Section 1: Introduction

1.0 Introduction

Sustainability as a concept is quite recent and is very much at its initial stages of development. As countries get more and more industrialised, and many developing countries receive 'developed country' status, production increases and there is therefore a resultant increase in residual waste generation. This in turn creates many problems to the earth and its environment. Further, in order to sustain the highly increasing consumer driven production, a large amount of materials are used up, thereby increasing the amount of energy consumed in addition to material consumption. During the consumption of energy, there are many noxious and hazardous chemical by products that are produced, most notably carbon dioxide and sulphur dioxide amongst many others. This in turn has significant impacts to plant and animal life on earth, thereby affecting the food chain and bio diversity.

It is a commonly held misbelief that the transportation sector is the largest consumer of energy and the largest producer of hazardous waste. However, there is strong evidence to suggest that the majority of material and energy consumption is accounted for by the building sector. Celik (1994) and AboulNaga & Amin (1996) state that in Europe, more than half of all materials taken from the natural environment are used in the construction sector and more than 40% of energy consumed is from the construction industry. By extension, this will also mean that more than half of all manufacturing waste produced will hail from the construction industry and more than close to half of all CO_2 production in Europe in the manufacturing stage or latter stages will come from the building sector.

Moreover, 40% of total CO_2 emissions in developing countries are accounted for by residential buildings, with 40% consumption of energy, close to 70% use of electricity, use of one tenth of clean water, which also cumulatively results in the generation of 50% of non-Industrial waste (USGBC 2008).

The Middle East is one of the fastest developing locations in the world. The discovery of oil in the mid twentieth century has seen very sudden growth and development in the region, which has quite obviously placed a significant load on the earth's resources and environment Wrong practices in the construction industry apart, the sheer magnitude and scale of the developments in the UAE alone suggests that there will be major loads on the minerals and energies at its disposal with a corresponding increase in the generation of waste and Co_2 emission. According to the WWF (2006), the UAE has an ecological footprint of 11.9 global hectares per person.

AboulNaga & Elshetawy (2001) suggest that the UAE has a much higher figure for materials and energy consumption and resultant CO2 emissions from the building sector than the global average. Al Sallal et al (2013) state that cooling and air conditioning alone accounts for 75% of electricity consumption during the hot summers in Abu Dhabi.

Therefore, for the aforementioned reasons and others that will be discussed, the building sector has a large imperative to work towards mitigating the consumption of energy and resources.

Communities and nations, from the very beginnings of time have sought to adapt to the natural environments around them. This is evident from the phenomena observed in various parts of the world in various different climatic conditions. These phenomena can be observed in human activity typologies like in housing and its adaptation to the natural environment and by various plant and animal organisms as is seen to be observed in the study of biomimicry.

Whilst human beings on a personal level modified their behavioural patterns and security systems like clothing to keep warm in colder climates and cool in hotter climates, their residential dwelling places and patterns were also symptomatic of the requirement to harmonise with the natural environment around them. Traditional or vernacular architecture therefore has a greater propensity to be designed to be in harmony with the natural environment than to be against it.

On the basis that traditional or vernacular architecture harnesses the qualities of the natural environment to provide comfort to the occupants, it makes traditional architecture less of a burden to the environment and therefore more sustainable. In addition to the sustainable design features inherent to traditional architecture, traditional architectural patterns usually employ materials from the immediate locality of the building site. This helps reduce environmental pollution that occurs from material transportation and facilitates the natural progression to disposal of waste back to the environment with less of it converting into unusable and non-bio degradable materials.

Al Sallal et al (2013) opine that with the discovery of oil in the UAE and the rapid rates of construction that ensued in the building and infrastructure sectors, competition amongst developers and the need for fast project completion resulted in negligence of traditional architectural methods that used to maintain the levels of sustainability in the UAE. Further, Al Masri & Abu-Hijleh (2012), Khattab (2001) and Al Sallal et al (2013) produce research to reinforce the understanding that rapid rates of globalisation and the development of communication has resulted in many design ideas being imported from other countries to the UAE.

There are many instances to be seen where contemporary UAE architecture is a result of un-researched architectural concepts and analyses. In the quest for modernisation, the demand for reconciling modern technological advances with traditional wisdom of the past has been ignored, this has resulted in what Asfour (1998) called the 'dark side of the equation', where he criticises the notion of 'cut & paste' architecture, the architecture of imposing Western trends unthinkingly into UAE architecture with no consideration of the affect it would have on the local environment. What is also important, as identified by Asfour (1998) is that direct replication of traditional concepts of the past mindlessly is as damaging as direct replication of Western concepts.

There are many reasons for which modern architects tend to lazily copy from the West as opposed to scrutinising and studying local traditional architectural patterns. Al Zubaidi (2007) opines that the reason there seems to be a lack of trust on local traditions of the past is that these traditions are associated with poverty and economic regression. Therefore, the assumption that Western trends that are historically associated with prosperity and technological advancement is seen to be as more reliable and superior. This has led to what Ghandoour (1998) identifies as the bastardization of traditional Arab architecture that has suffered due to rampant misinterpretation.

Therefore a situation arose where non-local design attributes were imported from other countries that succeeded in satisfying aesthetic criteria but failed on the sustainability criteria. For instance, generous use of glazing in cold European countries perform the dual function of being aesthetically appealing and facilitating the ingress of sunlight. However, when the generous use of glass as a design concept is imported to hotter climates like in the UAE, the need arises to increase energy loads on the cooling system to offset the overheating caused by excessive ingress of solar rays.

Most modern architectural techniques have failed in not allowing the environment to play its part and thereby allowing wrong practices to seep into construction methods. These wrong practices include unsuitable building form and orientation, failure to incorporate passive shading and other cooling techniques, use of plants that require water intensive irrigation systems and the high use of interlocking pavements in the outdoors. These wrong practices satisfy aesthetic requirements when properly manoeuvred but generate very high cooling and lighting energy demands (Al Sallal et al 2013).

The term traditional architecture has been very carefully chosen in this instance for this research. There are varying terms that are loosely used to describe various related concepts. For instance, some of the terms used in scholarly publications are folk architecture, vernacular architecture and traditional architecture. Folk architecture is characterised by certain societies and communities, but the masonry wasn't necessarily done with the involvement of trained professionals. Vernacular architecture stems from and bears characteristics analogous with societies and communities but was built with heavy input from trained professionals. Therefore, vernacular architecture tends to exhibit a heavy sense of discipline in design details and structural forms that satisfy very purpose made design criteria (Noble, 2007).

Vernacular architecture as defined by the Encyclopaedia of Vernacular Architecture of The World *"...comprises the dwellings and all other buildings of the people. Related to their environmental contexts and available resources they are customarily owner- or community-built, utilizing traditional technologies. All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of life of the cultures that produce them".*

Therefore, due to the liberty with which the terms folk architecture and vernacular architecture is used, Traditional Architecture as an all encapsulating holistic term will be used for the purposes of this research. It will be noticed that traditional architecture and vernacular architecture as terms are interchangeably used in this research, but for the purposes of this research it will be considered that they both refer to the same.

Therefore, traditional architecture techniques analysed in this research will be techniques used all over the world in architectural works which are deemed to be either folk architecture or vernacular architecture. These techniques may be cooling systems, heating systems, aesthetic forms that allow for convenient ingress and egress or any other architectural technique that can be viewed as being important to discuss from a sustainability point of view.

Kimura K (1994) identifies that although traditional architecture is held in high esteem and widely recognised to be a historically important aspect of modern architecture, traditional architecture is mostly recognised for the aesthetic components that it consists of and rarely for the various design techniques that have been deliberately put in place to achieve thermal comfort at minimum fuel consumption. Traditional architecture stems from the immediate locality in which it is present and draws inspiration from the bioclimatic needs of a building. Therefore, modern architecture can derive lessons from traditional architecture in the ways in which olden buildings responded to the climatic demands of the locality.

Indigenous traditional architectural systems both in the UAE and around the world were acquired by trial and error and were modified directly to include comfort levels in a natural way. Khattab (2001) identifies that vernacular architecture in the UAE was a result of adherence to tradition, abundance of suitable material and the dire need to respond to the complexities of the harsh environment.

Therefore, the applicability of traditional architecture in modern buildings, with particular emphasis on wind catchers, will be analysed in this research.

1.1 Aims and Objectives

Aim:

This research will seek to analyse how *traditional architectural techniques can be incorporated into modern buildings to increase comfort levels by natural ventilation, with particular emphasis on wind catchers.*

Objectives:

- Explore traditional architectural techniques used in the UAE and assess the extent to which they were able to satisfy human comfort requirements.
- Analyse the design and function of wind catchers to investigate their performance as traditional cooling devices.
- Identify the extent to which wind catchers can be incorporated into modern residential buildings as a means to reduce energy loads on cooling by optimising thermal comfort through natural ventilation. Wind catchers are to be investigated in terms of their height, area of their wind tower openings, the percentage opening of

the wind tower opening, the impact of the floor to ceiling height when a wind catcher is incorporated into a space, orientation of the wind tower and the impact of the wind catcher when operating in a space with a window.

Section 2: Literature Review

2.0 Literature Review

This section will seek to identify the various researches that have already been done on traditional architectural techniques and their application in modern architecture. In order to aid this, the steps below will be followed –

- Traditional architectural techniques from a few parts of the world where sustainable strategies that can be useful to the UAE in theory or practice will be analysed. Even though traditional techniques in general will be mentioned, emphasis will be on techniques used for cooling. The analyses will include how they were effective in reducing energy consumption and or how they can form the theoretical basis for challenging some of the modern architectural techniques used.
- Analyse research that has been carried out in the effectiveness of integrating traditional architectural techniques in modern architecture, how they were implemented and the extent to which success was achieved.

2.1 Comfort Standards and Sustainable Design Strategies

Depending on where in the world they live, humans experience all kinds of weather and environmental phenomena and patterns. These can usually be defined in terms of understandable sensations such as temperature, noise or light. What the environment characterises doesn't necessarily suit the parameters that need to be satisfied in order for humans to be in a state of thermal, visual or auditory comfort. The very purpose of traditional building design techniques therefore is to create an enclosed or open space that gives refuge to humans to be closest to the most ideal standards of comfort.

Therefore, the extent of the design of sustainable architectural techniques is defined based on the requirements of human comfort parameters. This makes it paramount therefore that human comfort parameters are understood. It is rare that the ideal standards of human comfort can always be met; therefore design considerations take into account the ability of human beings to adapt. Mishra & Ramgopal (2013) identify that the adaptive capacities of humans can be classified as physiological, behavioural and psychological. The levels of comfort requirements vary from individual to individual, and differ in reference to age, gender, ethnicity, rate of metabolism and many other factors. Therefore, for the purposes of this research, the human standards in question will be for an adult human wearing comfortable clothing.

ASHRAE, formerly known as the American Society of Heating, Refrigerating and Air Conditioning Engineers, is a world renowned authority on human comfort standards. Standard 55 of ASHRAE, *Thermal Environmental Conditions for Human Occupancy* defines the requirements of indoor comfort taking into consideration the various other relating factors. These factors include airspeed, thermal radiation, temperature, humidity, activity level and clothing (University of Washington 2013). According to ASHRAE, the temperature of a building occupant in winter attire amounting to 0.8-1.2 clo (1 clo is the thermal insulation for a resting person to be at comfort at 21°C or 0.155 m^2K/W) is in the range of 20°-23.5° C, and the best temperature range for occupants in summer when their attire is of 0.35-0.6 clo is in the range of 22.5°-26°C. Therefore, these temperature ranges will be the basis on which matters to do with human thermal comfort will be assessed.

Sustainability has been defined in numerous ways and has been used in very many contexts. The more general and better known definition of Sustainability is the notion that the needs of the present generation be satisfied without discounting or compromising the requirements or the needs of the future generations (Steele 1997). This quite robustly suggests that that the resources of the present day should be used to the optimum to satisfy the current needs, but what it refers to as bad practice is the wasteful or inefficient use of resources.

For instance, AboulNaga et al (2000) performed a study on the energy use patterns in residential dwellings in Al Ain city that showed that 40% of the cooling energy was being used to cancel heat gain from the walls and the roof and could reach up to 75% if the glazing were to be taken into consideration. The same study showed that yearly energy used can be reduced by up to 55% when glazing is minimised by providing windows in only two elevations.

As was discussed above, the construction industry is the industry that consumes the most amounts of the earth's resources. Therefore, it is important that sustainability practices should be strictly implemented. Issues that influence the sustainability of the construction industry were debated at the 1992 Rio earth summit. Amongst the recommendations discussed are the following –

- Investigation of methods where construction materials can be reused and recycled.
- The regulating of design procedures and principles to be energy efficient.
- Incentivising the development of traditional design techniques in modern construction methods.
- The use of local and indigenous construction materials.

All the points mentioned above directly stipulate the use of sustainable design strategies. It is also evident that the providing of incentives to use traditional architectural strategies has been given importance; this is due to the significant amount of sustainability facets that are satisfied by traditional architectural strategies. Moreover, of the points mentioned above, reusing and recycling of materials and the use of local indigenous materials which have been considered to be sustainable, are also characteristics intrinsic to traditional architectural techniques.

Having established that traditional architectural techniques are very high in the standards of sustainability that can be achieved, traditional architectural techniques will be discussed in detail in sections below.

2.2 Influence of climatic factors on building design

As is discussed below, traditional architectural techniques are usually a response to the climatic characteristics of the location in which it is placed, even though other factors like culture and demography also influence design decisions. Amongst the reasons for many modern buildings to be less efficient is that they tend to neglect the influence of climatic factors on the built environment. Evidence for this, as pointed out by Al Sallal et al (2013) is seen in the many architectural design practices and procedures imported from other countries that do not have similar weather patterns or due to the high demand for the supply of dwelling spaces that does not give enough time for builders and developers to take into consideration the climatic effects on buildings if they are to be competitive in the market.

Moreover, the classification of environments based on the localities in which they are situated usually exhibit design elements that are similar, both in aesthetics and in function. House in tropical climates such as India, Sri Lanka or Bangladesh which tend to be hot for most of the year and rainy for other parts exhibit the use of long eaves in the roofs with deep haunches, the depth of the haunch facilitates the smooth flow down of rainy water and the long eaves act as shading devices to control the ingress of sunlight. Countries in the Gulf region, like Iran, Saudi Arabia or the UAE are characterised by wind catchers attached to the building as a means of cooling for the occupants sitting inside. Western European countries on the other hand which are warm or moderate in the summers and extremely cold in the winters have thick solid walls that act as thermal masses that can store heat during the day when the sun is out and gradually release the heat when in the night and the air is cooler.

Further to this, countries in Western Europe or other similar regions that have to deal with the four seasons (Summer, Autumn, Winter, Spring) have to design dwelling spaces that have to ability to be resilient to the diverse unique challenges posed by the environmental characteristics of the different seasons. In England for instance, the use of deciduous trees in the immediate vicinity of the building aids to protect the indoor environment form excessive heat gain in the summers by the leaves that block sunlight from coming in, and in the winters they shed leaves to facilitate the ingress of sunlight to help warm the cool insides by solar radiation.

Therefore, the influence of climatic factors on the building has to be taken into consideration when designing, this is a facet of design that traditional architectural techniques show more evidence to have taken seriously than the percentage of modern architectural examples that do not.

2.3 Traditional Architectural Techniques

Traditional architectural techniques have been used ever since the very early stages of man, as a result of dwellings having to respond to climatic variations around them, therefore, traditional architectural techniques usually are a direct result of environmental and weather conditions in a particular geographical area. Buildings of traditional architecture are thus better equipped by design to resist the challenges posed by environmental conditions like heat, cold, wind, rain etc (Serefhanoglu & Gedik 2007). Although modern buildings too can be made to be responsive to the challenges posed by the environment, they usually do so at a much higher energy cost. Designers in the past were not privy to weather data and were not aware of HVAC technologies. Therefore, the optimum results for human comfort can only have been achieved by the design of the dwelling itself.

Serefhanoglu & Gedik (2007) suggest that modern architects should draw upon the techniques that were used in traditional architecture and incorporate them into modern architectural techniques in order to reduce the load on energy consumption. These techniques can be anything from those that were used in the past, and include the taking into account of solar orientation, wind patterns, courtyards, wind catchers, local materials, thermal mass and other heating and cooling systems.

Therefore, it is evident as confirmed by Schiller et al (2007), that irrespective of the scale of the dwelling, a building has an effect on the environment and the external environment reciprocally has an effect on the building. Moreover Zhai & Previtali (2010) identify that vernacular architectural traditions finely reconcile all matters to do with the nature of the built environment and the limitation of resources and technical expertise. Unlike in the modern construction industry in the highly globalised world that it exists, where architects or builders more often than not hail from countries other than the ones they build in, traditional architectural techniques usually solicited local techniques that drew lessons from a deep understanding of climatic conditions, culture, socio-economic conditions and religion (Dili et al 2010). Moreover, it is important to understand, as confirmed by Ratti et al (2003) that when some sections come across to be not responsive to climatic conditions, that is because they are a response to socio-economic or cultural conditions.

Therefore, the interwoven consequence of buildings and the environment are best recognised by traditional architecture. The scientific basis on which traditional architecture relies upon is an amalgam of climatic condition in the vicinity of the building, thermal comfort standards and the extent of heat gain or heat loss (Hastings 1995).

Traditional architectural systems of Korea and India from outside the Middle East in addition to architecture from the Middle East was analysed, the reason for selecting Korea and India is that during the warm and humid months of the year, traditional architectural techniques used specifically in these two countries can be relevant to study their effects for devising similar strategies in the UAE.

2.4 Traditional architectural techniques used in Korea

Traditional cooling techniques vary from country to country and are reflective of the needs posed by the environment. Therefore, Korean dwelling spaces are evidence of spaces that have responded to such climatic needs. Due to its geographical location, Korea has four unique seasons which are radically distinguishable. Since Korea takes a peninsular land form, there are equally unique impositions on the environment by the climates in the ocean and the climates in the continent. As a symptom of the oceanic climate, the summers are characterised by very damp and hot climates, the winters are very cold. Mild temperatures and humidity ranges characterise other times of the year. Moreover, Korea has more than three fourths of the country covered by mountains; therefore there are variations in climatic conditions from region to region (Kim 2006).

Kim (2006) further opines that traditional Korean houses are usually based on the foot of mountains. Therefore, due to the effect mountains have on the velocity of wind, Korean traditional architectural techniques have the added onus of having to control the effects of the wind. Korean summers tend to be hot and damp; this makes the need for ventilation to be of paramount importance. To alleviate the negative effects of the windless summer days, Korean traditional architecture has developed a system where wind can be generated to provide ventilation.

In the rear end of homes would usually be the foot of mountains, where there will be an active garden with trees and shrubs. In the front of the building is located a forecourt known as a *madang*. This madang usually has a floor made out of clay and therefore is vulnerable to the extreme heats where the heat is absorbed by the clay ground and stored. Therefore, a temperature variation occurs between the region in the rear where the garden is and the front where the hot forecourt is. This differential in temperature gives rise to an artificial convection current that flows from the less warm areas to the warmer areas as illustrated in Fig 2.1.

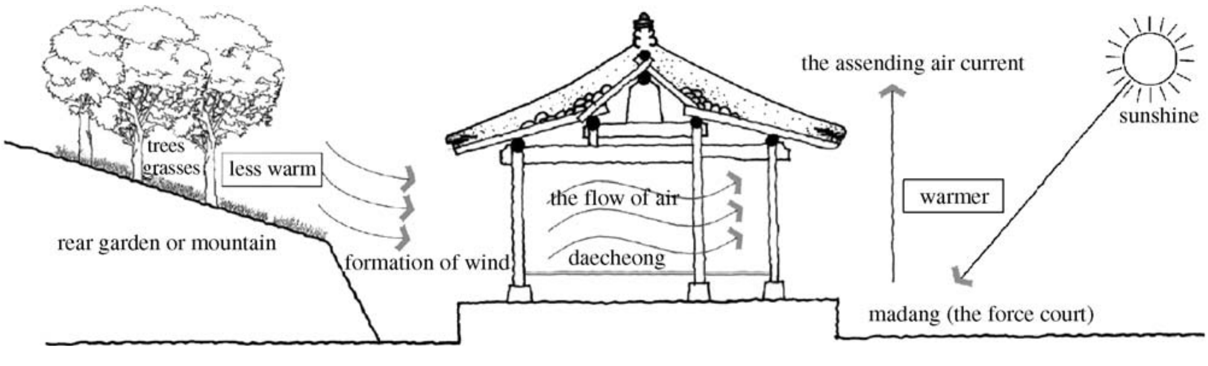


Figure 2.1 Wind flowing from cooler to warmer areas (Kim 2006)

Kim (2006)further opines that the wind that comes from the mountains isn't strong enough in their velocity to offer substantive cooling, however, as wind flows downwards and is blocked by the wall surfaces of the *daecheong*'s, they collect and increase in pressure. Therefore, having small openings in the walls will allow to gush in at higher pressures than normal, as smaller the cross sectional area of the opening, greater the pressure of the air passing through.

The author further states that daecheongs are closed in the cold winters so that cold air does not ingress to the spaces, but due to the disregarding of traditional architectural techniques by modern Korean architecture, HVAC systems are used in the hot summers, thereby increasing the reliance on fossil fuels and increasing the carbon footprint through energy consumption.

Many countries across the world that are characterised by high incident angles of sunshine usually do use eaves as a shading device. However, as is confirmed by Kim (2006), the specific designs of the eaves in countries like Japan, Korea or China have to be mentioned in particular. The designs of the depth of the eaves, which are different in the cases of China, Japan or Korea, are reflective of the sun's angle with the horizontal.

As is shown in Fig 2.2, the highest sun angle in Seoul, Korea is 76° in the summers and the lowest is 29° in the winters. Therefore, the angles of the eaves take into account these natural phenomena in traditional architectural design. Therefore, heating by solar radiation can be avoided in the summers and solar radiation can ingress through lower angles to warm up internal spaces in the winters.

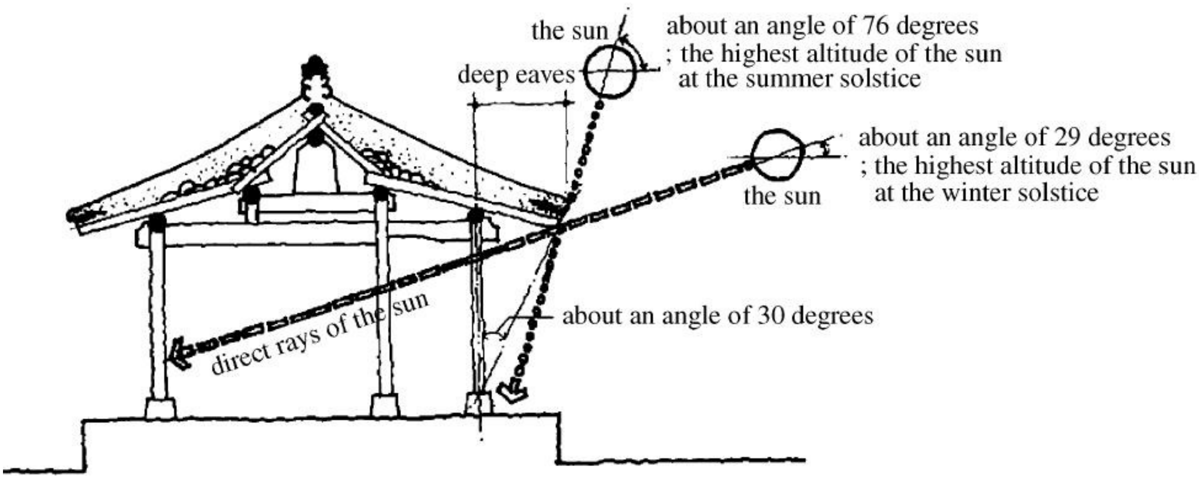


Figure 2.2 Depth of the eaves responding to sun angles (Kim 2006)

Whilst Kimura (1994) elucidates that the concept of using eaves as shading devices has fairly successfully been incorporated in modern Japanese architecture, where high rise apartment complexes use deep balconies to shade the levels below in the southern facades, Kim (2006) states that due to the speed of construction in contemporary Korean architecture, this matter is not taken into account. Korean contemporary architecture do not heavily characterise the use of eaves, and even if they do they are usually very short. Therefore, sunlight seeps deep into buildings and increases the indoor heat levels. Moreover, the increased propensity to use glass in the facades of buildings means that more and more buildings in Korea are subject to the use of Green house effect, thereby having a significant load on the energy costs that will be spent on cooling.

Ondol-bang is the main liveable area in Korean dwellings. It derives its name from the Korean heating system known as *Ondol*s. Ondol is an intrinsically Korean floor heating mechanism that exploits the differences in temperature ranges in a space (Yeo et al 1995 & Park et al 2001). The area nearest to the fire space is the warmest, therefore there is a difference in temperatures between the space where the fire is lit and the space that is furthest from the fire which will be much cooler. Therefore as seen in Fig. 2.3, this difference forces a convection current, thus, wind blows from the cooler areas to the warmer areas.

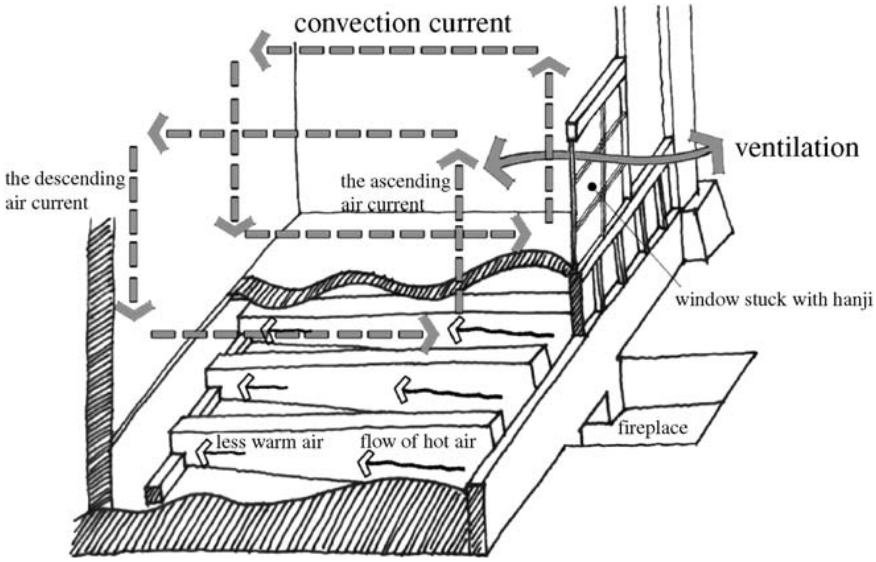


Figure 2.3 showing the function of the convection current (Kim 2006)

Moreover, the floors of the Ondol are made of clay, a natural material that has the capacity to absorb moisture when it is in excess and will gradually discharge the absorbed moisture when the moisture content in the air surrounding it drops. Further, the high insulating properties of clay means that the space is comfortably modulated according to the variations in wind and moisture (Kim 2006).

In addition to this, Kim (2006) states that all walls and floors are papered with *hanji*, a fibrous material which has the capacity to breathe due to the minute perforations that are inherent to its structure. Therefore, the breathing property of hanji controls humidity levels and can help ventilate the inner spaces. Thus, hanji, which is handmade paper made from mulberry trees is used to exploit its low thermal conductivity properties and the capacity it has to diffuse daylight (Lim 2002 & Lee 2004).

Moreover, Kim & Park (2010) analysed the effects that traditional Korean openings can have if integrated in a contemporary house. This traditional opening is constructed by having a wooden frame and hanji. The purpose of the study was to understand if the application of the traditional technique would have energy savings if applied to a contemporary house. The results confirmed through CFD simulations that airflow rate increased thereby establishing that natural ventilation can be provided even if there are low wind pressures. In addition to this, the strategy has the capacity to prevent cold drafts during the winters when heating is used; this is further to achieving a heat recovery of 25%.

The conclusion the authors (Kim 2006) arrive at is that traditional rooms have mechanisms that use zero energy where air can be purified and humidity levels can be maintained with the necessary amount using hanji. Korean contemporary architecture however tends to ignore these traditional methods ; walls now are mostly concrete and wallpaper are not the hanji, thus these materials emit volatile organic compounds (VOC's) that emit noxious substances that contribute to an unhealthy indoor air quality.

2.5 Traditional architectural techniques used in India

Traditional architectural patterns in parts of India are analysed in this section. India is a vast country with various different climatic conditions. The Bureau of Energy Efficiency outlines that the Indian construction industry has a growth rate of 9.5% compared to 5.2%, the world construction growth rate (BEE 2013). Moreover, after energies consumed for general industries, the construction industry is the second largest energy consuming sector in India (BEE 2013). It is further noted by the BEE (2013) that should energy efficiency measures be integrated in the Indian construction industry, the extent to which energy savings can be achieved lie in the range of 40%-50%. There are various measures that can be adopted to bring about these results; Kumar et al (1994) opine that buildings which consider passive solar techniques and use them in combination with active systems would be one of the better ways of overcoming this issue. India is also a country that is partly characterised by tropic or humid conditions. Therefore, this section will seek to outline some vernacular traditional techniques that have been useful in providing cooling in Indian dwellings. Kumar et al (1994)'s theory is consolidated by Al Azzawi (1994) who confirms that in the modern era where energy efficiency is much sought after, vernacular architecture has much to offer.

Singh et al. (2011) analysed passive architectural techniques in India in the three main bioclimatic zones found in North East India, warm & humid, cool & humid and cold & cloudy, as also identified in Fig 2. 4 for the entirety of India. However, for purposes of this section, some of the techniques they mentioned under warm & humid conditions will be reviewed in this section amongst other mentions.

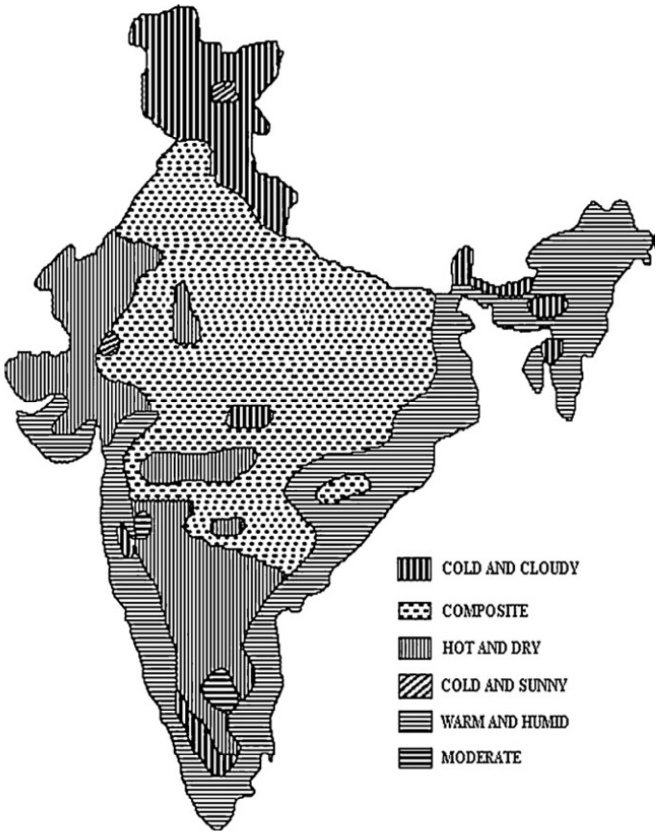


Figure 2.4 Bioclimatic variations in different regions India (Priya et al 2012)

In a tropical setting like in parts of India, where solar patterns need to be observed critically to inform the design of a building, it is important that the building is oriented in the correct form. Singh et al (2011) opine that building forms that usually feature in vernacular architecture in the warm areas are commonly understood to be U-shaped and or elongated in plan. The reason that buildings usually have a larger footprint and are elongated is that this exposes the building surfaces to prevailing wind conditions. Greater the elongation of the building, greater the surfaces exposed to the wind, and therefore heat gained by solar radiation can be released fast (Singh et al 2011). Furthermore, it should be notes that heat gain can also be more if the elongated side is exposed to the sun for the most part of the day, i.e. South facing.

