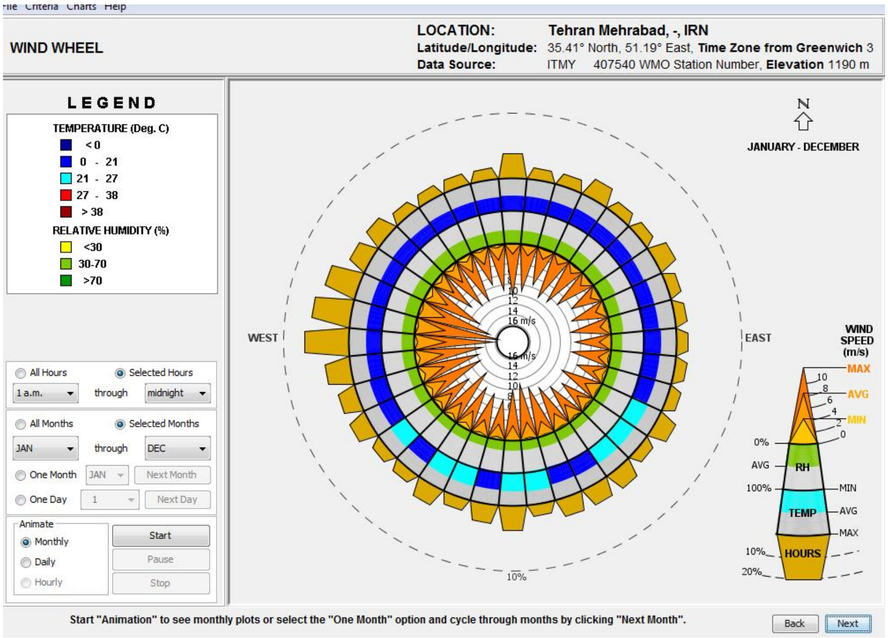
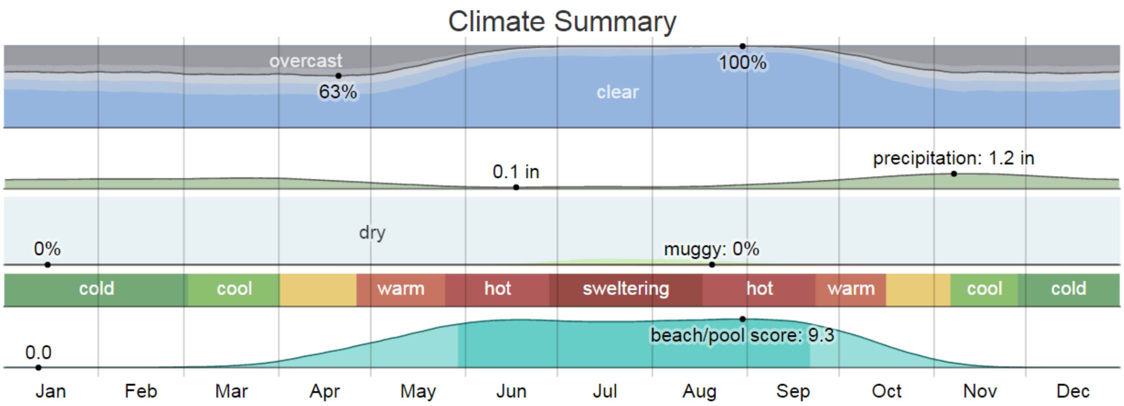
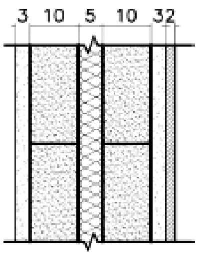




A summary of Tehran climatic data as shown by (Weather Spark, n.d.)

Appendix 3: Prototype material

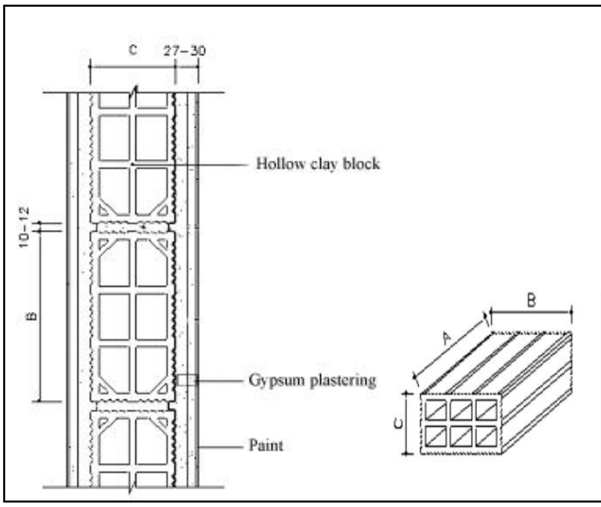
- External wall: ACC block with 6 layers as above with the U-value of 0.37 w/m2k provides a high degree of comfort for buildings occupants especially in cold season of Tehran (Mohammad & Shea, 2013).



Plaster lining (3 cm)
AAC block (10 cm)
Cavity filled with expanded polystyrene (EPS) (5 cm)
AAC block (10 cm)
Sand & cement mortar (3 cm)
Exterior stone finishing (2 cm)

External wall material detail

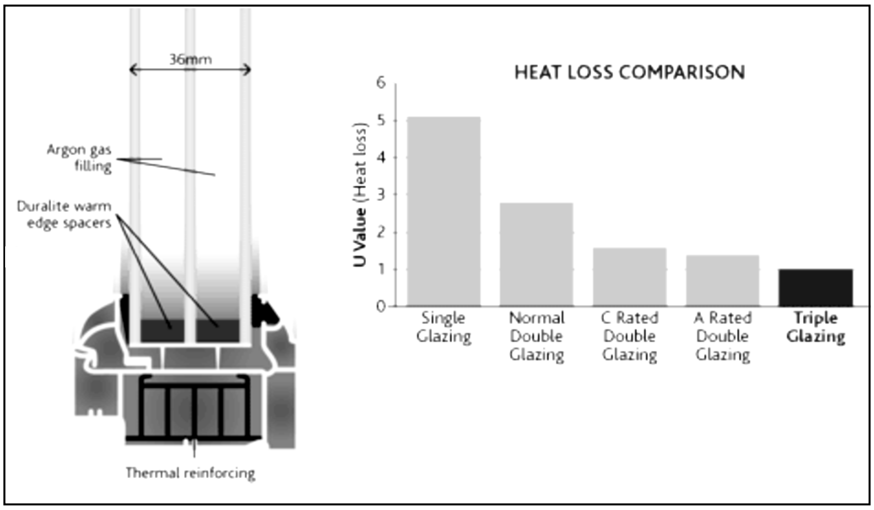
- Internal walls: the internal wall material is hollow clay block with the details illustrated below. This material is one of the commonly used internal walls in Iran (Planning and Budget Organization).



