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THE IMPACT OF USING THE WIND CATCHER AS A SUSTAINABLE PASSIVE COOLING TECHNIQUE IN TRADITIONAL HOUSE (SUDAN-KHARTOUM)

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
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ETHICAL STATEMENT

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- All data, information and documents presented in this thesis have been obtained within the scope of academic rules and ethical conduct,
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Abdallah Ahmed ABDALLAH ALI

31/05/2021

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(Ph.D. Thesis)

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ABSTRACT

The People of Sudan are faced with a growing problem with indoor climate conditions in the houses because of high outdoor temperature in the house during dry seasons. Daily temperature can reach up to 47 degrees in the dry season of summer. The Wind catcher is a ventilation technique for natural cooling. Wind catchers have been used for years in several countries with hot-dry climates in the Middle East. Even so, it is never been used in Sudan. This research takes into consideration the socio-cultural dimension problems, local climatic conditions, and context, to improve the cooling system in conventional buildings and reduce energy consumption in Khartoum. This study will create a modern conventional sustainable building design that utilizes a wind catcher as a passive cooling technique. This research aimed to examine the effect of the different criteria that effecting on the designs of the wind catchers and determines how they affect the internal air temperature in Sudan-Khartoum. Traditional methods are believed to offer the potential for developing appropriate passive ventilation or cooling solutions for contemporary Sudanese homes. Four-stage research has been proposed to achieve the above-mentioned goals. This research attempted to: (a) analyze the efficiency of dwelling layout in terms of design configurations and mass, house structure design, and building materials used, (b) identify those factors causing high power consumption in typical Sudanese homes, and then (c) establish passive cooling techniques that can be used and introduced to Sudan's hot dry areas. Every stage of this study implements specific research methods: site visits, local survey analysis, and simulation evaluation, and utilizes a simulation program (DesignBuilder) program to evaluate various designs of the wind catcher, and then obtain the best design for building in Khartoum's hot areas. The addition of water spray increases the relative humidity and decreases the air temperature inside the houses. This old traditional technique could be merging with new building designs in Khartoum-Sudan to raise the green concept in the buildings located in the hot dry areas.

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Key Words : Wind catcher, Natural ventilation, Water spray, Khartoum City
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RÜZGAR BACASINI GELENEKSEL EVDE SÜRDÜRÜLEBİLİR PASİF SOĞUTMA TEKNİĞİİ OLARAK KULLANMANIN ETKİSİ (SUDAN-KHARTUM)

(Doktora Tezi)

Abdallah Ahmed ABDALLAH ALI

GAZİ ÜNİVERSİTESİ
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Mayıs 2021

ÖZET

Yazın kurak mevsiminde günlük sıcaklığın 47 ^{o}C dereceye kadar ulaştığı Sudan'da konutlardaki iç mekan konfor koşulları insanların yaşam koşullarını zorlamaktadır. Bu amaçla doğal soğutma için bir havalandırma tekniği olan rüzgar bacası uygulaması, Orta Doğu'da sıcak-kuru iklime sahip birçok ülkede kullanılmaktadır. Sudan'da bugüne kadar hiç kullanılmayan bu teknik, bu araştırmanın konusu olarak ele alınmıştır. Araştırmada, Hartum'da geleneksel binalarda soğutma sistemini iyileştirmek ve enerji tüketimini azaltmak hedeflenirken, sosyo-kültürel boyut sorunları, yerel iklim koşulları ve bağlamı dikkate alınmıştır. Çalışmada, rüzgar bacasını pasif bir soğutma tekniği olarak kullanan modern, sürdürülebilir bir bina örnek olarak tasarlanmıştır. Bu tasarım sırasında rüzgar bacalarının tasarımındaki farklı uygulamalar ele alınarak, Sudan-hartum'daki konutlarda iç hava sıcaklığını nasıl etkilediğinin belirlenmesi amaçlanmıştır. Geleneksel yöntemlerin, çağdaş Sudan evleri için uygun pasif havalandırma veya soğutma çözümleri geliştirme potansiyeli sunabilmesi için yorumlanabileceği düşüncesi ile yukarıda belirtilen hedeflere ulaşmak için dört aşamalı bir araştırma önerilmiştir. Bunlar; (a) konut düzeninin verimliliğini tasarım konfigürasyonları ve kütle, konut tasarımı ve kullanılan yapı malzemeleri açısından analiz edilmesi, (b) geleneksel Sudan evlerinde ısıl konfor şartlarının sağlanamamasının nedenlerinin incelenmesi ve Sudan'ın sıcak ve kuru bölgelerinde uygulanabilecek pasif soğutma tekniklerinin incelenmesi. (c) rüzgar bacasının tasarımındaki farklı etkilerin ayrı ayrı simüle edilerek sonuçlarının elde edilmesi, (d) elde edilen sonuçların değerlendirilmesi ve yorumlanması. Çalışmada rüzgar bacasının çeşitli tasarımlarını değerlendirmek ve ardından en uygun tasarımı elde etmek için simülasyon programı (DesignBuilder) kullanılmıştır. Hartum'daki konutlar için bulunan en uygun sonuca ulaştıktan sonra bu uygulamaya su spreyi ilavesi ile bir hibrid çözüm önerisi de getirilmiştir.

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Anahtar Kelimeler	:	Rüzgar bacası , Doğal havalandırma, Su spreyi, Hartoum Şehri
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TABLE OF CONTENTS

Page

Page

Page

Page

Page

Page

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

Figure **Page**

Figure **Page**

Figure **Page**

Figure **Page**

Figure **Page**

Figure **Page**

Figure **Page**

SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below along with explanations.

Symbols	**Explanations**
Cm	centimeter
m	meter
mm	millimeter

Abbreviations	**Explanations**
AC/h	Air Changing /hour
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air
BS	Building Simulation number
BS0	Building Simulation without wind catcher
CFD	Computational Fluid Dynamics
	Conditioning -Engineers
DW	Dimensions of Wind catcher
FD	Form Dimension
H	Height of the wind catcher
NV	Number of Vent
OD	Opening Direction
P	Partition type
RD	Room Dimension
SBS1	Selective Building Simulation design 1
SBS2	Selective Building Simulation design 2
WD	Windows Design
WL	Windows Location

1. INTRODUCTION

Architectural problems in hot dry regions

In recent years, the hot-dry areas of the Middle East have been subjected to costly and uncomforTable architecture. That architecture is mostly focused on Modern Movement principles. This modern architecture, often recognized as global or international architecture, depends solely on mechanical devices, and disregards the environment of the area. Wide windows have become common in the external walls of buildings, as well as the thickness of the whole walls is significantly minimized. Such negligence consumes a lot of energy. According to Fathy notes, 9 square meters of glass in a structure allows gain about 2.5 KW of power when subjected to solar radiation on a hot transparent tropical afternoon. A total of about 3.5 KW of cooling energy is needed to sustain a sTable level indoors(H. Fathy, 1986). During the winter, natural gas and other oil-based materials are literally burned to warm homes. However, during the summer, electricity is the only source of energy required to cool the houses. In most oil-producing nations, all oil products and energy are heavily subsidized for varied purposes, mostly as result; individuals are unaware of the true importance of these resources. As an effect, the dwellings constructed in these towns or cities are completely reliant on electrical cooling and heating systems, and when the electrical power is shut off for any reason, then residents of the cities must suffer severely from overheating.

Oil, which is the primary energy source, is mainly used in the industry and transportation, but a large amount of this energy was used for air - conditioning in the construction sector in recent years. That excessive usage of this precious material has produced several environmental issues, the much more serious of which is that oil reserves are obviously low, and therefore this operation cannot be sustained much more. Although the electricity used for heating is not particularly important in hot dry areas, the main issue is a high demand for refrigeration and air conditioning. Passive devices will, in the end, become a necessary option for future generations. After all, global warming and the use of alternative energy technologies will change many of these issues. Fortunately, generations of practice are available when one recognizes the ideals of conventional design in the old quarters of settlements in hot dry areas that we can use to overcome those problems and provide us with thermal comfort inside our buildings and homes.

Architectural design in hot dry climate areas is more able to adapt and extremely suiTable to the surrounding area, in comparison to the current condition in new construction in terms of resource conservation and compatibility with the local environment. So many researches and studies have also been conducted on traditional buildings and their relationship to energy conservation to present.

As a result of these studies undertaken in different time periods and different countries, local architectural methods are considered sustainable and energy efficient , even though some of them are just no longer suiTable to be used due to changes in living conditions in terms of the ecological, social, aspects, economic, and cultural. Throughout view of both the urban style and the building structure, it is widely assumed that conventional architecture is better suited to local climate, topographical features, and available services.

Several seminal books in the field of traditional buildings, such as those by Hassan Fathy, Amos Rapoport, Paul Oliver, Edward Brian, and Victor Olgyay, have been used as references for this research, with regard to the relationship among traditional buildings and their reaction to local environment needs, each of these resources present traditional design as a clever architectural approach for humans to stay comfortably in their climate. Unfortunately, numerous new houses today have no link to their background, local environment, even consumer comfort needs. The main challenge in this aspect is to understand the basic architectural design techniques and values of traditional buildings.

This thesis used climatic responsive strategies in local traditional architecture design as a reference point to understand how environmental conditions affect design and architecture, and how dwellings could be more adaptive. One of the key goals of this research is to study passive cooling design methods in order to recognize their true value and contribute meaningfully to new residential design in Khartoum city. This research doesn't really aim to examine all passive cooling techniques; however, it focuses on the main type of internationally recognized passive cooling (natural ventilation by using wind catcher technique) that could be used to increase thermal comfort in dwellings and it was specifically described in the research study.

Problem of the research

People of Sudan who live in hot dry areas are having a tough time adjusting to the surrounding atmosphere. This problem has several reasons, some of which may be due to harsh weather conditions and the other to the country's poor economic conditions. One big issue that almost any person should be aware of; is the impact of increased energy use on the atmosphere, since most countries in the area focus completely on fossil fuels for energy production, which would raise air pollution and ozone-depleting gas emissions (greenhouse effect). Currently, conventional construction methods are still used in the cities, but they overlook the passive cooling and ventilation strategies imported from their forefathers, forcing residents to rely on active cooling and mechanical systems, which push their monthly bills to levels which most people cannot afford. Yet another problem would be the shortage of electricity supplies, which would bring more stress on the people of Sudan.

As a result of the wars that have prevailed in various parts of Sudan since independence until now, economic development has arisen only in the northern part of the country, along with modernization, population growth due to internal displacement from many other regions of Sudan, and housing requests, that have resulted in significant mass residential construction buildings, especially in Khartoum. This rapid urbanization resulted in new housing developments being built without regard for passive cooling building techniques or thermal comfort requirements that were found in conventional buildings. Due to low quality construction specifications, new residential buildings are generally built unsatisfactorily and in poor methods. A substantial majority of these houses are constructed with thin exterior walls, insufficient insulation, without shading, and large glazed windows that do not provide for natural ventilation and cause heat gain in these buildings. As a result, individuals are using a massive amount of energy used by mechanical ventilation systems for cooling in order to ensure indoor comfort pleasure. All of this, coupled with a lack of sustainable building laws and codes in Khartoum, is leading to a rise in energy load demands during the hot season. Excessive use of non - renewable energy sources would also expand environmental risks. Nonetheless, no meaningful steps have been taken to address these issues in Khartoum. Therefore, this study is established to be a cornerstone or step forward towards fixing this issue and suggesting an architecture approach for many other issues like;

- The growing need for foreign building materials has resulted in a wide variety of house designs, so, connection between conventional architecture elements and modern were broken, and the traditional design identity became lost.
- Housing architecture planning and design today does not fulfill the area's environmental and social needs and does not adapt well to the climate conditions, leading to the use of additional resources.
- The large variety of the planning and construction of housing buildings in Khartoum does not produce sufficient formal standards for housing.