Whilst vernacular architectural techniques are usually better suited to be environmentally friendly, they can also be difficult to implement in modern times. Due to increased population densities and lack of space, buildings tend to develop vertically and less so horizontally. However, this is a particularly important aspect to consider and needs to be implemented when and wherever possible. Indraganti (2010) opines that contemporary buildings in India are being designed by using materials such as aluminium and glass, irrespective of which climatic zone they exist in and mechanical heating or cooling is then used to offset the negative effects of bad planning and lack of consideration of climate and external conditions.

Further analyses were conducted by Indraganti (2010) on the residential areas and the architecture of Marikal village in the Andhra Pradesh. Marikal is a dry area and traditional vernacular settlements have developed accordingly. The houses are arranged as dense compact clusters dictated by narrow streets and alleyways. This arrangement is typified in hot-dry areas in many other parts of the world (Koenigsberger 2010 and Ratti et al 2003). This arrangement results in much reduced sky view factors and helps to mitigate loss of long wave at night (Saleh 1999).

Indraganti (2010) mentions that these dense settlements in the Marikal village shared a central open space; this large open space was used for many night time and day time activities. The floors were usually coated with cow dung, and therefore reduce overheating and controlled the reflective glare. Due the very low thermal conductivity of the finishes, the floor also cooled off very fast. Moreover, the strength of this strategy is aided by Rijal et al (2002) who suggest that mud floors have lower surface temperatures and better overall thermal performance. This open space, according to the author, was also useful in fostering a much more sustainable cohesive social framework due to communal interactions that were facilitated in the space.

This particular strategy, though works well in that particular instance, cannot directly be used in modern buildings. The differences in modern lifestyles and social setups mean that the use of cow dung as a coating on the floor will not necessarily be suitable, due to various reasons such as smell, aesthetic appeal and inconvenience of maintenance. However, due to its effectiveness as a material, similar materials in modern markets can be used to achieve the same effect.

Singh et al (2011) and Indraganti (2010) both identify that in the warm and humid climate and hot-dry climates, walls with varying thicknesses are used in traditional settings. The very high thicknesses of the walls, up to 510 mm according to Singh et al (2011) facilitates the thermal massing properties of the construction as is identified by Kruger & Givoni (2008). Therefore, these walls can absorb heat and store it during the day when there is a lot of atmospheric heat and gradually release the heat at night when the air is cooler. Moreover, a time lag (time taken for heat to pass through, more resistive a material, greater the time lag) of 10-15 hours can be achieved by wall thicknesses of 380mm -510 mm according to studies carried out by Singh et al (2011). Another prominent feature in the walls is that they have a mortar plaster, with lime as a coating on top. This helps achieve convenient colour tones that aid visual comfort. This particular type of coating is to be seen commonly used even in contemporary buildings.

However, thicknesses in walls, though a prominent feature of vernacular architecture, is now fast diminishing due to various reasons. Some of the commonly attributed reasons for the reduction of wall thicknesses in contemporary buildings or dwelling spaces are the rising demand for fast paced construction, dearth of materials and increased material costs. Moreover, according to most of the research material analysed, one of the greatest reasons behind the fast change of vernacular architectural techniques in general and the construction of walls in specific is the rapid change and speed of technological advancement. Rural electrification has given rise to the use of ceiling fans or air conditioners in warm areas and heating devices in cool areas. Therefore, the comfort levels that can be achieved by mechanical means have offset the need to have dwellings designed to passively provide thermal comfort to the occupants.

This phenomenon is evident in the work done by Indraganti (2010) who stresses further that the house form and typologies have significantly changed to accommodate the vagaries of technological advancement. The same author elucidates that in Table 2.0 that walls built by traditional construction means and materials have greater thermal performances than other walls.

Table 2.1 Showing Thermal performance of traditional walls (bold lettering) vs contemporary walls. L is the wall thickness. (Indraganti 2010)

Function	Description of the cross section	Overall thickness (m)	Surface conductance		Thermal properties of the layers						U-value ($W/m^2 K$)	Heat capacity ($kJ/m^3 K$)
			Outdoor ($W/m^2 K$)	Indoor ($W/m^2 K$)	Layer-1		Layer-2		Layer-3			
					L (m)	k-value (W/m K)	L (m)	k-value (W/m K)	L (m)	k-value (W/m K)		
Brick wall (external)	0.230 m Thick brick wall with 0.018 m thick external and 0.012 m internal cement plaster	0.26	13.18	8.12	0.018	0.721	0.23	0.84	0.012	0.721	1.94	1360
Mud wall (external)	**0.450 m Thick mud wall with 0.025 m thick lime plaster on both sides**	**0.45**	**7.78**	**8.12**	**0.025**	**0.73**	**0.45**	**1.25**	**0.025**	**0.73**	**1.47**	**2050**
External masonry wall	**0.600 m Thick granite stone masonry wall (unplastered)**	**0.6**	**7.78**	**8.12**	–	–	**0.6**	**2.92**	–	–	**2.19**	**2132**
Concrete roof	0.2 m Thick concrete roof with 0.012 m thick soffit plaster	0.212	22.7	9.48	–	–	0.2	1.274	0.012	0.721	3.09	168
Tiled roof	**0.01 m Thick tile roof 0.25 m thick over mud infill, laid over 0.006 m thick bamboo/reed matting**	**0.266**	**22.7**	**9.48**	**0.01**	**0.84**	**0.25**	**1.25**	**0.006**	**0.14**	**2.47**	**2050**
Slate roof	**Two layers of 0.012 m thick overlapping slate stone slabs with 0.008 m thick cavity**	**0.024**	**22.7**	**9.48**	**0.012**	**1.53**	**0.008**	**0.026**	**0.012**	**1.53**	**2.11**	**2212.5**

However, wall thicknesses have significantly dropped over the past few years. Wall thicknesses that were as high as 500mm have now been reduced to as low as 230 mm to facilitate the demand for greater speeds of construction and space reduction due to the increases in land prices (Indraganti 2010).

Further, Indraganti (2010) identifies that houses in Marikal have mud infills in roofs, these mud infills which are approximately 200mm thick are placed on reed matting. Some houses even had overlapping layers of slate. As an added feature, some roofs had small openings that were needed to facilitate the exit of hot air. Yet, more and more people are now opting to use Reinforced Concrete Slabs (RCC) which in some instances have toxic properties and have a load on the environment, in addition to the use of RCC slabs, Galvanised Iron (GI) sheets or asbestos sheets which have little or no thermal massing properties and are found to be physically hazardous or chemically dangerous to health.

Most of the research analyses of the traditional architectural techniques in India were heavily dominated by materiality, wall thicknesses, openings for ventilation, deep eaves & other shading forms, orientation and general arrangement of building and street layout. Another architectural feature that was heavily used in traditional Indian dwellings was the use of courtyards. Whilst courtyards in houses in the Middle East are a common feature, courtyard houses in India seem to exhibit functions that are a direct reflection of climatic ramifications of Indian Architecture as is identified by Priya et al (2012). The use of courtyards will be discussed further in the following sections.

Another traditional technique used effectively in coastal regions in India is the wind catcher. During the day, as hot air is stagnant inside the house, the wind catcher takes in cool air from the outside and pushes away the hot air from the inside (Fig 2.5), this maintains a regular air interchange between the insides and the outsides.

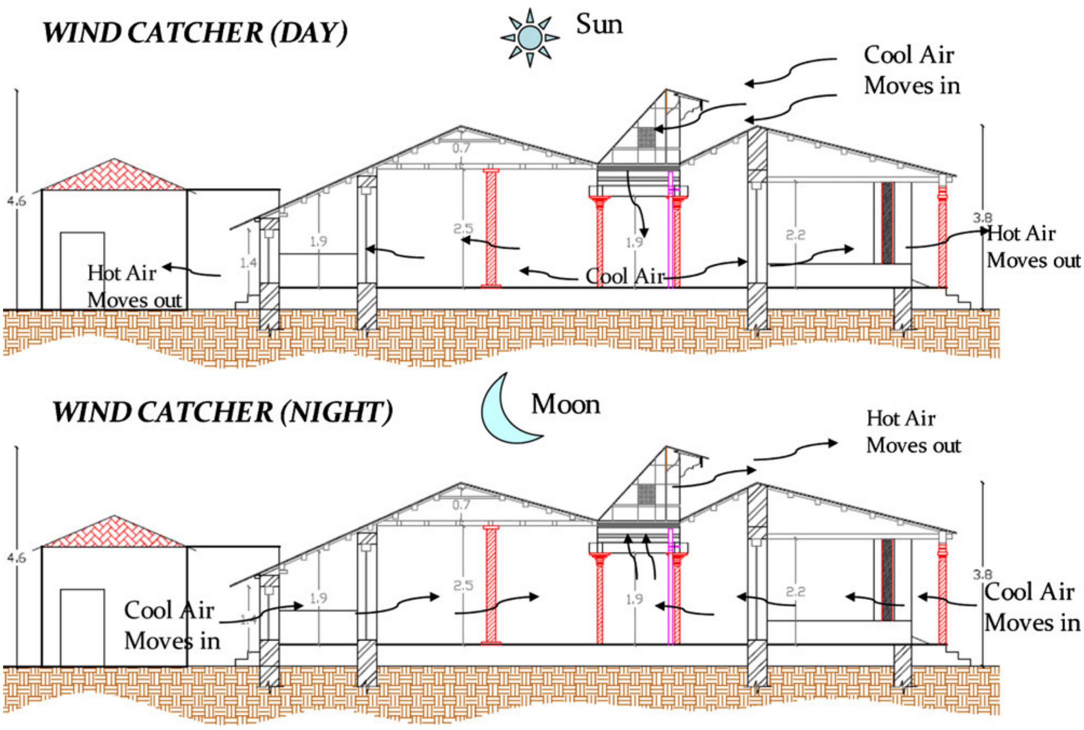


Figure 2.5 Air interchange facilitated by wind catchers (Priya et al 2012)

Due to increases in technological knowhow and commonly found technical facilities, architectural and behavioural patterns that were once seen to be in harmony with nature are becoming increasingly less sustainable and more dependent on fossil fuels. (Indraganti 2010). This therefore impacts the overall environmental, economical and social equilibrium in the community. When reliance on technology increases and in the event comfort cannot be derived from technological advancements due to shortage in supply or technical malfunction, these occupants have to limit themselves to living in thermally uncomfortable settings due to not having comfort provided by the building skin. Therefore, the divergence of contemporary architectural patterns from being sensitive to culture and climate to becoming insensitive to these requirements has made way to a plethora of environmental, physical and physiological problems as identified by Indraganti (2010), Upadhyay et al (2006) and Hanaoka et al (2009) amongst many others. Thus, the need is very clear in many literatures that the lessons that can be derived from traditional architectural techniques is important to alleviate the various thermal comfort inadequacies that stem from not considering core requirements of human comfort and climatic standards.

The environmental and thermal benefits of traditional architecture is further emphasized by Priya et al (2012) who identify that traditional architectural techniques understand the ramifications of local climates and therefore are innately more flexible and adaptable to provide thermal comfort to the occupants. Moreover, Indraganti (2010) and many other researchers including Singh et al (2007), Saleh (1999) and Dili et al (2010) are of the opinion that should the building techniques that informed traditional architectural means be implemented in modern buildings, modern buildings can become more sustainable due to the much lesser amounts of energy that they will potentially consume.

Overall, many kinds of literature analysed identify how much the gradual reduction and disappearance of traditional architectural techniques has given rise to thermal comfort and energy complications. Literatures as outlined above, also identify how the integration of traditional architectural techniques in modern architectural systems will help to mitigate some of the ill thought out effects that erupt as a result of haphazard planning of modern architecture. Priya et al (2010) confirm this when they state that the integration of traditional architectural techniques will control and limit the reliance on artificial methods of comfort and enhance energy efficiency to provide better and healthier levels of thermal comfort. Many research materials relating to India identified therefore show that traditional architectural have to be scrutinised to learn from them and thereby use that knowledge to good effect by integrating them to modern architecture.

2.6 Selected analysis of Traditional Cooling Systems used in the Gulf region

This section will discuss Traditional architectural techniques which were so used in order to provide cooling to the occupants inhabiting a dwelling. Examples will be from several parts of the Middle East and the Gulf regions with particular emphasis on dwellings in the UAE.

As was discussed in section 2.2, the discovery of oil in the UAE led to a construction boom that steered the UAE from sustainable architectural techniques. Al Zubaidi (2007) identifies that communities that were recognised by their mud wall typologies have now become much more sophisticated commercial capitals well integrated into the global economy. The speed of construction imposed upon the building boom in the late 20th century was so rushed that despite the levels of technical advancements and expertise, there was a lot of room for carelessness that results in mistakes *vis a vis* matters of sustainability (Zandy 1991). Due to the abundance of oil and the relatively cheaper financial costs involved for energy, ventilation that used to be satisfied by means of clerestories or small windows and wind catchers were replaced by energy intensive mechanical means of ventilation (Zubaidi 2007).

This section identifies some of the traditional architectural techniques used in the Gulf region with particular emphasis on the UAE. Due to the various different typologies of buildings that exhibited the traditional style, for consistency of analysis, the focus will be on traditional residential buildings.

Considering the hot-dry conditions of most Gulf countries, the building orientation plays an extremely important role in providing adequate thermal comfort. If the sun path diagram for a particular site or building isn't analysed prior to the planning of a building and the allocation of spaces for various functions, overheating can result in many complexities that will drive occupants to seek comfort through mechanical means to offset the bad planning procedures. This is confirmed by Al Zubaidi (2007) who identifies that outdoor living spaces are oriented to protect the space from wind-borne dust. Moreover, Hinrichs (1987) mentions that factors like wind shadowing and solar reflection from adjacent buildings will contribute to the negative influence of micro climatic conditions. Therefore, well thought out and well planned building orientations will be responsible for the lessening of cooling loads due to minimised solar penetration through openings in the building envelope and also making maximum use of prevailing wind directions for ventilation (Clair 2007).

Further, as shown in Fig 2.6 and as confirmed by Clair (2007), the geographic positions of the UAE generally means that the most of the solar radiation in the summer is East and the West facing walls and south facing walls in the winter. Therefore, there is strong evidence to suggest from examples in traditional architectural techniques in the UAE and the Gulf region that the orientation of the buildings were mostly considered and different spaces defined by their function were determined according to their orientation as is reflected in Fig 2.7 where dwelling spaces like rooms are placed on the northern facade and utility spaces like storage and kitchen are placed in the southern facade.

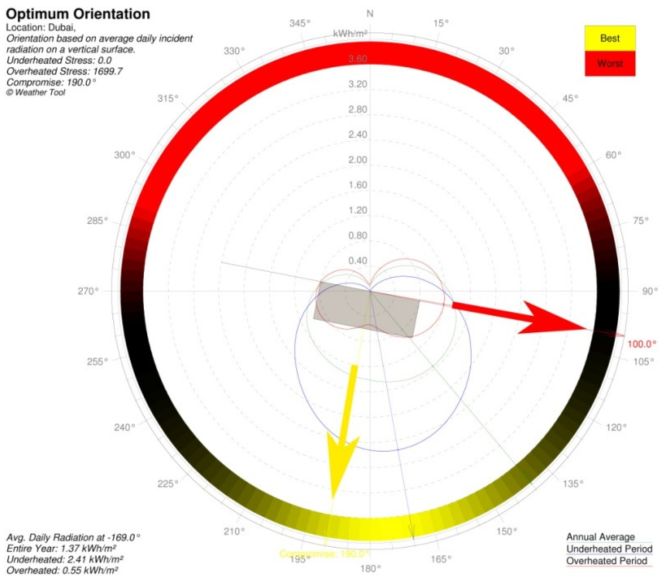


Figure 2.6 Optimum orientation for buildings in the UAE. (Ecotect)

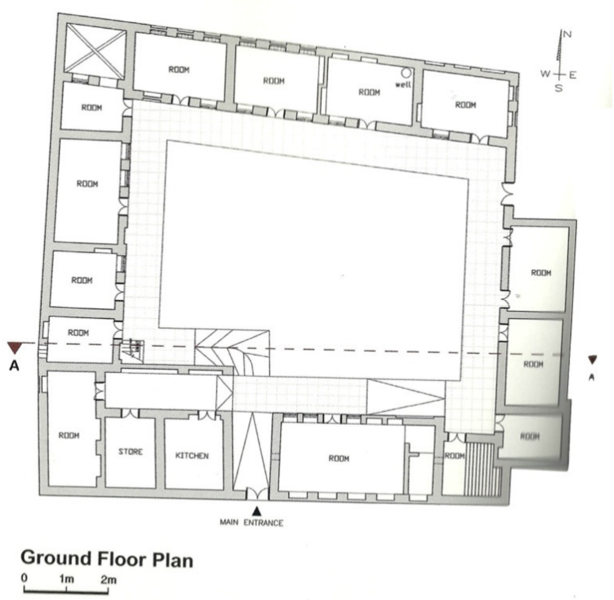


Figure 2.7 Allocation of functional spaces in respect to orientation in a traditional house in Dubai (Dubai Municipality, 2011)

Moreover, the building envelope itself had a significant role to play in the sustainability effects of dwelling spaces. Unlike in contemporary buildings where the role of the building envelope has is much reduced, the building envelope in traditional buildings usually formed the first lines of defence from harsh weather conditions. Collier (1995) identifies that the building envelope recreates the internal environment by modulating the influence of external climatic conditions to suit human comfort levels. This is reinforced by Giovani (1998) who states that the fundamental role of the building envelope is to resist heat transfer, prevent & reflect solar radiation and thereby minimise heat and solar gain to create thermally suitable cool conditions inside.

As is seen in sites of traditional architecture in the UAE, like in Bastakiya and Shindagha, the building materials used in traditional architectural buildings were largely indigenous and locally found. As identified by Al Zubaidi (2007), these materials were found to be suitable to be used in the climatic conditions in which they naturally occur. Traditional architectural dwellings in the UAE and the Gulf usually consisted of sand or clay bricks, stone, locally available timber or trunks from the ubiquitous palm trees; therefore they are extremely low in their levels of embodied energy (Kim & Rigdon 1998). Traditional building materials in the UAE also conform to the selection criteria as elucidated by Oliver (2003) who opines that the suitability of building materials used in various cultures may be assessed in terms of the material properties in reference to structure, the methods in which these properties are used and their resilience to the challenges posed by the climate.

Due to the socio-economic conditions in Dubai, during the time of construction of the traditional buildings in question materials that were most feasible to be obtained were locally found natural materials. Therefore, traditional buildings in the UAE were used as materials in their naturally occurring state that were existing in harmony with nature and were also overcoming the challenges the climate posed to their existence. Therefore, traditional buildings in the UAE satisfied most sustainability requirements that contemporary buildings fail to satisfy.

Thermal massing was another way in which houses in the UAE and the Gulf kept cool during the day and comfortable and less cold during the nights. The functional concept of thermal massing was discussed in previous sections. Al Zubaidi (2007) identifies the *'sirdah'* as seen in Iraq as one of the ways in which thermal massing was used to good effect. Therefore, as can be seen in Fig 2.8, the sirdah creates a cooler internal environment when the external environment is very hot. A sirdah is usually ventilated with a wind catcher (to be discussed in detail later) which sucks in fresh air, this is facilitated by an air exchange due to further openings at the lowest level of the basement (Al Zubaidi 2002).

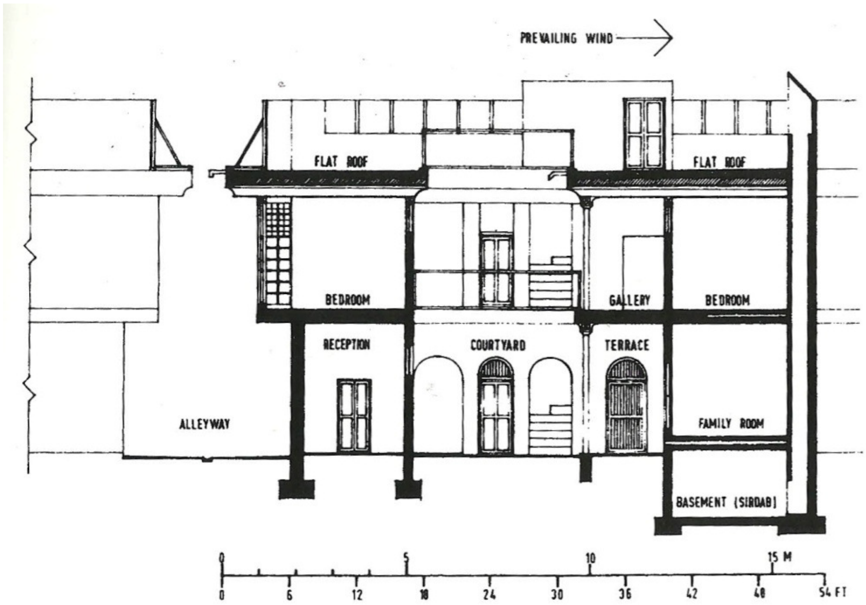


Figure 2.8 Sirdah used in houses for thermal mass and cooling. (Edwards et al, 2006)

2.7 Wind catchers

Among the prominent cooling techniques in the Middle East is the wind catcher, known as *'badgir'* in Iran, *'malqaf'* in some parts of the Levant and as *'barjeel'* in some other parts of the Gulf including the UAE. In order to establish clarity, it must be noted that the word 'wind catcher' is used to denote the wind catcher as a traditional architectural device, and the word ‘wind tower’ refers to the wind tower as a design and functional element within the wind catcher.

For reasons that will be inferred later on, the wind catcher is most effective in it is function in hot-dry and hot-humid conditions. Ghaemmaghami & Mahmoudi (2005) state that the history of the wind catcher goes up to the 4th century BC where wind catchers were observed to be in existence by a Japanese expedition in north eastern Iran. However, Shorbagy (2010) states that a wind catcher with two openings was illustrated in the Pharaonic house of Neb-Amun which was depicted in his tomb around 1300 BC.

Wind catchers help make the building cooler in the same way that modern coolers work, except that they use only natural energy (Eiraji & Nambar 2011). Ghaemmaghami & Mahmoudi (2005) elucidate that as wind energy is of extreme importance to architects, they try to incorporate the characteristic effects of wind to achieve thermal comfort by convection, ventilation and air flow into the interior space, this is further confirmed by Hinrichs (1987) who identifies that the purpose of a wind catcher is to collect air from above it and channel it through the wind tower and into interior spaces. Fig 2.9 below identifies how wind is exploited at the various times of the year in a house in the UAE during the summer.

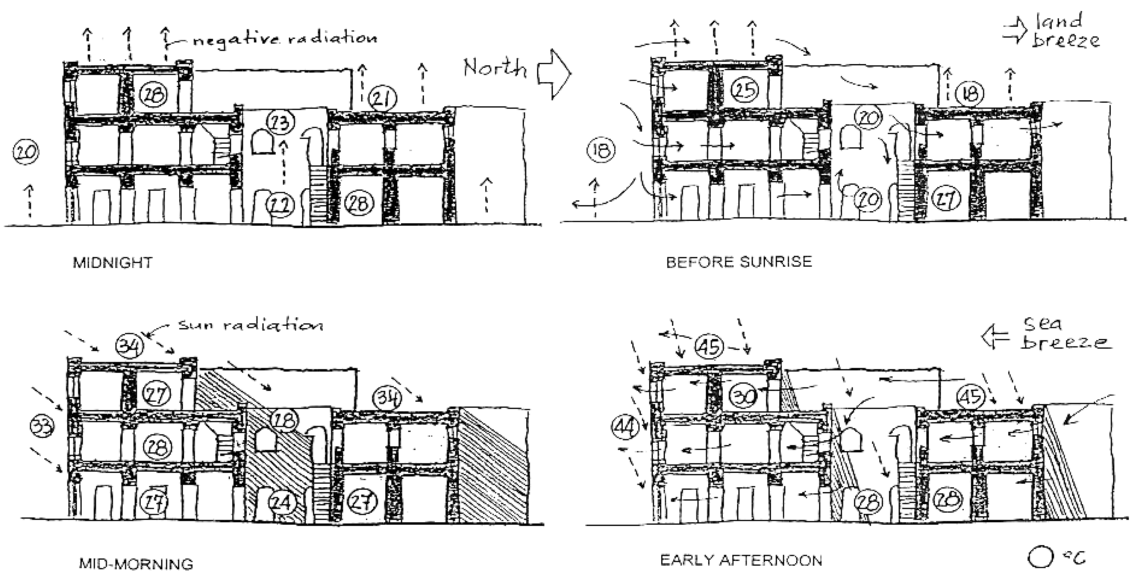


Figure 2.9 Summer wind affecting a UAE house. (Al Zubaidi 2007)

Further, Montazeri & Azizian (2007), opine that the function of the Badgir is to take in air streams from the outside and channel it into the building or courtyards so that occupants can be cooled by enhancing heat transfer by means of convection and evaporation.

Wind catchers are usually the tallest structures that visually tower over as the highest point in a building. Taller the tower, greater the access to high speed winds and the dust free environment. Moreover, having wind towers in high spaces alleviates the possibility of wind flows being obstructed by other urban fragments, like tall buildings or other towers (Fig 2.11)

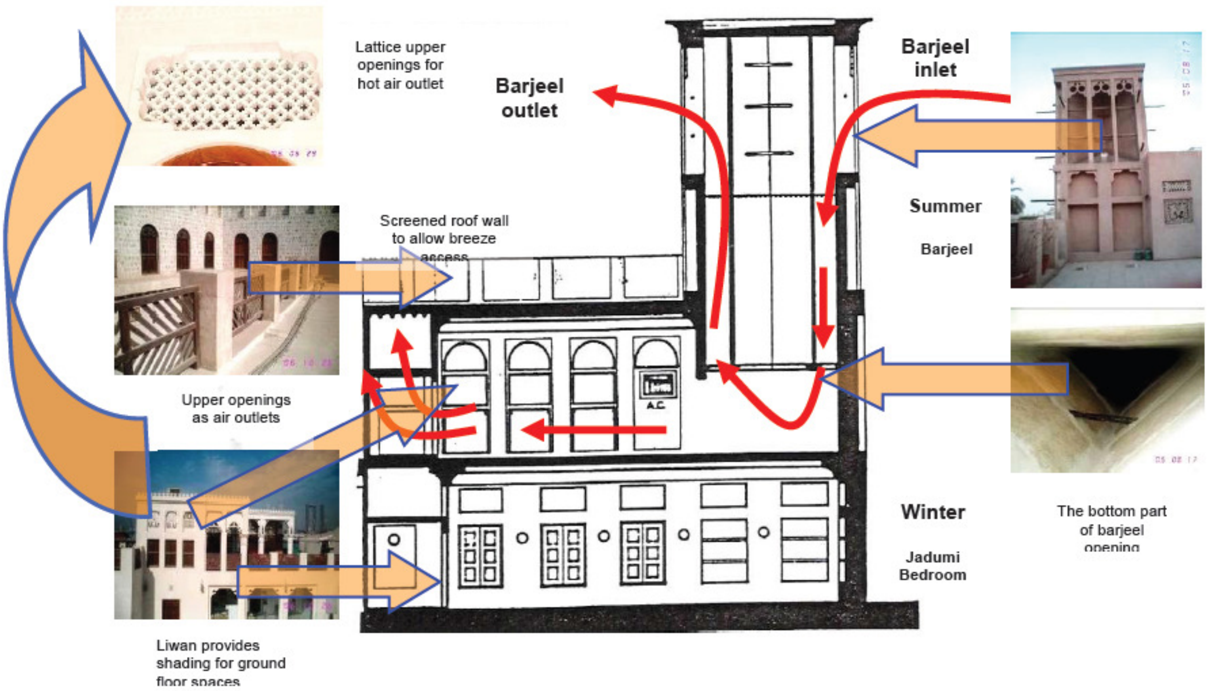


Figure 2.11 Various elements of a wind catcher (Al Zubaidi, 2007).

Wind catchers are usually placed at about 15m above ground level, as the wind velocity at that height is far greater by at least twice the ground speeds. Since the wind tower uses the air (once captured from the outside) within an enclosed channel, the force from the air is concentrated due to absence of air loss. The purpose of the tower is also to increase the velocity of the wind travelling downwards, this also helps dissipate heat. Therefore, the wind that enters the wind catcher would have cooled enough when it reaches occupants inside (Al Zubaidi 2007 & Al Rostomani 1991).

Wind towers need a minimum of two openings if they are to work from first principles. One opening would face the direction of the wind to attract cool air and the other opening would face leeward to let out hot recycled air (Shorbagy 2010). However, Ghaemmaghani & Mahmoodi (2005) point out that wind towers can be built with multi directional orientation in order than cool wind is gathered from all four geographical directions. Research was also found to express the feasibility and indeed applicability of using uni-sided wind towers as part of the wind catcher.

Wind towers are mostly divided by separations in the inner shaft. Whilst one or many shafts work towards attracting the breeze, the other shafts work as air outlet passages. Therefore the hot air escapes through the 'chimney effect'. According to most research, the chimney effect functions on the principle that as air increases in temperature, it also increases in density. Therefore, the variations in temperature in the many parts create several pressure regions, some with positive pressures and some with negative pressures. Therefore, variations in pressures create air currents.

Hot and dry regions can have very low moisture levels in the air due to lower levels of relative humidity. Therefore, to increase the moisture content in the air and to increase the coolness, some geographical locations in the Gulf regions (like Bastakiya in Dubai) have moist fabric or mats installed at the top of the shafts so that these will provide a source of moisture that can amalgamate with the wind blowing inwards to provide cooling.

Many traditional residences have a system where the moisture of the cloth can be maintained consistently, this phenomenon is verified by Ghaemmaghami & Mahmoodi (2005) and Eiraji & Nambar (2011). The former also infers that where wind speeds are low, the size of the openings in the towers can be made smaller, so that the pressure of the wind blowing inwards increases as air has to flow through a smaller sized opening, as is encapsulated by the Bernoulli principle.

Wind catchers usually vary from region to region, based on various criteria such as climatic conditions, architectural aesthetics, function and typology of the building. Depending on the climatic conditions and their specificities like wind speeds, humidity, temperatures and cloud conditions, the technical features of the wind towers will also vary. Shorbagy (2010) identifies these as uni-directional wind catchers or multi directional wind catchers. The multi directional wind catchers are further broken down by Ghaemmagami & Mahmoudi (2005) as being two directional, four directional or eight directional.

Shorbagy (2010) and Ghaemmagami & Mahmoudi (2005) seem to have varying explanations of what one directional wind catchers are. Shorbagy (2010) explains that the uni-directional wind catchers are more like a tower that covers a courtyard. This probably means that there is a tall central tower with provisions for sitting areas in the base of the tower, like in a courtyard. This tower would have facilities for cool air to enter and for hot air to escape. The sitting areas around the tower would have much lower ceilings so that the effect of the breeze can be felt on the occupants, than merely providing a cool environment, thereby creating a faster manner in which occupants can cool off.

On the basis that the wind catchers visually face the directions of the wind, it may be assumed that the architecture of the uni directional wind catcher would facilitate the fast ingress of air from one direction. Shorbagy (2010) therefore mentions that the wind tower was flat on top, so that the upper layer of air can be heated up by getting it to be exposed to the sun. Thus the covered courtyard therefore has what is called a *malqaf* or a wind catcher that channels breezes from the top to the living spaces below. Therefore, the uni directional wind catcher usually has an opening facing the side of the wind catcher that has the strongest prevailing wind.

Multi directional wind catchers therefore, have more than one opening. This facilitates the ingress of wind from various directions. The purpose of multi directional wind catchers however, is not just to attract wind from many directions. What this also means is that the shaft itself is partitioned, in most instances into two, four or eight, this does not discount the possibility that the shafts were partitioned into other numbers (Ghaemmagami & Mahmoudi 2005 and Keshtkaran P 2011). This also means that the number of openings has to be facilitated by the external shape and appearance of the shaft. Some shafts are known to have looked octagonal in shape, the wind tower would therefore be partitioned and sub partitioned by any other material.

The making of the shafts to be narrower and elongated achieves another advantage as explained by basic physics. When the speed or volume of air entering the tower remains constant, and when the area of the shaft and inlets are made narrower, the speed with which the cool air descends into the living spaces below increases. It is suggested by most research authorities, that a moist cloth was placed at the top of the wind tower, so that when the breeze blows inwards, the moist cloth can further cool the wind and reduce its temperature before it goes down through the wind tower.