value in cm	hollow clay block
250 ± 3	A
200 ± 2	B
100 ± 2	C

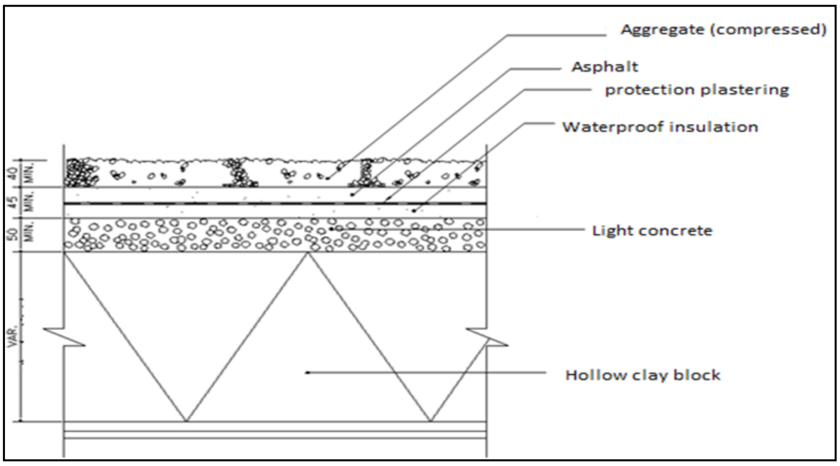
Internal wall material detail

- Office and atria windows: the windows material is triple low E (e2=e5=1) clear 3 mm/13mm filled with argon (figure below). Windows play an important role in consumption of energy in buildings. Using multiple glazing windows helps to reduce the energy consumption and contributes greatly in the heating costs (UBCT, n.a). ArpanCo (n.a) and UBCT (n.a) claim that the u value of single glazed façade is around 5 W/m^2k and a double glazing façade is about 1.6 W/m^2k. However by adding another glazed unit, the u-value can go down by half reaching 0.8 W/m^2k for a triple glazing façade. This number as stated by UBCT (n.a) reflects the considerable impact of triple glazing façade. Therefore this thesis also uses triple glazing for the external envelope.



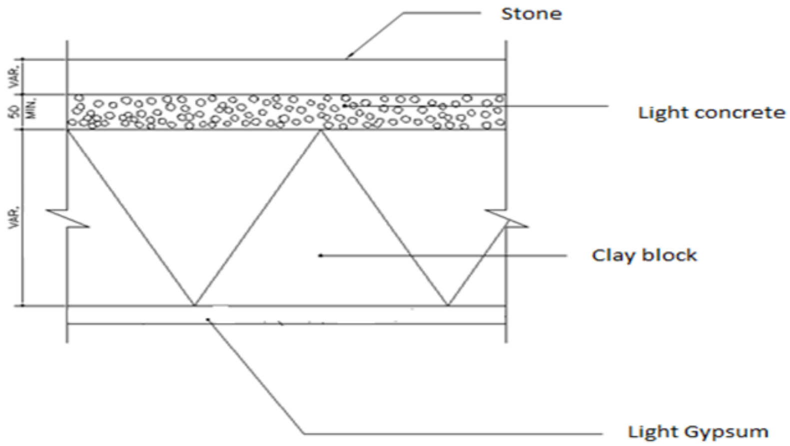
Material detail of the windows

- Roof: the roof commonly used in Tehran is a flat roof with the specification of the U-value 1.03 W/m^2k and details illustrated below.



Material detail of the roof

- Office floor: the typical floor material used in offices is illustrated below with the U-value of 1.30 W/m^2K.



Material detail of the floor

- Shading: The type of shade in Tehran semi arid climate which helps most in energy loads is known to be highly reflective blinds positioning outside. This option is selected via doing few simulations and its effect on buildings

Appendix 4: Regression analysis of all secondary parameters including airflow

The two tables below show that with the prototype circumstances in cool season and the atria being closed from top. The airflow rate inside the offices is another output that differs in prototypes; however, this thesis does not investigate this parameter as it is related to fluid dynamics, which is outside the scope of this research and also it has an insignificant role in the heating load results in the square and rectangular prototypes.

Rectangular prototype	*Coefficients*	*P-value*
Intercept	-140.9322546	4.52191E-05
Heat gain via glazing gain (MWh)	-1.003630921	0.000314874
solar gain via external window (MWh)	0.367390273	0.052643067
Heat loss via external windows (MWh)	0.893318881	3.22688E-18
solar gain via internal window (MWh)	-0.691954335	0.015418332
heat loss via internal windows (MWh)	0.357051227	3.82755E-05
airflow rate (ac/h)	1.395097108	0.300464847

Square prototype	*Coefficients*	*P-value*
Intercept	42.74563676	0.853927547
Heat gain via glazing gain (MWh)	2.408783707	0.112777628
solar gain via external window (MWh)	-3.280525646	0.085007354
Heat loss via external windows (MWh)	1.298778753	0.002774586
solar gain via internal window (MWh)	-0.020455216	0.970238181
Heat loss via internal windows (MWh)	-0.284814811	0.218756511
Airflow (ac/h)	-89.92302509	0.221832479

Appendix 5: Example of output data

Data Outputs for prototype of Rec 1 sided (H)-W (as an example) in the Warm season and cool season NV mode and in working hours only is shown as the average of 6 months. Some of the terms have been changed in the thesis txt. As such the list is as follow:

In this thesis 'glazing' is referred to as 'glazing gain', 'internal natural ventilation' is referred to as 'internal window heat loss' and 'external air' is referred to as 'external window heat loss'.