Even so, there are noticeable distinctions with the traditional buildings when looking at the architectural properties of new residential constructions, which can be seen to be an important indicator of how the urban environment is planned.

Research hypothesis and questions

The wind catchers as a passive cooling technique are widely used throughout the world, including the Middle East in a variety of climatic conditions; however, there is no historical evidence of wind catchers being used in Sudanese buildings.

Sudanese people use a lot of mechanical ventilation devices to provide cool air to their buildings, which causes a lot of electricity usage and high costs of bills. The usage of a wind catcher as a passive cooling technique in traditional Sudanese buildings in general, and Khartoum houses in particular, could provide more thermal comfort and increased ventilation for individuals who live there. To identify and utilize this type of traditional passive cooling ventilation system and to be applied in Khartoum houses, the most effective and efficient elements or criteria that affect the design of the wind catcher and will provide dwellers with more cool air during the hot hours of the summer It must be tested and then determined before being utilized in Sudanese houses which are located in the hot dry area.

The criteria that could be affected by the design of the wind catcher are;

1. The dimension of the wind catcher,
2. The height of the wind catcher,

3. The opening direction in the wind catcher,
4. The Number of the vent in the wind catcher,
5. The partition in the wind catcher,
6. The dimensions of the room in the target area,
7. The Living room Windows Location,
8. The Living room Windows Design.

The essential focus of this research is to find answers to the following questions;

1. What are the basic concepts of hot dry climate designs and how we can provide thermal comfort in Khartoum houses?
2. What do we benefit from traditional buildings in order to suggest a passive cooling strategy application?
3. What were the climatically responsive architecture methods that provided conventional people with thermal comfort without the need for power generation or advanced technology?
4. How Sudan and Khartoum’s traditional and contemporary design is being shaped?
5. How we can use a wind catcher as a passive cooling technique in Sudanese residential buildings to provide them with a natural ventilation system?
6. What are the parameters that could enhance the performance of the wind catcher in Khartoum?

Research aim

Wind catchers may still be rooted in the early neighborhoods of countries such as Iran, Iraq, and Egypt, and now have proven to be valuable study resources. This type of wind catcher may be utilized in current architecture in Sudan as a base for sustainable development in the shape of traditional buildings, giving more comforTable ventilation to Sudanese residents without the utilization of mechanical ventilation systems. This needs good comprehension of the concepts that guide their functioning. As a consequence, the goal of this research is to establish and publish a systematic approach to the construction and design of conventional wind catchers that is relevant to the building of Sudan. The primary goal of this research is to evaluate the benefits of using the concept of wind catchers in the traditional architecture of Khartoum by determining and evaluating which element or criteria of the wind catcher could be more effective in the wind catcher's performance.

The thesis research is proposing a wind catcher application in a current low-rise single-family residential building in Khartoum. Furthermore, rather than analyzing a few models and generalizing the findings, this analysis prefers to use a wide range of wind catchers in order to categorize the typical features of their success. This research follows the technique of properly modeling the physical environment as well as the wind catchers themselves to obtain a good understanding of their results. The approach is focused on the following criteria in order to enhance their cooling efficiency;

- The volume of air flow, as well as the direction of it, needs to be more reliable.
- The materials must be flexible enough to allow architects to modify them to meet a specific need.
- Standard wind catchers' physical and visual features can be simplified, but, the overall structure must not be overlooked.
- The end result should also be physically appealing and adapTable to the urban environment in which they are used.
- The final outcome must be possible in terms of locally produced materials but does not rely heavily on mechanical equipment.

The updated version is supposed to be more suiTable for hot dry region's middle and low - income class structure. No life without air conditioning, but also no living in a fully artificially maintained climate is possible. As a result, the most rational and preferable option will be a naturally balanced environment design.

Furthermore, this research emphasizes the importance of systematically integrating passive cooling methods, as well as the principles of local architectural building design, into contemporary housing design. Besides that, it suggests taking advantage of the most recent applications of passive cooling design techniques and traditional buildings by developing strategies that are in coordination with the new lifestyle. So, the author claims that such research opens up the door to lowering the huge volumes of cooling energy required to provide comfort conditions.

The secondary objectives to achieve this task are;

1. To research the literature on residential thermal comfort in general, as well as in hot dry climates.
2. To investigate the design characteristics of traditional buildings in a hot dry climate in order to understand essential concepts and identify the optimal way of reducing energy usage, specifically cooling energy during the hot season.
3. Modeling would be used to create alternative energy-efficient models based on natural ventilation and evaluate their efficiency.

Research methodology

Studies of wind catchers can involve different research orientations which may fall roughly into the categorization of culturally-oriented, town planning-oriented, sociologically oriented, and ultimately purely technically-oriented research. Such research based on their purposes constitutes a continuum stretching between cultural and aesthetics, and purely functional concerns. As a consequence, although the research's primary focus is on technical aspects, other factors will not be ignored because there is no specific difference at all between them. This research has four stages;

1. Stages one; studying the literature,
2. Stages two; performing a field study,
3. Stages three; performing an analytical simulation,
4. Stages four; analyzing the findings (fig.1.1).

Stage one; reviewing the literature

The following considerations have been discussed to explain the impact of the criteria related to environment and climate conditions;

1. Both the climate of hot dry areas overall and also the weather of Khartoum in particular, have been studied.
2. The concepts of residential and architecture design for hot dry areas were examined. The research focused on the effect of the hot environment on the spatial arrangement, structure's shape, materials, and orientation.
3. Thermal comfort and natural ventilation have been studied.

4. The usage of passive cooling techniques in a hot dry climate has been reviewed.
5. The architectural sense of conventional wind catchers has been studied. Investigating the history of the wind catchers in modern architecture and the Middle East will give us a wide understanding of the theme. After obtaining such a viewpoint, the efficiency of wind catchers was evaluated, as well as field experiments from different authors.
6. The efficiency of a wind catcher in different climates is compared to a wind catcher in a hot dry climate in order to better understand why a wind catcher is used.

Stage two; field study

The next step of our research approach focuses on a qualitative field analysis in Khartoum after reviewing recent literature on the subject. This field study looks at the use of climate-responsive techniques in residential design in Khartoum's historic center. In order to do these, we had to study the diversity in the traditional Sudanese architecture in general in both villages and small towns and to get acquainted with the characteristics of the architecture design, and the building construction methods that have been used by them. In terms of housing features, this study examined the residential households to describe and establish climate-responsive architecture strategies such as; construction techniques, house plans, building materials, courtyard, natural ventilation methods, and the use of rooms.

Stage three; performing an analytical simulation

In this research, by using DesignBuilder program, 47 simulations have been performed. In each simulation, the effect of the different criteria affecting the designs of the wind catchers have been tested, and determine how they affect the internal air temperature of the living room, taking into consideration that area is the most commonly used during the day.

The criteria that affect the design of the wind catcher are:

1. The dimension of the wind catcher,
2. The height of the wind catcher,
3. The opening direction in the wind catcher,
4. The Number of the vent in the wind catcher,
5. The partition in the wind catcher,

6. The dimensions of the room in the target area,
7. The Living room Windows Location,
8. The Living room Windows Design.

To identify the criteria that may reduce the air temperature inside the living room in Khartoum climate, three variables were been tested for each one of the eight criteria that affecting on the design of the wind catcher, this has been performed by fixing the seven criteria and testing three variables in the eighth criteria. Changing between the criteria each time can determine which of these eight criteria is the most influential when designing a wind catcher and leads to reduce the air temperature inside the living room. Three different times during the day were selected to take temperature readings,

- 4 am: where external temperatures are lowest,
- 2 pm: where external temperatures are highest,
- 10 pm: where outside temperatures start decreasing significantly.

The best values and results from these three criteria were selected and combined in a new design and simulated again. In the last simulation, the Water spray is added for testing the effect of evaporation cooling on the windcatcher.

Stage four; obtaining the results

Each stage of the analysis has its own consequence, but the final stage is the most important. The results from the previous stages were combined and presented, in the main conclusion, a set of recommendations for further studies were made.