Wind towers are mostly four sided, though there may be instances when the wind catchers take on the shape of other polygons in cross section. Al Zubaidi (2007) identifies that whilst a circular barjeel can be seen in the Ibrahim Madfa'a Majlis in Sharjah, circular wind towers are extremely rare. Another additional technique used in conjunction with the wind tower or integrated to the wind tower are air pullers. They allow an opening through a recess that allows winds to ingress through the gap between two layers of the wall, Fig 2.12. The wind when it collides with the wall, its direction of travel is changed to enter the building (Al Zubaidi 2007 & Al Shindagah 2014).

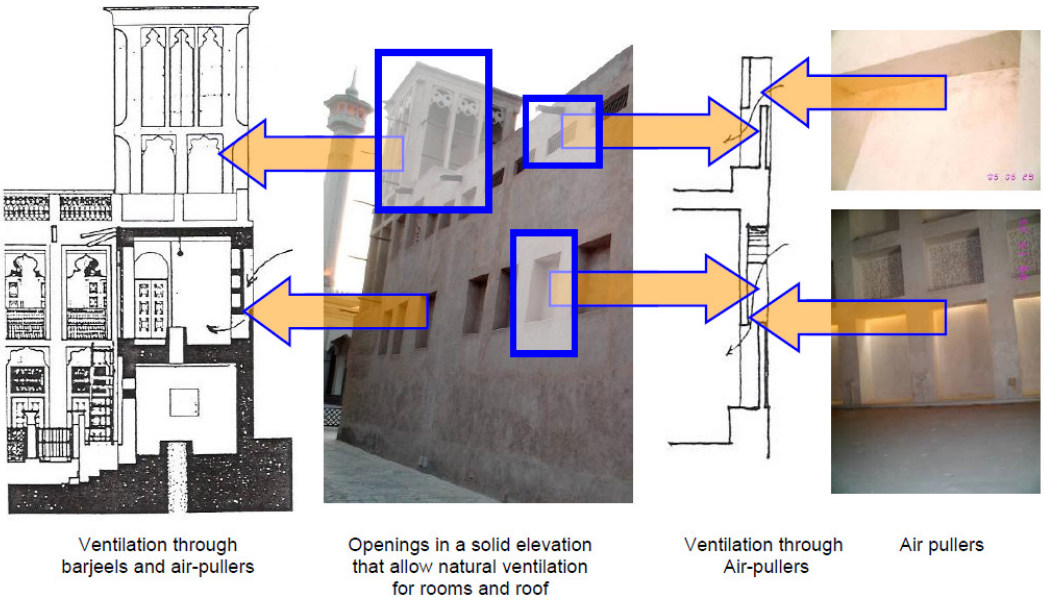


Figure 2.12 The various ventilation strategies within a wind catcher (Al Zubaidi,2007)

In addition to the advantages of the wind catchers in their operation in the UAE, Bahadori (1994) identifies disadvantages of the wind catchers that have been echoed by many other researchers.

- Due to the wind catchers having openings that expose the interiors to the outside, it can be an easy access point for dust and insects.
- If wind towers have multiple openings, air entering through one opening may be lost through another opening.
- If the material of the tower has a low specific heat capacity, the heat absorbing thermal mass capacity will be insufficient to cool the hot air in summer days passing through the tower.
- Due to its inherent characteristics, the evaporative cooling potential of air can possibly not be utilised to the optimum.
- The use of wind catchers can be used only in areas where there are sufficient wind currents.

It has to be emphasised here that the purpose of trying to find new and or sustainable means of energy is not to entirely replace active cooling or heating systems. Whilst such apparatus would be ideal, it must be understood that if a system can be created that can reduce the dependence of occupants on active systems quantitatively, with passive systems at least as a supportive system, then that itself is a means in which the loads on the earth's natural resources can be controlled.

Poshtiban et al (2007) identify that in a wind tower, it is important that all other air inlets are blocked and only the opening that has the most air coming through is kept open. This way the air would have a strong uni directional wind coming in that would be stronger and avoids the cancelling of winds that come in from opposing directions.

Wind catchers therefore are an extremely effective and geographical location specific traditional architectural strategy to provide cooling indoors, the many technical facets of the wind catcher system that are incompatible with modern times can be researched so that they can be entirely alleviated or mitigated.

2.8 Integrating traditional sustainable strategies in modern buildings

Trying to imitate the function of wind catchers in modern buildings have been tried by various designers and researchers. Wind towers continue to be built in modern buildings in very many parts of the Middle East. Poshtiban et al (2007) tried to replicate the function of a wind catcher in a modern building. The purpose was to create a cooling environment indoors without the consumption of additional energy. In addition to research that has been conducted to assess the feasibility of integrating traditional architectural techniques in modern buildings, there are instances where this has already been done.

For various reasons, some of which have been identified above, traditional architectural techniques are reappearing in the streetscapes of the UAE and the Arab world. Whilst in some instances they serve no technical purpose and are mere aesthetic elements, in some other instances they do contribute to mitigating energy loads and providing passive means of comfort.

In the 1970's, the rate at which modern architectural techniques and materials permeated into common usage in the UAE meant that traditional and sustainable methods were overlooked, as was identified above by Zandy (1991) and Al Zubaidy (2007). Therefore, lifestyles changed and due to the abundance of wealth and ease of access to fossil fuels, reliance on mechanical ventilation for cooling made homes and other buildings to be designed with the ease of mechanical ventilation in mind. With this phenomenon began the consistent decrease in the usage of traditional architectural techniques.

However, even in this period, there were instances where new architectural projects used traditional architectural techniques. The rapid change of UAE architecture to an architectural culture that was devoid of its identity persuaded local authorities to seek an implementation of regionalism into contemporary architecture. This led to the slow rejuvenation of traditional motifs being used in modern contemporary architecture. Among the motifs, the wind catcher was identified as the most prominent due to the necessity for natural ventilation to cool the insides of the building by having consistent wind flow (Al Zubaidy 2007).

The researcher last cited also identifies that the most prominent building that features a wind tower amongst modern buildings of that era is the Souk Al Markazi in Sharjah built in 1977 as shown in Fig 2.13. Natural ventilation to the insides were obtained by the use of barrel vaulted roofs to which wind towers were installed, this ensures adequate ventilation by natural means.

Al Zubaidi (2007) further identifies the Al Ittihad school based in Dubai as another instance of traditional architecture being integrated into contemporary architectural patterns. The school was designed on a composition of several individual buildings that formed clusters. The various academic sections of the school were divided along these buildings that were arranged in a spiral form surrounding a central administrative block. In addition to this Cantacuzino & Browne (1977) and Al Zubaidi (2007) mention that the kindergarten school designed by Arab architect Jafar Tukan in 1977 which also used a clustered formation utilised a wind catcher for partial satisfaction of its cooling requirements.

Figure 2.13 Souk Al Markazi in Sharjah with vaulted ceilings and wind catchers

(www.thepurplejournal.wordpress.com accessed on 12.01.2014)

Privacy being one of the very important elements in Islamic culture, Arab traditional architecture featured a lot of screening systems to maintain privacy for occupants at home, particularly women. The screening systems in the Middle East became sophisticated and popular to the extent that that *mashrabiyya* (as seen in Fig 2.14) concept was emulated by many modern architects both in the UAE and in other parts of the world.

2.14 Mashrabiyya in the Zahaby House, Cairo. (www.mit.edu accessed on 11.01.2014)

Mashrabiyya are commonly known to be perforated screens that were usually made out of wood. They not only provided privacy, but they diffused daylight before it ingresses – thereby reducing solar heat gain and they also provided cooling by promoting mini wind currents through the perforations and in instances working in conjunction with courtyards and wind catchers (El Amrousi & Shakour 2013).

In France, Jean Nouvel's *Institute du Monde Arabe* features the use of screening devices that were inspired by the mashrabiyya (Fig 2.15). Several of these devices were used that occupied a large portion of the facade. The perforations were thermo sensitive and opened and closed depending on the movement of the sun, so that just the adequate amount of solar penetration would take place. Moreover, in the UAE, the Al Bahar towers in Abu Dhabi designed by Aedas in 2012 feature thermo sensitive screens inspired by the mashrabiyya (Figs 2.16-2.18). These screens are integrated to a curtain walling system that is fixed 2m from the main structure. The screening consists of triangles that are constructed with fibreglass and have been programmed to open and close depending on the position of the sun. Therefore, solar penetration and resultant radiation can be mitigated leading to a reduced load of energy used for cooling. This is confirmed by the design team who identify that "*the cocoon-like buildings are based on a pre-rationalised geometric form, fine-tuned via parametric design tools to achieve optimal wall to floor area ratio. A solar-responsive dynamic shading screen further decreases solar gain. This 'Mashrabiya' acts as a secondary skin that mediates daylight and reduces glare. The system is driven by renewable energy derived from the photo voltaic panels. The south facing roofs of each tower incorporate photo-voltaic cells, generating approximately five percent of the total required energy from renewable energy sources*" (Freshome.com 2012).

Figure 2.15 Interior of the Institut du Monde Arabe with screening devices.

(http://www.campusfranceindiablog.com accessed on 12.01.2014)

Figure 2.16 Screening devices open to allow sunlight. (www.freshome.com accessed on 12.01.2014)

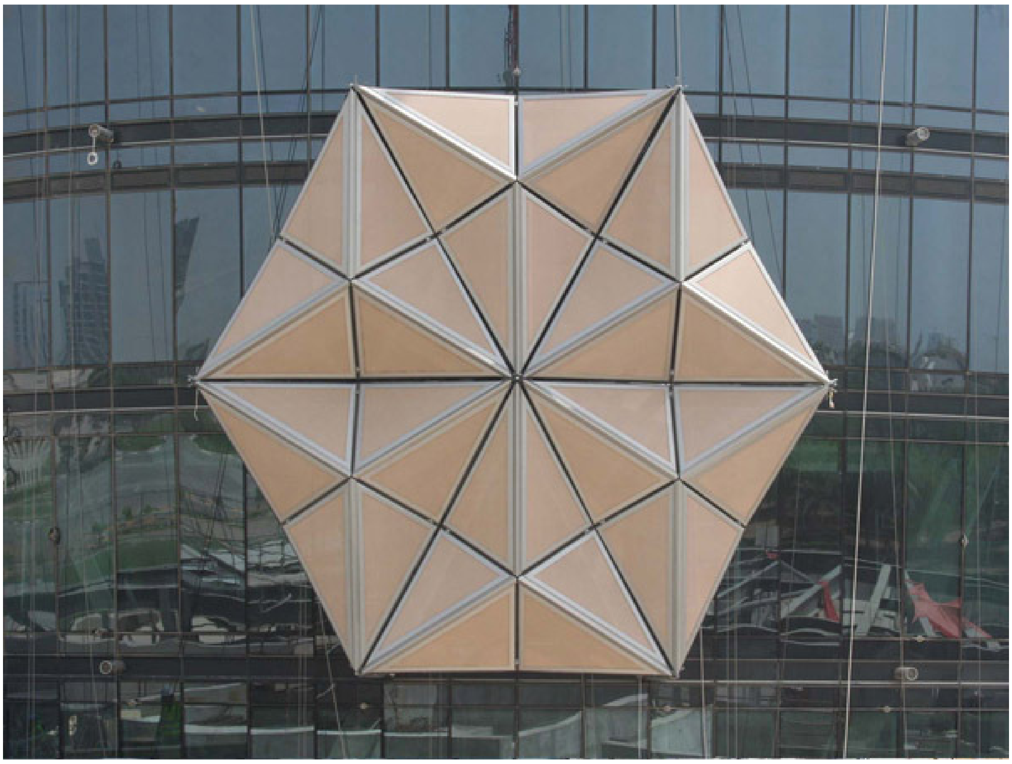


Figure 2.17 Screening devices closed to block sunlight. (www.freshome.com accessed on 12.01.2014)

Figure 2.18 Traditional technological inspiration integrated in the modern Al Bahar towers (www.freshome.com accessed on 12.01.2014)

The Abu Dhabi Central Market by Norman Foster (Fig 2.19), fully opened in 2013 heavily features the use of gridded screens inspired by the mashrabiyya concept. Although extensive use of timber in this project cannot be entirely condoned as the type of wood used isn't mostly native and therefore is high in embodied energy, but the ingenious manner in manner in which the mashrabiyya concept has been incorporated into this large modern architectural project is remarkable. The large perforated screens allow light to get in and illuminates the spaces below with filtered daylight, thereby providing light and avoiding solar gain and harmful UV rays, this has a resultant reduction in mechanical use of energy for cooling.

Figure 2.19 Traditional architectural techniques integrated into the Central Market Abu Dhabi.

(www.shewe.yolasite.com 2014).

One of the more prominent instances of traditional architectural practices being used in modern architecture is to be seen in Madinat Jumeirah in Dubai, built in 2004 (Fig 2.20). Madinat Jumeirah is a luxury resort in new Dubai built to emulate the sustainable traditional techniques prevalent in UAE architecture (Haggag 2008). The use of traditional eco-friendly architectural principles result in reduced energy costs, reduced load on the environment, reduced pollution and enhanced occupant health.

Figure 2.20 Traditional architectural techniques integrated into the Madinat Jumeirah, Dubai.

(www.simplypoor.com 2014).

The following are identified as some of the traditional techniques used in Madinat Jumeirah (Haggag 2008):

- Carefully calculated shading devices are used in the southern facade. These shading devices are designed to block the high winter sun from penetrating into the insides and allowing low winter sun to ingress into the building.
- Abundant use of vegetation, pools, canals and other water bodies to provide evaporative cooling.
- Natural ventilation has been used to the optimum by the design, provision of air inlets and outlets in the walls to promote air transfer, atria, courtyards and other means of natural ventilation.
- Wind catchers to facilitate cool air ingress.

- Internal airflow promoted almost entirely by natural means with little or no use of mechanical ventilation systems.
- Insulation placed on the inside and very thick building envelope to accentuate thermal mass effect.

Many research studies analyses showed that the integration of traditional architectural techniques in modern buildings can result in the reduction of energy consumed by mechanical ventilation. Some examples of these modern buildings were highlighted above.

Calautit et al (2013) did studies to analyse the effect of integrating heat transfer devices in wind towers to create a comfortable internal environment in harsh conditions. Their studies, done mostly by CFD analysis identified that the heat transfer devices worked well in conjunction with evaporative cooling systems. The system they devised showed potential to reduce air temperatures in the insides by at least 15 K. Thus, integrating this system in modern architectural systems, it is understood, has the potential to significantly reduce energy costs lost otherwise to mechanical cooling systems, Fig 2.21.

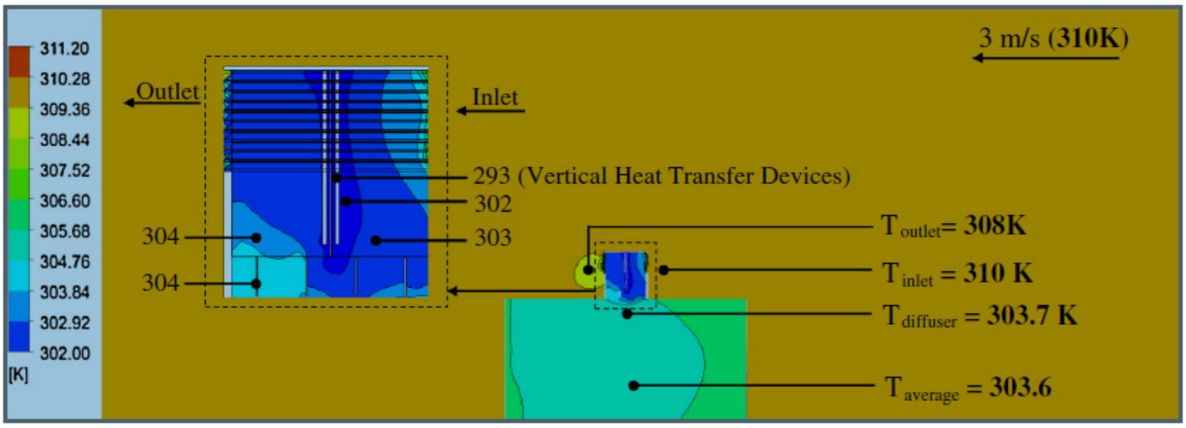


Figure 2.21 Temperature contour taken during tests by Calautit et al (2013).

Based on the studies done on the Malqaf type of windcature used in the Middle East (Fig 2.22), Al Asir (2005) and Calautit et al (2012) identify that the wind catcher with a few more additional techniques can function efficiently in modern times. An example of amalgamating modern systems with the wind catcher is seen in the works of Suleiman and Himmo (2013)

(Fig 2.23) who proposed the use of a uni shaft, where during winter, air that is heated can come into the interior spaces down the shaft and warm them, this system also functions in the summer when the device shown by annotation 3 is sealed.

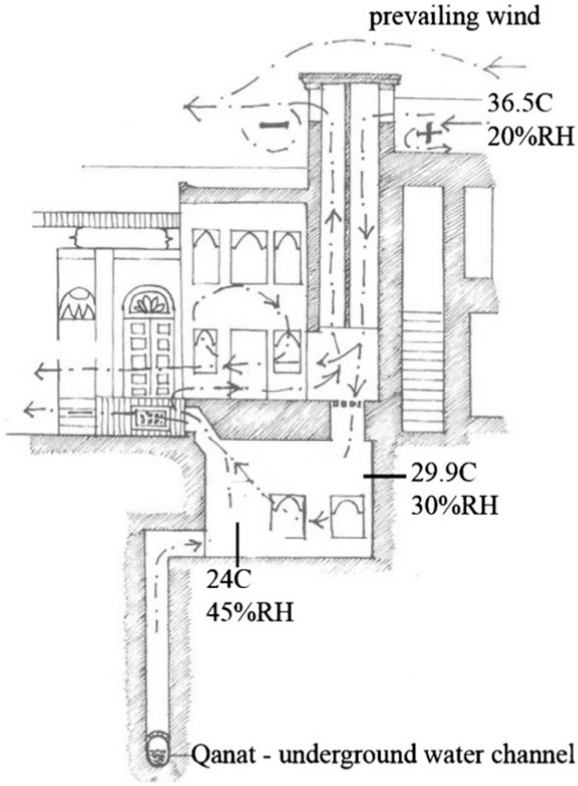


Figure 2.22 How the traditional Malqaf works (Roaf 2001)

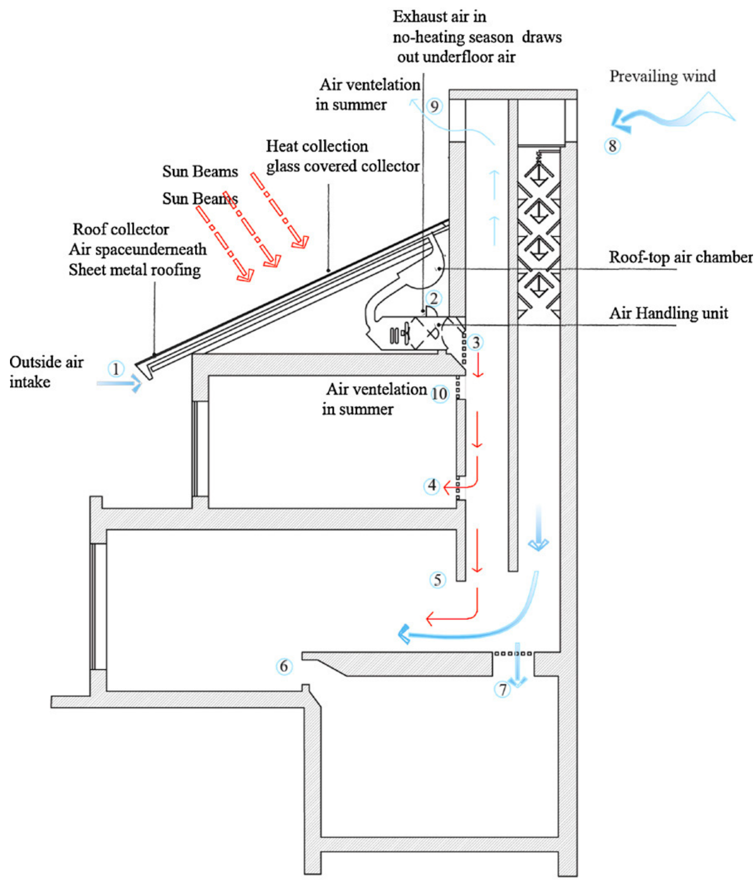


Figure 2.23 Modern wind catcher techniques (Suleiman and Himmo 2013)

In their concluding remarks, Suleiman and Himmo (2013) identify that the wind catcher as a traditional technique can certainly be used in modern buildings, with certain complementary contemporary technological apparatus integrated into the system.

Work done by Bardran (2003) shows how the Malqaf can be feasible in most microclimatic conditions in Jordan. For this, Badran (2003) used an experimental set up that proved that the Malqaf can be efficient to be used (in the modern buildings) in most microclimatic requirements and that the square profile for the wind tower will be the most suitable. Experimental studies conducted by Bouchahm et al (2011) show that the strategies they had used by the employment of wet pipes integrated into the wind catcher works best in the hottest and driest days of the year, thereby establishing that they system analysed satisfies the period of the year when mechanical ventilation is most used and when the demand for cooling is at its highest.

Conclusions made by Asfour & Gadi (2013) identify that integrating the wind catcher with curved roofs have significant effects in optimising air flow through a wind catcher and works particularly well in conditions that are influenced heavily by deep plan buildings. When Montazeri & Azizian (2008) performed experiments to study the natural ventilation performance of one sided wind catchers, they were able to conclude that the one sided wind catcher has a lot of potential to operate in urban settings to act as a natural ventilation device; this helps to offset the comfort desired by use of mechanical ventilation systems. Giabaklov & Bullinger (1996) carried out research on the integration of systems that have passive evaporative cooling. Whilst the model they proposed could not be constructed for financial reasons, the theoretical conclusions suggested that using water droplets in passive architectural techniques that use natural ventilation is a strategy that can be used in modern architecture. Abu Hijleh & Al Masri (2012) identify that the traditional courtyard form in midrise buildings can have a significant effect in reducing energy in climates similar to those of the UAE.

There are numerous instances where literature analysed identifies that traditional architectural techniques, including wind catchers, can work well in modern times, though certain changes may have to be made to increase their efficiency.

Several attempts have been made to study the feasibility of integrating wind catchers in modern buildings. However, as was evident in the literature reviewed, and as confirmed by Suleiman & Himmo (2013), analyses of the effectiveness of wind catchers integrated into buildings in live projects were rarely found. Many experimental and theoretical studies have been carried out to discuss the performance of wind catchers, but the assessment of their performance has largely been restricted and limited by the tests having been carried out under laboratory conditions. This is evident in the works of Edwards et al (2006), Jones & Kirby (2009), Montazeri (2011) and Montazeri & Azizian (2008) in addition to the many other research bodies cited above. Of the literature mentioned, the works of Jones & Kirby

(2009) however showed semblances of evidence obtained empirically though they weren't entirely empirical.

In a very extensive and detailed study of wind catchers found in many parts of the Middle East of both modern and traditional architecture, Hughes et al (2012) emphasise on the importance of wind catchers and the many variations of wind towers in their applications in modern buildings. By identifying that *"successful wind tower technologies existing today can promote a starting point for the research required to develop practical guidelines for the design of future wind towers",* Hughes et al (2012) not only praise and thereby approve of the use and suitability of wind catchers in modern architectural techniques, but they also identify that much more research should be conducted to enhance the applicability of wind catchers in modern buildings.

2.9 Literature review concluding remarks

Korea, India and the Middle East have some of the cities that have very high rates of development, industrialisation and commercialisation, therefore, they exhibit commonalities in the reasons for which traditional architectural techniques reduced. Having realised this, and in trying to rejuvenate traditional sustainable strategies to reduce their ecological footprint, these countries could share research to understand solutions that will be suitable not just to their own country. Almost all literature analysed confirm that integrating traditional sustainable techniques, especially courtyards and wind catchers in modern buildings will help mitigate the pernicious effects of over use of mechanical ventilation and fossil fuels by providing clean and healthy ventilation strategies for homes and other dwelling spaces in the Middle East and the UAE.

Section 3: Methodology

3.0 Methodology

This section will outline the methodology that has been employed in order to do the studies that were outlined in previous sections in order to satisfy the aims and objectives that lead towards results and discussions. Prior to performing any research on the subject itself, studies and research were performed to understand the various methodologies that had been approached by other researchers on the subject of sustainable design and the advantages of integrating wind towers in modern buildings. With understanding of the nature of work carried out by other researchers, the most suitable methodology that will yield optimal results was selected to be the chosen methodology for this research.

3.1 Field measurements

Field measurements involve the study and analysis of various building conditions on site and the impact they have on the various climatic conditions upon which they exist and vice versa. These involve mostly the study of existing buildings as was the case with Dili et al (2008). Although by definition, the creation of a life size project can be carried out to study their impact, this rarely takes place.

Dili et al (2008), who studied the influence of passive architectural techniques of traditional residences in Kerala, India, placed electronic sensors in various locations of the house, like in the courtyard at different heights, in bedrooms, adjacent to bathrooms and around verandas. These sensors made measurements of temperatures at regular intervals. Therefore, in order to fully understand the impact of the thermal setting, temperature readings had to be taken over a period of a few months and a few seasons. In addition to temperature sensors, relative humidity sensors were also used to measure the impact humidity levels have on comfort. This study was useful to understand the field measurement technique as a methodology for this research, as it sought to measure the comfort impact of traditional homes with temperature and humidity as two imposing parameters.

A similar study was carried out by Priya et al (2012) who sought to analyse the solar passive features of traditional architecture in coastal regions in South India.

Field measurements (as in the cases above) are usually time consuming and it is true for most parts of the world that measurements will have to be taken across the whole calendar year as different seasons impact the sensory readings in different ways. This in itself was a limitation that affects many researchers who usually do not have an entire calendar year just to carry out field measurements.

However, field measurements are the closest any methodology can get to experiencing the truest impact of various parameters such as wind velocities, temperature levels, humidity levels, radiance & illumination levels amongst other parameters. It must be noted however that these results are usually read by electronic sensory devices. Therefore, even though the experience is the most accurate, the sensitivity and the accuracy of the sensory devices has a very important impact on how useful or not this method can be.

There were no specific literature that were found that mention the use of field measurements to study the impact of wind towers on the comfort levels of the occupants.

3.2 Scaled models and laboratory measurements.

Most of the research studied involved the creation of scaled models and their use in laboratory measurements. A fair amount of emphasis is given to studies carried out by means of scaled models and laboratory experiments as this was one of the more prevalent methods that were used. In most instances, laborarotory measurements involved the creation of a scaled model that was used for analysis by the artificial creating of natural phenomena within a confined space, like winds and humidity levels. There are many advantages to the use of this methodology like the flexibility in operation and the lesser chances for error if the scale is correctly observed, the inability to recreate a model and setting of the real setting to an agreeable level of tolerance would significantly affect the accuracy of the results. However, this method gives the researcher a greater level of freedom to control the setting and studies as it allows for a convenient scale to be created.

The design proposed by Poshtiban et al (2007) is that of a uni directional wind catcher; however this is based on an intelligent structure. The wind catcher has the ability to rotate freely to receive wind from the direction where it is the strongest; this is by having gear based rotating shafts that can freely move around the axes. A motor gear box activator is used to smoothen the process of rotation.

The reference direction signal was decided upon by the use of a fuzzy supervising controller. The intelligence required by the wind catcher to decide which direction to turn is provided by the fuzzy controller. The fuzzy controller itself gets its information by the various sensors that have been installed to aid the fuzzy controller. The information received by sensors includes wind direction & speed, ambient temperature and battery voltage (Poshtiban et al 2007).

These data combine to optimise the movements of the wind catcher. The electrical energy that is required to run this system was provided by solar cells, but a battery was also used as a backup energy source should there be fluctuations in the energy levels provided by the solar cells.

The outputs from the fuzzy controller gave stipulations for the difference between the angle of the wind catcher and the angle of the wind direction. This data was further fed into the software operational system that then goes on to influence the direction of the wind catcher. The regulator parameters of the fuzzy controller, certain linguistic rules were created to determine the various fuzzy sets. For instance, a force of 0-2 was established for wind speeds of 0-11 kmph as a minimum, and from 10-12 were attributed to wind speeds of 88-118 kmph. To be certain that this device will be effective under any climatic conditions; it was tested on twelve different conditions with three temperature states, i.e. hot, moderate and cold, and from wind speeds, i.e. normal, slightly strong and strong. These conditions were simulated using MATLAB that illustrated that the fuzzy logic controller provides considerable control performance in varying conditions that it operates in.

The experiment and simulations carried out by Poshtiban et al (2007) gave rise to various conclusions. A simple structure such as the one used with further development can be used for domestic uses as a sustainable cooling system. The fact that it uses solar cells and a 12V battery indicates that its reliance on more harmful sources of energy is mitigated and the low cost features mean that this can be used in rural areas.

Moreover, Bahadori (1981) tested the pressure coefficients in windtowers by placing a scaled model in a wind tunnel. Therefore, atmospheric winds were simulated by the use of horizontal rods and vertical screens. This setup also helped to identify the distribution of prime coefficients due to the impact of adjacent houses and courtyards.

Karakatsanis et al (1986) took into advance stages some of the research that was carried out by Bahadori, this also includes some of the studies carried out that involved scaled models. Karakatsanis et al (1986) were able to study models that were tested in the boundary layer wind tunnel laboratory. This exercise helped them to succeed in estimating the amount of natural ventilation that ingress into a building and the related pressure coefficient.

Further, as was elucidated above, the number of openings in the wind tower has an impact on the pressure and speed with which the air flows in. In addition to this the shape of the openings of the wind tunnel too impacts the physical attributes of the air flow that goes in. ElMualim & Awbi (2002) carried out tests and simulation exercises to determine the difference in performance of wind catchers that were cut to square sections or circular sections. It is commonly understood that the square shape would be more efficient in getting wind streams across; this understanding was confirmed by tests carried out my ElMualim & Awbi (2002) who confirmed that the rigid and sharp vertices of the non-circular shapes form a bigger area of flow separation and greater variations in pressures across the divide.

Montazeri & Azizian (2008) created a 1:40 model of an ancient one sided wind catcher as seen in Yazd, Iran. This was created to be used for experimentation in an open working subsonic wind tunnel. The direction that the wind flows in and the shape of the windcatcher are the two most fundamental factors that impact the distribution of air pressure and the rate at which it will stream into the building (Montazeri. H & Azizian R 2008). Therefore, these tests that were carried out by the authors were conducted for air angles that were in the range of 0-180°, the tests were carried out at increments of 15°.

Static pressures at different points of the model were tabulated by the positions of internal pressure taps that were set up on different surfaces on the model. Moreover, the authors mention that they measured the induced air flow rate by pitot and static tubes that were set up at the bottom of the channel. This model as shown above in Fig 3.1 was in turn installed on a scaled model of a house. Measurements of pressure coefficients were by means of mathematical formulae.

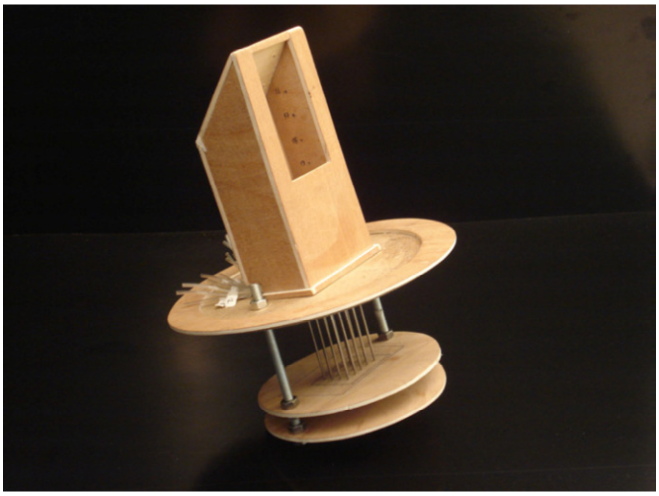


Figure 3.1 Scaled model used by Montazeri & Azizian (2008)

Moreover, when atmospheric wind was simulated, it has to be noted that the profile of the wind was almost uniform. Therefore, this method tries to recreate wind patterns that are at very high altitudes from the surface of the earth. A boundary layer gets created at lower levels in the wind profile due to aerodynamic forces. Thus, there is a discrepancy in experiments that work with models with uniform flow and these experiments that involved life sized buildings. The discrepancy is that there is a significant variation in the pressure distribution between the two scenarios. This study by Montazeri & Azizian (2008) therefore also studied technical matters that inform and are affected by this discrepancy.