	Warm season NV mode
Room Electricity (MWh)	124.09
Lighting (MWh)	12.06
DHW (Electricity) (MWh)	12.71
Air Temperature (°C)	28.46
Radiant Temperature (°C)	29.66
Operative Temperature (°C)	29.06
Outside Dry-Bulb Temperature (°C)	25.39
Glazing (MWh)	679.17
Internal Natural vent. (MWh)	-453.34
External Air (MWh)	-427.79
General Lighting (MWh)	12.06
Computer + Equip (MWh)	124.09
Occupancy (MWh)	33.11
Solar Gains Interior Windows (MWh)	25.74
Solar Gains Exterior Windows (MWh)	518.58
Mech Vent + Nat Vent + Infiltration (ac/h)	26.45

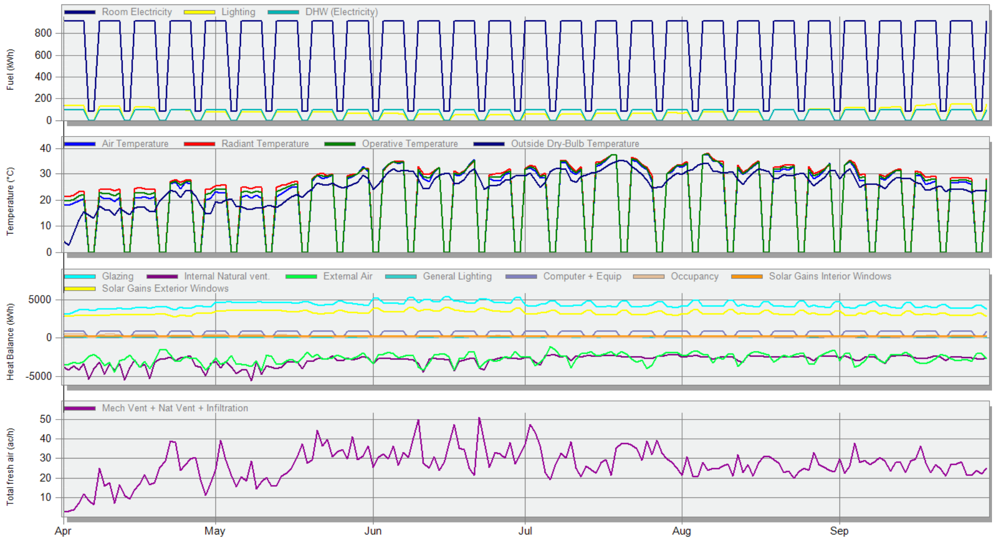
	Cool season NV mode
Room Electricity (MWh)	123.17
Lighting (MWh)	25.82
DHW (Electricity) (MWh)	12.61
Air Temperature (°C)	20.43
Radiant Temperature (°C)	22.91
Operative Temperature (°C)	21.67
Outside Dry-Bulb Temperature (°C)	9.11
Glazing (MWh)	409.94
Internal Natural vent. (MWh)	-64.97
External Air (MWh)	-469.83
General Lighting (MWh)	25.82
Computer + Equip (MWh)	123.17
Occupancy (MWh)	61.39
Solar Gains Interior Windows (MWh)	16.43
Solar Gains Exterior Windows (MWh)	388.34
Mech Vent + Nat Vent + Infiltration (ac/h)	3.44

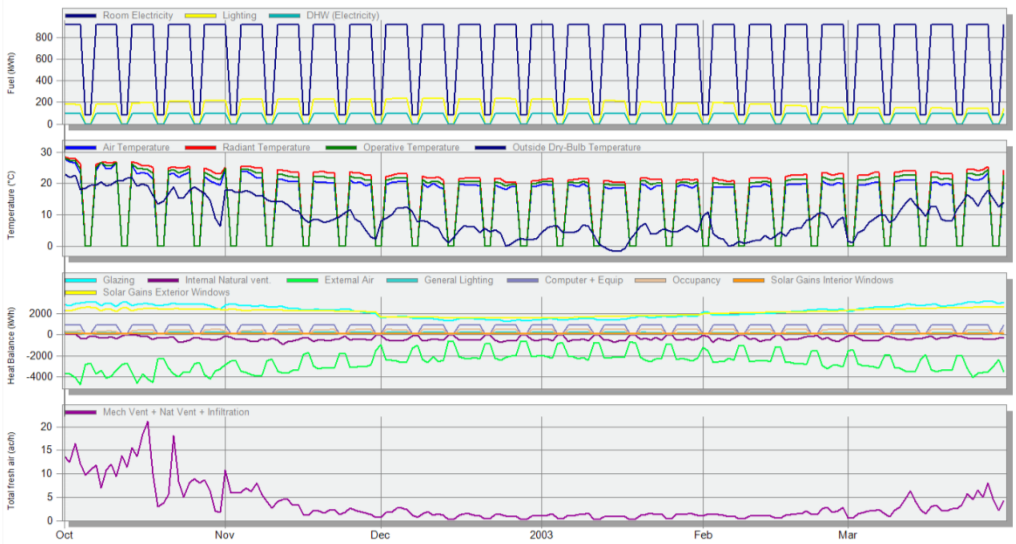
Monthly output data of Rec 1 sided (H)-W prototype in NV mode and in working hours only.

Month	Apr	May	Jun	Jul	Aug	Sep
Room Electricity (kWh)	20779.61	21694.67	19111.57	21694.67	20860.65	19945.59
Lighting (kWh)	2698.56	1709.62	1215.29	1536.15	1988.10	2913.94
DHW (Electricity) (kWh)	2133.81	2230.80	1939.83	2230.80	2133.81	2036.82
Air Temperature (°C)	21.31	25.35	30.82	32.27	32.36	28.51
Radiant Temperature (°C)	23.95	26.97	31.33	32.85	32.99	29.73
Operative Temperature (°C)	22.63	26.16	31.08	32.56	32.67	29.12
Outside Dry-Bulb Temperature (°C)	16.30	21.74	28.25	29.87	30.07	25.90
Glazing (MWh)	100.83	120.75	122.40	113.63	113.63	107.94
Internal Natural vent. (MWh)	-100.43	-89.96	-73.04	-62.38	-63.37	-64.16
External Air (MWh)	-79.19	-76.60	-69.12	-66.25	-64.67	-71.96
General Lighting (MWh)	2.70	1.71	1.22	1.54	1.99	2.91
Computer + Equip (MWh)	20.78	21.69	19.11	21.69	20.86	19.95
Occupancy (MWh)	9.88	7.92	3.70	3.24	2.99	5.38
Solar Gains Interior Windows (MWh)	3.82	4.50	4.63	4.51	4.38	3.90
Solar Gains Exterior Windows (MWh)	79.45	92.07	92.79	85.66	86.39	82.21
Mech Vent + Nat Vent + Infiltration (ac/h)	16.73	27.29	32.11	30.90	24.77	26.79