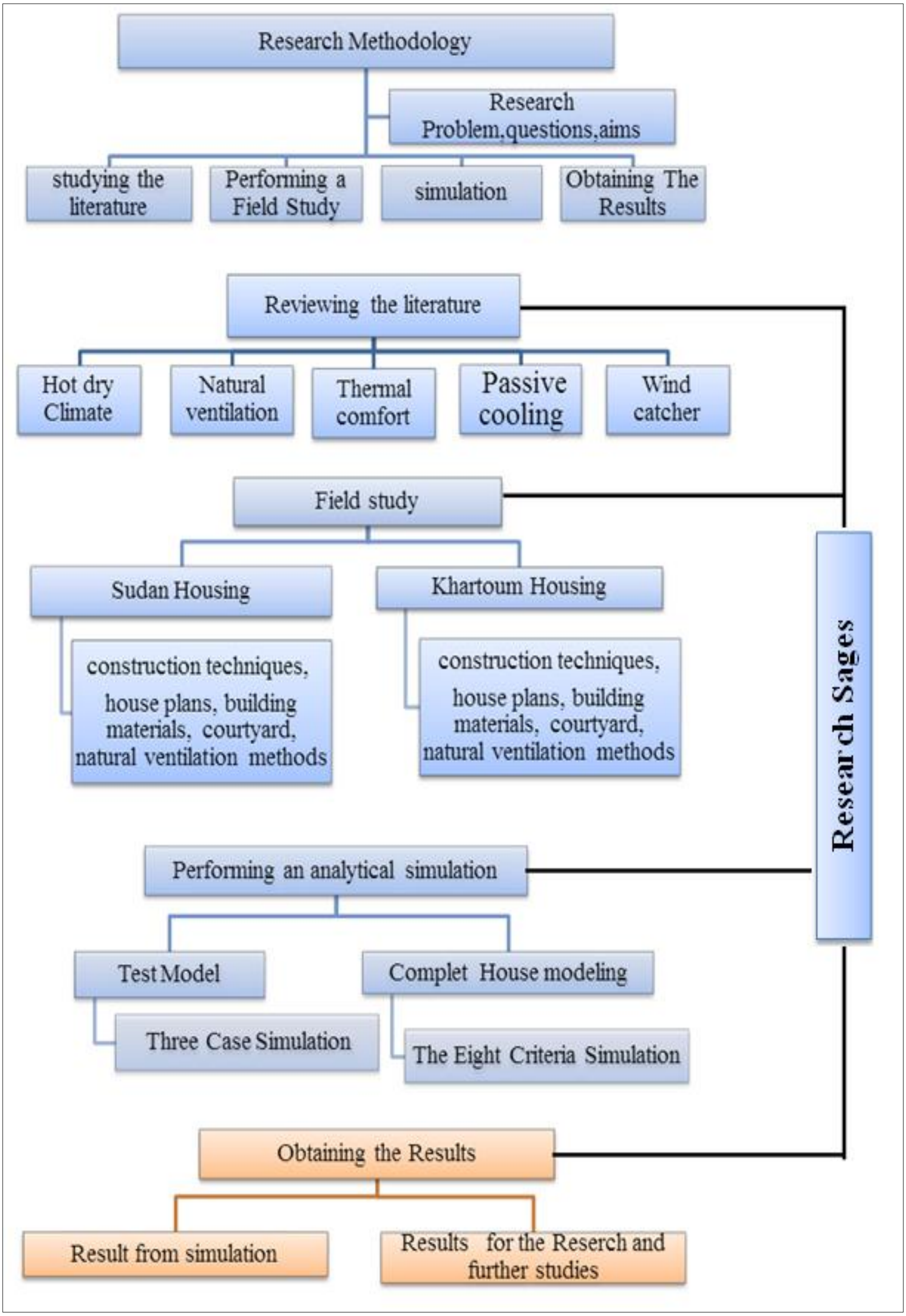


Figure 1.1. Research methodology

2. BASIC CONCEPTS OF CLIMATE AND THERMAL COMFORT

The climate has played a significant and prominent role in human evolution and growth, as it has a profound influence on his life, appearance, and the design of his dwelling architecture. Since ancient times, man has understood the vital value of climate in his life and has attempted to adapt to it using different means at his hand, so he tried with various means available to him to adapt to this factor and that by adapting according to the conditions provided by the surrounding environment. Man has been interested in preparing a place that provides him with both protection and thermal comfort from the influence of climate change around him, as it is noted throughout the long history of urbanization that climate was a decisive and dominant factor in determining the shape and pattern of urban tissues and buildings throughout the world due to the diversity and variation of climatic conditions for each region. In recognition of the significant impact of climate on architecture and construction in its many types, it is crucial to recognize the climatic factors influencing design and their relationship to human thermal comfort. As a result, we will concentrate on the concept of climate and its most important elements in this chapter. We'll also address the world's climatic divisions and the most significant factors impacting them. We'll also look at the idea of thermal comfort for people inside buildings and the different factors that influence it.

2.1. Climate Definition

Climate is defined as the average state of the atmosphere over a given time scale (hour, day, month, season, year, decade, etc.) and for a given region. The set of conditions reported for several cases of the defined periods delivers the average-state statistics for a given time scale, which contain all deviations from the mean (Houghton et al., 2002).

It’s also defined as "the total of metrological or meteorological phenomena that characterize the middle state of the atmosphere at some point on the earth's surface."(Hartmann, 2015). Thomas Blair in his book (Climatology: general and regional.), claims that climate refers to "all the changes that occur in the elements of weather from day to day"(Blair, 1942).

Another researcher defined the word climate as: "regions with certain temperatures, humidity, wind speeds and drought(Camuffo et al., 2020).

As Givoni explained, "Climate is the product of an accumulation of weather phenomena in a region over many years."(Baruch Givoni, 1992).

Here it is necessary to distinguish between climate and weather, as the climate is the integration of weather elements and conditions in a region over the years. Hence, it seems that both climate and weather have many common elements, "but they are at the same time different, as the latter represents the accumulation of weather changes over a short period. Therefore, we are talking about the weather today or this week, that is, in a specific period," While climate represents a system that collects all weather phenomena and represents the accumulation of daily weather conditions over a long period, including the climate of a site or region, (Houghton et al., 2002).

2.2. Climate Elements

Climate conditions in a region are determined by the multiple elements of climate, and when linking climate to architecture, construction and thermal comfort for humans, the basic elements that must be taken into account are solar radiation, air temperature, relative humidity, wind speed, and direction and rain, and the effect of each of these factors varies. From one region to another, solar radiation, for example, is the most important factor in some areas and has the greatest impact on its climate, while rain and humidity are the basic factors that must be taken into account in the design in other regions, and more than one of these elements may meet, which increases the design problem with climate thus complicates the designer's task(B. Givoni, 1974).

Solar radiation is perhaps the most significant climatic factor. This is due to the fact that the sun is the primary source of heat on the planet's surface; Treworth and Horn both stated that "The main engine that drives the earth's atmosphere, moves the oceans, and changes weather conditions is solar radiation's energy. Foremost, this makes the world a suiTable living environment for plants, animals, and humans"(Belda et al., 2014)

2.2.1. Air temperature

The location of a region on the earth determines its temperature values depending on its distance from the sun during the year and the angle of receiving the sun's rays; however, it is seen that the temperature environments of different places in the same latitude are not the same. The reason for this is the intensity of solar radiation that varies from region to region, the effect of atmospheric conditions on solar rays, the earth-atmosphere relationship, and the amount of energy resulting from the physical change of material and the direction and intensity of air movements(Özdemir, 2005).

Average temperature values for the summer period are quite high in hot-dry climates. Concerning global temperature differences between day and night increase up to around 15ºC-20ºC. Temperatures that reach extreme values at noon in the summer months rapidly decrease after the sun goes down. The same effect can be seen during the winter months, which are not very cold during the day(Meir, 2002).

2.2.2. Solar radiation

The sun is the most important sustainable energy source for the world. The sun's rays reaching the earth through the atmosphere have the ability to heat the surfaces. To benefit from the passive heating feature of solar radiation in building design, it should be used at the maximum level in the period when heating is needed and at the minimum level in the period when heating is not needed(Iqbal, 2012).

Building surfaces are affected by solar radiation in three ways: direct, diffuse and reflected radiation. The heating effect created by radiation on the surface depends on the radiation angle (azimuth angle, elevation angle, and zenith angle), atmospheric conditions, direction, and altitude from the sea (Figure 2.4). In addition, texture in the settlement scale has an effect on solar radiation gain. From time to time, depending on the position of the sun, physical barriers around the building (neighboring buildings, plants, etc.) may block the sun's rays. For this reason, while designing, the data of the surrounding tissue should be carefully analyzed according to the desired state of solar radiation(Mallon et al., 2017).

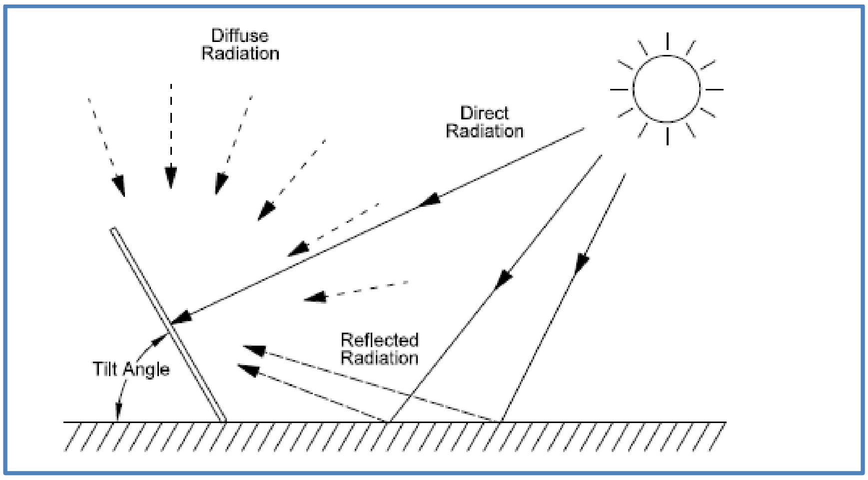


Figure 2.1. Types of solar radiation (Mallon et al., 2017)

2.2.3. Outdoor humidity

Humidity; It can be defined as the amount of water vapor in the air, the absolute humidity and relative humidity are used as criteria when talking about climatic data. The high amount of humidity in the air causes the actual temperature values to feel higher or lower than they are. For this reason, solutions such as lowering the high humidity with ventilation and increasing the low humidity with the use of the water element have been developed in order to ensure comfort conditions in the interior. Also, the external air humidity rate that causes deterioration in building materials due to the condensation effect should be taken into consideration while designing the shell (Nguyen et al., 2016).

2.2.4. The wind

The wind is the air that flows from high pressure to low pressure points due to atmospheric pressure differences. The prevailing wind direction and strength is an important factor in guiding artificial circles. While designing, other climatic factors should be taken into account and the effect of the wind should be taken into account. In hot and humid climates, winds with cooling properties should be used, and in cold and dry regions, winds that will exacerbate these climatic effects should be avoided (Koçlar Oral, 2010). In addition, while designing the settlement tissues, the wind directing situations of the buildings should be evaluated and microclimatic effects should be prevented (Kormaníková et al., 2018).

2.2.5. Precipitation

It's the amount of water that falls (rains) as a result of the creation of a cloud, which is normally caused by evaporation of surface water (part of the water cycle), Precipitation is a key element in determining when water levels in rivers and creeks would rise or fall, as well as the viability of outdoor activities (Konya, 1982).

2.3. Climate Classification

One of the most recent and widely agreed classifications is that of Koppen, fig.(2.1), which uses the climate-vegetation relationship as a criterion. He divided the world into five sections, each with its own letter (A, B, C, D, or E). These are based on temperature considerations, with the exception of B, which is based on the relationship between the mean annual precipitation measured in mm (or inches) and the seasonal annual temperature measured in °C (or °F). The precipitation level isn't taken into account in this classification, and high-land regions aren't considered (Chen et al., 2013). These five sections or zones are; A.Tropical rainy zone, B.Arid climatic zone, C.Warm climate zone, D.Cold climatic zone, E. The polar zone.

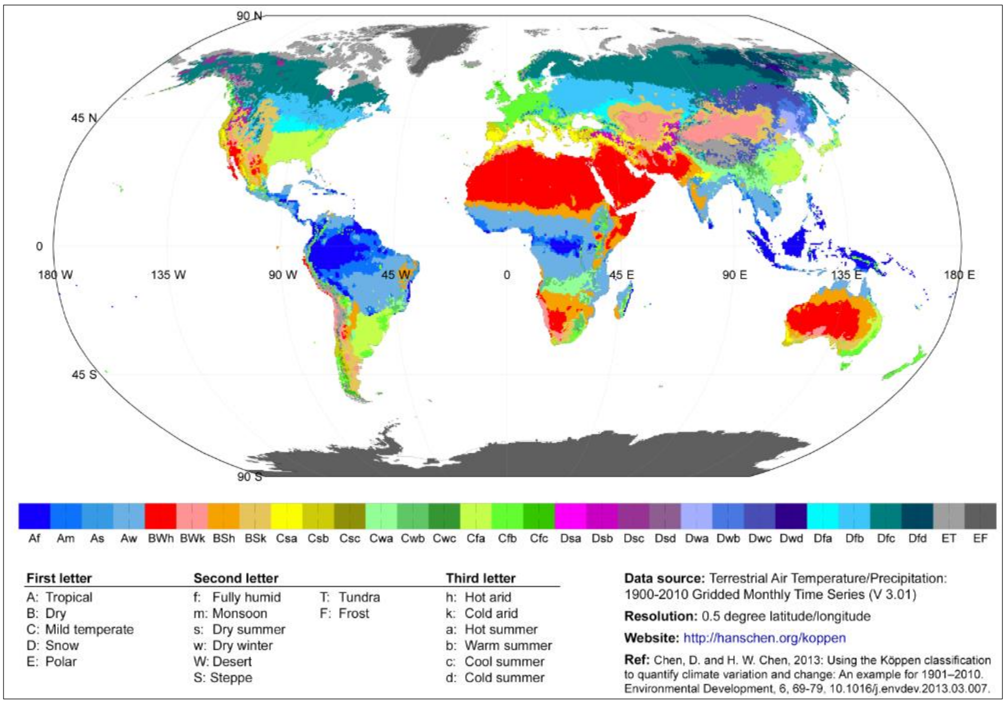


Figure 2.2. Koppen climate classification (Chen et al., 2013)

Despite the importance of this classification, which is used in several references and has undergone many attempts to improve it, this climatic zone classification as a geographical classification should only be used for agricultural and plant purposes and cannot be used to design buildings where human needs and comfort are the primary considerations. Perhaps a classification with this consideration is very important in the design of buildings, which implies the ability to divide the world into climatic zones in which buildings have an almost identical vocabulary with minor variations arising from varying traditions and social practices of various populations. Despite the advancement of research on the subject, there is currently no global classification or division of climatic regions for the purposes of building design. Even so, many climatic divisions have been developed that are design-appropriate. These divisions depend on temperature and relative humidity as a basis for classifying geographical areas and considering them as similar climatic zones. Conceivably the most common of these divisions is that which divides the world into four basic climatic regions and into several climatic regions belonging to them, and this is by specifying a coefficient called drought coefficient or drought index, where many climatic regions were produced as set by Givoni (B. Givoni, 1974).