Further, hydrodynamic analyses were carried out with the use of smoke injection. The smoke was successful in aiding to recognize the flow patterns of wind into and above the wind catcher model. When the wind tunnel was functioning, smoke was injected vertically from a point, this visually illustrated to the said researchers how there are differences in pressure coefficients at the various ledges, particularly the lower ledge of the opening. This significant variation in the pressure coefficients reduces the efficiency of the wind catcher. Furthermore, that there is a 'wake' region means that the speed of the distribution through the tunnel is also reduced. This experiment was repeated for various air incident angles by rotating the wind catcher along the axis as shown in Fig 3.2.

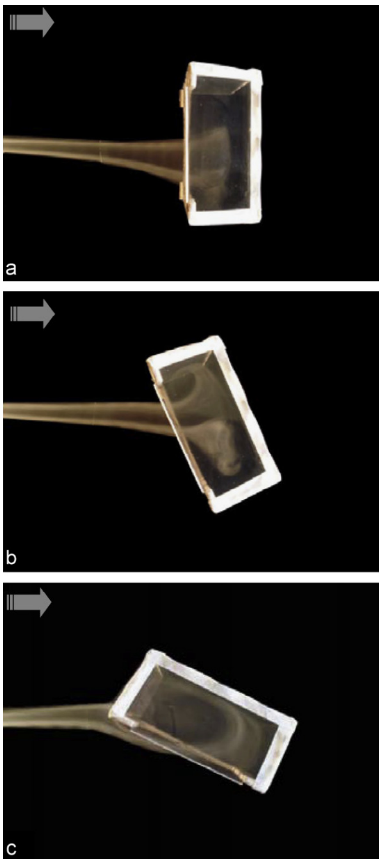


Figure 3.2 Smoke injection studies carried out to study flow patterns (Montazeri & Azizian 2008).

Laboratory set ups can be inconvenient to create and may include the use of highly sophisticated and expensive apparatuses. In this instance, it was impractical to recreate a laboratory setting for cost, time and practical inadequacies.

3.3 Case studies and surveys

Case studies were a relatively common methodology that was used to understand the effect of sustainable architectural techniques in general and wind towers in particular. However, whilst the case study analyses usually were theoretical essays and technical details of existing projects they sometimes served more to be a documentation of the existing as opposed to discovering new combinations and formations. The surveys were usually a collation of views of respondents who were made to spend time in settings that were deemed to be sustainable features.

Nematchoua (2014) did a questionnaire based study where residents were asked to respond to questions that sought to assess the differences in thermal comfort and energy consumption in traditional and modern architectural settings in Cameroon. This method is useful in understanding the human feelings towards comfort in terms of the satisfaction or dissatisfaction in dwelling in a certain setting, it will also be useful in understanding how people feel about the energy costs or the effects of using certain mechanical devices in their homes, but the responses can be largely dependent on the knowledge and technical understanding of the participants. Therefore, the researcher will need to factor in the levels of technical understanding of the participants in the types of questions that will be asked. An advantage of this methodology however is that due to the advent and wide spread nature of the internet and social media, questionnaires and surveys can be distributed with extreme speed and can reach thousands if not millions of potential participants, if the researcher so wishes.

Case studies were used in many instances such as the one by AboulNaga & Elsheshtawy (2001) who sought to review current sustainable practices in the UAE. This was done by surveying existing projects and buildings and analysing their sustainability potential. These included both traditional and contemporary projects, the study also aimed to create a list of assessment tools that can identify measureable attributes.

Furthermore, Keshtkaran (2011) studied many of the sustainable architectural features of traditional buildings in Yazd Iran. As was identified in section 2, Yazd has many traditional sustainable attributes including wind catchers that help to provide thermal comfort without the use of mechanical means. This study sought to do a historical and theoretical review of the many architectural motifs that function as sustainable systems. A similar study on Iran was carried out by Eiraji & Namdar (2011) who studied the already existing sustainable systems of traditional architecture in Iran. This was slightly different to Keshtkaran (2011) in that traditional expertise prevalent in Iran in providing thermal comfort was analysed with a technical emphasis that involved mentioning how sustainable devices were successfully used to mitigate the ill effects of high temperature and humidity levels. In addition to this, Kimura (1994) did a study of vernacular traditional technologies that were being used in contemporary buildings. This study was an interesting case study collation of various traditional techniques that benefit occupants and the environment to this day and how the use and enhancement of these technologies can be beneficial in providing thermal comfort and reducing energy costs used for cooling or heating.

All in all, case study analyses provide a very insightful and important method in understanding and listing out the various different facets of sustainable architectural techniques, the extent to which they can be applied and the levels of success achieved in implementing these systems.

The advantage of this methodology is that they usually provide a lot of information and a lot of knowledge that is extremely useful to researchers. Findings on various topics are usually synthesized and necessary information is filtered from information that is less necessary, thereby increasing the focus of the topic. There aren't any obvious drawbacks in this method, except that discovery of new information would be of existing or known phenomenon and may not be successful in identifying or inventing new systems. Furthermore, case study analyses may be irrelevant beyond a certain time frame, they can become outdated or obsolete with time and new findings can abrogate them. This is a significant limitation in that whilst some old research papers can be still very much relevant, other old papers may not be so, therefore identifying which research body based on case studies and surveys are relevant and which are not is a challenge. However, case study or survey analyses can be extremely useful in creating the foundation for or supporting other methodologies and works well when combined and coordinated with other methods.

3.4 Simulation

Simulations and Computer based numerical modelling software are a useful method that can be used to replicate a natural setting within the confines of a computer. Therefore studies done in a simulation software for a particular geographical location alleviates the need to travel to a certain setting to carry out field measurements. Simulations therefore give the researcher a significant amount of flexibility in creating their own settings and the testing variables and parameters that cannot be enacted in real life or do not have live examples from the past.

Limitations manifested in many other methodologies can be alleviated by the use of simulations. These include restrictions due to cost factors in setting up a lab or experiment, travel costs, time & geographical constraints or other contexts that are difficult to attain. Furthermore, simulations provide the feasibility of enacting real life buildings in similar settings to others that cannot be built. For instance, the influence of the orientation of a wind tower can be simulated in computer software without having them built at 1:1 or at a smaller scale. Moreover, existing projects and buildings can also be assessed by recreating them in simulation software to be analysed. Thus, very old buildings that are fragile and unsafe to trod on or worked at can be now analysed using simulation methods. In some instances however, the extra high cost of simulation software can be a limitation. However, in most instances there are subsidised student packages and research funding that can cover these costs. Another limitation of simulation software is that the natural setting is inbuilt as weather data files and over time they can become irrelevant with changes in climatic conditions, this is a slow process but is an occurrence nonetheless. Moreover, numerical simulations aren't validated on their own and have to be validated with the use of other research or with comparisons for research figures obtained by field measurements. As testified by Arnfield (2003), the validation in some instances is more on the probability of the result than a direct comparison. However, upon validation, simulation tools are an extremely cost effective and accurate tool to be used.

Calautit et al (2013) used Computational Fluid Dynamic methods (CFD) to understand the effect of a heat transfer device integrated to wind towers in hot and dry conditions. ANSYS 12.1 Fluent software was used to create computational models of various wind towers. This model was used to compare the effects of evaporative cooling across various conditions and parameter values. In addition to this, Hughes et al (2012) exhibited the extensive use of simulation software to develop various strategies that can be employed to develop the wind catcher as a commercially viable modern product. Naturally, this warrants the very extensive need for a tool such as simulation devices as the viability of wind towers for its redesign for commercial use cannot be tested using other methodologies. There were numerous other instances where computer simulations were the most appropriate manner to test various variables and parameters.

3.5 Methodology selection

The selection of the methodology was based on careful understanding of the merits and limitations of the methodology types discussed in previous sections. Merits of the systems though important do not have much of an impact in the selection, rather the selection of the methodology rested largely on the limitations of the various methodologies and the limitations of the research to be conducted. Furthermore, the selected methodology has to be able to sufficiently give alternative means to achieve the objectives that can be achieved through the use of experiments, scaled models, case studies, surveys and other methods.

Therefore, on this basis, the methodology selected to conduct this research is computer simulations.

There are many limitations in carrying out this research. For a research practicality point of view, the most difficult part would be that the research and observational recordings need to be conducted for every single hour of the year, i.e. the entirety of 8760. This would not only be time consuming, but it comes with it a plethora of practical issues, particularly the need for many volunteers and research personnel. This can therefore be alleviated by the use of simulation software that can conduct the analysis for the entire year within a few seconds or minutes.

Moreover, different building conditions, different wind tower configurations and different times when the windows are to be open & closed and deciding when the windows are to be open and closed based on the comfort requirements of the occupants would be odious and time consuming to carry out in real life as a research. Therefore, the flexibility that simulation software can offer in terms of dictating various different configurations and variables is most apt.

In addition to this, the use of simulation software helps the researcher to avoid the extra instrument and equipment costs that come with this research. Measuring temperature and humidity levels would warrant the use of extremely sensitive sensors which cannot be afforded at this level. Wind speeds and wind pressures cannot be studied in this research without simulations for the lack of access to wind tunnels and or laboratories.

Therefore, this methodology was selected after having taken careful consideration of the above.

3.6 Software selection

There are many computer simulation software that are currently in use. However, the software type had to be determined based on how relevant it was for the research and what it needed to achieve. The software had to be able to do the following –

- Make calculations based on internal and external temperature levels.
- Take into account temperature conditions, humidity levels, wind velocities & pressures and general weather data files for cities in the UAE.
- Take into account external climatic conditions and reflect results that include ramifications of their application.
- Convenient to use in modelling to allow the flexibility of multiple construction types.
- Be able to make a model with a construction method that is used in the UAE.
- Have the capacity to impose formulaic conditions that determine operational capabilities and limits of windows and other openings.
- Perform CFD (Computational Fluid Dynamics) calculations within a confined space.

There are many software in the market that can use thermal modelling and CFD, like IES VE Fluent and many others. However, the aforementioned factors were strictly scrutinised. It must also be understood that there are cost constrains that need to be taken into account as thermal modelling software are extremely specialised and are therefore expensive. Therefore, based on the requirements above, after careful thought coupled with the fact that IES VE 2013 has a student package that can be purchased at a subsidised cost, this software was used for this research, the start up image was captured off a screen print as is shown in Fig 3.3.

Figure 3.3 IES VE 2013 start up image

Further, Crawley et al (2008) have done a summary of many simulation software and identified their capabilities as is shown in Fig 3.4.

	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	IDA ICE	IES 〈VE〉	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Interior surface convection																				
• Dependent on temperature	X	X					P		X		X	X	X		X	X	X	X		X
• Dependent on air flow	X						X		P		X		X		X			X		E
• Dependent on surface heat coefficient from CFD									E		E		X							
• User-defined coefficients (constants, equations or correlations)		X	X	X	X				X		E	R	X		X	X	X	X		X
Internal thermal mass	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Automatic design day calculations for sizing																				
• Dry bulb temperature	X	X	X	X	X	X	X	X	X	X		X	X	X	X	P		X	X	
• Dew point temperature or relative humidity			X	X		X	X		X	X		X	X	X				X	X	
• User-specified minimum and maximum			X	X		X	X		X	X		X	X	X	X			X	X	
• User-specified steady-state, steady-periodic or fully dynamic design conditions			X									X	X	X				X	X	X

X feature or capability available and in common use; P feature or capability partially implemented; O optional feature or capability; R optional feature or capability for research use; E feature or capability requires domain expertise; I feature or capability with difficult to obtain input.

Figure 3.4 Summary of simulation software and their capabilities (Crawley et al 2008)

In addition to satisfying the selection criteria mentioned above, IES VE can also take into account factors such as occupancy levels, heat generated due to levels of activity, identifying heat sources within the space and attributing values to them and having the capacity to do unique analysis of thermal and other physical conditions both for the internal environment and the external environment. The MacroFLO and MicroFLO options in the software have the capacity to analyse natural ventilation and their influence on the internal environment as derived from the weather data files and the ability to comprehensively monitor and report internal air movements within and through adjacent spaces. One of the useful capacities of MacroFLO is that it can specify the percentages to which the windows are open at a given time. Thus, this gives the researcher to analyse the effects of windows not only when they are fully closed (0% open) or fully open (100% open), rather it can specify a range of values for windows to be open from 0-100%.

In addition to this, Vista and VistaPRO provide very convenient and graphical useful interfaces where the results of simulations can be both seen and analysed. These results can be seen for every day of the year and in most instances for every hour of the year. The capacity of IES VE to give results in a format that can be directly exported to Microsoft Excel opens a whole range of possibilities for numerical and chart based analysis through Microsoft Excel.

In order to ascertain that the results derived are correct and they can be relied upon to be accurate, it is important that the software and the methods are validated. In this instance, validation of the software is performed by assessing the works of other researches from peer reviewed journals that have used IES and validated them.

IES VE has been the choice simulation software for many researchers who used it for various purposes and specifically for thermal analysis and or CFD simulations. These include Masri & Abu Hijleh (2012), Rajapaksha et al (2003), Kim et al (2012) and AlmHafdy et al (2013) amongst many others.

Masri & Abu Hijleh (2012) used IES VE to investigate the influence of courtyards and the ventilation created as a result on internal environments. The capacity of IES to take into account shading, solar intensities, temperatures and humidity factors into a synthesized format was useful in carrying out this research. On a related note, Rajapaksha et al (2003) used IES to investigate the passive cooling effect of ventilated courtyards in warm humid tropics. This study by Rajapaksha et al (2003) sought to identify the effects of varying temperature transfers as a result of the courtyard and the influence it has on the micro climate. The IES analysis was used to identify air flow patterns that occur as a result of this. On the subject of courtyards, AlmHafdy et al (2013) also used IES to analyse the effects of various courtyard configurations and understand the configuration that was most suited for the particular micro climate in question. The study of AlmHafdy et al (2013) was based in Malaysia, the integrated weather data files in IES that is available for many geographical locations made it useful for them in this regard. Kim et al (2012) studied the advantages of using external shading devices in residential buildings and their contribution to enhanced thermal performance. The convenient modelling interface that IES has made it easy for Kim et al (2012) to try many different shading options with varying materials and angles that helped them identify the optimal or most suitable type of shading device.

Rajapaksha et al (2003) used the IES simulation software utilising the standard k-ε turbulent model with isothermal conditions found out that that results obtained by computer simulations closely matched the results obtained by field measurements. Furthermore, amongst the other research papers that verify the validity of IES as an accurate simulation tool, Masri & Abu Hijleh (2012) verify the validation of IES for thermal analysis and CFD studies.

In addition to IES VE, Autodesk Ecotect and Autodesk AutoCAD were used as secondary and supporting software.

3.7 Selection of the site

The site selected was a Ground+1 storey residential building of total height 7.5m in Abu Dhabi, UAE. This particular building was selected for the fact that it was a relatively typical housing design that is prevalent in Abu Dhabi and therefore results derived from this study can be applied for other similar buildings.

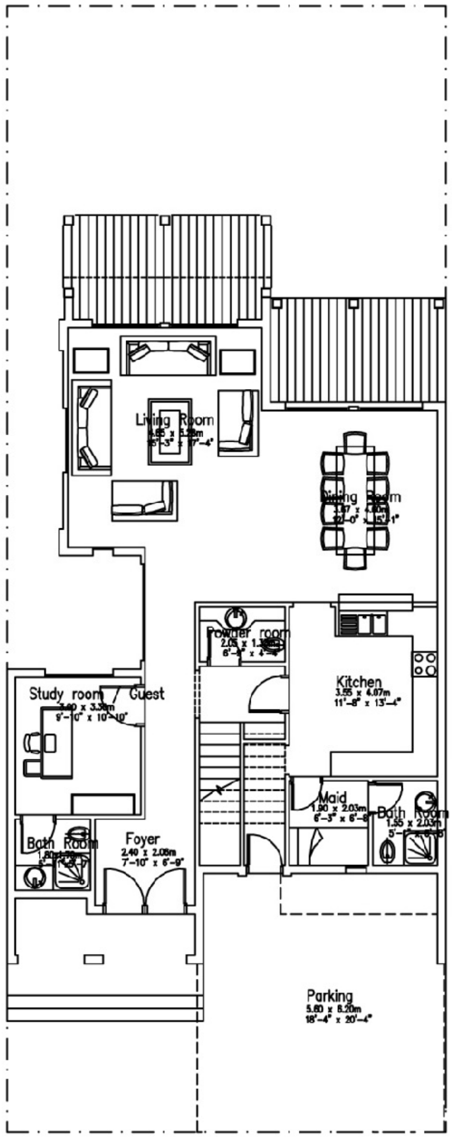


Figure 3.5 Ground Floor Plan of site selected (Lacasa, 2014)

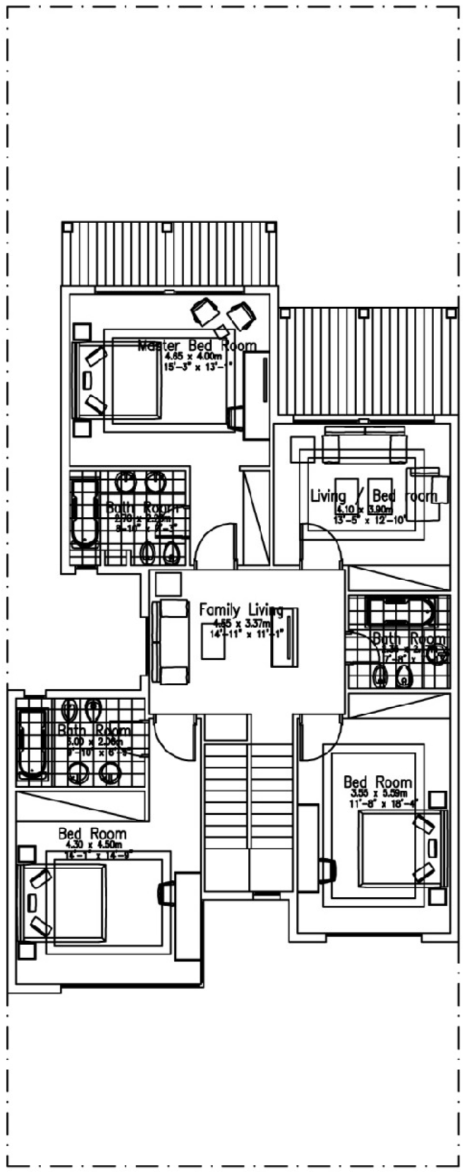


Figure 3.6 First Floor Plan of site selected (Lacasa, 2014)

The site above was planned to be in a normal Abu Dhabi suburb with several other similar buildings in the vicinity and was in a residential area.

The Master Bedroom in the north of the first floor was used to analyse its thermal effects. Upon understanding the thermal condition of this particular room, it was modified to accommodate a wind catcher and several similar simulations were conducted to test various parameters as will be outlined in Section 4. As is identified by the red arrow in Fig 3.7, the in built wardrobe was converted into a wind catcher. The bathroom was made slightly smaller to move the door so that a wind tower of cross sectional area 4.2 m^2 could be inserted.

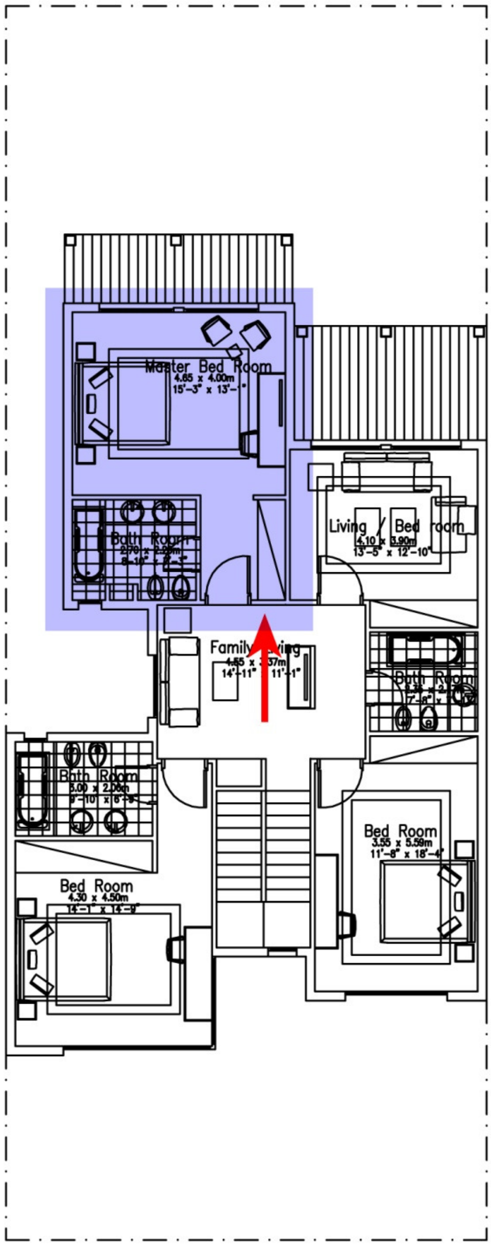


Figure 3.7 First Floor Plan with indicative location of wind tower

The Master bedroom highlighted in blue in Fig 3.7 will henceforth be referred to as the existing case.

3.8 Abu Dhabi Weather

In order to understand the climatic impact on residential buildings in Abu Dhabi, the Abu Dhabi weather patterns need to be understood in terms of geographical location, temperature levels, humidity factors, wind speeds and precipitation. It must be noted that even though the case study is primarily for a residence in Abu Dhabi, due to the very similar weather patterns in the other Emirates in the UAE, this study is also applicable for other emirates with very negligible modifications. Therefore, this study is for the entire UAE, despite the fact that the case study is located in Abu Dhabi. Case studies from other parts of the UAE could have been obtained, but Abu Dhabi was selected since it is the administrative capital of the UAE and is the largest emirate.

Abu Dhabi is located in the in the middle East looking out to the seas of the Arabian Gulf and bears coordinates 24°28′N 54°22′E as figures extracted from Google Earth. With an area of approximately 67,350 km^2 it is the largest emirate in the UAE occupying over 85% of the entire land mass.

By virtue of its geographical positioning, Abu Dhabi has a hot arid climate, where the summer months are known to have hot temperatures and windy conditions whilst the winter months are known to be cooler. As is characteristic of other emirates and other parts of the middle East, Abu Dhabi usually has clear blue skies for most of the year except for some of the winter months where occasional rain is observed with cloud cover relatively higher than the summer months. Fig 3.8 identifies the stereograph for the solar position for Abu Dhabi, thus is indicative of the solar position right throughout the year. Furthermore, even though Abu Dhabi receives wind from almost all directions, the most prominent wind directions is from the North West direction with more than 20.1% of the wind (Windfinder.com, 2014). The yearly average for winds in Abu Dhabi is 11.17 knots which is the equivalent of 5.74 ms^{-1} as Figs 3.9 & 3.10 indicate. Although the average summer temperature is approximately 39 °C and the average winter temperature is approximately 23 °C, maximum temperature levels in Abu Dhabi can go up to about 48°C and minimum temperatures (mostly at night) can go down to about 6-8 °C. In the graphical illustration of Fig3.9 the wind speeds have been given in knots.

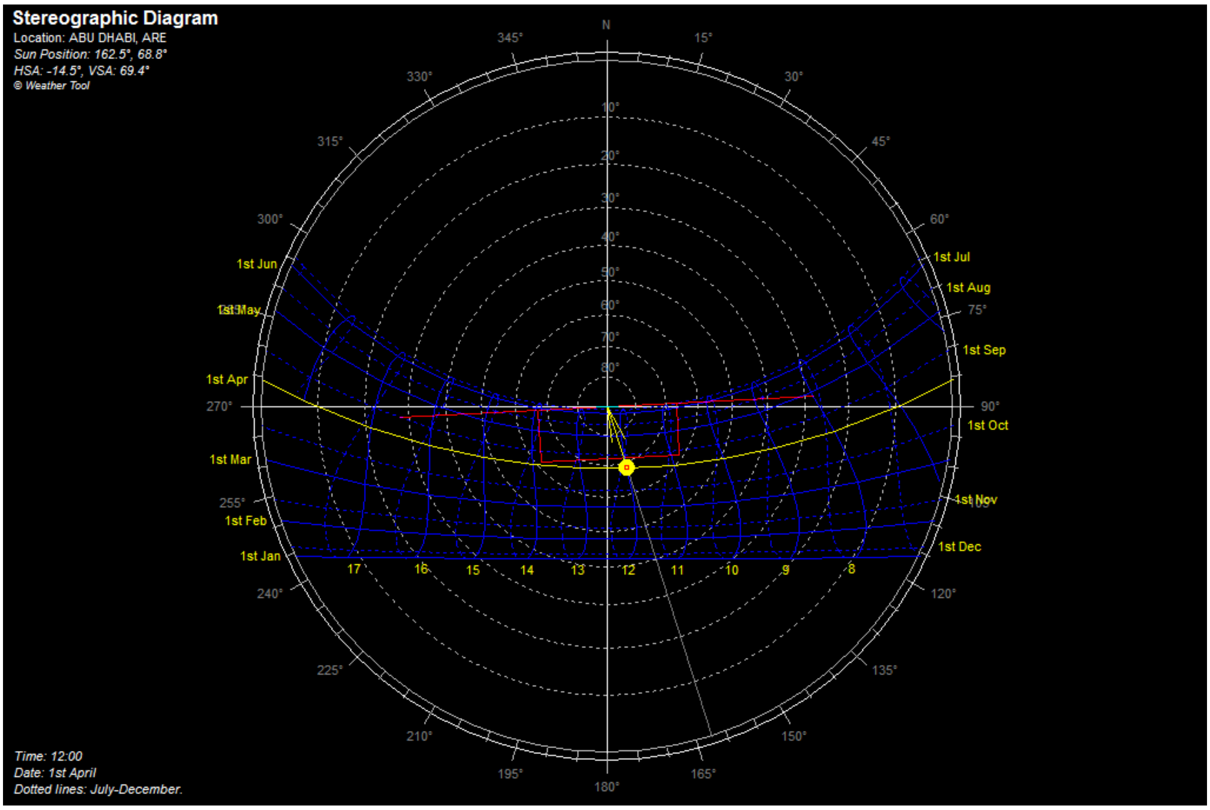


Figure 3.8 Stereograph solar position of Abu Dhabi (Ecotect)

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant Wind dir.													
Wind probability >= 4 Beaufort (%)	29	40	43	44	49	48	46	46	38	32	27	26	39
Average Wind speed (kts)	9	10	10	10	11	10	10	10	9	8	9	9	9
Average air temp. (°C)	21	23	26	31	36	37	39	39	36	32	28	23	30

Figure 3.9 Average temperatures and wind speeds (Windfinder.com, 2014)

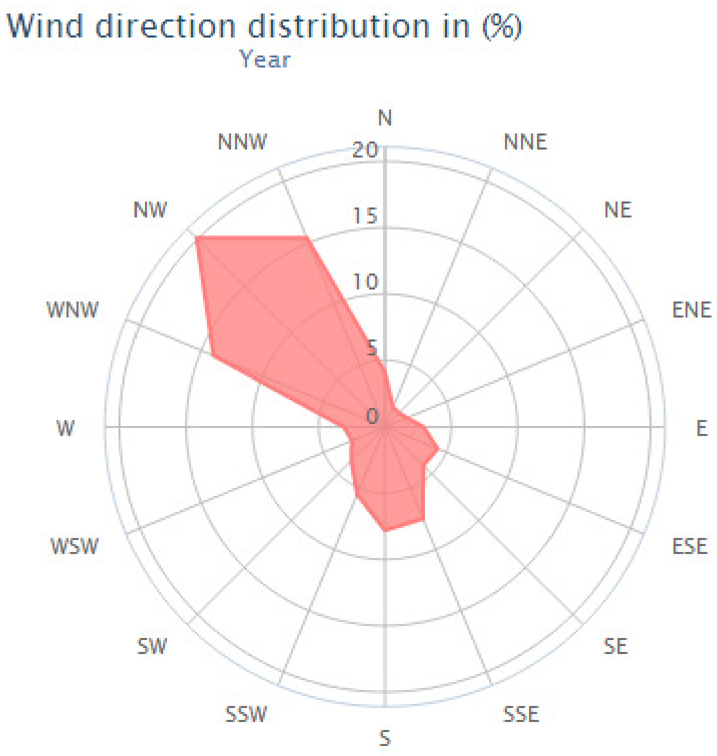


Figure 3.10 Prominent wind directions from the North West (Windfinder.com, 2014)

Fig 3.11 identifies the humidity percentages in Abu Dhabi across the year. According to IES VE, when the simulation was run to assess the external humidity levels, a minimum of 6% was recorded at 12pm on the 31st May and a maximum of 100% at 1pm on 13 January, on average across the year Abu Dhabi records external relative humidity levels of 60.6%.

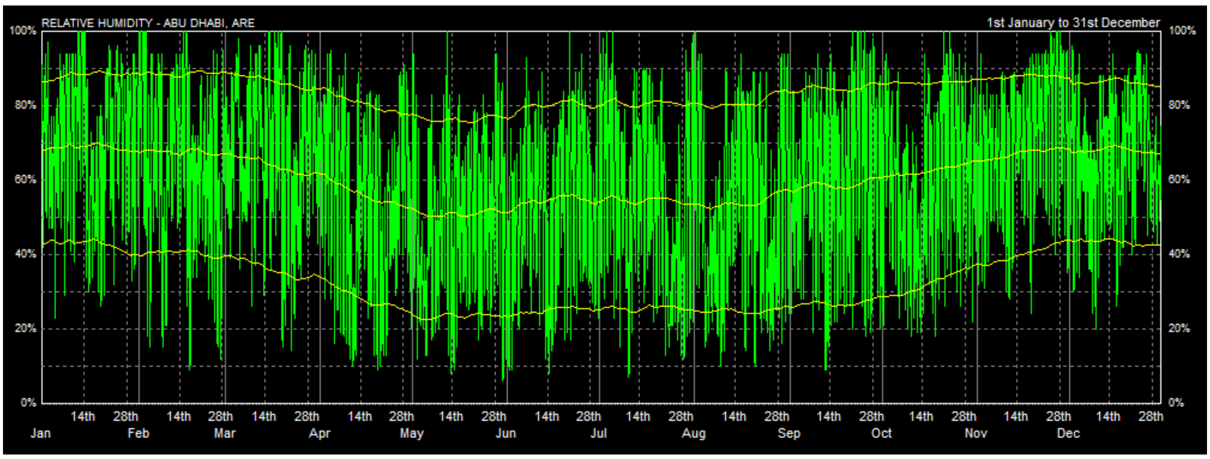


Figure 3.11 Annual humidity levels in Abu Dhabi (IES VE, 2014)

The human comfort range in terms of humidity conditions is generally understood to be 30%-70%. Therefore, when these data was sought, it transpired that Abu Dhabi's external relative temperature is within this range only for 4543 hours of the year. Thus, of the total of 8760 hours a year, the comfortable external relative humidity in Abu Dhabi is only for 51.8% of the year.

Section 4: Model Set Up

4.0 Model set up

This section outlines the procedure followed in setting up the IES VE model and the various steps that have been followed in order to achieve the required results. Not all steps have been outlined, in order to avoid stating what is generally understood to be an inevitable procedural step, only the steps that are specific to these simulations have been outlined.

4.1 Setting up the existing case

ModelIT, the modelling wizard in IES, was used to construct the existing building as it is. All rooms and storeys were modelled as they are. Adjacencies & window positioning have an influence on the thermal performance of the spaces and therefore the building was modelled as it exists as identified by Fig 4.1.