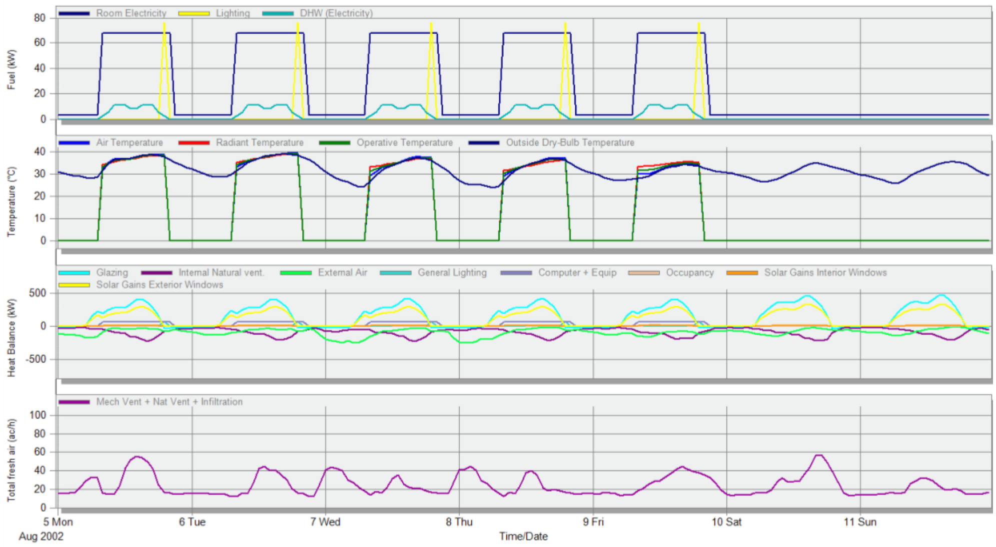
Month	Oct	Nov	Dec	Jan	Feb	Mar
Room Electricity (kWh)	21694.67	19945.59	20860.65	21694.67	18949.49	20026.63
Lighting (kWh)	4521.08	4762.97	5116.07	4835.91	3498.24	3084.86
DHW (Electricity) (kWh)	2230.80	2036.82	2133.81	2230.80	1939.83	2036.82
Air Temperature (°C)	23.48	21.04	19.27	18.97	19.24	20.48
Radiant Temperature (°C)	25.63	23.81	21.47	21.00	21.93	23.54
Operative Temperature (°C)	24.55	22.42	20.37	19.99	20.59	22.01
Outside Dry-Bulb Temperature (°C)	17.79	11.42	5.59	3.89	4.98	10.66
Glazing (MWh)	90.25	75.71	46.88	49.53	59.93	87.64
Internal Natural vent. (MWh)	-8.23	-13.62	-11.99	-11.42	-9.47	-10.24
External Air (MWh)	-109.94	-88.60	-58.18	-58.03	-64.11	-90.97
General Lighting (MWh)	4.52	4.76	5.12	4.84	3.50	3.08
Computer + Equip (MWh)	21.69	19.95	20.86	21.69	18.95	20.03
Occupancy (MWh)	9.25	9.67	10.94	11.57	9.97	9.99
Solar Gains Interior Windows (MWh)	3.32	2.71	2.10	2.27	2.55	3.48
Solar Gains Exterior Windows (MWh)	75.98	69.00	50.89	54.40	59.97	78.09
Mech Vent + Nat Vent + Infiltration (ac/h)	10.25	3.61	1.17	0.98	1.31	3.12

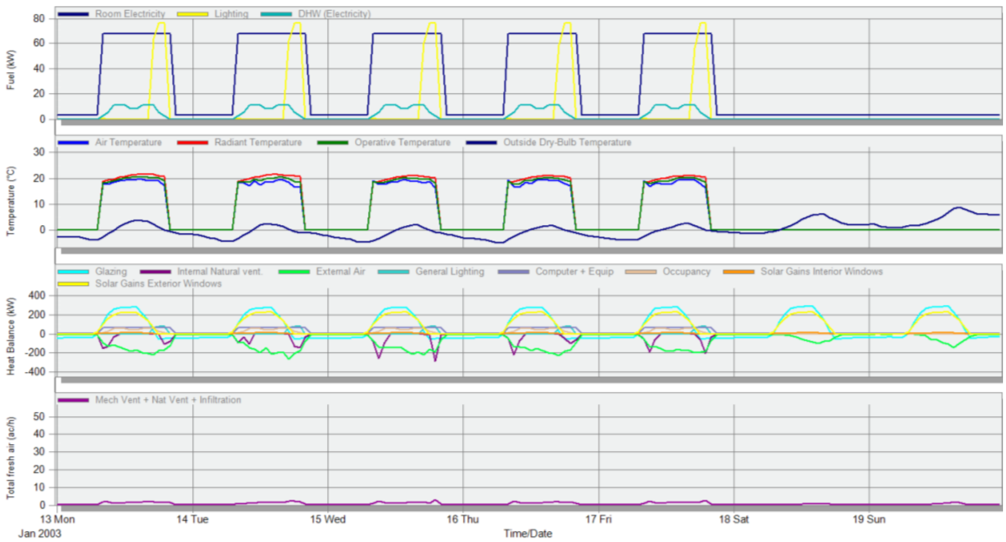
Daily output data of Rec 1 sided (H)-W prototype in NV mode and in working hours only over a year.





Overview of Rec 1 sided (H)-W weekly output data in the warmest (August month) and coldest (January month) week of the year.