Hot climatic regions

1. Hot dry areas, hot desert regions.
2. Hot tropical rainy areas and coastal tropics regions.
3. Hot dry and warm humid sub-continental regions.

Warm temperate climatic regions

1. Mediterranean continental regions.
2. Mediterranean Coastal regions.`
3. Mediterranean Mountainous regions.

Cold temperate climatic regions

1. Continental cold temperate regions.
2. Coastal cold temperate regions.

Cold climatic regions

1. Continental cold (Siberia).
2. Coastal cold regions (Norway).
3. Cold desert regions.
4. polar regions.

2.4. Characteristics of Hot and Dry Climates

At latitudes between 15 and 35 degrees north and south, two bands of hot-dry regions can be found. About a third of the world's countries are in hot, dry climates. Arid regions can be found in North Africa, Central Asia, Western North, and South America, and Central and Western Australia.

2.4.1. Drought

Drought is the most important characteristic of desert areas, and it is known as the state in which the amount of precipitation does not allow the growth of plants (Grove, 1977). The climate of hot and semi-arid regions is characterized by the drought caused by the trade winds that blow regularly on the equatorial region from the southwest and northwest towards the equator, and which lose the largest amount of water vapor, and this drought is characteristic of some characteristics that affect Directly on the physiological comfort of the human being, and the architectural design such as water scarcity and lack of green spaces, fig 2.3 (Azlitni, 2005).

2.4.2. Solar radiation

The sky is clear most of the months of the year, especially the hot ones, which makes the sunlight strong, direct, and sharp, as it exceeds 900w / m² over a horizontal area. And generally, the solar radiation that is given to the earth without any objection or barrier causes this surface to heat up to 70 degrees Celsius during the day, while at night there is a rapid loss of temperature by radiating long waves, causing this surface to cool down to 15 degrees Celsius. In addition to direct radiation, we find the reflection, which increases the intensity of radiation, especially since the neighboring areas reflecting the sun are dry and light-colored, and the sky for most of the months of the year is without clouds (B. Givoni, 1974). Several studies have shown that the exterior walls of the building receive different percentages of solar radiation, according to the direction of each one. Horizontal area, such as roofs in hot regions, receives about 20 percent less than the total number of the remaining vertical spaces (Danby, 1982). Furthermore, the great impact of solar radiation on dry areas is due primarily to the reasons mentioned by one of the researchers (Phillips, 2004) as follows;

- The duration of solar radiation is long (the duration of insolation), especially in summer, where it is limited to between 9 and 16 hours.
- High-intensity solar radiation.
- The importance of the reflection angle (solar angle and azimuth).

2.4.3. Air temperature

The air temperature in hot and dry areas ranges between 43 and 23 degrees Celsius during the day and 15 to 25 degrees Celsius at night, a temperature difference of 10 degrees Celsius, which distinguishes the climate in these hot areas during the summer. As a result, the air temperature in these zones covers a wide range of variations, which directly affects the internal thermal conduction conditions (B. Givoni, 1974).

2.4.4. Relative humidity

The relative humidity of the air is proportional to the temperature of the air, and it can drop to less than 20% after sunset and rise to 40% at night. Precipitation is minimal, varying from 50 to 150 mm annually, and it usually originates at high altitudes and evaporates before reaching the earth's surface (B Givoni, 1976).

2.4.5. Winds

Winds play a significant and essential role in changing the shape of the landscape and degrading the soil in hot dry areas. It has been observed that its speed is usually low in the morning, increases in strength in the middle of the day, and peaks after midday. This does not rule out their existence in the form of sand and dust storms and the prevailing winds over all of these areas, which are those coming from the southwest and northwest towards the equator. In the hot, dry regions, it has been noticed that the winds from the south are cold in the winter but are considered drier in the summer (Danby, 1982).

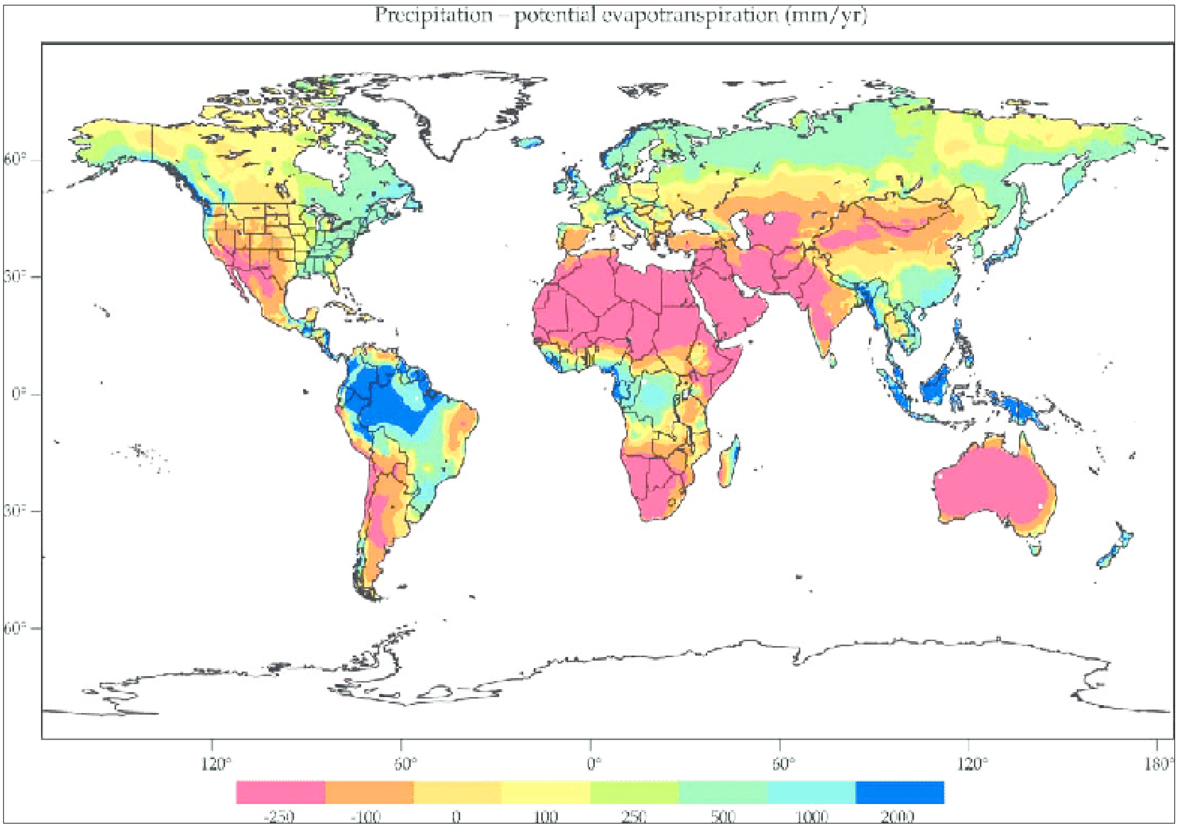


Figure 2.3. Global map of annual precipitation (Givnish, 2002)

2.5. Microclimate Concept

Despite global climatic divisions, the climate of each geographical region varies from that of another region in the same climatic region due to a variety of local factors that have a significant impact on the climatic conditions in this or that region. This creates climatic conditions specific to each of them that differ from those general characteristics that can describe general climatic regions. Therefore, it is imperative to study the climatic conditions of each site to be studied and to identify the conditions and factors that affect this climate. The local climate conditions, which include winds, temperatures, humidity, and solar radiation at one point, whether on a building's roof or on one façade without the other, can be defined as the microclimate (Rosenberg et al., 1983).

The microclimate is affected by several local factors, which are as mentioned by Mazuz (Masmoudi, 2004) as follows;

1. The height of the site and its decrease at sea level.
2. The degree of site exposure to sunlight and prevailing winds.
3. The shape and size of any nearby water sources, if any.
4. The topography of the site and the soil composition of the surrounding area.
5. Green cover (trees, green fields, grasses, etc.)
6. Buildings and facilities erected around the site (buildings, streets, parking lots, embankments, etc.)

Factors affecting microclimate

The air temperature is perhaps the most affected element of the climate by the local factors surrounding a site. The air temperature in the highest mountainous area varies significantly from the air temperature in the valleys. Due to the refraction and absorption of solar rays, before they enter the lower area of the mountain, the strength of solar radiation at the top of the mountain is greater than that at the bottom.

The amount of solar radiation that enters an area is affected by the surrounding mountains blocking the sun's rays from that area, creating the so-called mountain shadow on that area, which delays or Accelerate the sunrise or sunset, and the amounts of rain falling on the areas exposed to rain are more affected by the mountains than those located on the opposite side, which greatly affects the plants and green cover in that area (Dimoudi et al., 2013). Furthermore, the influence of the mountains, the height of the site above the sea level, and its decrease, the nature of the surfaces surrounding the site also affect the elements of the climate at that site. Green areas around a particular location help to reduce the sun's rays, while distant areas lead to increased heat absorption and radiating it out into the atmosphere, raising the temperature of the air and therefore the feeling of discomfort, even though the temperature of the environment is sufficient and within the limits of human thermal comfort, a high building can impact the winds in this location, acting as a windbreaker and causing different patterns of air movement around the building. Furthermore, to the dampening role, it can play in hot climates and preventing rays, high trees can cause a difference in the patterns of wind movement around them. Depending on the nature of the trees, the sun will hit the surrounding buildings (Georgi et al., 2006). In general, any change made by the designer to the site on which he works, such as design a building, removing or planting a tree or group of trees, or proposing a paved area for parking, would have effects on the site that could be negative or positive. And the area surrounding this site, as well as the ramifications, must be thoroughly investigated and assessed before any further work on the site is undertaken (Masmoudi, 2004).