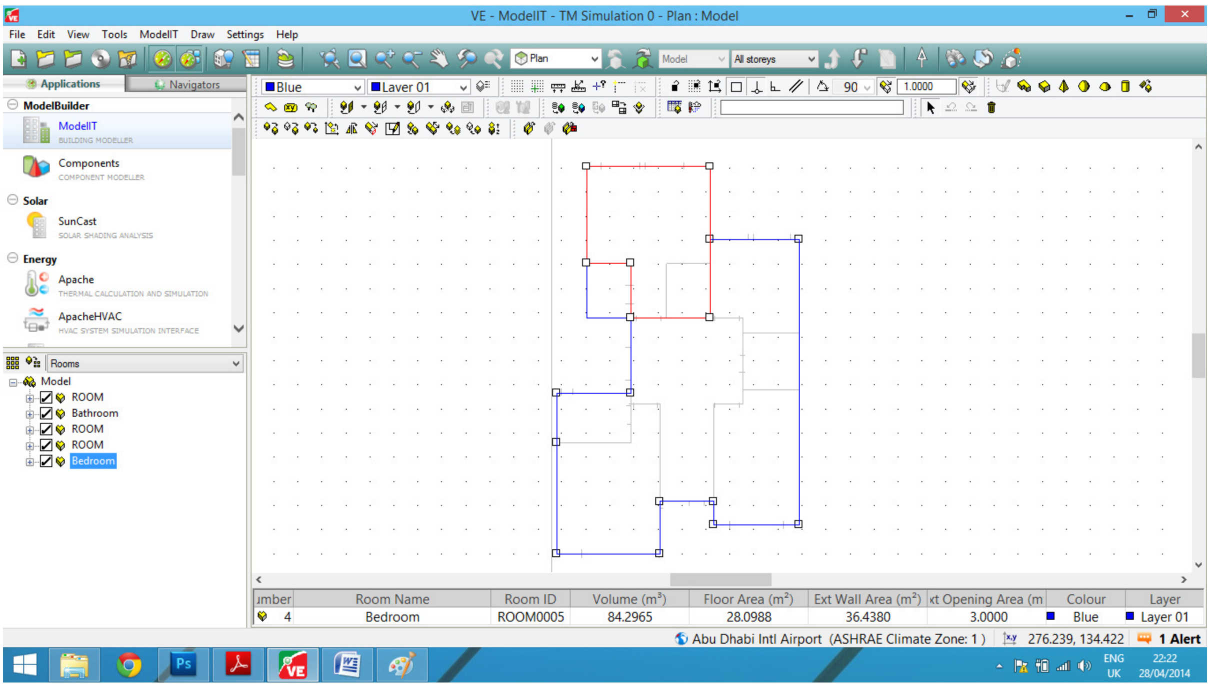


Figure 4.1 Modelling of the existing building using ModelIT (IES)

It is evident in the lower right hand corner of Fig 4.1 that the weather data file has been set to Abu Dhabi International Airport (ASHRAE Climate Zone 1) which is automatically selected by the software as being nearest to the site when the location selection wizard intrinsic to IES – APLocate, is used.. This is the closest weather data that can be obtained for Abu Dhabi.

This selection is set before any simulation is done, as this ensures that all climatic and weather conditions will be determined according to this location. Moreover, the construction type was the standard construction usually used in existing modern residential buildings in Abu Dhabi with block walls of U-Value 0.35 with thickness of 300mm blockwork with 60mm Styrofoam insulation in the middle as shown by Fig 4.2. The provision for creating this type of wall is obtained from the material range provided in the IES Building Template Manager.

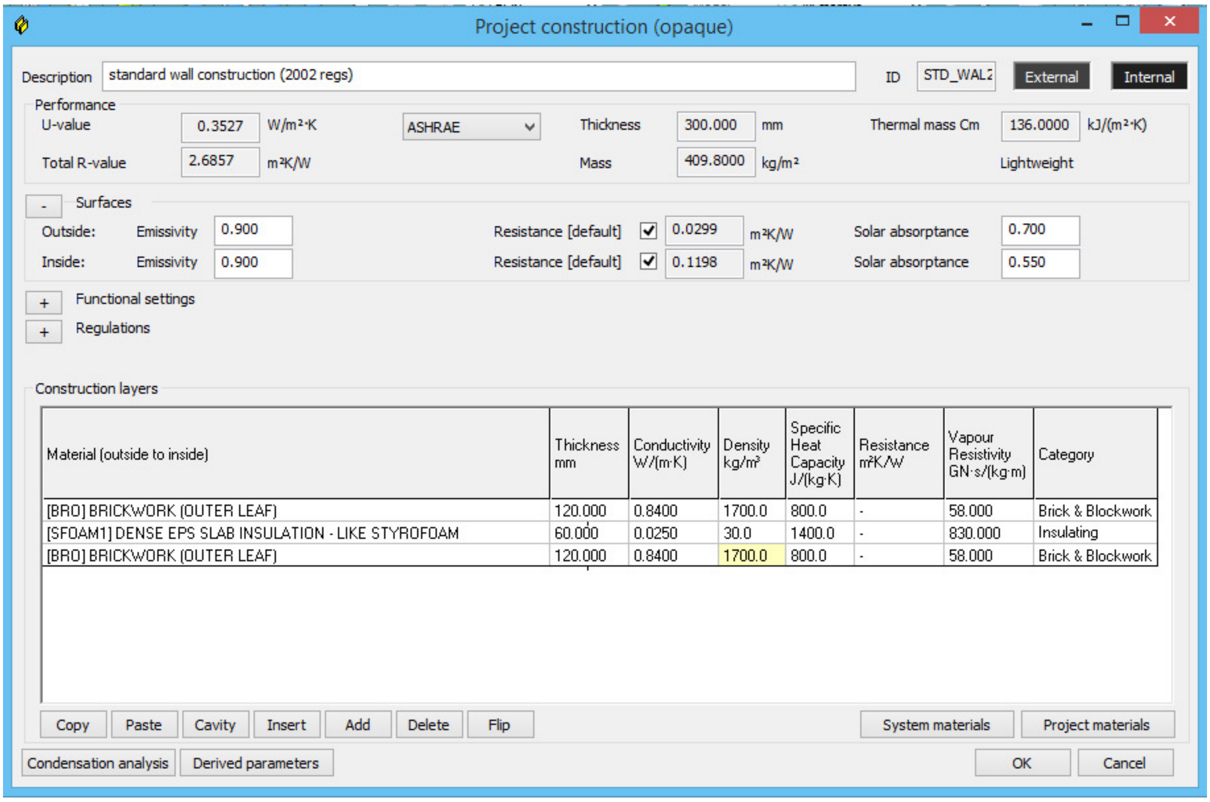


Figure 4.2Wall construction type (IES)

This construction type was maintained in every single simulation in order that the variations in materials and construction will not influence the simulation results. The model used all the existing conditions of the building, but imposed the condition that all windows will be closed right across the year and that no mechanical ventilation means are to be operated. The completed model is shown in Fig 4.3.

The existing case (room selected for simulation in the existing building) modelled had the following characteristics – a floor to ceiling height of 3m, a window of area 3 m^2 and the window open 0% (i.e. fully closed)

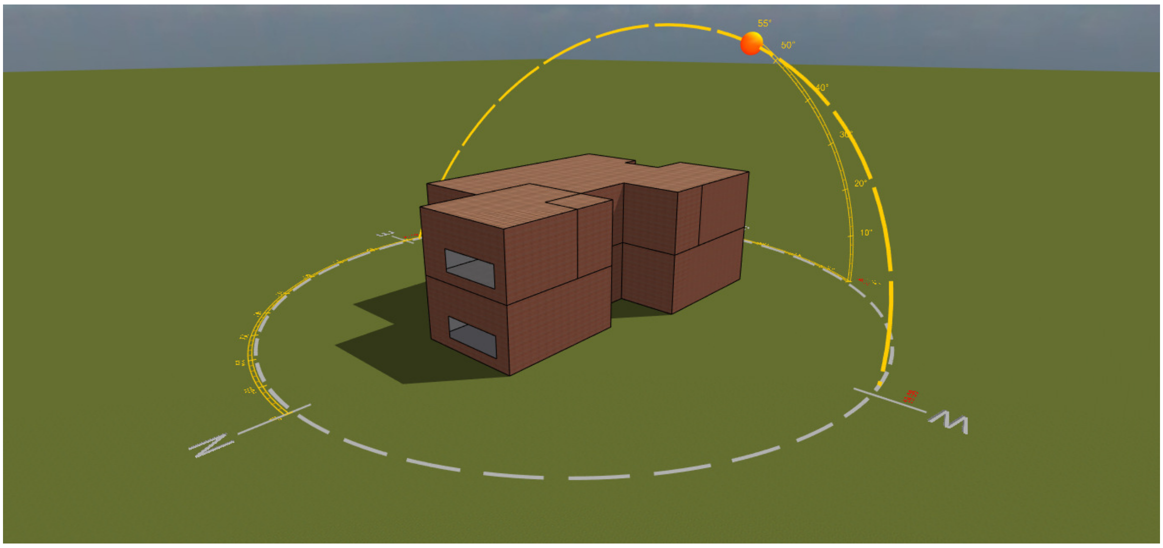


Figure 4.3 Existing model upon completion of modelling on IES (IES)

Upon completion of the building model, the thermal simulation wizard Apache was enacted to run a thermal simulation for the building. Upon the completion of the thermal simulation run by Apache, Vista was used to get results for the external conditions in Abu Dhabi as exemplified by Figs 4.4 & 4.5. In addition to Vista, IES also has VistaPRO which is used for advance analysis of simulations conducted by Apache.

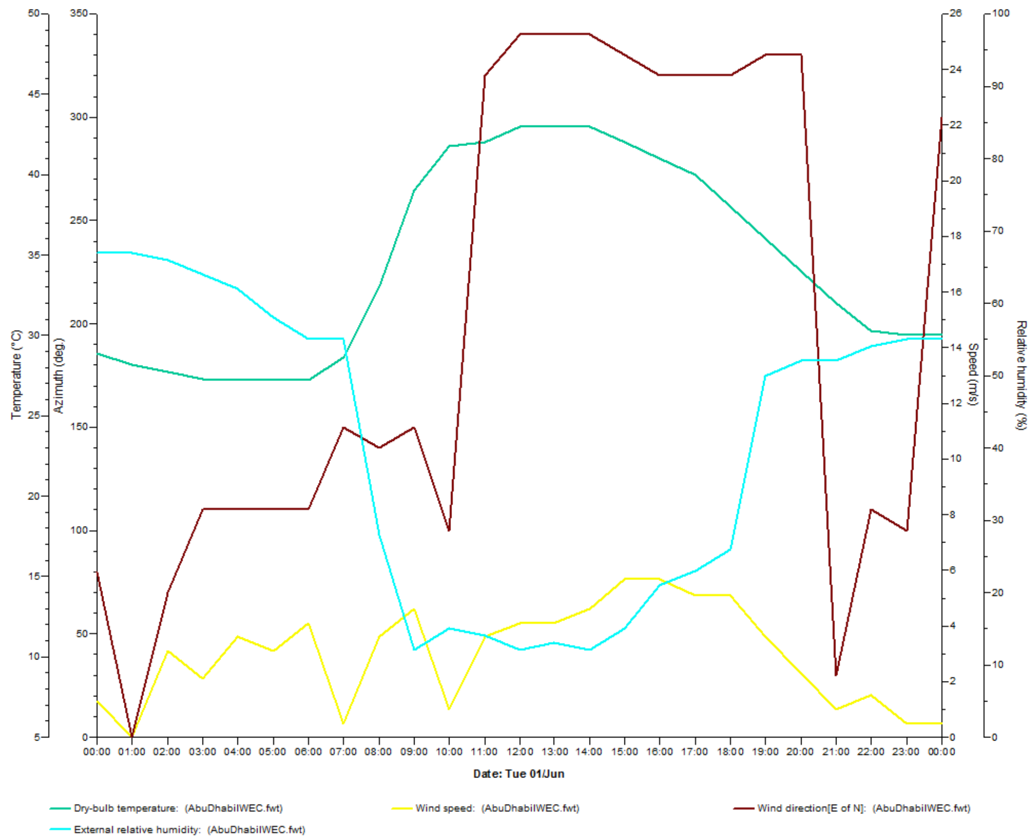


Figure 4.4 External weather conditions in Abu Dhabi on 1 June (IES)

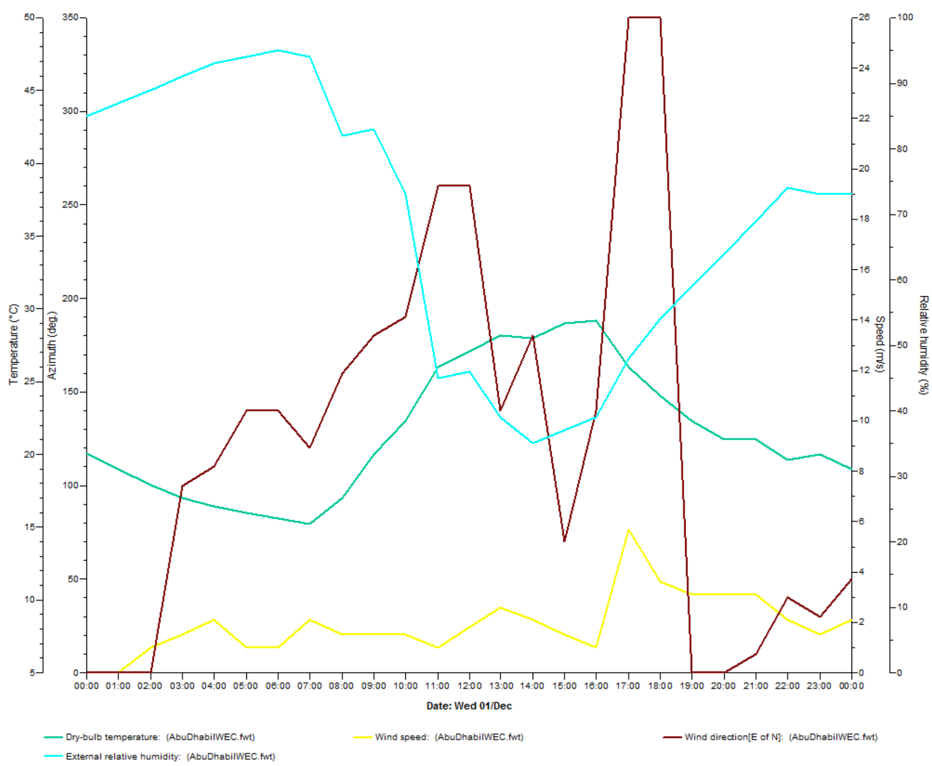


Figure 4.5 External weather conditions in Abu Dhabi on 1 December (IES)

The dates in Figs 4.4-4.5 have been selected as they are amongst the warmest and coldest days respectively in Abu Dhabi.

Having completed an Apache simulation, a MicroFlo CFD was used to run a detailed CFD analysis of existing case.

4.2 Testing out other parameters and models

Having simulated the existing case for results for comfort conditions that included temperature and humidity levels, many other configurations were tested out. The other models tested were all modelled with a wind tower. Furthermore many parameters were tested to analyse their impact on the internal comfort conditions. The parameters tested were the impacts of floor to ceiling height, height of the wind tower, orientation of the wind tower, area of the window, percentage opening of the wind tower openings and the percentage opening of the window openings. It was understood that all these parameters will have an effect on the internal thermal comfort levels.

Therefore, a minimum of 22 different simulations were carried out as shown in table 4.1, using Apache and MicroFlo and the results were analysed using Vista and VistaPRO to test the 22 different combinations of parameters. In addition to the minimum of 22 simulations, further simulations were carried out in certain instances to narrow down the accuracy of the results as is evident in section 5.

The configurations that take into account the many different combinations together with the results they yielded have been outlined in the Test Matrix in Appendix A. For instance, one of the combinations for the space tested included the following configurations – Floor to ceiling height of 3m, wind tower of height 5m, orientation of wind tower facing north west, window of area 3 m^2, wind tower opening of area 4m^2,percentage window opening of 25% and a percentage wind tower opening of 100%. In the test matrix this particular combination is referred to as case 4 and is illustrated in Fig 4.6. All combinations are given a respective case number for ease of understanding and communication.

Table 4.1 Test Matrix used for case study combinations

Test Matrix

	Case Number	Floor to Ceiling Height (m)	Height of Windtower (m)	Orientation of WT	Area of Window (Sq.m)	Area of Wind Tower opening (Sq.m)	Percentage of Window opening (%)	Percentage of Windcatcher opening (%)	Degree Discomfort Hours	Number of hours internal temperature is 18-26 C°
Existing Case	0	3	0	0	3	0	0	0	48668.25	2838
Reference Case	1	3	5	NW	3	8	25	100	29783.25	3230
Parameter 1	2	4	5	NW	3	8	25	100	28951.99	3232
	3	5	5	NW	3	8	25	100	28629.51	3263
	4	6	5	NW	3	8	25	100	28092.89	3272
Parameter 2	5	3	3	NW	3	8	25	100	30545.05	3237
	6	3	7	NW	3	8	25	100	29078.32	3230
	7	3	9	NW	3	8	25	100	28724.69	3231
Parameter 3	8	3	5	NE	3	8	25	100	29730.82	3268
	9	3	5	SW	3	8	25	100	31270.12	2920
	10	3	5	SE	3	8	25	100	31178.62	2907
Parameter 4	11	3	5	NW	4	8	25	100	30143.34	3219
	12	3	5	NW	5	8	25	100	30463.68	3215
	13	3	5	NW	6	8	25	100	30752.06	3205
Parameter 5	14	3	5	NW	3	2	25	100	27775.71	3291
	15	3	5	NW	3	4	25	100	29254.69	3230
	16	3	5	NW	3	6	25	100	28990.55	3251
Parameter 6	17	3	5	NW	3	8	0	100	29997.55	3212
	18	3	5	NW	3	8	50	100	29626.64	3246
	19	3	5	NW	3	8	100	100	29413.42	3268
Parameter 7	20	3	5	NW	3	8	25	0	48515.62	2492
	21	3	5	NW	3	8	25	25	33348.26	2961
	22	3	5	NW	3	8	25	50	31355.81	3091

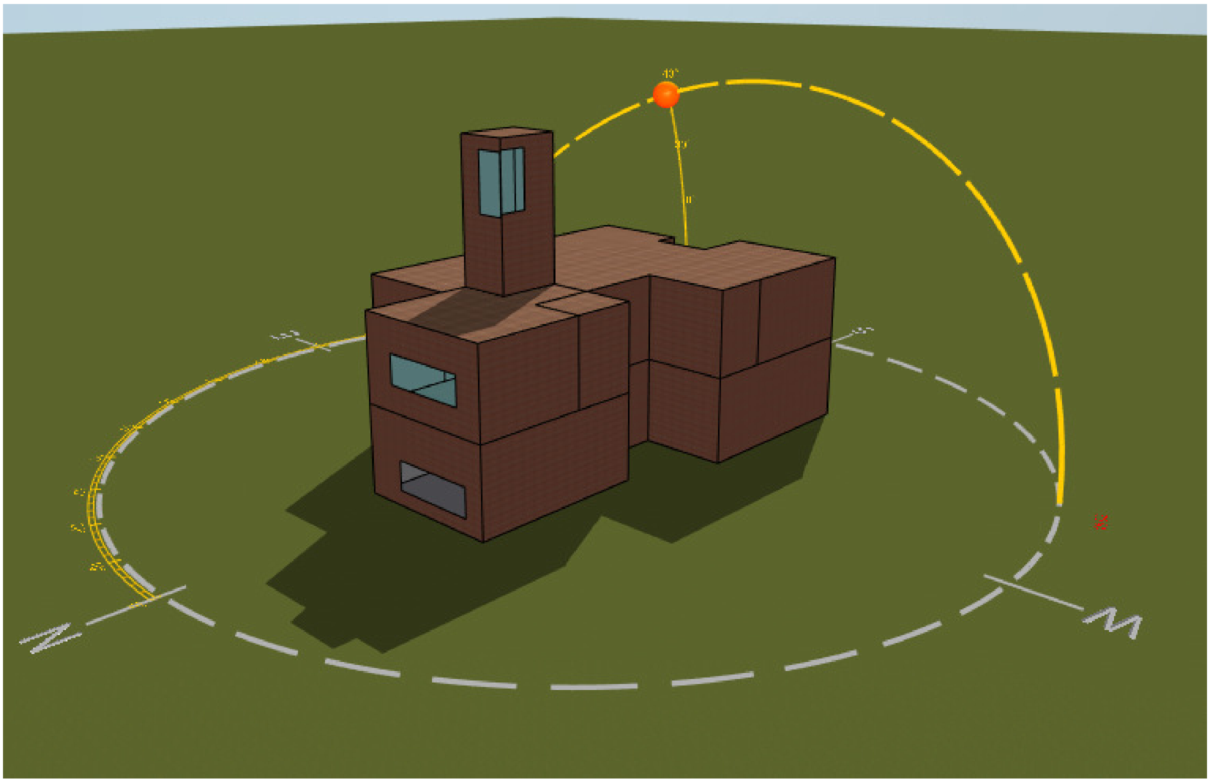


Figure 4.6 Illustrated model in case 15 (IES)

4.3 Condition for window or wind tower opening to be operable (opening profile)

Windows are usually opened or closed depending on the weather conditions outside or the internal conditions in the space. Therefore, depending on how internal and external temperature conditions and external relative humidity levels operate occupants usually open or close windows to allow or disallow external air into a space, either as a means of allowing external cool air into the building or allowing internal hot air out of the building. Therefore, opening profile was set for the windows to be opened only when it satisfies one of the following two conditions.

1. *Outside relative humidity is less than 80% (occupants would be at discomfort when relative humidity exceeds 80%) and room temperature is greater than 26°C and outside temperature is less than room temperature*
2. *Outside relative humidity is less than 80% and room temperature is less than 18°C and Outside temperature is greater than room temperature.*

Therefore, the window and wind tower openings will operate only when the two conditions mentioned above are satisfied, this formula being set in IES is shown in Figs 4.7 & 4.8.

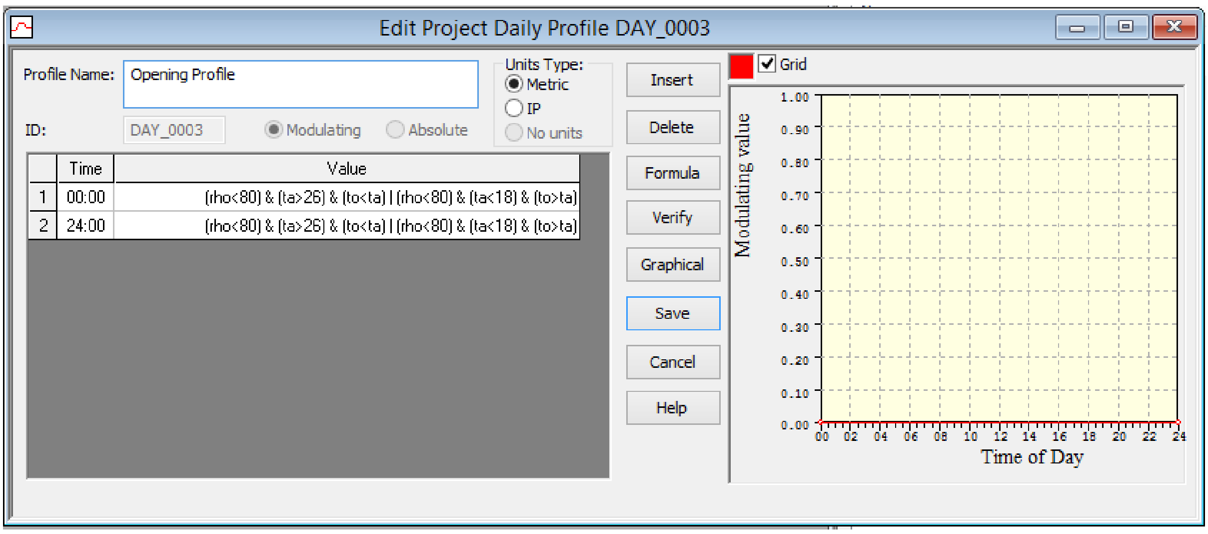


Figure 4.7 Setting up of window opening formula (IES)

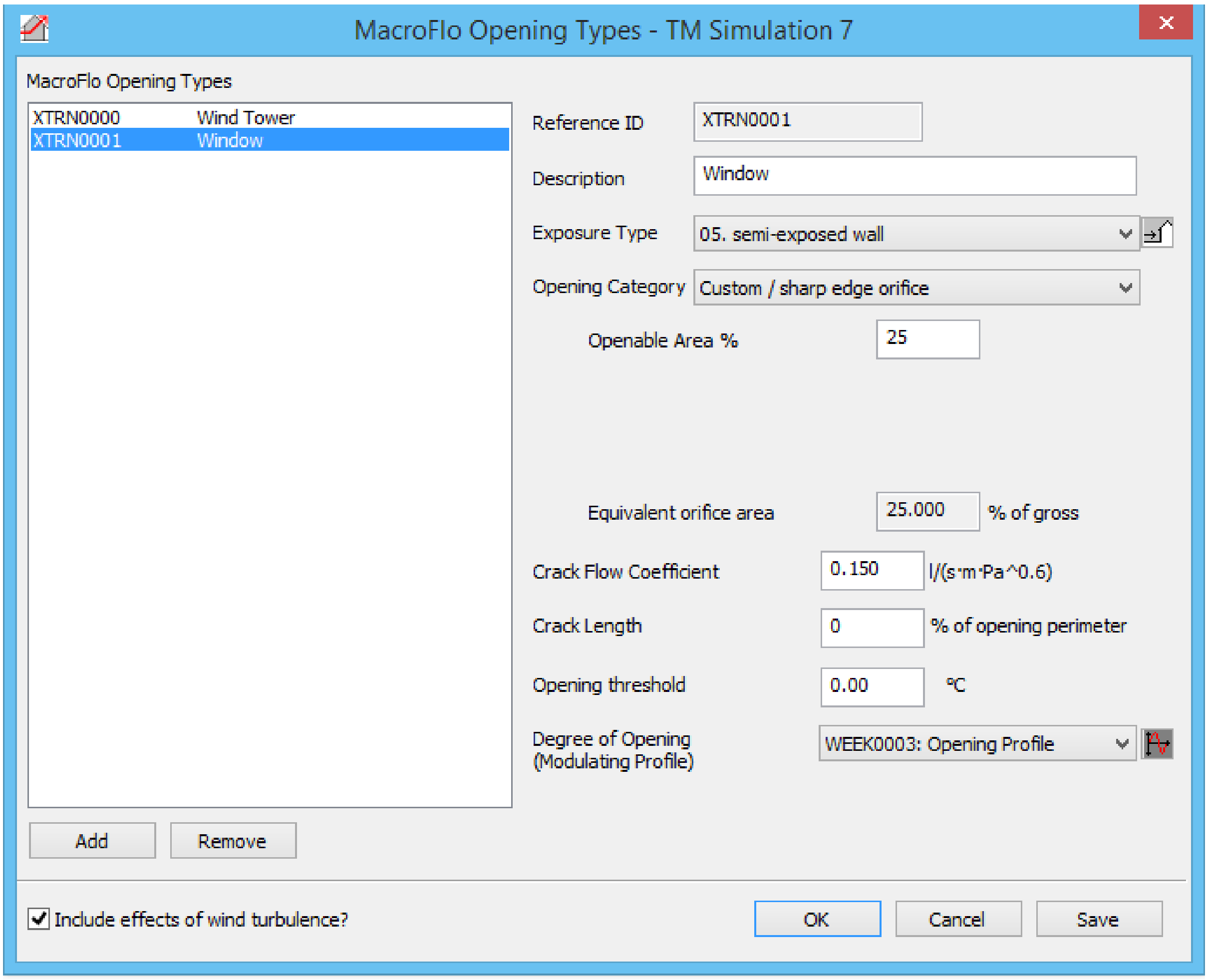


Figure 4.8 Degree of opening according to Opening Profile

Several simulations were done to test if this formula works properly and the results were analysed and validated by technical staff from IES VE office in Glasgow, UK. That this formula works can be seen in Figs 4.9 and 4.10.

Figure 4.9 External relative humidity and external and internal temperature conditions for 14 July

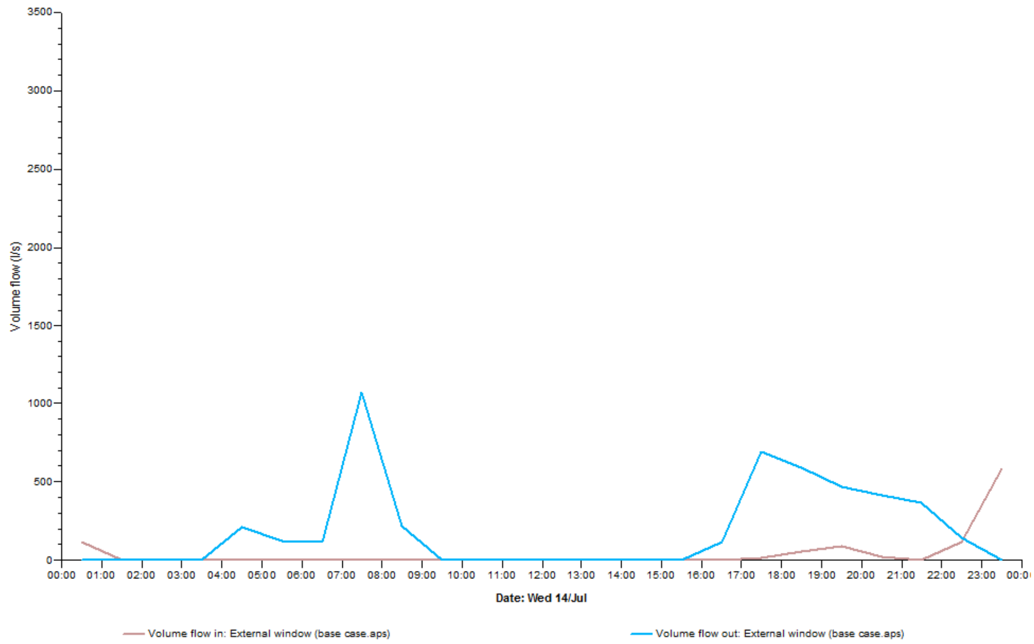


Figure 4.10 Air flow in and out for July 14

Fig 4.10 shows that there is no air flow in or air flow out from 1.30am to 3.30 am and 9.30 am to 3.30 pm. By absence of air movement during these times, it is evident that the windows are closed at the times mentioned. When these times are scrutinised in Fig 4.9, it is evident that there is zero air flow during these periods due to the fact that the conditions imposed for the window to be opened have not been satisfied. Therefore it can be concluded that the formula imposed on the window and wind tower opening for it to be operable functions accurately.

In addition to this, range tests were used in IES to establish how many hours a year were within the 18-26 °C thermal comfort range as shown in Fig 4.11.