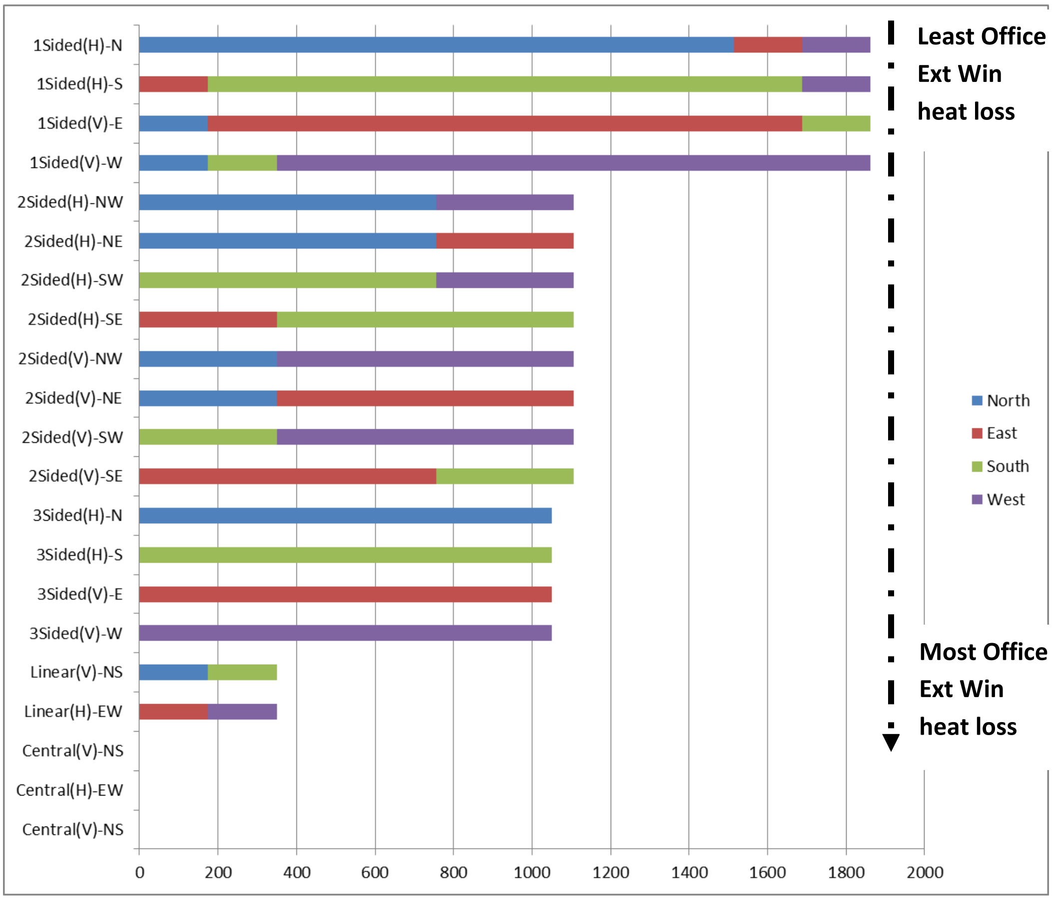


Appendix 6: External window heat loss, external window area and heating loads in rectangular prototype

Figure below is ordered from least to most external window heat loss and shows the relationship between external window heat loss, external window area and heating loads in rectangular prototype. It shows that an atrium on the south and east, and offices exposed to the north and west result in greater heat loads and more heat loss via the external window in office occupancy hours. It seems that the 'external window heat loss' is the dominant factor or parameter which has the most effect on the heat load results, compared with other parameters as has been verified via regression analysis also.

External atria win area in order of external win heat loss

External atria win area	North	East	South	West
1Sided(H)-N	1513.68	174.72	0	174.72
1Sided(H)-S	0	174.72	1513.68	174.72
1Sided(V)-E	174.72	1513.68	174.72	0
1Sided(V)-W	174.72	0	174.72	1513.68
2Sided(H)-NW	756.84	0	0	349.44
2Sided(H)-NE	756.84	349.44	0	0
2Sided(H)-SW	0	0	756.84	349.44
2Sided(H)-SE	0	349.44	756.84	0
2Sided(V)-NW	349.44	0	0	756.84
2Sided(V)-NE	349.44	756.84	0	0
2Sided(V)-SW	0	0	349.44	756.84
2Sided(V)-SE	0	756.84	349.44	0
3Sided(H)-N	1050	0	0	0
3Sided(H)-S	0	0	1050	0
3Sided(V)-E	0	1050	0	0
3Sided(V)-W	0	0	0	1050
Linear(V)-NS	174.72	0	174.72	0
Linear(H)-EW	0	174.72	0	174.72
Central(V)-NS	0	0	0	0
Central(H)-EW	0	0	0	0



External window position and area value m^2 (from least to most external window heat loss)

Appendix 7: Inflation rate and building life span in Iran

As shown in figure below, the inflation of the country over the last 10 years (2007-2017) has been between 10 to 50 percent (Economics, 2018)

The inflation rate in the past 10 years (Economics, 2018)

The life span of the buildings are 25 to 30 years in Tehran whereas some countries have 200 years lifespan in their buildings. So buildings need to be renewed quickly due to their poor design (Trackpersia, 2016).

Appendix 8: Window areas of square prototype

The graph of window areas in square meter are as below:

Window area in each prototype:

Square window area/4282.32 façade area	Office external window area	Atria external window area	Overall external window façade area	office Internal window area	overall office internal and external window area	overall façade window to wall ratio percentage	DB software %
1 Sided atria	1087.13	1564.50	2651.63	642.35	1729.48	61.92	59.37
2 Sided atria	1301.66	1028.16	2329.82	616.90	1918.56	54.41	52.50
3Sided atria	1507.30	514.08	2021.38	925.34	2432.64	47.20	46.30
Linear atria	1515.36	493.92	2009.28	1284.70	2800.06	46.92	46.32
Central atria	1712.93	0.00	1712.93	1233.79	2946.72	40.00	40.00
Base case	1712.93	0.00	1712.93	0.00	1712.93	40.00	36.57

Office external window area :