2.6. The Concept of Ventilation and Human Comfort

Air circulation systems aid in creating a comforTable micro-climate in the ventilated zone. The micro-climate term includes air quality as well as the thermal environment. As a result, these two criteria of delivering appropriate air quality and a suiTable thermal environment should be addressed together when developing natural ventilation systems. It is important in this approach to achieve thermal equilibrium between both, the internal environment and the human body (Narguess, 2009). There four environmental elements that influence the thermal body's balance are: mean radiant temperature, air temperature, water-vapour pressure in the air, and air velocity, as well as three personal variables: thermal insulation of clothes, metabolism, and Activity (Littler, 1984). The rate of heat produced in the human body by metabolism, as well as the effect of external factors on the rate of heat loss to the atmosphere through respiration, evaporation, radiation, conduction from the body's surface, and convection, are required to determine the heat equation for the human body (Narguess, 2009). Equation 2-1 can be used to describe this:

$$\mathbf{H=M+W+R+C+T-E-HLR} \qquad \text{(Eq 2.1)}$$

Whereas;

H= heat storage in the body.

M= metabolic rate.

W= mechanical work done by the body.

R= heat transfer by radiation.

C= heat transfer by convection.

T= heat transfer by conduction.

E = evaporative heat loss.

HLR = heat lost by respiration.

If the H value is positive, it indicates that the body temperature is increasing, a negative value means that the temperature is decreasing. When H equals 0, the body is indeed in thermal equilibrium. This assumes that since the amount of heat consumed by the body equals the amount of heat released into the atmosphere, a comforTable condition can be achieved (Schiano-Phan, 2004). Even so, only because the sum of the equation is equal to 0 does not mean the body is still at comfort; certain areas of the body may seem to feel cold, and others seem to feel hot (Schiano-Phan, 2004). As a consequence, thermal comfort can be described as a state of mind that indicates the comfort with the thermal surrounding environment (Kiel, 1987). Eventually, according to Humphrey's analysis, there is indeed a direct relationship between comforTable temperature and habit (Humphreys, 1978).

2.6.1. The importance of thermal comfort

There are several compelling reasons why thermal comfort is so critical in building architecture;

- The impact of thermal comfort on user satisfaction is important and valuable.
- The temperatures that people want to achieve in their housing and the volume of electricity used in the building have a direct relationship.
- When people are uncomforTable in a house, they want to make themselves more pleasant. Normally, this results in the utilization of more energy and, in certain cases, perhaps the loss of an existing structural low-energy system (Crichton et al., 2009).

Natural or mechanical forces may cause ventilation and air movement in a building. Natural ventilation would be more effective and reasonable due to the adverse consequences of artificial powers, even if natural ventilation has certain limits. For instance, in naturally ventilated buildings, building configuration and orientation have a substantial impact on efficiency; as a result, they are less versatile than mechanically ventilated buildings in addressing problems that might occur due to required changes over the building's life cycle. Furthermore, since naturally ventilated structures benefit from wide openings, they appear to be noisy, because large openings allow much more noise and also fresh air to reach the space at the same time. As a direct consequence, the position of naturally ventilated structures is critical, and it could be advisable to reduce them in noisy environments (Narguess, 2009; Santamouris, 2013).

2.6.2. The effect of air movement on thermal comfort in hot climates

The ventilation intensity needed for cooling and maintaining a comforTable thermal atmosphere is greater than the amount of ventilation needed for keeping a good interior temperature (Heiselberg, 2002). Natural ventilation helps to maintain the required indoor air quality by moving air across a house. The minimum ventilation rate needed in a built environment to have appropriate oxygen for breathing, dilute metabolic CO2, and dilute odor is shown in Table 2-1. It's important to note that the level of ventilation needed in a structure is heavily influenced by activity. As a result, the ventilation requirements vary depending on the activity and behavior of the inhabitants.

Table 2.1. Amount of air needed to maintain accepTable indoor air quality (Narguess, 2009)

Source	Purpose of ventilation	Minimum recommended value (l/s/p)
CIBSE (1986)	oxygen for breathing	0.3
HSE Guidance Note EH22 (1988)	oxygen for breathing	0.5
CIBSE (1986: B2-3)	dilution of metabolic CO_2	5
HSE Guidance Note EH22 (1988)	dilution of metabolic CO_2	2
CIBSE (1986: B2-3)	dilution of odour	8
HSE Guidance Note EH22 (1988)	dilution of odour	9

Airspeed is considered the most important of the six variables affecting comfort conditions, particularly in hot climates, since it has a major impact on human thermal comfort in dwellings. Firstly, increasing airflow through the skin's surface increases heat transfer through convection, this enhances thermal response significantly. It also improves sweat evaporation from human skin, reducing the discomfort created by wet skin in high-humidity environments (Baruch Givoni, 1994; Szokolay, 2004). These processes work closely to provide a cooling effect and increase human thermal comfort. To achieve the required evaporation, it is suggested that sufficient high air velocities around the body of individuals in a room be preserved (Baruch Givoni, 1998). If the outside temperature is higher than the skin temperature (35°C), it's a smart idea to increase the interior air velocity because cooling via convective and evaporative effects will act in different ways. It's important to remember that in warm and humid climates, rising airflow in a building will also be beneficial and accepTable, even though the temperature of the outside air is greater than the temperature of the inside air (Givoni, 1994).

The beneficial impact and effect of indoors air velocity on individual thermal response were developed in the 1950s (Fountain and A., 1993); suggested that it is always possible to increase thermal satisfaction temperatures by around 0.55K with each extra $0.15ms^{-1}$ elevation of ventilation over the skin surface of building users if the indoor air temperature does not really exceed 33 degrees Celsius. In a physiological analysis, (Givoni, 1969) investigated the effect of airspeeds as high as 4 ms1 on thermal comfort; a clear comforTable feeling was found, and At 30 degrees Celsius interior ambient temperature and 2 ms1 airspeeds, inhabitants were observed to be relaxed and did not mind the extra wind (Baruch Givoni, 1992).

Increased indoor air velocity would be sufficient even though average temperatures reached 37 degrees Celsius, as it would minimize skin sweat. Givoni also suggested that such an internal average velocity of 1.5 ms^{-1} was suiTable for improving satisfaction at such an air temp of 28 degrees Celsius, whereas an internal airspeed with 2 ms^{-1} was sufficient for an air temp of 32 degrees Celsius if the day temperature variation was less than 10 degrees Celsius (fig 2.4), (Baruch Givoni, 1992, 1998).

The effect of increasing airspeeds from 0.15 ms^{-1} to 0.45 ms^{-1} on individual satisfaction for different temperatures varying between 24 degrees Celsius and 32 degrees Celsius, and relative humidity varying from 50percent to 90percent in Bangladesh have been investigated by Mallick (1996), where experienced hot and humid by environments; the analysis found the comfort temperature levels increased with such an increase of airspeeds (Mallick, 1996). Even so, as seen in Table 2-2, this was found to be efficient for specific values, for airspeeds less than $0.3ms^{-1}$, no substantial improvement in comfort was found. As a result, the study says that airspeeds less than $0.3ms^{-1}$ will only improve indoor environmental quality but not provide cooling or thermal comfort.

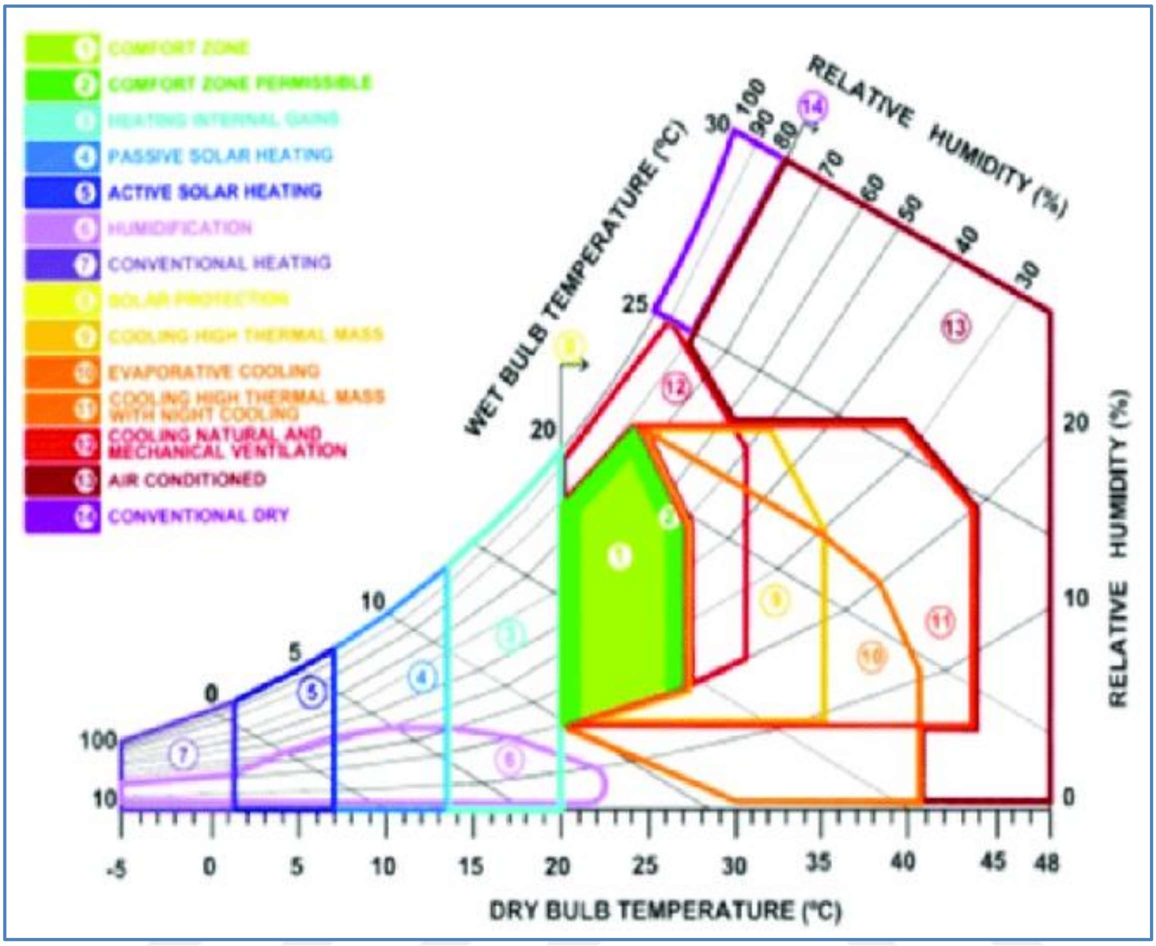


Figure 2.4. Psychometric chart for givoni 1992 (Nnaemeka, 2019)

Table 2.2. Comfort temperatures for different airspeeds (Mallick, 1996)

Fan speed setting	Air speed	Comfort temperature range (ºC)	Mean comfort temperature (ºC)
None	0	24-33	28.9
Low	0.15	24-33	29.5
Medium	0.3	26.4-35.2	30.9
Fast	0.45	27-35.8	31.6

Trying to elevate airflow is often necessary for air-conditioned enclosed areas. the occupants' thermal perception in an air-conditioned office space in Hong Kong, which is a hot country, with temperatures ranging from 25°C to 30°C and relative humidity ranging from 50 percent to 85 percent have been investigated by Chow (2010).

The effect of rising air velocity on thermal comfort limits can be seen in Table 2-3. When air velocity was increased from below 0.2 ms^{-1}, the top limit comfort temperature was increased from 24.9 degrees Celsius to 26.4 degrees Celsius, and when airspeed was increased to 1.0 ms^{-1}, the top limit comfort temperature changed from 26.8 degrees Celsius to 28.3 degrees Celsius, that 1.5 degrees Celsius improvement (T. T. Chow et al., 2010).