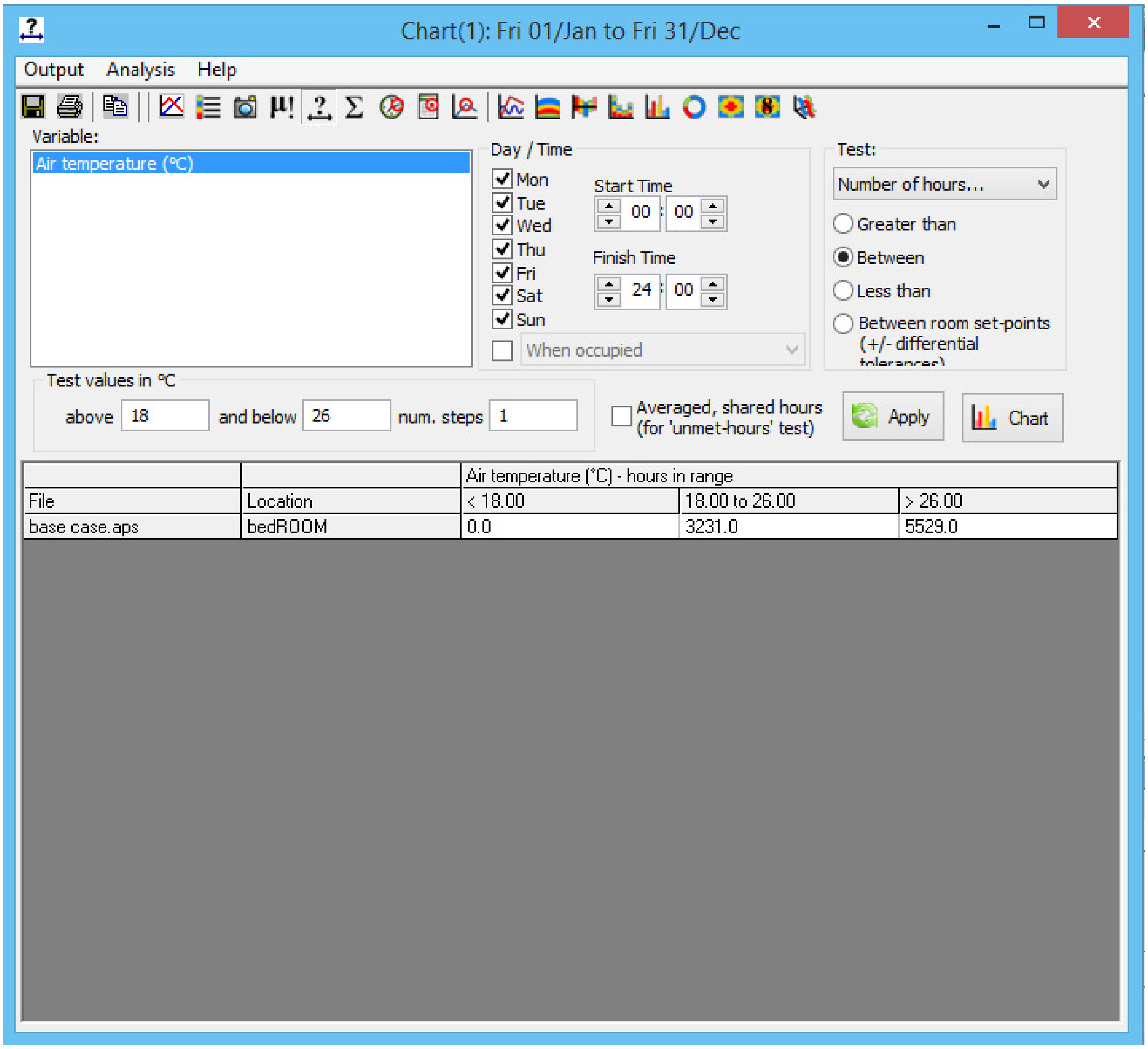
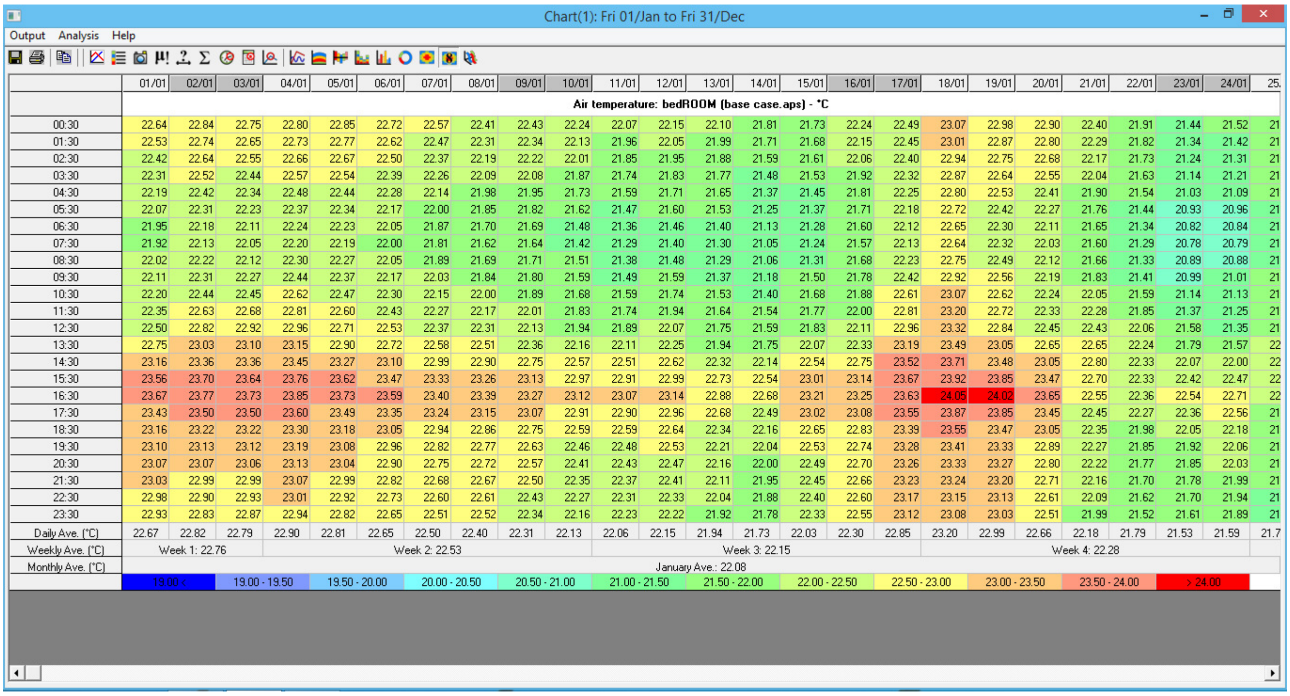


Figure 4.11. Range test showing total hours annually in the thermal comfort range (IES)

Degree Discomfort hours (DDH), which is discussed in detail in Chapter 5 was calculated on an Microsoft Excel file after the internal temperature figures for each case was obtained for every single hour of the year as graphically illustrated in Fig 4.12.


Chart(1): Fri 01/Jan to Fri 31/Dec

Output Analysis Help

Air temperature: bedROOM (base case.aps) - °C

	01/01	02/01	03/01	04/01	05/01	06/01	07/01	08/01	09/01	10/01	11/01	12/01	13/01	14/01	15/01	16/01	17/01	18/01	19/01	20/01	21/01	22/01	23/01	24/01	25.
00:30	22.64	22.84	22.75	22.80	22.85	22.72	22.57	22.41	22.43	22.24	22.07	22.15	22.10	21.81	21.73	22.24	22.49	23.07	22.98	22.90	22.40	21.91	21.44	21.52	21
01:30	22.53	22.74	22.65	22.73	22.77	22.62	22.47	22.31	22.34	22.13	21.96	22.05	21.99	21.71	21.68	22.15	22.45	23.01	22.87	22.80	22.29	21.82	21.34	21.42	21
02:30	22.42	22.64	22.55	22.66	22.67	22.50	22.37	22.19	22.22	22.01	21.85	21.95	21.88	21.59	21.61	22.06	22.40	22.94	22.75	22.68	22.17	21.73	21.24	21.31	21
03:30	22.31	22.52	22.44	22.57	22.54	22.39	22.26	22.09	22.08	21.87	21.74	21.83	21.77	21.48	21.53	21.92	22.32	22.87	22.64	22.55	22.04	21.63	21.14	21.21	21
04:30	22.19	22.42	22.34	22.48	22.44	22.28	22.14	21.98	21.95	21.73	21.59	21.71	21.65	21.37	21.45	21.81	22.25	22.80	22.53	22.41	21.90	21.54	21.03	21.09	21
05:30	22.07	22.31	22.23	22.37	22.34	22.17	22.00	21.85	21.82	21.62	21.47	21.60	21.53	21.25	21.37	21.71	22.18	22.72	22.42	22.27	21.76	21.44	20.93	20.96	21
06:30	21.95	22.18	22.11	22.24	22.23	22.05	21.87	21.70	21.69	21.48	21.36	21.46	21.40	21.13	21.28	21.60	22.12	22.65	22.30	22.11	21.65	21.34	20.82	20.84	21
07:30	21.92	22.13	22.05	22.20	22.19	22.00	21.81	21.62	21.64	21.42	21.29	21.40	21.30	21.05	21.24	21.57	22.13	22.64	22.32	22.03	21.60	21.29	20.78	20.79	21
08:30	22.02	22.22	22.12	22.30	22.27	22.05	21.89	21.69	21.71	21.51	21.38	21.48	21.29	21.06	21.31	21.68	22.23	22.75	22.49	22.12	21.66	21.33	20.89	20.88	21
09:30	22.11	22.31	22.27	22.44	22.37	22.17	22.03	21.84	21.80	21.59	21.49	21.59	21.37	21.18	21.50	21.78	22.42	22.92	22.56	22.19	21.83	21.41	20.99	21.01	21
10:30	22.20	22.44	22.45	22.62	22.47	22.30	22.15	22.00	21.89	21.68	21.59	21.74	21.53	21.40	21.68	21.88	22.61	23.07	22.62	22.24	22.05	21.59	21.14	21.13	21
11:30	22.35	22.63	22.68	22.81	22.60	22.43	22.27	22.17	22.01	21.83	21.74	21.94	21.64	21.54	21.77	22.00	22.81	23.20	22.72	22.33	22.28	21.85	21.37	21.25	21
12:30	22.50	22.82	22.92	22.96	22.71	22.53	22.37	22.31	22.13	21.94	21.89	22.07	21.75	21.59	21.83	22.11	22.96	23.32	22.84	22.45	22.43	22.06	21.58	21.35	21
13:30	22.75	23.03	23.10	23.15	22.90	22.72	22.58	22.51	22.36	22.16	22.11	22.25	21.94	21.75	22.07	22.33	23.19	23.49	23.05	22.65	22.65	22.24	21.79	21.57	22
14:30	23.16	23.36	23.36	23.45	23.27	23.10	22.99	22.90	22.75	22.57	22.51	22.62	22.32	22.14	22.54	22.75	23.52	23.71	23.48	23.05	22.80	22.33	22.07	22.00	22
15:30	23.56	23.70	23.64	23.76	23.62	23.47	23.33	23.26	23.13	22.97	22.91	22.99	22.73	22.54	23.01	23.14	23.67	23.92	23.85	23.47	22.70	22.33	22.42	22.47	22
16:30	23.67	23.77	23.73	23.85	23.73	23.59	23.40	23.39	23.27	23.12	23.07	23.14	22.88	22.68	23.21	23.25	23.63	24.05	24.02	23.65	22.55	22.36	22.54	22.71	22
17:30	23.43	23.50	23.50	23.60	23.49	23.35	23.24	23.15	23.07	22.91	22.90	22.96	22.68	22.49	23.02	23.08	23.55	23.87	23.85	23.45	22.45	22.27	22.36	22.56	21
18:30	23.16	23.22	23.22	23.30	23.18	23.05	22.94	22.86	22.75	22.59	22.59	22.64	22.34	22.16	22.65	22.83	23.39	23.55	23.47	23.05	22.35	21.98	22.05	22.18	21
19:30	23.10	23.13	23.12	23.19	23.08	22.96	22.82	22.77	22.63	22.46	22.48	22.53	22.21	22.04	22.53	22.74	23.28	23.41	23.33	22.89	22.27	21.85	21.92	22.06	21
20:30	23.07	23.07	23.06	23.13	23.04	22.90	22.75	22.72	22.57	22.41	22.43	22.47	22.16	22.00	22.49	22.70	23.26	23.33	23.27	22.80	22.22	21.77	21.85	22.03	21
21:30	23.03	22.99	22.99	23.07	22.99	22.82	22.68	22.67	22.50	22.35	22.37	22.41	22.11	21.95	22.45	22.66	23.23	23.24	23.20	22.71	22.16	21.70	21.78	21.99	21
22:30	22.98	22.90	22.93	23.01	22.92	22.73	22.60	22.61	22.43	22.27	22.31	22.33	22.04	21.88	22.40	22.60	23.17	23.15	23.13	22.61	22.09	21.62	21.70	21.94	21
23:30	22.93	22.83	22.87	22.94	22.82	22.65	22.51	22.52	22.34	22.16	22.23	22.22	21.92	21.78	22.33	22.55	23.12	23.08	23.03	22.51	21.99	21.52	21.61	21.89	21
Daily Ave. (°C)	22.67	22.82	22.79	22.90	22.81	22.65	22.50	22.40	22.31	22.13	22.06	22.15	21.94	21.73	22.03	22.30	22.85	23.20	22.99	22.66	22.18	21.79	21.53	21.59	21.7
Weekly Ave. (°C)	Week 1: 22.76			Week 2: 22.53							Week 3: 22.15							Week 4: 22.28							
Monthly Ave. (°C)	January Ave.: 22.08																								

19.00 <	19.00 - 19.50	19.50 - 20.00	20.00 - 20.50	20.50 - 21.00	21.00 - 21.50	21.50 - 22.00	22.00 - 22.50	22.50 - 23.00	23.00 - 23.50	23.50 - 24.00	> 24.00

Figure 4.12. Internal temperature figures for the space for every hour of the year (IES)

The temperature figures as shown in Fig 4.12 can be copied by IES and directly exported to Micrsoft Excel. Microsoft Excel was then used to determine the degree discomfort hours for every case (further details in Chapter 5).

All the different conditions were modelled and the opening profiles were imposed on every single model studied. All models were constructed and simulated using Apache and MicroFlo according to the combinations outlined in Appendix A.

Apache was further used to tabulate energy consumption for the existing case in order to estimate energy savings in the optimum case. When the existing case was simulated with the air conditioning to be on, the condition imposed was that the air conditioning should be automatically switched on when the internal temperature exceeds 26°C.

Section 5: Results & Discussion

5.0 Results & Discussion

This section outlines the results obtained from the simulations that were concluded as was set out in the methodology section. The IES software gives temperature values inside the room for the 8760 hours of the year. The various combinations and parameters were assessed according to two indicators.

- The number of hours in which the internal temperature ranges will be within 18-26 C°. This is to be reported as a percentage of hours a year or as the number of hours. Number of comfort hours is defined as the number of hours in the year in which the indoor temperature is between 18°-26° C.
- Degree Discomfort Hours (DDH) is defined as the sum of the number of hours the indoor temperature is outside the temperature comfort range of 18-26 C° multiplied by the difference between the indoor temperature and the upper (if too hot) or lower (if too cold) limit of the comfort range; i.e.

  $(T_{indoor} - 26)$ if $T_{indoor} > 26$ C° or $(18 – T_{indoor})$ if $T_{indoor} < 18$ C°

It was determined that greater the number of hours in which the internal air temperature remained in the range of 18°-26° C better the combination of the parameters. This range was decided upon careful study of the thermal comfort ranges as specified by ASHRAE's Standard 55 which is titled *'Thermal environmental conditions for human occupancy'*. As was identified briefly in earlier sections, ASHRAE outlines that for humans wearing winter clothing of 0.8-1.2 clo, the thermal comfort is in the range of 20°-23.5° C, when occupants wear summer clothing that is in the range of 0.35-0.6 clo, thermal comfort is specified to be in the range of 22.5°-26° C. In addition to these ranges, Standard 55 identifies that for sedentary occupancy, the temperature should not drop to figures below 18°C in order to maintain a room temperature that will be thermally comfortable. Therefore, considering the specifications in Standard 55 and the physiological capacity of humans to adapt to their environment, the Thermal Comfort Range (TCR) for this research was considered to be in the range of 18°-26° C. The number of hours in which the space was within the thermal comfort range will henceforth be referred to as HTCR. For simple understanding, it can be stated that *lesser* the value for DDH the more comfortable it will be and *greater* the value for HTCR the more time of the year the space can be considered comfortable.

Therefore, the values of the two aforementioned indicators will be used to assess the improvement of the comfort level of the space as compared to the existing case, i.e. no windtower. Analysis of the simulation results of the existing showed that the existing space had a DDH of 48668.25 C^o hr and a TCR was 2838 hours, i.e. 32.4% of the year.

In the analyses in this section, references will be made to various cases which are in fact the many combinations and configurations. The constituent parameters that make the various cases can be seen in Appendix A.

5.1 The Reference Case

In order to vary the parameters, a new configuration that included natural ventilation was created so that the other cases can be varied relative to the parameters in this particular case, henceforth this case will be referred to as the reference case. The various cases will be compared to the existing case and the reference case.

The reference case comprised of the following parameters – Floor to ceiling height: 3m, Orientation of wind tower: NW, Area of window: 3m, Area of wind tower opening 8m^2, Percentage of window opening: 25%, Percentage of wind tower opening : 100%. Thus, this case was found to have a DDH of 29783 C^o.hr and an HTCR of 3230 hours. Thus, the reference case when naturally ventilated was successful in maintaining the TCR for 392 hours more than the existing case and was therefore found to be within the TCR for 36.8% of the year. The DDH was also reduced by 18,885 C^o.hr. The reasons for this can be attributed to the fact that the window was open 25% of its maximum opening range compared to 0% of the existing case. Moreover, air transfer and circulation takes place from the 5m high wind tower with openings of 8m^2, a condition that the existing case does not have.

That the reference case exhibits favourable results in increased HTCR and decreased DDH, both of which would mean that the energy spent on cooling can be decreased by hundreds of hours augurs well and creates a case for analysis of other results in order to find the most optimised combination. All results are highlighted in Appendix A.

5.2 Impact of Floor to Ceiling Height (FCH)

When studying the impact of the floor to ceiling height (FCH) as a parameter all parameters of the reference case were kept constant but various options were analysed for the height of the floor to ceiling. Since the reference case had a floor to ceiling height of 3m and already analysed, these consisted of set parameters with floor to ceiling heights of 4,5 & 6m.

When air is heated it becomes lighter and moves upwards, thereby resulting in buoyancy effect. Therefore, the upper limit of the room is bound to have warmer air compared to cooler air at the level of the floor. When all other parameters, including occupier activity is kept constant, the room will get cooler with increased volume in the space, the reason for this being that there is greater room for air circulation. Moreover, a greater volume of air will mean that there will be greater thermal capacity which will result in the air being able to absorb more heat before the temperature rises to a capacity that it cannot absorb. Greater the floor to ceiling height, the greater will be the distances and the separation between the layers of varying temperatures, i.e the difference in height between the layer of hot air towards the ceiling and the cold air towards the floor will be greater. Greater the distance between the floor to the ceiling, greater will be the variation in temperatures between the two points. This is further testified by the CFD analyses done to measure temperature levels in the rooms. CFD was performed for the reference case where the floor to ceiling height is 3m and Case 4 where the floor to ceiling height is 6m; the results are shown in Fig 5.1 & Fig 5.2.

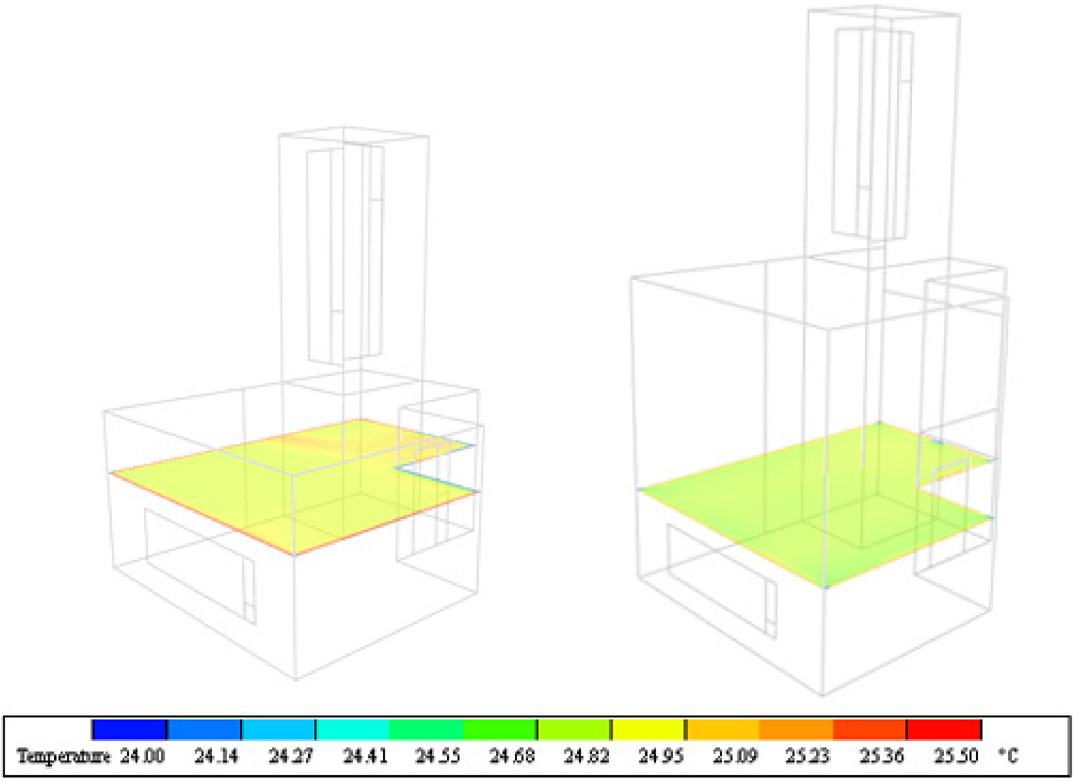


Figure 5.1 Temperature levels in case 1 (FCH=3m) & case 4 (FCH=6m) on April 1 in perspective

As seen in Fig. 5.1, the temperature key was defined to be within the range of 24-25.5 ° C. It is understood that Case 4 will have a lesser temperature value at an occupant height of about 1.8m compared to case1. However, one of the limitations of IES CFD as identified in the methodology section is that CFD results are given as a temperature range and not as numerical figures, therefore this cannot be graphically elucidated beyond what has been shown. Two temperature slices were obtained at 1.8m for both cases. The slices, as graphically illustrated in the CFD images, show that the space with a height of 3m has a temperature range at 1.8m of 24.95-25.23 ° C compared to the space with a height of 6m where at 1.8m the temperature lies in the range of 24.41-24.82 ° C. Therefore, when averaged out, the case with the higher ceiling shows an average temperature of 24.61° C at 1.8m and the case with the lower ceiling shows an average temperature of 25.09° C at 1.8m.

Thus, greater the height from the floor to ceiling, greater the comfort levels at the height of the occupants. The results obtained from the simulations with varying floor to ceiling heights are plotted in the graph identified as Fig 5.2. The percentage values for DDH refer to the percentage decrease in DDH in comparison to the existing case and the percentage values for the Comfort Hours refer to the increase in comfort hours in comparison the existing case. For instance, the case with a 3m floor to ceiling height had a HTCR of 3230 hours compared to the HTCR of the existing case which was 2838 hours, thus the HTCR of the case with 3m floor to ceiling height has an HTCR increase of 13.8%.

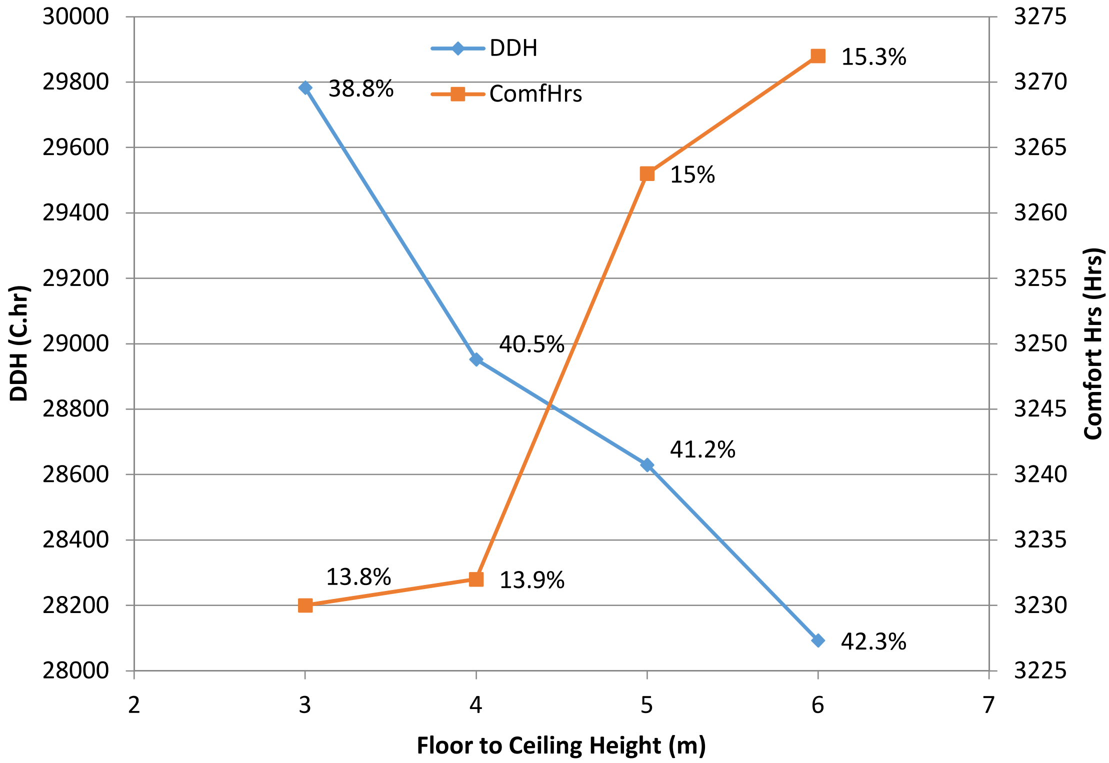


Figure 5.2 DDH & HTCR when floor to ceiling height is varied

It was noted that there wasn't a particularly big difference between ceiling heights 3m and 4m, though there was a significant difference in results of the HTCR between 4m & 5m and again only marginal difference in the HTCR between 5m & 6m. HTCR for the 4m floor to ceiling height was 3232 hours, thereby making it only two hours better than the reference case and 13.9% better than the existing case. The most beneficial case was case 4 where the floor to ceiling height was 6m. In this instance, simulations yielded a result of 3272 hours for

HTCR thereby making it 15.3% better than the existing case (FCH = 3m)with 434 hours annually being in the TCR greater than in the existing case.

Though there were sharp differences between 4m-5m in the HTCR ranges, the difference in DDH ranges were relatively more proportional as the heights changed. The DDH values reduced with the increase in height with the floor to ceiling height of 6m showing the most favourable results with a reduction of DDH by 28093 C^{o}.hr or 42.3% from the existing case.

Even though from an energy perspective, having a floor to ceiling height of 6m would be the most favourable in terms of significant reduction of DDH or the amount of hours a year in which occupants can be in comfort only by the use of natural ventilation without dependence on mechanical means, there are other factors that need to be considered. A 6m high floor to ceiling height would increase the amount of materials that would be used, this will be manifested in thicker structural walls or columns, a thicker floor slab since this room is on the first floor level and potentially deeper or wider foundations. Therefore, unless designed entirely using sustainable materials, which is a rarity in mass housing schemes in the UAE, the building will increase in embodied energy thereby offsetting to a certain extent the energy and cost benefits yielded by reduction in mechanical means of cooling.

5.3 Impact of the height of the wind tower

The differences in the heights of the wind towers did not seem to significantly impact the different results that were obtained, this corresponds to the research done by Calautit et al (2013) who observed that there was only a marginal decrease in evaporative cooling temperature coming in proportion to increase in height and they observed a temperature difference of approximately 3.5 K (this figure is given in Kelvin as opposed to °C is because Calautit et al (2013) give their figures in Kelvin, however 1 °C = 1K when discussing temperature difference) in the air at the outlet point of the wind towers of heights in the range of 4-10m as is shown in figure 5.4,This conveniently matches the range of the heights of the wind towers in this research which are in the range of 3-9m, results of which are shown in Fig 5.3.

It must be noted however that this refers to evaporative cooling and not temperature, however validating the fact that the height difference does not have a significant impact on the temperatures, Calautit et al (2013) mention in their concluding remarks that heights were not considered in the designs they made as they did not elicit a significant influence.

Even though there was a HTCR difference of 0.3% from the case where the wind tower height was 3m to case 1 where the wind tower height was 5m, that figure was also similar for wind towers of height 7m and 9m. However, when compared with the existing case that has no wind towers, the HTCR value was 3237 hours, a 14.1% increase.

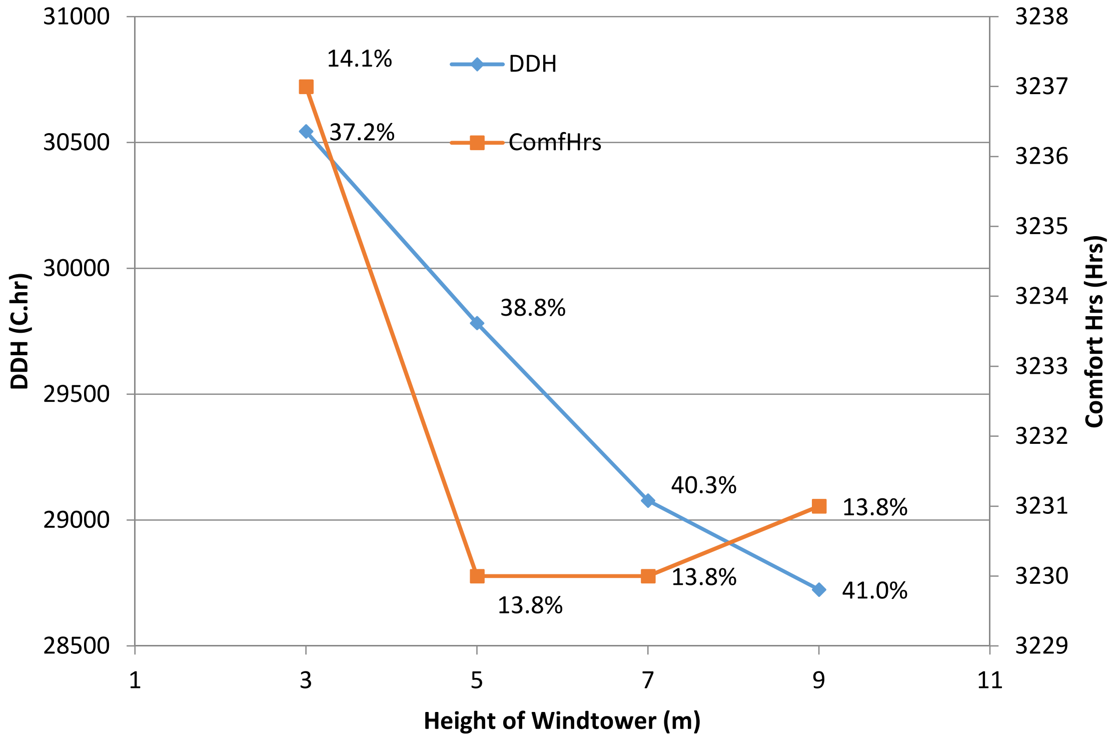


Figure 5.3 DDH & HTCR when Wind tower heights are varied

Thus, on average the different wind towers were 14.5% or 3232 hours better than the existing case. There were however more prominent changes in the results for DDH. Whilst a wind tower of 9m was 41% better than the existing case, the wind tower of 3m was 37.2% better than the existing case, thereby making the wind tower with 9m to be 3.8% more favourable in terms of DDH than a wind tower of 3m.

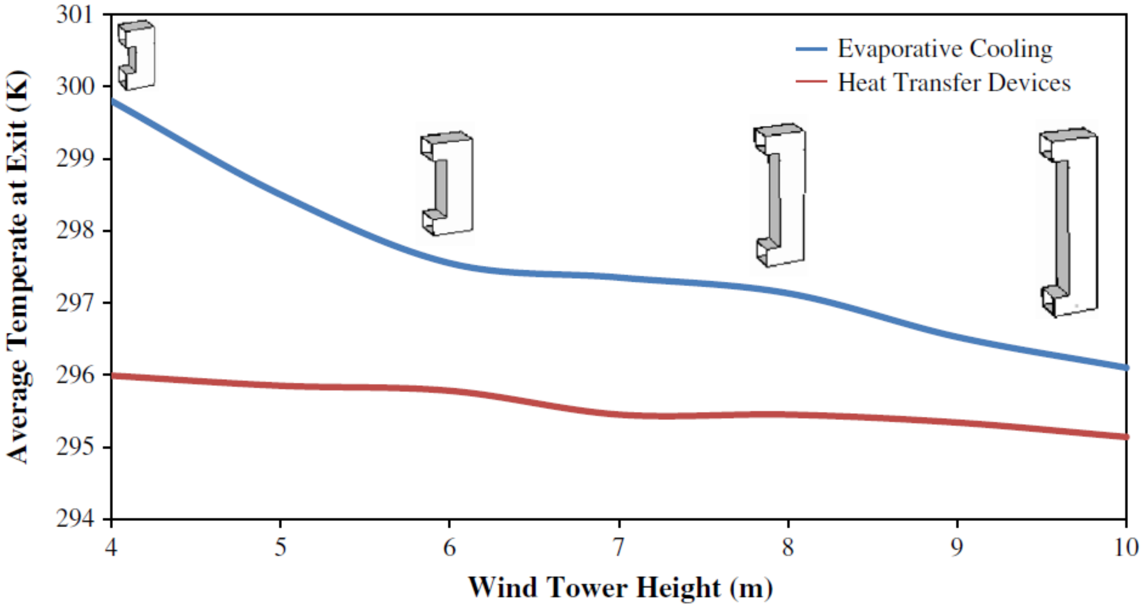


Figure 5.4 Effect of wind tower height on evaporative cooling at the outlet point (Calautit et al 2013)

There is an interesting correlation between the heights of the wind towers and the different results that were yielded in terms of DDH and HTCR. As the wind towers increased in height, the HTCR reduced (i.e. got *less* beneficial) and the DDH reduced (i.e. got *more* beneficial). This is an interesting paradox that can be attributed to the following reason.