External office win area	North	East	South	West
1Sided-S	428.232	329.448	0	329.448
1Sided-E	329.448	0	329.448	428.232
1Sided-W	329.448	428.232	329.448	0
3Sided-S	428.232	428.232	222.6	428.232
2Sided-SE	428.232	222.6	222.6	428.232
2Sided-SW	428.232	428.232	222.6	222.6
3Sided-W	428.232	428.232	428.232	222.6
3Sided-E	428.232	222.6	428.232	428.232
3Sided-N	222.6	428.232	428.232	428.232
1Sided-N	0	329.448	428.232	329.448
2Sided-NE	222.6	222.6	428.232	428.232
2Sided-NW	222.6	428.232	428.232	222.6
Central	428.232	428.232	428.232	428.232
Linear-EW	428.232	329.448	428.232	329.448
Base-Central	428.232	428.232	428.232	428.232
Linear-NS	329.448	428.232	329.448	428.232

Office internal window area:

Internal office win area	North	East	South	West
1Sided-S	0	0	642.348	0
1Sided-E	0	642.348	0	0
1Sided-W	0	0	0	642.348
3Sided-S	0	308.448	308.448	308.448
2Sided-SE	0	514.08	514.08	0
2Sided-SW	0	0	514.08	514.08
3Sided-W	308.448	0	308.448	308.448
3Sided-E	308.448	308.448	308.448	0
3Sided-N	308.448	308.448	0	308.448
1Sided-N	642.348	0	0	0
2Sided-NE	514.08	514.08	0	0
2Sided-NW	514.08	0	0	514.08
Central	308.448	308.448	308.448	308.448
Linear-EW	642.348	0	642.348	0
Base-Central	0	0	0	0
Linear-NS	0	642.348	0	642.348

Atria external window area:

External atria win area	South	East	West	North
1Sided-S	1070.58	246.96	246.96	0
1Sided-E	246.96	1070.58	0	246.96
1Sided-W	246.96	0	1070.58	246.96
3Sided-S	514.08	0	0	0
2Sided-SE	514.08	514.08	0	0
2Sided-SW	514.08	0	514.08	0
3Sided-W	0	0	514.08	0
3Sided-E	0	514.08	0	0
3Sided-N	0	0	0	514.08
1Sided-N	0	246.96	246.96	1070.58
2Sided-NE	0	514.08	0	514.08
2Sided-NW	0	0	514.08	514.08
Central	0	0	0	0
Linear-EW	0	246.96	246.96	0
Linear-NS	246.96	0	0	246.96

Overall façade external window area on each direction:

External facade win area	North	East	South	West
1Sided-S	428.232	576.408	1070.58	576.408
1Sided-E	576.408	1070.58	576.408	428.232
1Sided-W	576.408	428.232	576.408	1070.58
3Sided-S	428.232	428.232	736.68	428.232
2Sided-SE	428.232	736.68	736.68	428.232
2Sided-SW	428.232	428.232	736.68	736.68
3Sided-W	428.232	428.232	428.232	736.68
3Sided-E	428.232	736.68	428.232	428.232
3Sided-N	736.68	428.232	428.232	428.232
1Sided-N	1070.58	576.408	428.232	576.408
2Sided-NE	736.68	736.68	428.232	428.232
2Sided-NW	736.68	428.232	428.232	736.68
Central	428.232	428.232	428.232	428.232
Linear-EW	428.232	576.408	428.232	576.408
Base-Central	428.232	428.232	428.232	428.232
Linear-NS	576.408	428.232	576.408	428.232

Office overall window area (internal and external):

	North	East	South	West
1Sided-S	428.23	329.45	642.35	329.45
1Sided-E	329.45	642.35	329.45	428.23
1Sided-W	329.45	428.23	329.45	642.35
3Sided-S	428.23	736.68	531.05	736.68
2Sided-SE	428.23	736.68	736.68	428.23
2Sided-SW	428.23	428.23	736.68	736.68
3Sided-W	736.68	428.23	736.68	531.05
3Sided-E	736.68	531.05	736.68	428.23
3Sided-N	531.05	736.68	428.23	736.68
1Sided-N	642.35	329.45	428.23	329.45
2Sided-NE	736.68	736.68	428.23	428.23
2Sided-NW	736.68	428.23	428.23	736.68
Central	736.68	736.68	736.68	736.68
Linear-EW	1070.58	329.45	1070.58	329.45
Base-Central	428.23	428.23	428.23	428.23
Linear-NS	329.45	1070.58	329.45	1070.58

Appendix 9: Window areas of rectangular prototype

Window areas of rectangular models in square meter are as below:

Window area in each prototype:

rec window area/4541.04 façade area	Office external window area	Atria external window area	Overall external window façade area	office Internal window area	overall office internal and external window area	overall façade window to wall ratio percentage	DB software %
1 Sided atria	1071.17	1863.12	2934.29	908.28	1979.45	64.62	62.05
2 Sided atria	1373.90	1106.28	2480.18	663.77	2037.67	54.62	52.84
3Sided atria	1396.42	1050.00	2446.42	932.40	2328.82	53.87	52.76
Linear atria	1676.64	349.44	2026.08	1816.56	3493.20	44.62	44.78
Central atria	1816.42	0.00	1816.42	1562.40	3378.82	40.00	40.52
Base case	1816.42	0.00	1816.42	0.00	1816.42	40.00	36.35

Office external window area:

External office win area	North	East	South	West
1Sided(V)-W	232.85	605.47	232.85	0.00
1Sided(H)-S	605.47	232.85	0.00	232.85
1Sided(H)-N	0.00	232.85	605.47	232.85
1Sided(V)-E	232.85	0.00	232.85	605.47
2Sided(H)-NW	302.73	302.74	605.47	162.96
Linear(H)-EW	605.47	232.85	605.47	232.85
Linear(V)-NS	232.85	605.47	232.85	605.47
2Sided(V)-NW	162.96	605.47	302.74	302.73
2Sided(H)-NE	302.73	162.96	605.47	302.74
3Sided(H)-N	185.47	302.74	605.47	302.74
3Sided(V)-W	302.74	605.47	302.74	185.47
BASE(H)-EW	605.47	302.74	605.47	302.74
2Sided(V)-SW	302.74	605.47	162.96	302.73
2Sided(V)-NE	162.96	302.73	302.74	605.47
2Sided(H)-SW	605.47	302.74	302.73	162.96
Central(H)-EW	605.47	302.74	605.47	302.74
BASE(V)-NS	302.74	605.47	302.74	605.47
2Sided(H)-SE	605.47	162.96	302.73	302.74
3Sided(V)-E	302.74	185.47	302.74	605.47
2Sided(V)-SE	302.74	302.73	162.96	605.47
Central(V)-NS	302.74	605.47	302.74	605.47
3Sided(H)-S	605.47	302.74	185.47	302.74