Table 2.3. Comfort airspeeds at working environment with air-condition systems under the climates of Hong Kong (T. T. Chow et al., 2010)

Air temperature (°C)	Comfort air speed (ms^{-1})	Range of air speed for 90% comfort (ms^{-1})	
		Lower bound	Upper bound
25	<0.2	0	0.99
26	0.59	0	1.63
27	1.22	0.18	2.26
28	1.85	0.81	2.9
29	2.49	1.45	3.53
30	3.12	2.08	4.17

Air speeds of around 0.2 ms^{-1} were found to be ideal for internal air temperatures of 25 degrees Celsius, while higher speeds varying between 1.2 ms^{-1} to 3.1 ms^{-1} were required for air temperatures of 27 degrees Celsius to 30 degrees Celsius. The research also revealed that rising air velocity by 1 ms^{-1} actually resulted in a 2 degrees Celsius reduction in elevated indoor temperatures. Also, it was discovered that the optimum thermal comfort temperature in air-conditioned space in tropical areas was higher than what ASHRAE recommended. In comparison to decreasing air humidity or temperature, it was concluded that increasing airflow is both cheap and useful in improving thermal comfort in buildings within hot regions. Although increased airflow is beneficial and often needed to produce a cooling effect and improve thermal comfort, it may be uncomforTable and inconvenient in some situations. To address this issue, international standards and guidelines have been developed; for example, ASHRAE Fundamentals (2013) specifies the accepTable maximum indoor flow rate between 0.8 and 1ms. If the airflow rate exceeds the specified velocity, it could create problems, such as flying papers in a workspace (Baruch Givoni, 1994). On the other side, to avoid discomfort, (Hyde, 2000; Olgyay, 2015) suggested a max speed of 1 m/s. Furthermore, Olgyay (2015) characterized comforTable airflow as air movement when indoor air temperatures are higher than 23.9°C and uncomforTable air movement as air movement when interior air temperatures are lower than 23.9°C. So he showed the impact of multiple flow rates on an individual as depicted in Table 2.4.

Table 2.4. The effect of airspeed on human thermal comfort (Olgyay, 2015)

Air speeds (ms^{-1})	Probable effect on human
Up to 0.25 ms^{-1}	unnoticed
0.25-0.51 ms^{-1}	Pleasant
0.51-1.02 ms^{-1}	Generally pleasant with a constant awareness of air movement
1.02-1.52 ms^{-1}	Slight draught to annoying draught
Above 1.52 ms^{-1}	Requires corrective measures if work and health are to be kept in high efficiency

With regard to human responses to different air velocities, Szokolay (2004) came to a related conclusion, as seen in Table 2-5. According to the findings, airflow rates less than 0.25 ms^{-1} had little impact on human residents; those between 0.5 ms^{-1} and 1 ms^{-1} produced a good sensation, whereas speeds greater than 1 ms^{-1} produced discomfort. In areas with very extremely high velocities, it is also advised that inhabitants have complete control of ambient airflow (Szokolay, 2004).

Table 2.5. Various airspeeds and subjective reactions (Szokolay, 2004)

Air speeds (ms^{-1})	Subjective reactions
Up to 0.1 ms^{-1}	stuffy
Up to 0.2 ms^{-1}	Unnoticed
Up to 0.5 ms^{-1}	Pleasant
Up to 1.0 ms^{-1}	Awareness
Up to 1.5 ms^{-1}	Draughty
Above 1.5 ms^{-1}	Annoying

Therefore the ASHRAE limit in buildings that are naturally ventilated in tropical regions especially in residential buildings in Sudan will be much lower than should be suiTable or accepTable. With such a situation the maximum accepTable airflow depends on the temperature generated and comfort. For individuals in hot climates, the temperatures have usually been high and therefore airspeeds that are higher than those suggested by ASHRAE will still be comfort Table.

2.6.3. Natural ventilation mechanisms

Natural ventilation depends on air circulation to equalize pressure in the space. Natural ventilation allows new air to enter the building while also removing polluted and dirty surrounding air. Natural pressure variations across the building are created by temperature variations (stack effect), and wind, as well as naturally ventilated structures, benefit from this effect. In general, the effectiveness of natural ventilation is influenced by temperature differences and wind pressure (Narguess, 2009).

<u>The wind</u>

The wind pressure distribution around a building is based on the wind direction and the geometry of the building. In various parts of the building, natural ventilation will lead to different wind pressures (Clements-Croome et al., 2008). The windward side of a house or building, also known as the pressure zone, has positive wind coefficients, while the leeward side, also known as the suction zone, has negative wind coefficients.

Depending on the wind direction of the side façades of the construction, the positive or negative wind pressure coefficients can occur as seen in (fig.2.5). As a result, the pressure difference between the openings on the building and the scale of the openings is a significant factor in determining the air volume of air flow in the building. To calculate the rate of airflow within a building as a consequence of wind force, the frequency of wind pressure in each opening in the structure must be determined.

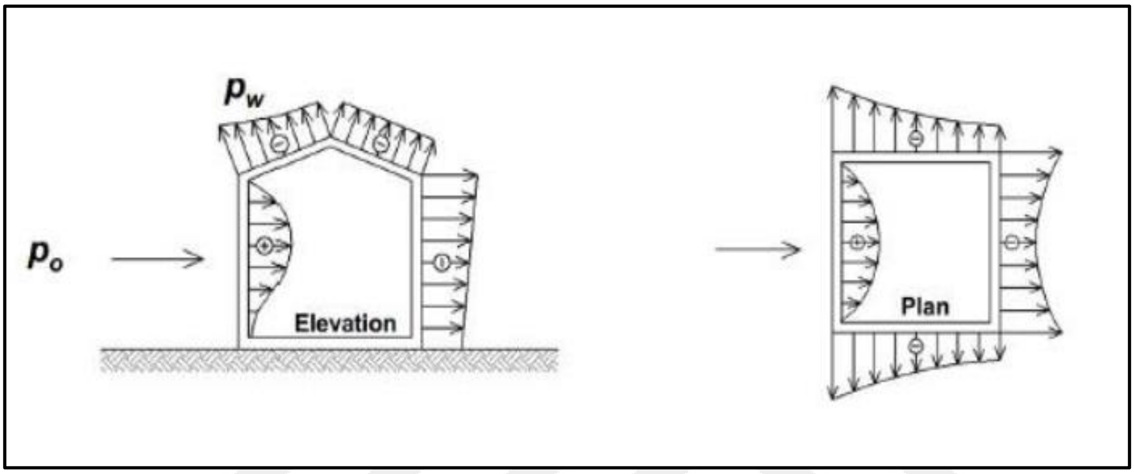


Figure 2.5. Wind pressure distributions (Clements-Croome et al., 2008)

In most cases, wind pressure on a structure's surfaces is not equally dispersed; so wind pressure spread reduces from the building's pressure zone's center outwards, as defined by Equation 2.2, which could be used to calculate pressure distributions at different parts of a structure (Saif, 2020).

PW= 0.5 Cp Po V^{-2} (Eq 2.2)

Where;

Pw = wind pressure;

Po= air density

V= wind speed

Cp = pressure coefficient

The pressure coefficient Cp differs relying on the building's geographical position, and the building's layout in case of wind speed, and also local plants (Kleiven, 2003).

Since Cp is determined by a range of variables, different points on a building's surface will have different pressure coefficient values. As a result, precisely determining the value of Cp at any given point on the building's surface is complicated. Relatively recently, Cp values were predicted using pressure measurements within a wind tunnel, generating Eq.2.3, which may also be used to calculate the value of the air pressure coefficient.

$$Cp = (P - Po) / 0.5\ Pov^{-2} \qquad \text{(Eq 2.3)}$$

In Eq. 2.3, P defines static pressure at a specific point on a building's surface (Pa), Po defines static pressure of a free wind stream that relates to Vr (Pa), V defines free wind stream velocity measured regarding the height of a specific opening or from a specific reference height (ms^{-1}), whereas O represents free stream density in (kgm3) (Saif, 2020). The wind speed at a given height can be determined as a feature of wind speed estimated at a height of 10 meters above ground level; the Meteorological Department usually calculates and reports it using the ‘Power law' air profile (Saif, 2020).

The wind pressure coefficient can also be calculated using a CFD simulation (computational fluid dynamics). The CFD simulation has been used since the 1970s, and more newly created packages are now usable. Most of the modeling software programs can only approximate average Cp values for various facades on a structure, while some can calculate the value of Cp at particular points in a facade within particular circumstances (Saif, 2020).

<u>The stack force</u>

Stack force is generated at an opening in a structure by variations in air densities, which lead to temperature variations between both the outside and inside of the structure, including over the openings on the building exterior. (Fig. 2.6, & 2.6, b) demonstrate how to stack pressure is generated in a significantly high structure with at least 2 openings at various heights. Stack pressure can also occur in a structure with a vertical stack, as seen in (fig. 2.6, c).

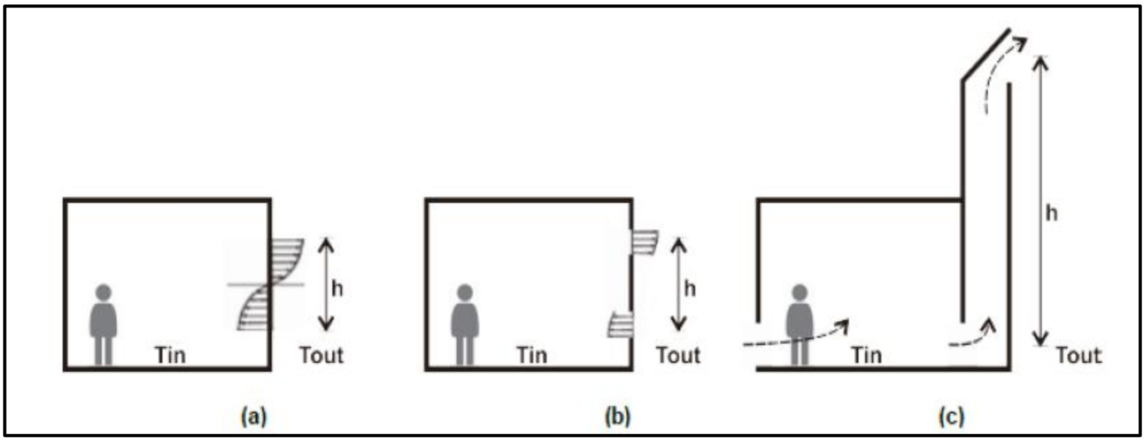


Figure 2.6. Stack natural ventilation: (a) one large opening room; (b) two various height openings building; (c) vertical stack (Szokolay, 2004)

Then if the air temperature within the house is greater than outside, the internal air pressure at higher levels within the house will also be higher than outside, whereas lower levels in the building will get a low pressure. Hot air travels up to the upper section of the house and is removed via the higher-level window, while cooler air reaches through the lower-level window and removes the hot air which has been pushed to the outside of the building (fig 2.7).