As confirmed by Calautit et al (2013) in Fig 5.5, the taller the wind tower greater the access it has to increase in wind speeds. In addition to this, Hughes et al (2013) identify that as wind towers increase in height, a greater negative pressure occurs as stronger winds pass over it as identified in Fig 5.6.

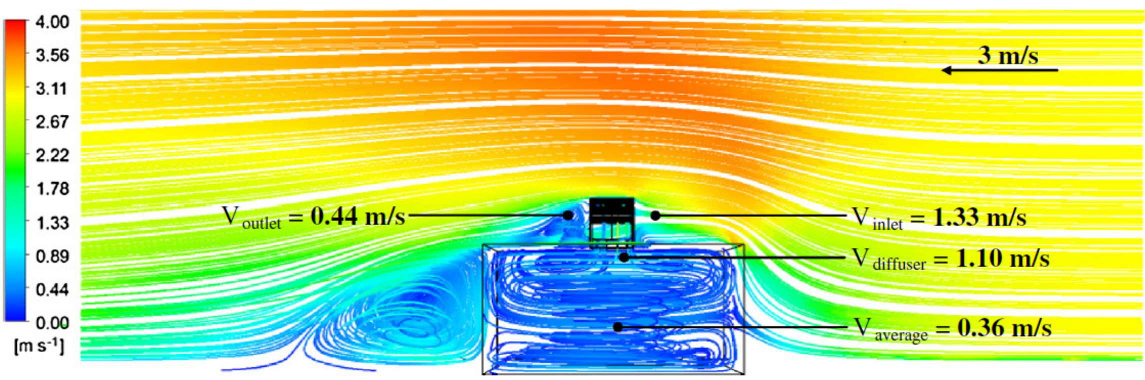


Figure 5.5 Increase in wind velocities with increase in height (Calautit et al 2013)

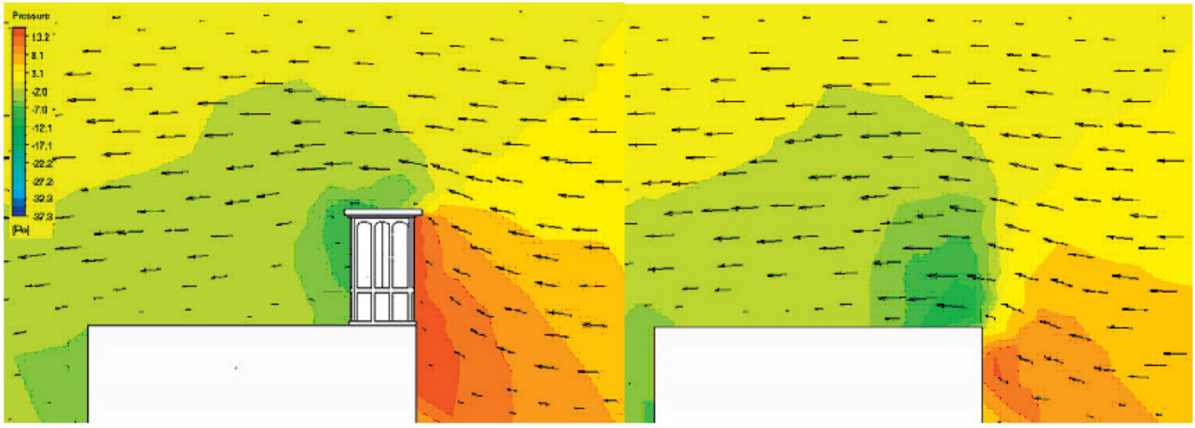


Figure 5.6 Variation in air pressures outside wind tower (Hughes et al 2012)

As the wind towers increase in height, they have more access to wind with fewer obstructions, and increased wind velocity. Since obstructions were not considered in the current model, the wind velocity increase as the height increases is more of a contributory factor than the absence of obstructions. With increased volume of airflow ingress and increased velocity, the room will have access to more cold air during cold months and more access to hot air in the hot months.

Furthermore, taller the tower the more that temperature stratification or a chimney effect will occur, which will result in more ventilation. Therefore, this wider range between lowest temperatures to highest temperature of the wind will result in reduced DDH. However, in the case of the wind tower of 3m, the wind velocities at the inlets will be lesser than at the inlets of heights 5, 7, or 9m. Therefore, even if these velocity variations aren't particularly significant, the room will be more towards the warmer end of the spectrum thereby resulting in a higher DDH. Among the reasons for which the air will be closer to being warmer is that the height of 3m is much closer to the warm ground levels and carrying of heat from other heat gain sources.

This is confirmed by Fig 5.7 that identifies the volumes flow in and out for one of the openings of their respective wind towers for case 5 and case 7. Whilst case 5 with wind tower of 3m exhibited an air exchange volume of 2657.63 x 10^3 m^3 (difference between total volume flow in and total volume flow out), case 7 with wind tower 9m exhibited an air exchange volume of 3108.65 x 10^3 m^3 . Thus, the taller wind tower of 9m had an air exchange annually that was greater than that of case 5 with wind tower of 9m by a volume of 451.02 x 10^3 m^3.

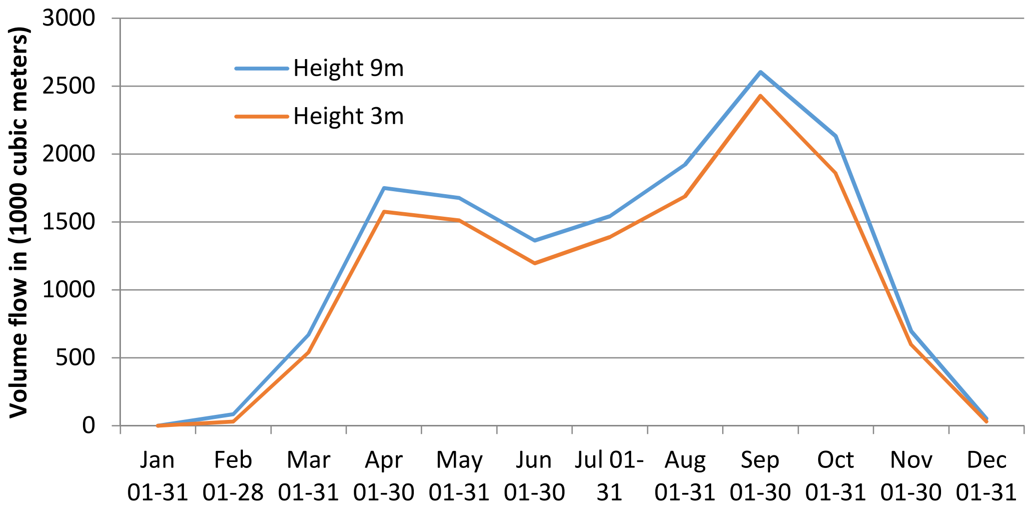


Figure 5.7 air flow volume for a single opening in wind tower heights 3m & 9m

Figure 5.7 also identifies that September and October are the months when all temperature and humidity profile conditions are satisfied best as reflected by the highest volume of air flow in. The second best month seems to be April with airflow volumes approximately in the range of 1500-1750 thousand m^3. The dip in the air flow volume in the months of June and July are due to the fact that external relative humidity levels are much higher. In all times of the year when there is an inflow of air, the wind tower of height 9m allows more air to ingress than the wind tower of height 3m.

5.4 Impact of the Orientation of the Wind tower.

This section comprises of the simulations carried out by maintaining all parameters as set, except for the orientation of the Wind tower which in these cases were varying parameters, the results are exhibited in Fig 5.8.

As was discussed in Section 3, the dominant wind direction yielding the greatest amount of airflow volume hitting the wind tower is from the North Western direction, owing to the geographical positioning of the UAE. On this basis, it was assumed prior to the simulations being performed that the wind tower with openings on the North-West will be the most effective. Even though this assumption was largely correct, there is one exception to the assumption.

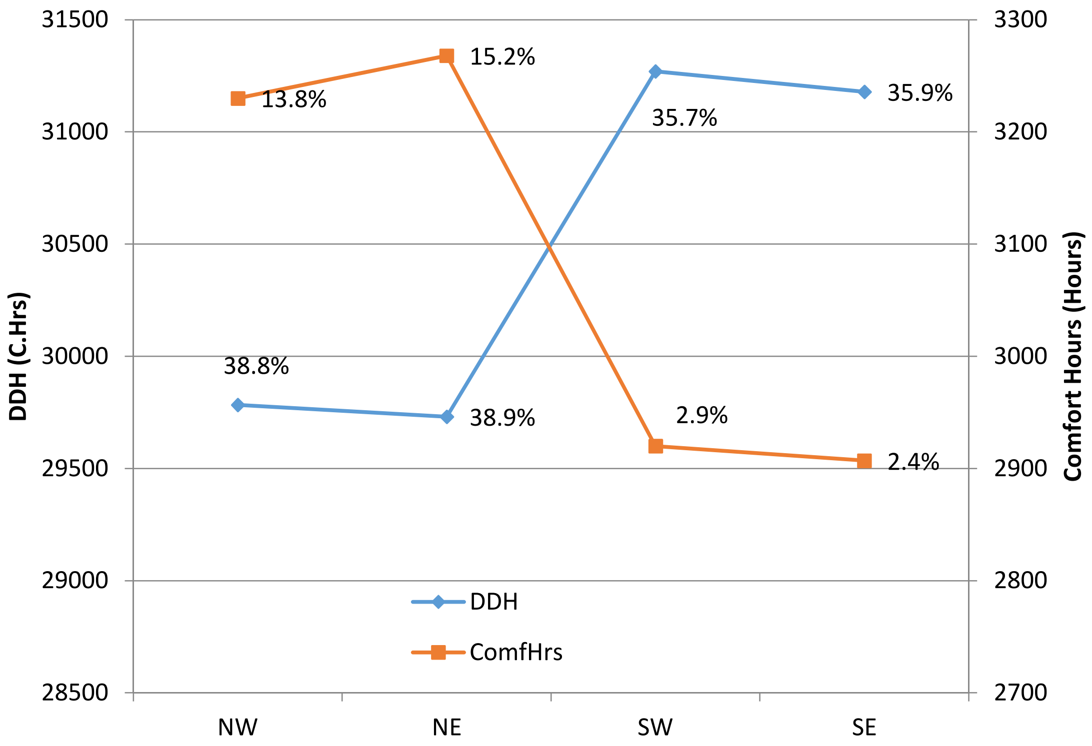


Figure 5.8 DDH & HTCR when Wind tower heights are varied

The Wind tower oriented towards the North East performed marginally better than the wind tower oriented towards the North-West. Whilst the wind tower oriented towards the North East yielded 3230 hours of HTCR, the wind tower oriented towards the North East yielded a HTCR of 3268hours, this is 68 hours more than that of the North West.

As was anticipated, the two orientations that performed the worst were those of the South-West and the South-East. The reasons for this are quite obvious in that wind blowing from the southern direction and colliding with the wind tower are extremely less and even if there were winds flowing from the south, they will largely be pushed away from winds flowing from the Northern directions. These details can be read in conjunction with the wind rose as identified in Section 3.

Case 8 where the wind tower openings were oriented towards the North East had a total annual airflow in of 20589.14 x10^3 m^3 and case 10 which had the wind tower openings were oriented towards the South East had a total airflow in of 20039.52 x 10^3 $m^{3,}$ thus the wind tower oriented towards the North East yielded an airflow in volume of 549.62 x 10^3 m^3 extra over the wind tower oriented towards the South East. For convenience of reading, this figure cannot be given in a percentage format in comparison to the existing case as the existing case had no ventilation.

The effect of this result was further reflected in the DDH figures that were obtained after the simulations. Whilst the wind tower oriented towards the North West performed 38.8% better than the existing case, the wind tower oriented towards the North East performed 38.9% better than the existing case, thereby making the wind tower oriented towards the North East to be the best performing wind tower orientation by outperforming the North West configuration by 0.1%. Therefore, for practical purposes it can be safely assumed that both the wind tower with North East orientation and the wind tower with North West orientation have the same performance levels. The wind tower openings function simultaneously as inlets and outlets, whether at a given time they perform as an inlet or an outlet is determined by the volume and pressure of the air coming in or the pressure of the air within the space. Therefore, the marginal outperformance of the North West configuration by the North East configuration can be attributed to the fact that air coming out from the wind tower can escape slightly more easily than being pushed in again by the dominant external winds flowing from the North West.

The South West and South East oriented wind towers produced only a HTCR increase of 2.9% and 2.4% in relation to the existing case compared to the North East and North West orientations that performed 15.2% and 13.8% better than the existing case. Thus, on average, in terms of HTCR figures, the Northern orientations performed 11.85% better than the Southern oriented wind towers.

5.5 Impact of the area of the window.

This section comprises of the simulations carried out by maintaining all parameters as set, except for the area of the window which in these cases was the varying parameter, the results are exhibited in Fig 5.9.

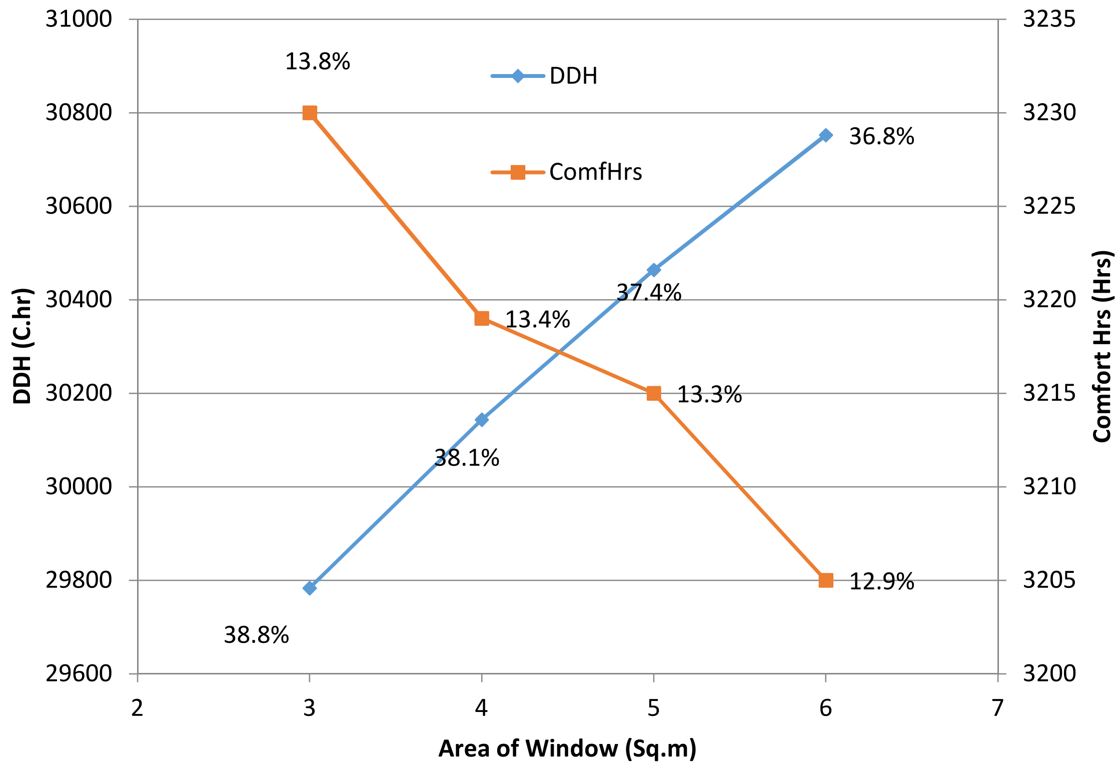


Figure 5.9 DDH & HTCR when the area of the window is varied

Of the four different window sizes that were used, the window with 3m² performed best, compared to 4,5, & 6m² in decreasing order. It must also be noted here that in all four instances, the windows were only open 25% and were not fully opened. Therefore, their sizes and their impact have to be judged on the percentage to which they were open.

The results indicate that the window with the smallest cross sectional area performs best in both results, with a 13.8% increase in comfort hours and a 38.8% decrease in DDH from the existing case, case 1 with the window opening of 3 m^2 performs better than all other instances. It is also interesting that the 3 m^2 window is also the size of the existing case. However, the existing case performs with an HTCR value of 2838 and DDH value of 48668.25 C^o hr compared to case 1 which has the same window area and yet yields an HTCR value of 3230 hours and a DDH value of 29783.25 C^o hr. In the existing case, the windows are open 0%, therefore theoretically it is as if the windows do not exist.

Therefore to further explore this phenomenon and establish reasons for these observations, another additional simulation was carried out for the existing case (Case 0) with the window being 25% open, so that it is exactly the same as Case 1 in terms of the window size and window opening. The same window opening profile formula was also applied as to the other windows and wind tower openings.

The results this configuration yielded were 3061 hours HTCR and 35604.97 C^o hr DDH, therefore the HTCR percentage value increased by 7.9% and the DDH decreased by a percentage value of 26.8%.

Thus, case 1 (Window area 3m^2), which uses the exact same configuration as the existing case, performs 5.9% better in terms of HTCR and 12% better in terms of DDH when the window in the existing case matches case 1. This clearly demonstrates that the use of wind towers in tandem with the window performs better in terms of thermal comfort than the use of windows alone, further strengthening the case to use wind towers for natural ventilation. The reason for this is that there is a far greater prevalence of air movement and air exchange owing to more inlets, outlets and variations in air speeds and pressure.

Unlike in some of the other instances, in this instance, there was a proportional correlation between the areas of the windows and the levels of thermal comfort in the room. As the window areas were increased, the thermal comfort ranges in the space decreased, it must be understood however that these results are true for the extent of the values used in this research and may differ as the values increase. This phenomena can be attributed to the fact that greater the area of the window, greater the amount of hot air that can ingress. As window areas increase, more warm air can come in during the warmer months and cooler air can come in during the cooler months. Another factor that needs to be considered is that as the area of the windows increase, the percentage of solar penetration also increases, thereby subjecting the room to increased temperatures due to solar gain. This would in turn increase internal temperatures beyond the upper band limit of the TCR, thus reducing the HTCR. Not only would this mean that mechanical ventilation methods will have to be used to alleviate these effects, but it would also have a net impact on the DDH that will make the room less energy efficient to keep within thermal comfort stipulations.

5.6 Impact of the area of the wind tower opening.

This part comprises of the simulations carried out by maintaining all parameters as set, except for the area of the wind tower openings which in these cases was the varying parameter, the results are exhibited in Fig 5.10.

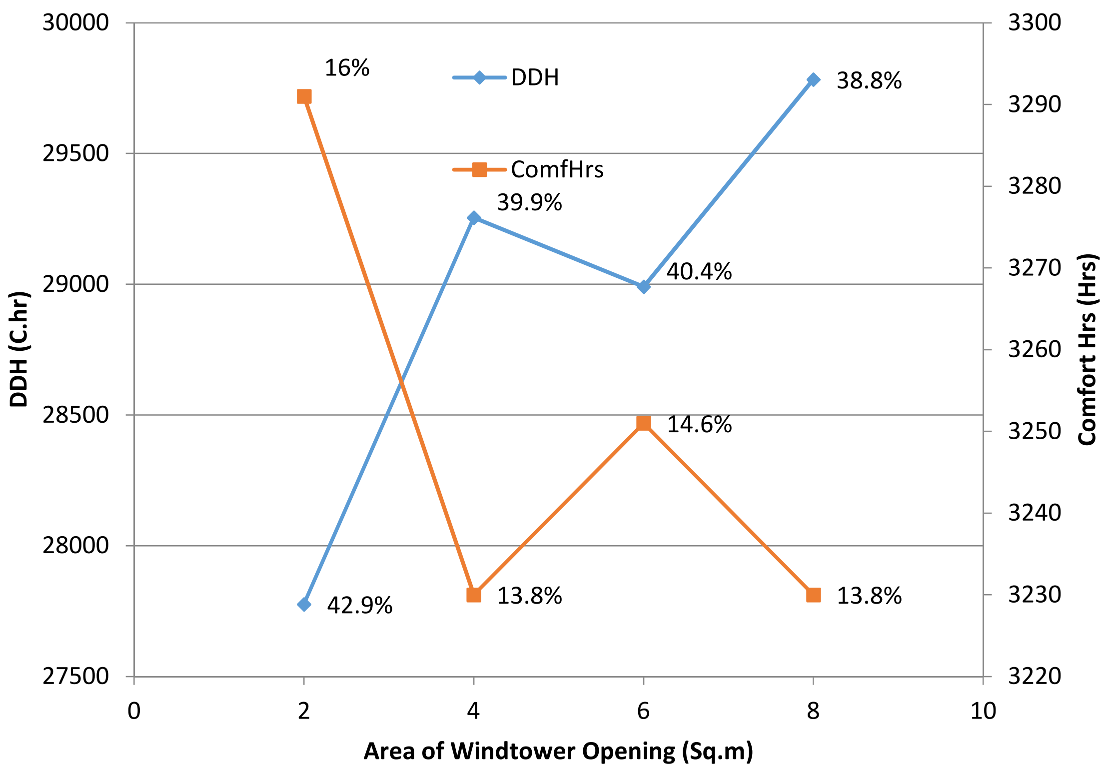


Figure 5.10 DDH & HTCR when the area of the wind tower openings are varied

The results obtained for both HTCR and DDH do not show a consistent trend. Rather, they show unique results that are particular for the values of the parameter use. Wind tower with openings $4m^2$ and $8m^2$ both performed similarly with regards to HTCR by being 13.8% or 3230 hours better than the existing case. However, Case 15 (Wind tower opening of area $4m^2$) performed marginally better than the reference case (wind tower of opening area $8m^2$). Case 15 showed a DDH reduction of 39.9% with 29254.69 C^o hr to the existing case whereas the reference case showed a reduction of only 38.8% with 29783.25 C^o hr to the existing case. Thus, case 15 was 1.1% better than the reference case in performance, making the reference case the worst performing wind tower opening area of the various cases.

What disturbs the consistency of a trend is the performance of case 16(i.e. the wind tower opening of $6m^2$). The wind tower with opening $6m^2$ performed better in terms of HTCR and DDH than both wind tower with $4m^2$ and wind tower with $8m^2$. Case 16 had 21 hours in the TCR more than the reference case and case 15 and had a 0.5% decrease in DDH than case 14 (i.e the wind tower opening of $2m^2$). The causes for this are unclear as it is rather unusual and is inconsistent with the trend. However, it may be that an optimisation occurs in the case with opening $6m^2$ that does not occur in the cases with openings $4m^2$ and $8m^2$ due to various factors, these factors may be air pressure on either side of the opening or air friction amongst other possibilities. This difference is only by 0.8% and therefore is not significant enough to warrant a very significant study on it.

The best performing configuration was Case 14 with wind tower with area of $2m^2$ which exhibited a 16% increase in HTCR with 3291 hours, making it have 453 hours more than the existing case in the TCR. Case 14 also showed a 42.9% reduction in DDH from the existing case.

On this basis, it may come across that smaller the area of the wind tower, greater the comfort levels in the room inside. However, this theory is refuted by case 20 where the percentage opening of the wind tower openings are 0%, i.e. the wind tower is not operative. Results for Case 20 show that the DDH is 48515.62 C^o hr making it only 0.3% better than the existing case which had a DDH of 48668.25 C° hr, and in terms of HTCR it performed *worse* than the existing case by having an HTCR value of 2592 making the existing case show 346 hours more in the TCR (i.e. -12.2%). Therefore, it can be safely assumed that the most optimised wind tower opening area lies in the range of 0 m^2 - 2 m^2.

Therefore, in order to establish the most optimised configuration, a simulation was further carried out by reducing the area of the wind tower opening to 1 m^2. This yielded the results highlighted in yellow in Table 5.1.

Table 5.1 Results yielded for Different wind tower openings

Area of Wind tower Opening (m2)	DDH (C° hr)	HTCR (hours)
0	48515.62	2492
1	27919.45	3281
2	27775.71	3291

Thus, as table 5.1 shows, wind tower with opening of 1m^2 performed better than 0m^2 but worse than wind tower with opening 2m^2. Therefore, it can now be assumed that the optimised window area may lie between 1 m^2 and 2 m^2.

Therefore, the simulation was repeated with wind tower opening of 1.5 m^2. Results obtained are highlighted in yellow in table 5.2.

Table 5.2 Results yielded for Different wind tower openings

Area of Wind tower Opening (m^2)	DDH (C° hr)	HTCR (hours)
0	48515.62	2492
1	27919.45	3281
1.5	27799.24	3287
2	27775.71	3291

Result for wind tower with opening 1.5 m^2, though performed better than wind tower opening of 1m^2, still performed worse than Case 14 (i.e the wind tower opening of 2m^2).

Therefore, the range was further increased be in the range of $2m^2 – 3\ m^2$. Results are shown in Table 5.3 and Fig 5.11.

Table 5.3 Results yielded for Different wind tower openings

Area of Wind tower Opening (m^2)	DDH (C^o hr)	HTCR (hours)
0	48515.62	2492
1	27919.45	3281
1.5	27799.24	3287
2	27775.71	3291
2.25	27830.11	3302
2.5	27866.76	3292
2.75	27907.96	3292

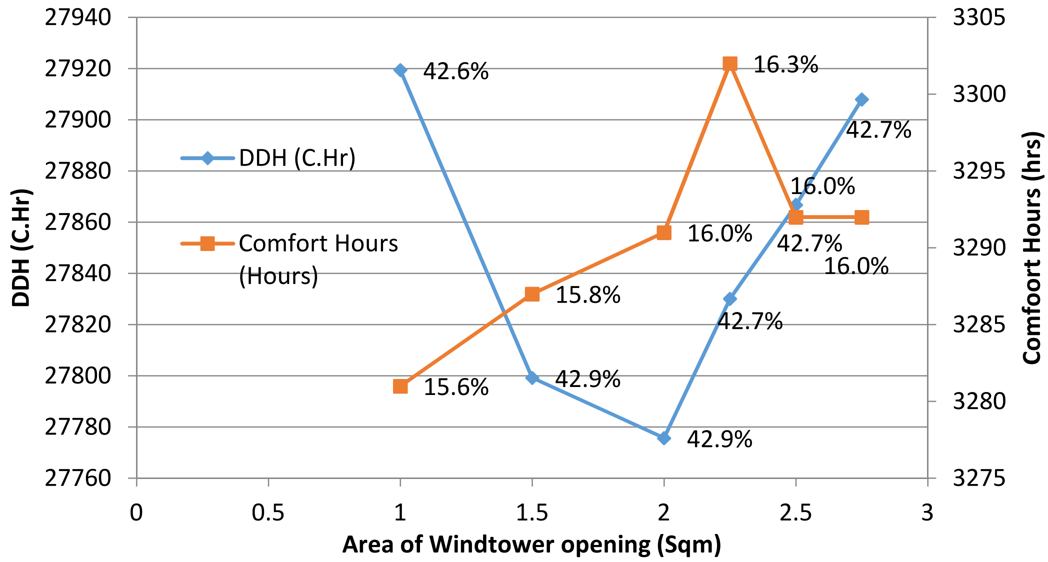


Figure 5.11 DDH & HTCR when the area of the wind tower openings are varied for optimum setting

As is seen above, several simulations were carried out until the comfort levels were decreasing. As the area of the wind tower opening keeps increasing beyond $2m^2$ the DDH increased correspondingly, suggesting therefore that the space was becoming less comfortable. The simulations were stopped at wind tower opening area of $2.75\ m^2$ as the DDH was increasing and the HTCR was decreasing indicating that the space was becoming less thermally comfortable. Therefore, from Table 5.3, it can be deduced that the optimum area for this current space would be to have wind tower openings in the range of 2m² – 2.25m².

Many different theories were analysed for why this phenomenon takes place. Amongst them was the understanding that the impact of the discharge coefficient may be being felt. Hult et al (2012) refer to the coefficient discharge as the ratio of the actual flow to the ideal flow and is used in equation (1) –

$$\boldsymbol{Q = C_d A \sqrt{(2\Delta P)/\rho}} \tag{1}$$

In formula (1), Q is the rate of flow through an opening, C_d is the Coefficient Discharge, A is the area of the opening, ΔP is the pressure difference across the openings and ρ is the fluid density.

Hult et al (2012) conclude that a coefficient discharge is used to add up loss along the path of the flow from the point of ingress, the internal space and the point of ingress into one single parameter. Furthermore, Allard & Utsumi (1992) elucidate that the discharge coefficient depends on the variation in temperatures on either side of the opening, though there are ambiguities as to the extent and magnitude of this.

Whilst the extent to which the coefficient discharge may affect openings of this size is unsure, the results obtained in this simulation may be due to the pressure differential that occurs between the inside and the outside of the wind tower openings created as a result of the different areas of the orifices. This phenomenon may be the reason for which the opening with 2m² performed the best amongst the smaller opening sizes shown in table 5.2.

Furthermore, air flows through smaller openings faster than they do in larger openings. Montazeri & Azizian (2008) found in their results, suggestions that variations in the pressure coefficients indicate a strong surge in speed as the air enters and then it decelerates as it goes down the air tunnel. Hughes et al (2012) opine that this variation was due to the separated flow of air. Therefore, as flows deviate in the region of air vortices, the air pressure decreases. This phenomenon may also have influenced simulation results in this section.

Further, the number of openings in the wind tower has an impact on the pressure and speed with which the air flows in. In addition to this the shape of the openings of the wind tunnel too impacts the physical attributes of the air flow that goes in. ElMualim & Awbi (2002) carried out tests and simulation exercises to determine the difference in performance of wind catchers that were cut to square sections or circular sections. It is commonly understood that the square shape would be more efficient in getting wind streams across; this understanding was confirmed by tests carried out my ElMualim & Awbi (2002) who confirmed that the rigid and sharp vertices of the non-circular shapes form a bigger area of flow separation and greater variations in pressures across the divide. Therefore, variations in the sizes can inform the shape and this therefore may have also contributed to the results obtained.

Moreover, simulation results shown in Fig 5.12 & Fig 5.13 for the 1st April at 10am identify that there is a greater volume of air exchange from the opening with lesser cross sectional area. The opening with 8 m^2 had an air entering at a speed of 913 l/s and air exiting at a speed of 819 l/s, thus at a given point there is an excess of 94 l/s entering through the wind tower. Case 14 which has an opening of 2 m^2 exhibited an air entering at speeds of 289 l/s and air exiting at speeds of 190 l/s. Thus, the air that entered through this opening exceeded the air exiting by 99 l/s. Thus, at a given point, the smaller areas shows that an extra 5 l/s of air enters through the smaller cross sectional area than the larger cross sectional area.

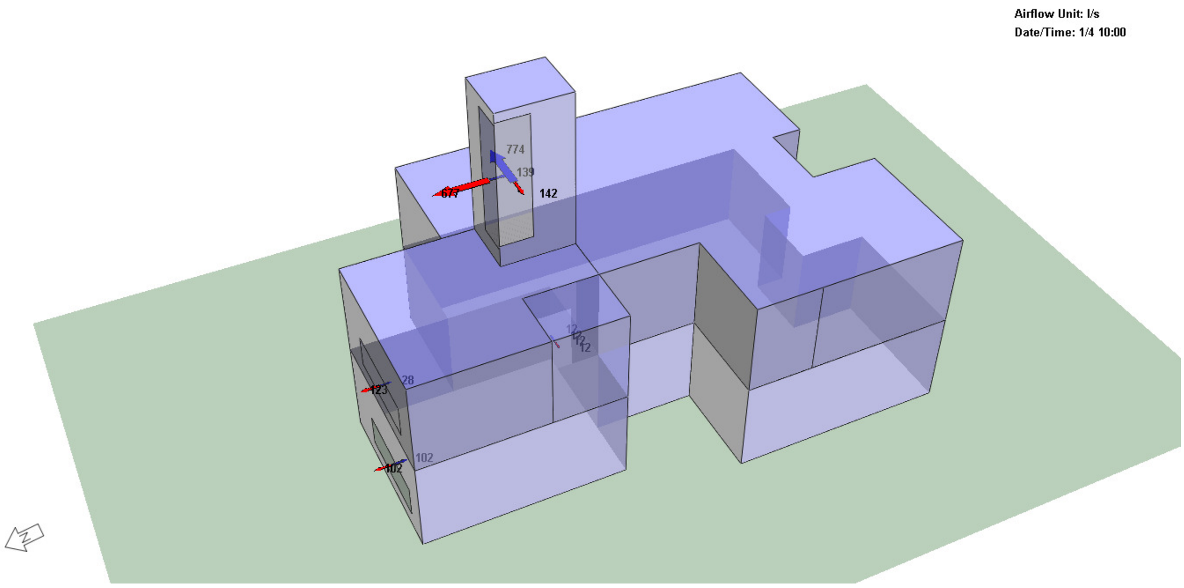


Figure 5.12 Air exchange through opening of 8m².