Office internal window area:

Internal office win area	North	East	South	West
1Sided(H)-N	908.28	0	0	0
1Sided(H)-S	0	0	908.28	0
1Sided(V)-E	0	908.28	0	0
1Sided(V)-W	0	0	0	908.28
2Sided(H)-NW	454.104	0	0	209.664
2Sided(H)-NE	454.104	209.664	0	0
2Sided(H)-SW	0	0	454.104	209.664
2Sided(H)-SE	0	209.664	454.104	0
2Sided(V)-NW	209.664	0	0	454.104
2Sided(V)-NE	209.664	454.104	0	0
2Sided(V)-SW	0	0	209.664	454.104
2Sided(V)-SE	0	454.104	209.664	0
3Sided(H)-N	630	151.2	0	151.2
3Sided(H)-S	0	151.2	630	151.2
3Sided(V)-E	151.2	630	151.2	0
3Sided(V)-W	151.2	0	151.2	630
Linear(V)-NS	0	908.28	0	908.28
Linear(H)-EW	908.28	0	908.28	0
Central(V)-NS	151.2	630	151.2	630
Central(H)-EW	630	151.2	630	151.2

Atria external window area:

External atria win area	North	East	South	West
1Sided(H)-N	1513.68	174.72	0	174.72
1Sided(H)-S	0	174.72	1513.68	174.72
1Sided(V)-E	174.72	1513.68	174.72	0
1Sided(V)-W	174.72	0	174.72	1513.68
2Sided(H)-NW	756.84	0	0	349.44
2Sided(H)-NE	756.84	349.44	0	0
2Sided(H)-SW	0	0	756.84	349.44
2Sided(H)-SE	0	349.44	756.84	0
2Sided(V)-NW	349.44	0	0	756.84
2Sided(V)-NE	349.44	756.84	0	0
2Sided(V)-SW	0	0	349.44	756.84
2Sided(V)-SE	0	756.84	349.44	0
3Sided(H)-N	1050	0	0	0
3Sided(H)-S	0	0	1050	0
3Sided(V)-E	0	1050	0	0
3Sided(V)-W	0	0	0	1050
Linear(V)-NS	174.72	0	174.72	0
Linear(H)-EW	0	174.72	0	174.72
Central(V)-NS	0	0	0	0
Central(H)-EW	0	0	0	0

Overall façade external window area on each direction:

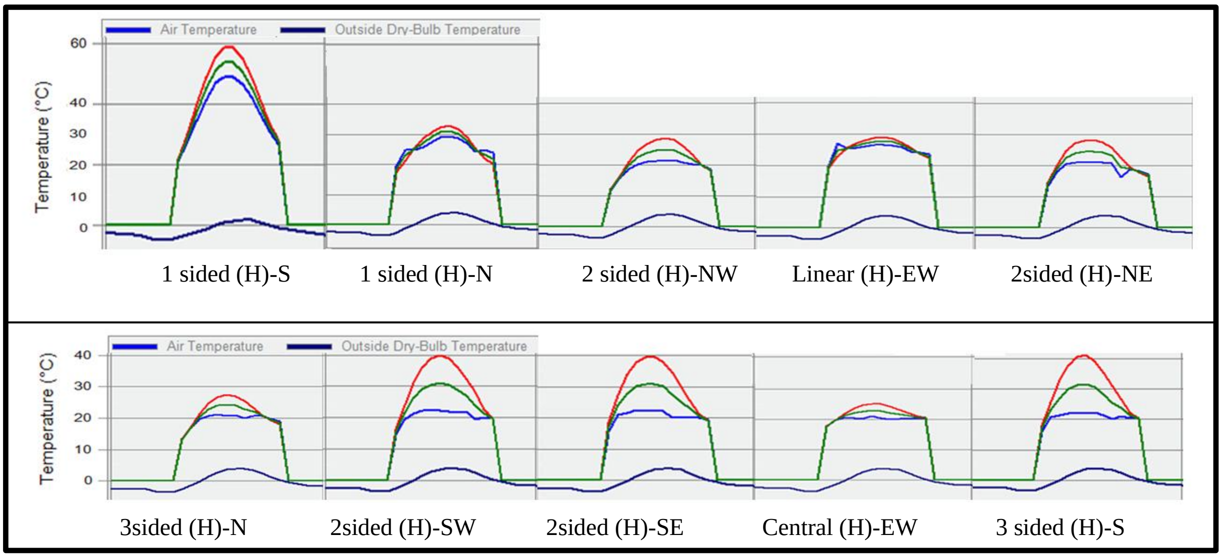
External facade win area	North	East	South	West
1Sided(H)-N	1513.68	407.568	605.472	407.568
1Sided(H)-S	605.472	407.568	1513.68	407.568
1Sided(V)-E	407.568	1513.68	407.568	605.472
1Sided(V)-W	407.568	605.472	407.568	1513.68
2Sided(H)-NW	1059.57	302.736	605.472	512.4
2Sided(H)-NE	1059.57	512.4	605.472	302.736
2Sided(H)-SW	605.472	302.736	1059.57	512.4
2Sided(H)-SE	605.472	512.4	1059.57	302.736
2Sided(V)-NW	512.4	605.472	302.736	1059.57
2Sided(V)-NE	512.4	1059.57	302.736	605.472
2Sided(V)-SW	302.736	605.472	512.4	1059.57
2Sided(V)-SE	302.736	1059.57	512.4	605.472
3Sided(H)-N	1235.472	302.736	605.472	302.736
3Sided(H)-S	605.472	302.736	1235.472	302.736
3Sided(V)-E	302.736	1235.472	302.736	605.472
3Sided(V)-W	302.736	605.472	302.736	1235.472
Linear(V)-NS	407.568	605.472	407.568	605.472
Linear(H)-EW	605.472	407.568	605.472	407.568
Central(V)-NS	302.736	605.472	302.736	605.472
Central(H)-EW	605.472	302.736	605.472	302.736