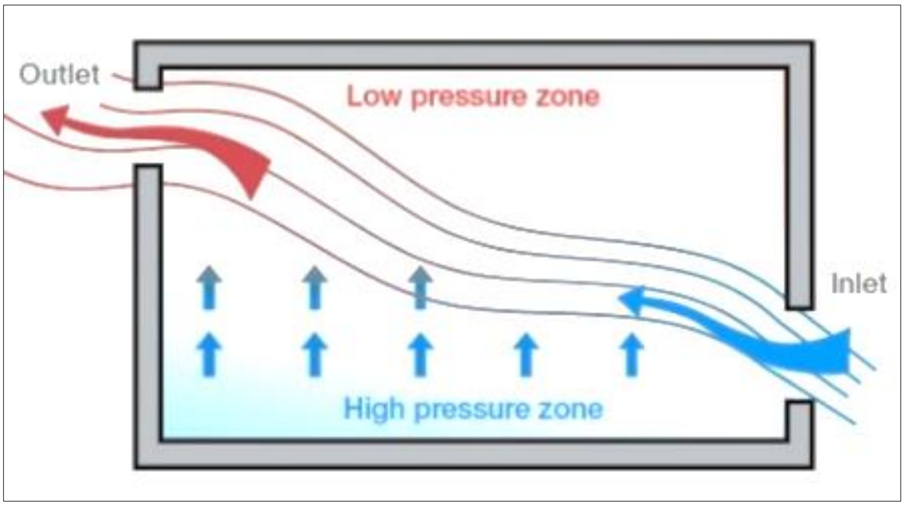


Figure 2.7. Natural ventilation in a room (Internet: Samantha, 2017)

The level at which the outside and inside pressures are equal is known as the Neutral Pressure Level (NPL) which also generates stack force. There is a balanced flow at this level, which means that the amount of air exiting the building is equal to the air amount entering the building. Air from outside the NPL will be pushed into the building through the outlets, while air downward should be brought in through the inlets (Allard et al., 2012). The location of the NPL in buildings is calculated by; the outside wind speed, the size, and position of the structure windows, the temperature differential between outdoor air temperature and indoor air temperature. The NPL is most common near the largest windows (Kleiven, 2003). The temperature differentials as well as the height difference between both the outlet and inlet in the buildings have a significant impact on stack force. Stack pressure rises as the distance between the inlet and outlet, and air temperature increases, and at the same time the volume of air movement within the structure rises as well (fig2.8), (Saif, 2020).

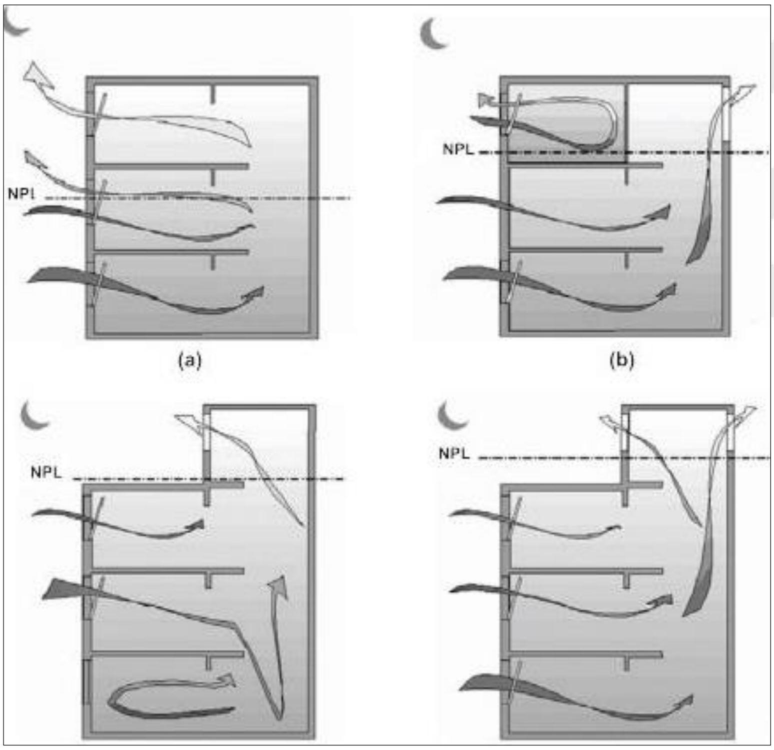


Figure 2.8. Different NBL locations with different opening designs room(Allard et al., 2012)

In general, the intensity of indoor airflow caused by stack force is less than that produced by wind force. The impact of stack force is comparatively lower in buildings that are a few floors (for example One or two), particularly in hot areas where the outdoor and indoor temperature differential is also limited because airflow intensity due to stack force is based on temperature between the outlet and inlet openings and height difference in a building.

Wind and stack force

The impact of both stack and wind forces on airflow within buildings is typical since they normally work in concert. Both powers can move in the same way and reinforce each other, or they can act in differing directions and balance out each other. All of that is illustrated in (fig 2.8) (Allard et al., 2012).

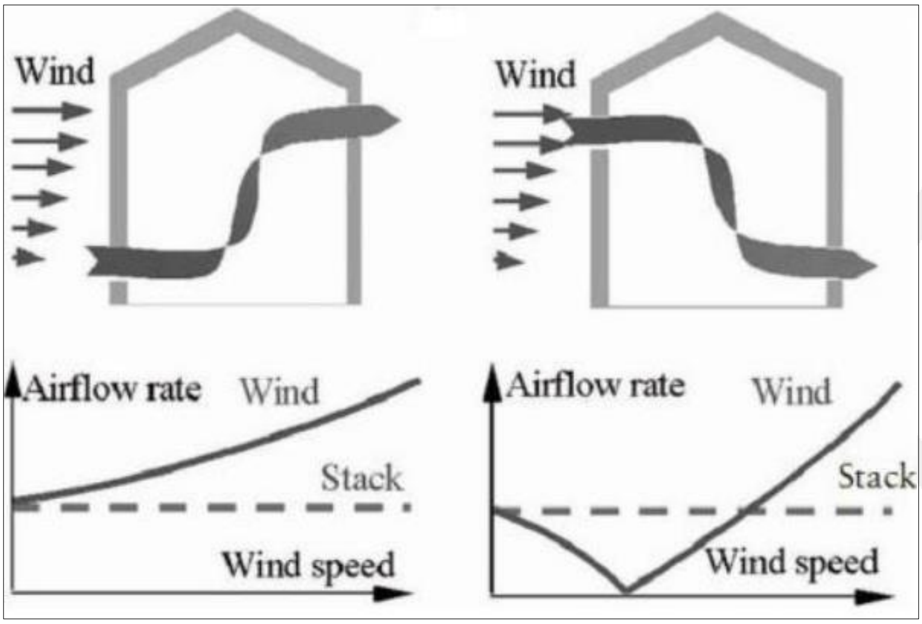


Figure 2.9. Stack and wind forces effect (Allard et al., 2012)

2.6.4. The principle of natural ventilation systems in buildings

As seen in (fig.2.9), the design principles that provide improved natural ventilation could be divided into three categories;

a) single-sided ventilation,

b) cross ventilation,

c) Stack ventilation.

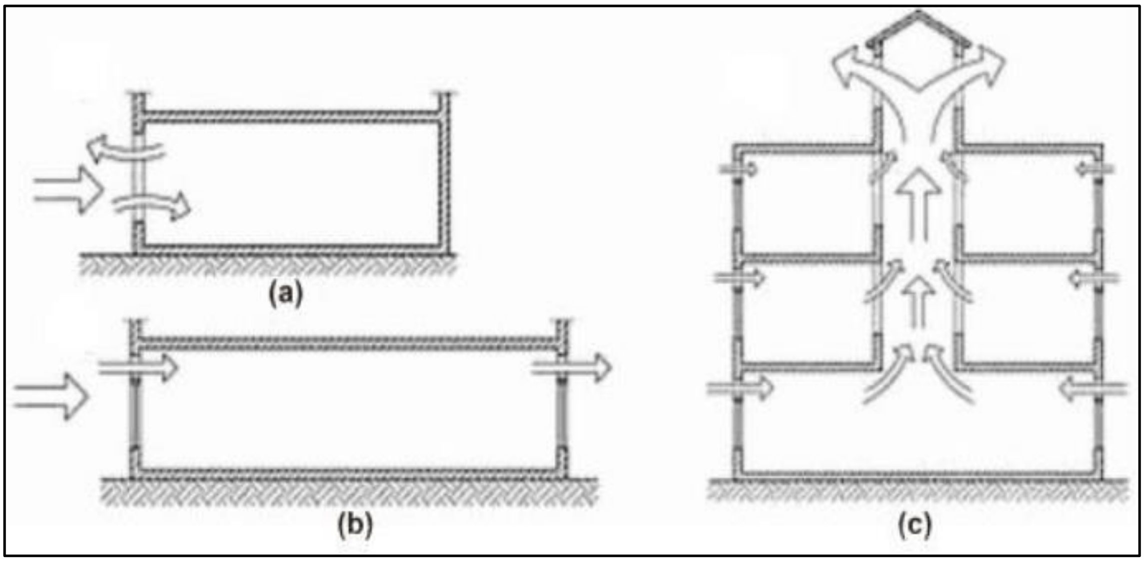


Figure 2.10. Design principles that provide improved natural ventilation (a) single-sided; (b) cross ventilation; (c) stack (Awbi, 2008)

Single-sided ventilation

As seen in (fig. 2.9(a)), this method of ventilation is distinguished by air normally entering and exiting a house through several openings or a single opening on a single side of the house or building. Airflow in a structure with single-sided airflow is influenced by a combination of wind force and stack force, all of which are affected by temperature differences and natural wind velocity outside and inside the structure (Larsen et al., 2007). The vertical positioning of the room is critical in this design. As external air velocity raised from $3ms^{-1}$ to $8ms^{-1}$, there was reverse air movement in research done by Allocca et al., (2003) where the room under analysis was situated midway in a three-story structure. In countries with hot and dry climates, airflow dominated by wind is natural in the summer months, while winds are strong and the temperature differential between both in and out of structures is limited. The study further proposed that single-sided ventilation efficiency be enhanced by incorporating at least two windows in the building's design, with the windows being of different height levels to provide stack influence (Allocca et al., 2003). Despite the fact that this model is commonly used in practice due to its simplicity it has a lot of drawbacks; there are low air levels, Air flow is difficult to regulate, and it is only effective in places close to the window. A variety of research, including those done by the CIBSE and the UK's Building Science Establishment (BRE), indicated that the depth of a room must be 2 to 2.5 times the height from the building floor to the rooftop or less than six meters, for comforTable internal ventilation be accomplished in single-sided ventilation

(Awbi, 2008; Clements-Croome et al., 2008; Kleiven, 2003). Single-sided ventilation is ideal for providing healthy indoor ventilation but is unable to provide create a cooling effect or thermal comfort inside buildings in hot and dry regions due to the poor airflow rate (Saif, 2020).