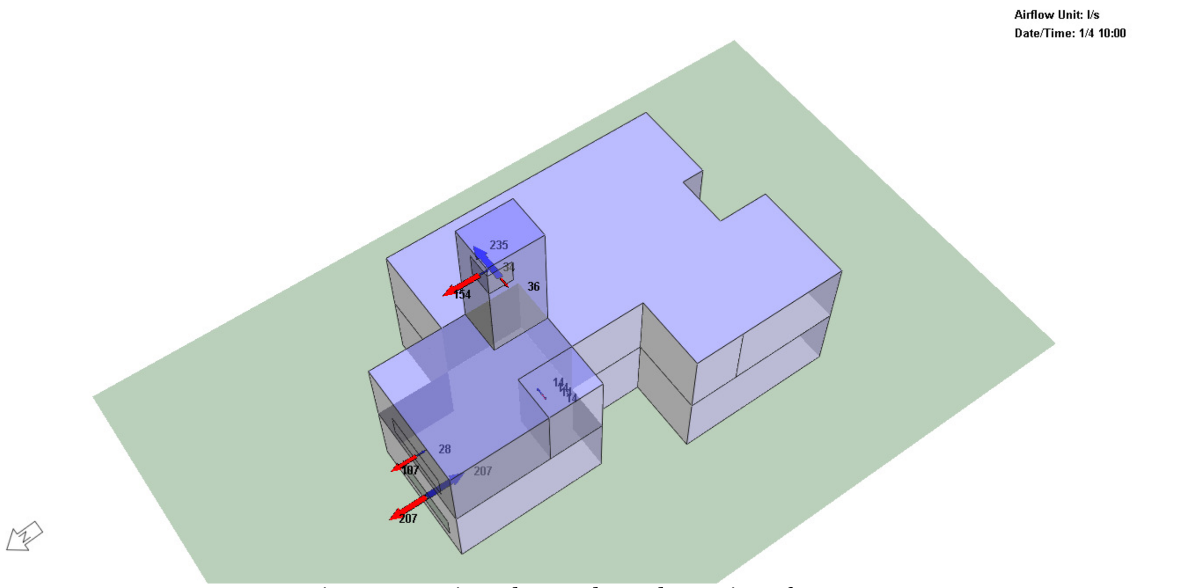


Figure 5.13 Air exchange through opening of 2m².

All in all, opening the wind tower openings in all cases showed that when wind towers are open, there is an increase in the HTCR and a decrease in the DDH. This is similar to the results reported by Bouchahm et al (2011) whose studies confirmed that in the night time, when the internal temperatures are greater than the outside temperatures, opening the wind towers in the room have a direct influence in reducing internal temperatures, the reason they attribute to this is the effect of the thermal inertia of the house envelope.

5.7 Impact of the percentage opening of window opening.

This section comprises of the simulations carried out by maintaining all parameters as set, except for the percentage of the window openings which in these cases was the varying parameter, the results are exhibited in Fig 5.14.

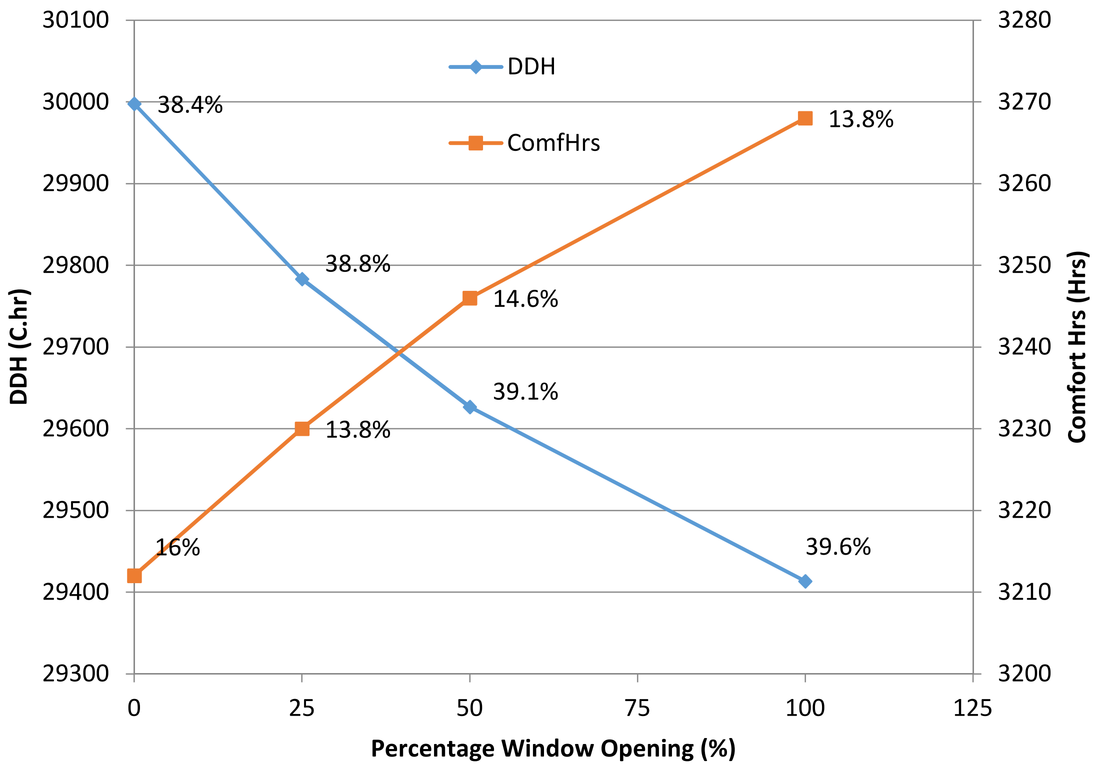


Figure 5.14 Variations of results as a function of percentage of window opening

The percentages that were considered in these simulations was when the window was open 0%, 25%, 50% and 100%, for a window of $3m^2$. Although with the increase of window opening percentages the internal conditions became more thermally comfortable with an increase in HTCR and a decrease in DDH, the results were largely similar with the difference between the best performing window opening percentage and the least performing window opening percentage being 56 hours, thereby the best configuration was only 2% better than the least performing configuration.

The differences in DDH were even more negligible, with the best performing case being only 1.2% better than the least performing configuration. When the window is fully closed, the DDH is 29997.55 C^o hr whereas when the window is fully opened the DDH is 29413.42 C^o hr, making the difference in DDH to be 584.13 C^o hr. Considering that the graphs plotted were fairly consistent in their shapes (except that they are inverted), in this case the influencing factors of DDH and HTCR act similarly.

These trends were observed when the window area is $3m^2$. It must be recalled from section 5.5 in which the best performing window area was $3m^2$ and not the largest window opening area which was $6m^2$. Therefore, despite the fact that the window performed slightly better with the increased percentage of opening, this does not necessarily mean that the window area if made larger will perform better. A window that is $4m^2$ when opened 25% had an HTCR value that was 13.4% better than the existing case and a window that is $3m^2$ when opened 25% had an HTCR value of 13.8%, thereby performing 0.4% better despite being $1m^2$ less in size.

The reason for this can be attributed to the fact that the windows open only when they satisfy the conditions as outlined in the methodology section, the crux of which is that the windows will be open only when it is favourable to have them open in terms of internal comfort. These conditions at which the windows will open were detailed in section 3.

To test this theory, the best performing case for the window opening percentages (case 19 with window opening of 100%) was re-simulated with the window open right throughout the day. The results are highlighted in table 5.4.

Table 5.4 Variation in DDH and HTCR when windows open 24 hours

Window opening condition	**DDH**	**HTCR**	**Reduction in DDH (%)**	**Comfort Hours Increase (%)**
Case 19 when Window open for 24 hours	32070.71	3199	34.1	12.7
Case 19 when Window open according to Profile	29413.42	3268	39.6	15.2
Difference	2657.29	69	5.5	2.5

Thus, it is clear that the windows perform better when the opening percentages are greater, as long as they are governed by an operating mechanism that determines when the window is to be open, how many hours of the year, and the internal and external temperature conditions. When Case 19 was re simulated with the window to be open 24 hours a day, the HTCR *reduced* by 69 hours and the DDH *increased* by 2657.29 C^o hr – thereby confirming that the internal space gets less thermally comfortable when the windows are open 24 hours a day. The reasons for this would be that when the window is open 24 hours a day for 365 days of the year, it will allow warm air that is outside the TCR into the room during the summer months and cool air that is out of the TCR during the winter months.

5.8 Impact of the percentage opening of the wind tower openings.

This section comprises of the simulations carried out by maintaining all parameters as set, except for the percentage of the wind tower openings which in these cases was the varying parameter, the results are exhibited in Fig 5.15.

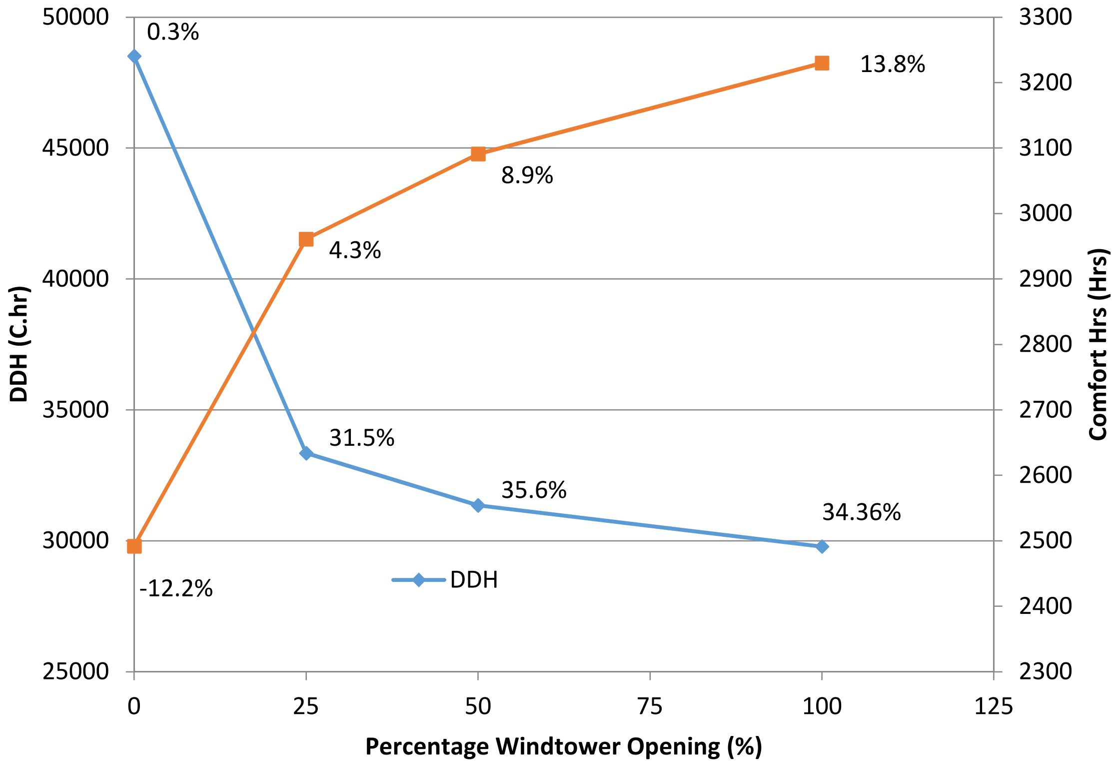


Figure 5.15 Variations of results as a function of percentage opening of wind tower opening

Unlike the impact of the percentage opening of windows, the difference between the best performing wind tower opening percentage and the least performing wind tower percentage was a very significant 26% in terms of HTCR and 34.33% in terms of DDH from the existing case. The least performing wind tower opening percentage performed -12.2% in terms of HTCR compared to the existing case and performed only a negligible 0.3% improvement in terms of DDH from the existing case.

In section 5.7, it was understood that the difference in HTCR results between windows opened 25% and 50% was a difference of 0.6%. However, in the case of wind tower opening percentages, the difference between 25% and 50% was 4.6%. The same is true for DDH as is identified in table 5.5. Table 5.5 identifies the different ways in which wind tower opening percentages and window opening percentages behave. The values for DDH and HTCR in table 5.5 are the figures obtained in relation to the existing case.

Table 5.5 Variations in results between window opening percentage and wind tower opening percentage

Opening Percentage (%)	Window Opening			
	DDH (%)	Difference in DDH	HTCR (%)	Difference in HTCR
0	38.4		13.2	
25	38.8	0.4	13.8	0.6
50	39.1	0.3	14.4	0.6
100	39.6	0.5	15.2	0.8
Opening Percentage (%)	Wind Tower Opening			
	DDH (%)	Difference in DDH	HTCR (%)	Difference in HTCR
0	0.3		-12.2	
25	31.5	31.2	4.3	16.5
50	35.6	4.1	8.9	4.6
100	38.8	3.2	13.8	4.9

It is evident that whilst the differences in results between the opening percentages of the windows are largely negligible by being in the 0.3-0.8% range, the differences caused by the percentage openings of wind towers are far more significant. Whilst the difference of DDH between the various opening percentages for wind towers lie in the 3.2% - 31.2% range, the difference in HTCR lie in the 4.9% - 16.5% range.

As was discussed in section 5.7, the wind tower openings for these simulations are conditional as was the case for the windows. Therefore, case 1 which had the best results for wind tower opening percentages were re-simulated with the wind tower openings to be open for 24 hours a day and 365 days of the year. The results are outlined in table 5.6.

Table 5.6 Variation in DDH and HTCR when wind towers open 24 hours

Wind tower opening condition	DDH	HTCR	Reduction in DDH (%)	Comfort Hours Increase (%)
Case 01 when Wind tower open for 24 hours	34678.97	2857	28.7	0.7
Case 1 when Wind tower open according to Profile	29783.25	3230	38.8	13.81
Difference	4895.72	373	10.1	13.11

Unlike in the instance of windows, the differences when the wind towers were open for 24 hours and the wind towers were open according to a profile were far significant. When the wind towers were open for 24 hours, the HTCR *reduced* by 373 hours, a 10.1% drop from when the wind tower openings worked according to a profile condition, and the DDH *increased* by 13.11%.

Therefore, for this instance, it is quite conclusive that wind tower openings have a far significant impact in the thermal comfort of the occupants than the window openings. However, it is also evident as in the instance of case 20 (percentage wind tower opening 0%), that the wind tower openings and the window openings function dependently and feed off the performance of each other. Another factor that differentiates wind tower openings from window openings is that whilst the window openings leave room for heat gained by solar penetration, wind tower openings do not leave provision for that.

Furthermore, the impact of the percentage opening of wind tower openings can be compared to the impact of the area of the wind tower opening. In both instances, the different parameter inputs for the area of the opening performed better than the percentage opening parameters. Although the DDH benefit figures in both parameters were similar, the percentage increase in HTCR varied quite drastically. Whilst the varying of areas in the wind tower openings yielded HTCR increases from the existing case of 13.8%, 13.4, 13.3% and 12.9%, the varying of the wind tower opening percentage yielded results of -12.2%,4.3%, 8.9% and 13.81%. Therefore, whilst the wind tower area parameter figures on average gave a HTCR increase of 13.35%, the wind tower opening percentages gave an HTCR increase of on 3.7%. Therefore, it is understood that the percentage opening of the wind towers tend to have a more tangible effect on the internal comfort levels. This is an important consideration that has to be taken into account when implementing wind tower opening strategies.

5.9 Assessing the optimal configuration

The best performing cases from each scenario were identified to be those with the following values.

- Floor to Ceiling Height – 6m
- Height of Wind tower – 9m
- Wind tower orientation – North East
- Area of window – 3 m^2
- Area of wind tower opening – 2 m^2
- Percentage of window opening – 100%
- Percentage of wind tower opening 100%

Therefore, the simulation was redone with the above as the parameter values. The results that were obtained were the following, DDH: 25609.31 C^o hr and HTCR: 3461 Hours.

Since the results obtained for the influence of the window opening percentages were similar, the simulation above was performed again for each of the window percentage opening configurations. The results are shown in Table 5.7.

Table 5.7 Results obtained for various window percentages.

Window Opening Percentage (%)	DDH (C^o hr)	HTCR (hours)	Reduction in DDH (%)	Increase in comfort Hours (%)
0	29077	3279	40.3	15.5
25	26903	3429	44.7	20.8
50	26147	3370	46.3	18.7
100	29413	3268	39.6	15.2

Thus, of the configurations that were tested, Table 5.5 testifies that the best configuration for the ideal case is when the window is open 100%. However, what is also evident is that the differences in results are still not very significant from each other.

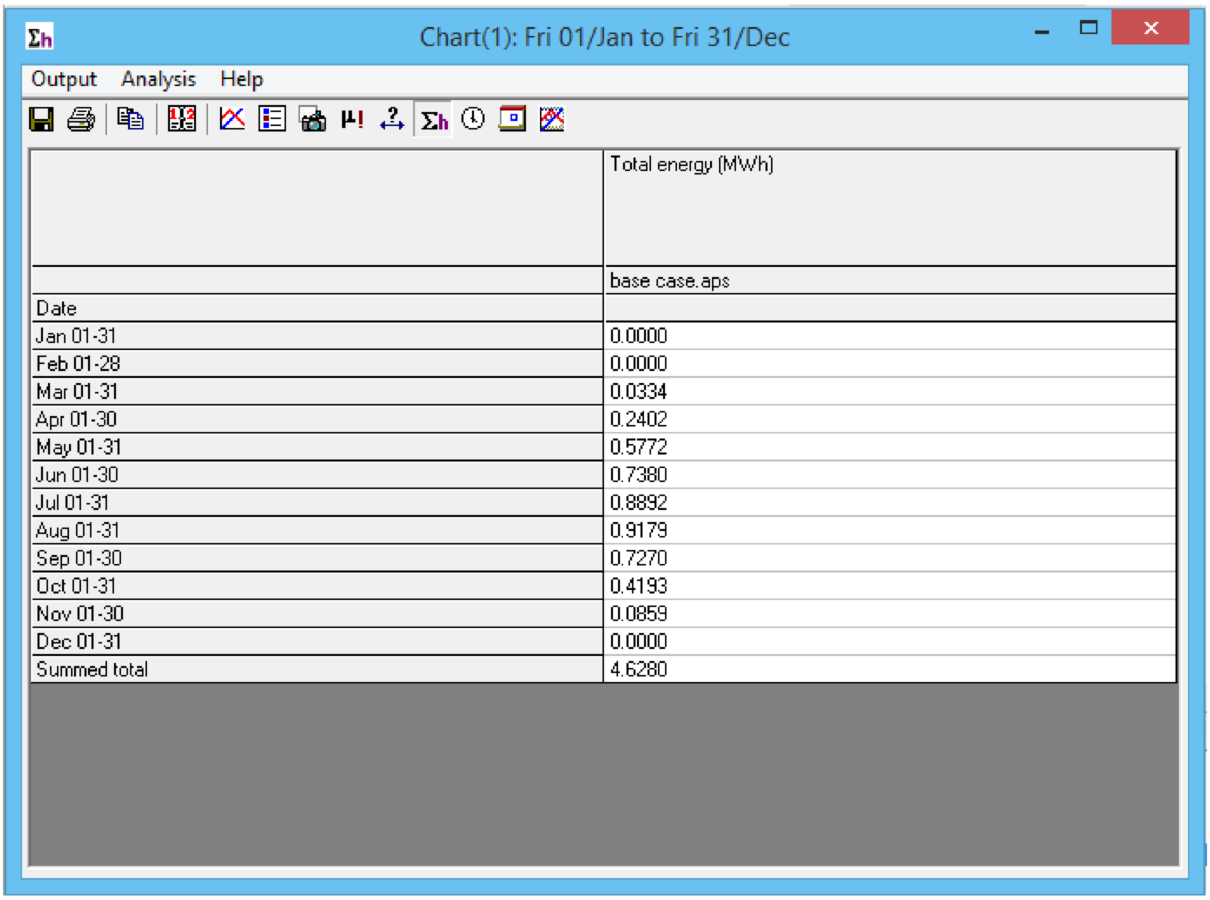
Therefore, the optimum case shows a 47.4% reduction in the DDH and a 22.1% increase in HTCR. Considering that the existing case has only 2838 hours in the TCR, with 3461 hours, the ideal case would have the occupants of the space in thermal comfort without mechanical ventilation for an extra 623 hours.

The best performing case was case 14 (FCH =3m, Height of wind tower = 5m, Orientation of wind tower = NW, Area of window = $3m^2$, area of wind tower opening 2m2, Percentage of window opening = 25% and percentage of windcatcher opening = 100%) with a DDH reduction of 42.9% and an HTCR increase of 16% from the existing case. Therefore, this ideal configuration outperforms the best case scenario by a considerable amount.

This is however the ideal case and there are issues in implementing this in real practice. For instance, In order to have a floor to ceiling height of 6m and a wind tower height of 9m, a huge amount of material costs will accrue due to the material usage and the structural ramifications that would have increased sub structure costs.

5.10 Comparison between existing case and optimum case in terms of energy consumption and CO_2 emissions.

When the air conditioning was switched on in the existing case whenever the internal air temperature exceeded 26°C, the entire energy spent was 4.628 MWh as is shown in Fig 5.16. Further, this energy consumption resulted in CO_2 emissions of 2393 $kgCO_2$.



	Total energy (MWh)
	base case.aps
Date	
Jan 01-31	0.0000
Feb 01-28	0.0000
Mar 01-31	0.0334
Apr 01-30	0.2402
May 01-31	0.5772
Jun 01-30	0.7380
Jul 01-31	0.8892
Aug 01-31	0.9179
Sep 01-30	0.7270
Oct 01-31	0.4193
Nov 01-30	0.0859
Dec 01-31	0.0000
Summed total	4.6280

Figure 5.16 Energy consumed for cooling in the existing case (IES)

Vista analysis also tabulated that the annual mean for the energy consumption in the existing case is 528.3 kWh.

As shown in Fig 5.17, the optimum case was found to have 5299 hours of the entire year when the internal room temperature is above 26°C.

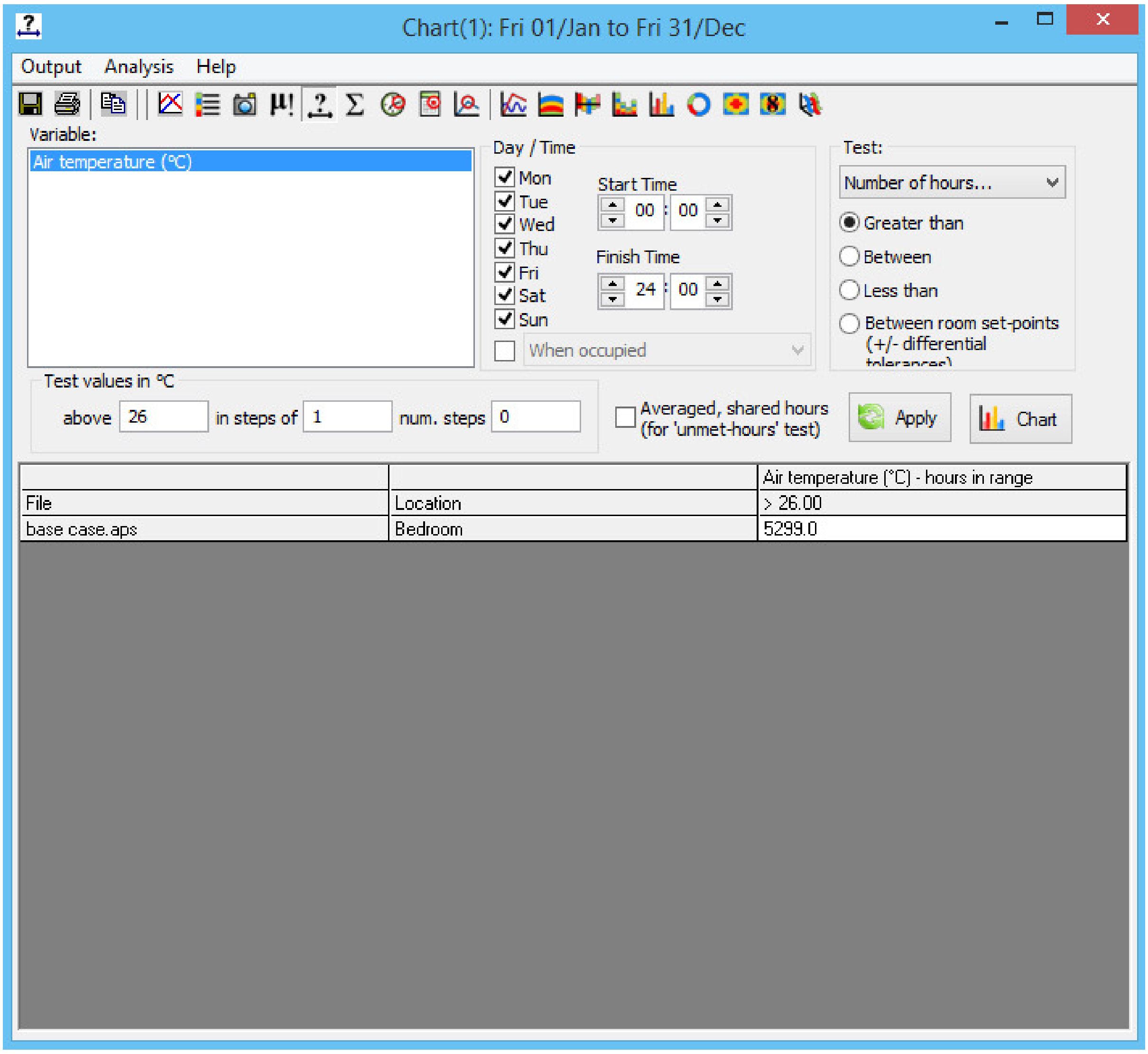


Figure 5.17 Hours the optimum case internal temperature is greater than 26°C (IES)

Therefore, on the basis that energy consumption for an hour is 528.3 kWh kW, the total annual energy consumption to keep the internal temperature in the optimum case to be less than 26°C will be 2799.46 kW compared to 4628kW of the existing case. Therefore, the optimum case is *estimated* to consume 1828.49 kW less than the existing case, which is an energy saving of 39.5%. This also means that there is an estimated 39.5% decrease in CO_2 emissions in energy consumptions in the optimum case.

Section 6: Conclusions & Recommendations

6.0 Conclusions & Recommendations

6.1 Conclusion

The purpose of this research was to investigate the feasibility of integrating traditional sustainable architectural techniques in modern buildings, with specific focus on wind catchers. The literature reviewed established the extent to which traditional architectural techniques are sustainable. Architectural techniques of South Korea, India, the Middle East and the UAE were analysed. The reason for selecting these countries as outlined in the literature review was that although they have different weather pattern to each other, they exhibited similar climatic trends in at least one of the annual seasons. They also used unique sustainability strategies to address the various challenges that were posed by climatic manifestations. Special emphasis was given to strategies used in the Middle East and the UAE in particular.

Wind catchers were used in the past to create a cooler and thermally comfortable interior in buildings, particularly residential buildings. As was discussed, due to rapid rates of construction and importing of design strategies mostly from the West, traditional techniques gradually reduced in use and are now used mostly for ornamental purposes. With the UAE cities becoming increasingly dense in population, and the increasing costs of energy and the looming prospect of oil running out possibly in decades to come, many observers have warned of the need to reintegrate traditional techniques in modern buildings to reduce dependences on fossil fuels and to reduce energy costs. The intention of this research therefore was to assess the feasibility of integrating traditional architectural techniques in existing buildings.

For this reason, an existing design of a residence that is not more than five years was selected. Having analysed the amount of hours a room in the house lay within the ASHRAE specified thermal comfort range and the annual degree discomfort hours were determined, the same house was redesigned with a wind catcher attached to it to assess the hours in the thermal comfort range and the degree discomfort hours. A test matrix was formulated that outlines several combinations involving parameters that included floor to ceiling height, height of the wind tower, orientation of the wind tower, area of the window, area of the wind tower opening, percentage opening of the window and the percentage opening of the wind tower opening. Although combining results of all the combinations resulted in the formulation of 22 different combinations and therefore 22 different simulations using IES VE 2013, at least another ten more simulations were conducted to increase the specificity of certain results. The results were tabulated primarily as increase in HTCR and decrease in DDH. The HTCR was considered to be the number of hours when the internal space was within the temperature range of 18°-26° C. The DDH was considered to be the sum of the hours that were found to be outside the CTR multiplied by the difference between the indoor temperature and the upper (if too hot) or lower (if too cold) limit of the comfort range.

The results obtained showed that the optimum case which had Floor to Ceiling Height of 6m, wind tower height of 9m with North West orientation, window area of 3 m^2, wind tower opening of 2 m^2, Percentage window opening of 100% and a percentage of wind tower opening 100% showed a DDH reduction of 47.4% and a 22.1% increase in the HTCR. However, the optimum case is a selection of the best possible parameters and there are practical complications in enacting this combination of parameters in real life. Even though elements of sustainability may be achieved by increasing the hours in the TCR and reducing the DDH, structural ramifications may result in unsustainable building practices that can be harmful to the environment. However, the best performing combination which isn't the optimised case showed a 42.9% reduction in the DDH and a 16% increase in the HTCR compared the existing case. Compared to the existing case, it is estimated that the optimum case records an energy saving of 39.5% for energy consumed for cooling. Since enacting these parameters in a real building is practically feasible, the environmental benefits yielded by this configuration due to lesser amounts of fuel spent on cooling will not be lost to unsustainable construction costs, both financial and environmental.

The results also confirmed that it doesn't necessarily mean that having a larger opening in the wind tower will ensure the most comfort. Rather, all parameters need to be carefully studied in order to design a well reconciled wind catcher model.

What this study confirms categorically however is that wind towers have a place in modern society and there is a very solid argument for modern designers to rethink their designs to suit traditional sustainable design techniques. Degree Discomfort Hours is a hitherto untested phenomenon and ascertaining these figures helps greatly in reducing power consumed to mechanically make spaces comfortable. Modern existing residences can be renovated to incorporate wind towers and new build residences can have wind towers incorporated in them in order to reduce dependence on mechanical means of ventilation to provide comfort to their occupants.

6.2 Recommendations for future study

- The cooling profile imposed on the windows (Section 4.3) takes into consideration external relative humidity, internal temperature & external temperature. Including this profile was key to the successful results that were obtained. Studies can be carried out how such a profile can be physically incorporated into windows after construction. This may involved the fixing of an electronic sensor on windows that would determine automatically when windows can be opened or closed depending on the profile they have been programmed to
- The current strategy for the window opening profile did not take into account wind velocities, impact of rain, dust levels in the internal or external air. Studies can be carried out to understand the impact these parameters will have for residences in the UAE in terms of thermal comfort. Results will determine the amount of hours that the windows will be operable per year.
- This study was carried out with figures attributed to the parameters, like area of the wind tower opening, area of the window or height of the wind tower. This research can be modified to include ratios. For instance, parameters can be in the form of a

ratio such as *height of the wind tower : area of the room or size of the wind tower opening : height of the wind tower*, these ratios will help determine the amount of wind towers of a certain size that need to be incorporated in a space of a certain area. Therefore, formulae can be created that can determine the number of wind towers that need to inserted to achieve a certain percentage of thermal comfort.

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Appendix A

This section has the test matrix and a summary of all results tabulated as shown in Appendix.

Appendix B

A sample cross section (case number 5) of a Microsoft Excel Sheet has been attached to identify how DDH was calculated.

A legend identifying what each colour signifies is shown at the last row of the first table.