Appendix 10: Examples of famous buildings with atria around the world

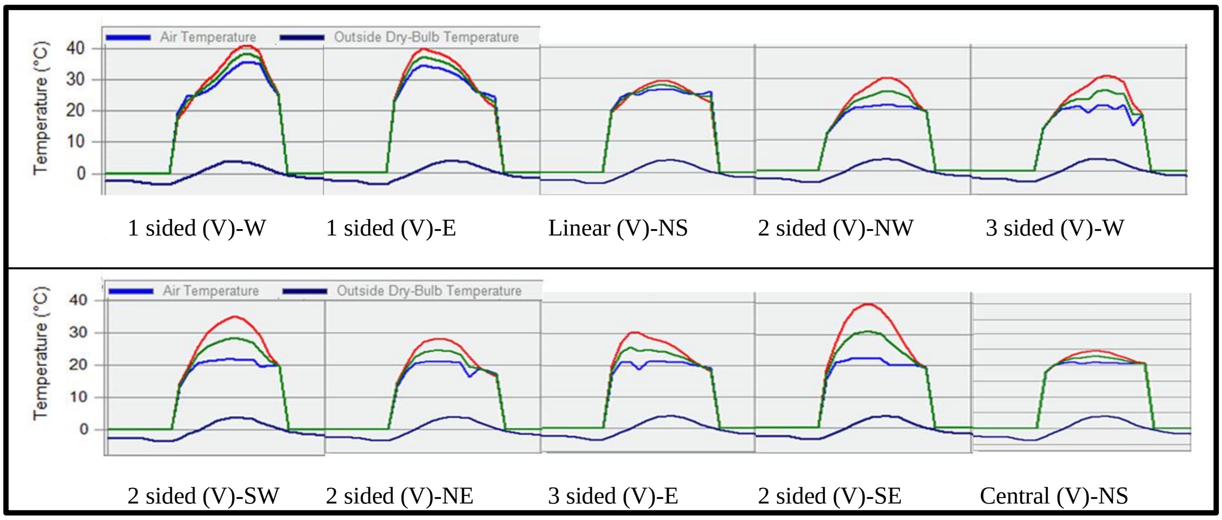
atrium type	climate	building name	year
1 sided atria	cold-humid continental	Manitoba hydro power	2008
1 sidedsouth	cold, temperate	National gallery of canada	1988
2 sided	cfa=humid subtropical-sydney	capita centre	1989
3 sided	AF=aquatorial fully humid-singapour tropical rainforest	National Library	2005
3 sided	humid subtropical	mode gakven cocoon tower	2008
3 sided	Temperate	Wain wright	1891
3 sided	Csa= warm and temperate	Carre dArt	1993
3 sided and open top	Csb=dry summer subtropical -SFO	Gap Inc. offices	2001
3 sided skygardens	temperate	Heron tower	2011
3 sided spiral	temperate-london	30 st mary Axe	2004
3 story +skycourt	mild and moist subtropical-shanghai	Genslers tower	2015
cenrtral	temperate- london	The Ark	1991
central	cfb oceanic	Waucques musuem of comic art	1906
central	temperate	Lloyds of london	1986
central	temperate	scotish office Victoria Quays	1995
central	continental- humid	Hearst Tower	2003
central	humid subtropical climate	Guangzhou international finance centre	2010
central	Bsk= semi-arid/steppe amman	Le Royal Hotel	2010
central	arid-(temperate)-syndey	Bligh street sydney	2011
central	arid-abudhabi-bwh	capital gate	2011
central	temperate-UK	Ionica Headquarters	1994
central (almost shaded louver)	Dfb=Humid continental	Debis house	1999
central +skygardens	temperate	Commerzbank	1997
central +skygardens	arid	Turre cube	2005
central and skycoart	dessert	NCB	1983
central sidlit	csb=warm summer meditaranian	901 cherry office corporate copus	1996
linear	cfa=humid subtropital	century tower	1991
linear	temperate,mild	paustian house	1987
Linear	temperate-Bonn	Post tower	2002
Linear and skycoart	temperate	Enerplex north building	1982
Linear top shade with windtower	cwb=subtropical high land	Eastgate	1996
linear-top closed	cfa-tokyo humid subtropical	panasonic multimedia centre	1992
skylits	semi-arid	caja Geanada headquarters bank	2001

Appendix 11: Atria air temperature

- Atria air temperature (light blue line) shown in all rectangular models positioned on the North-South axis on typical cold day



- Atria air temperature (light blue line) shown in all rectangular models positioned on the East-West axis on a typical cold day.



Appendix 12: Publications

The researcher has undergone trainings on Design Builder software and has been given a certificate of completing the training course by the software company themselves. The researcher has, moreover, attended the training session on Endnote software which involves quick and easy referencing. Also the researcher has attended the Council on Tall Buildings and Urban Habitat Conference (2013) with the title "Height and Heritage: The unique challenge of building tall in historic cities" on 11-13 June in London, UK. She experienced talking with firms and architects in the forefront of the design and construction industry early in her PhD journey. She also attended and helped with holding the 11th International post graduate research conference 2013 in Salford University with the title of "Built and Human Environment" on 8-10 April in Greater Manchester, UK. Moreover, the researchers publication as of today are as follow:

Publications:

Jaberansari. M & Kiviniemi. A (2013) Natural ventilation techniques in some modern high-rise and vernacular low rise buildings, Salford Postgraduate Annual Research Conference (SPARC) 2013: Theory, Practice, Impact, 5-6 June 2013

Jaberansari. M & Elkadi. H, (2016) Influence of different atria types on energy efficiency and thermal comfort of square plan high-rise buildings in semi-arid climate, International Conference on Energy, Environment, and Economics, 16-18 August 2016, Edinburgh, UK, 2, 144-149

Jaberansari. M & Elkadi. H (2016) Optimum atria type in terms of thermal comfort for high rise office buildings in the semi-arid climate of Middle East, 3rd International Building Performance Simulation Association Conference BSO Conference BSO 2016, 12th -14th September 2016, Newcastle, UK

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