Cross ventilation

This is also a ventilation concept in which air enters an indoor room via a window on one of the structure's sides, travels through the area within the structure, and then escapes through another window on a certain side of the building, which could be on the opposite wall, as seen in (fig. 2-9(b)). Two-sided airflow is another name for cross ventilation. Wind force pushes air from outside of the structure into the structure through windows on the windward section of the structure and out through windows on the leeward section of the structure. Where the vertical difference between building windows is significant, the stack force is allowed (Awbi, 2008). According to Carrilho da Graça et al., (2016), cross ventilation is effective even in rooms with a maximum depth of 12 m or a depth of 2.5 to 5 times the height of the ceiling. Furthermore, cross ventilation is a basic natural ventilation system that is efficient in rooms within hot climates it eliminates heat from a structure and increases comfort conditions by increasing physiological evaporation cooling (da Graça et al., 2016). The speed of air in a space with single-sided ventilation was around 10% to 20% of the prevailing wind speed while the velocity of air within a room with cross ventilation would be around 30% to 50% of the prevailing wind velocity. The size and location of windows in relation to external wind speed and space of external wind, as well as the vertical distance between the inlet and outlet windows, determine the air floor speed in a building Table 2.6 (Givoni, 1969). Roy et al. (1982) presented a methodology to measure the mean velocity of air within a cross-ventilated space without an inner partition, with room exposed to various paths of the wind and also varying of the size of the windows as can be seen in Table 2-7. The study's findings indicated that as the width of the windows increased, the average velocity of indoor air enhanced as well; the average air flow was highest while the inlet and outlet widths were made equal to the width of the room's walls. Furthermore, the study found that at various sizes of windows, a building or space aligned obliquely to the direction of the outer wind had a comparable significantly higher air velocity than with a room perpendicular to the path of the external wind. The findings confirm Givoni's (1994) suggestion that a building must be aligned obliquely to the direction of the wind. Givoni (1994) also proposed that openings be located on adjacent walls rather than opposite walls because the air from the outside would be pushed from the airflow openings directly out of the outlets if they were placed on opposite walls. Just a small portion of the space will be ventilated in this method, as seen in (fig.2.10. (a)). External air would flow into a larger region of the room if the windows were on adjacent walls, and the average air flow would be greater as the air changed direction throughout the room, as seen in Figure 2-10. (b).

Table 2.6. Average indoor air speed in ventilated rooms with Single and cross ventilation, as a percentage of external wind speed (Baruch Givoni, 1994)

Natural ventilation principle	Location of openings	Wind direction (incident to opening(s))	Total width of openings /indoor velocity as percentage to external wind speed (%)			
			2/3 of the wall		3/3 of the wall	
			Average	Maximum	Average	Maximum
Single-sided ventilation	Single opening in pressure zone	Perpendicular	13	18	16	20
		oblique	15	33	23	36
	Single opening in suction zone	Oblique	17	44	17	39
	Two opening in suction zone	Oblique	22	56	23	50
Cross ventilation	One opening in pressure zone and another in adjacent wall	Perpendicular	45	68	51	103
		oblique	37	118	40	110
	One opening in pressure zone and another in suction zone	Perpendicular	35	65	37	102
		oblique	42	83	42	94

Table 2.7. Average indoor air speed in a ventilated room with cross ventilation and different opening sizes in two wind directions (Allard.F, 1998)

Wind direction	Opening sizes according to the wall's width		Average indoor air velocity as percentage to external wind speed (%)
	Inlet width	Outlet width	
Perpendicular	1/3	1/3	35
	1/3	2/3	39
	1/3	1	44
	2/3	1/3	34
	2/3	2/3	37
	2/3	1	35
	1	1/3	32
	1	2/3	36
	1	1	47
Oblique (45°)	1/3	1/3	42
	1/3	2/3	40
	1/3	1	44
	2/3	1/3	43
	2/3	2/3	51
	2/3	1	59
	1	1/3	41
	1	2/3	62
	1	1	65

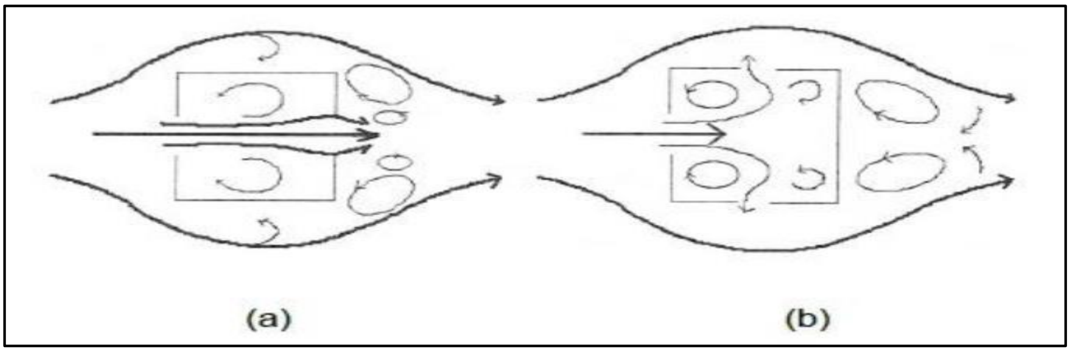


Figure 2.11. Paths of airflow in and around a building (a) opposite walls two windows; (b) adjacent walls two windows (Pavlou et al., 2009)

Even with similar openings, the cross ventilation principle achieved significantly uniform distribution and higher air speeds than the two-sided ventilation principle. This contradicts (Givoni, 1969) claim. The differences between the findings of (Givoni, 1969; Tantasavasdi et al., 2007) could be due to the fact that the two experiments used different methods; Givoni calculated velocities in a few positions due to experimental limitations, while CFD was used to calculate velocities around the room (Saif, 2020). Tantasavasdi et al., (2007) found that openings on opposite walls resulted in higher average air speeds and consistent air distribution throughout the room in their analysis. Furthermore, as the area of the opening raised 20% above the level of the floor, the overall average speeds around the space reduced; it was attributed to shorter circuiting as air from outside passed straight from the inlet opening to the exit opening through cross ventilation (Tantasavasdi, 2007).

According to the literature analyses, cross ventilation, specifically in indoor space with openings on opposite walls, one on the structure's windward side and the other on the structure's leeward side, is the most beneficial for producing high average air speed and consistently distributed airflow, which would be sufficient to improve the structure's comfort in a hot and dry climate.

The stack ventilation

Where the necessary air circulation within a room cannot be achieved purely by the influence of wind, stack ventilation could be used to increase the air flow. Since the influence of stack stress is comparatively minimal, it might be important to use large windows or at least 2 openings at various distances from the ground to produce much better results. As a consequence, stack ventilation is suiTable for high structures with more height room. In high-rise buildings with deep structures a vertical shaft with openings extended beyond the structure may be beneficial (fig.2.11). The pressure differential between the structure window, which operates as the inlet, and the outlet at the top of the stack which acts as the outlet, is important; this differential pressure is exacerbated by the negative pressure caused at the stack's opening. As a result of the large pressure gap between both the inlet and the outlet, the air within the structure is pushed up. Stack ventilation performance is unaffected by the structure's position in relation to the wind direction, and also the stack ventilation quality is unaffected by the wind direction (Santamouris, 2013).

Stack ventilation is limited. Inside the house or building, air flow is difficult to regulate, when the air velocity is limited. If the air temperature differential between the interior of the building and the external air temperature is within an accepTable range, it is possible to reach comforTable and healthy ventilation in a building and also suiTable air circulation for inhabitants using this principle. The stack ventilation concept, on the other hand, cannot increase thermal comfort in hot and humid climates.

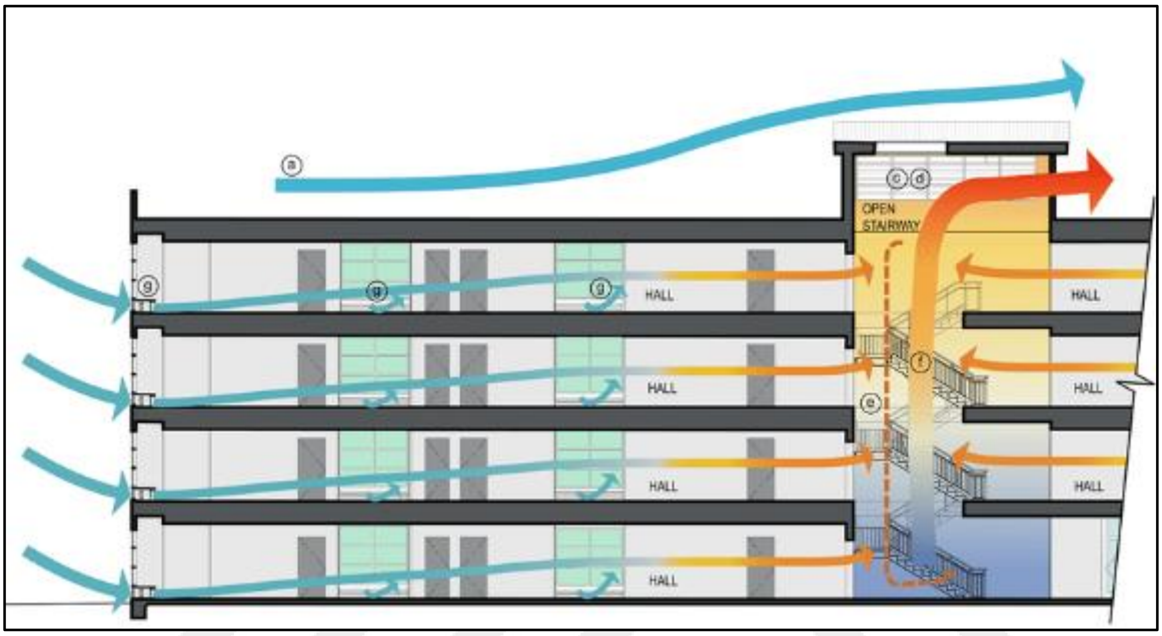


Figure 2.12. Stack ventilation in high building (Uzunhasanoglu, 2015)

3. PRINCIPLES OF PASSIVE COOLING AND HOT DRY CLIMATE VENTILATION METHODS

In hot climates, there have been no air conditioning systems for thousands of years to provide the cooling demand needed by buildings. Arabic, Roman, and Greek architecture used special ways of design as the only means of cooling their buildings. Some primary architectural features well established from those early ages include the use of enough thermal mass to temper the interior temperatures, as well as suiTable shading and urban design, the use of light colored surfaces, and ponds or fountains for evaporative cooling. After all, as a result of the industrial revolution and technological innovations, passive cooling has gone out of style, especially in developing countries, and has been replaced by HVAC systems. HVAC (Heating, Ventilating, and Air Conditioning) devices have become commonplace in developing countries over the past few decades. They're commonly used in non-domestic buildings to regulate interior conditions by providing adequate ventilation rates of heating, and cooling loads. They do, however, play a major role in the emission of greenhouse gases. And apart from CO2 pollution, which contributes significantly to climate change. According to Cook (1989), the expression "passive" was chosen to describe space conditioning techniques that are primarily regulated by natural phenomena and do not require the use of mechanical devices. In the 1970s, there was an oil embargo. Since then, there has been widespread consensus on the concept, as shown by the organization of Passive and Low Energy Architecture (PLEA) (Santos et al., 2018). We claim that, first and foremost, the building should function as an extension of its surrounding environment, in full dialogue with the microclimate and integrating the culture and desires of the region that will provide its inhabitants over decades, if not centuries, in accordance with the tenets of the Passive Low-Energy Architecture (PLEA) movement. This is accomplished by introducing appropriate technological solutions that take advantage of natural energy sources such as the sun and wind (among others) as well as nearby amenities. Whereas the first structures were mostly improvised shelters to keep humans safe, with the restricted locally available materials and design techniques, it was quickly found a way to take maximum advantage of the best of the local environment while defending against adverse weather. These objectives and constraints spawned a plethora of vernacular architectural and technological passive solutions that were naturally tailored to their time, location, resources, and culture. If a ‘passive' design is used, these may include the use of a fan or a pump, all of which are low-energy devices that can help increase the building's thermal efficiency (Baruch Givoni, 1994). According to (Mehdi N. Bahadori, 1985), cooling is characterized as the removal of heat from a space or from the air supplied to space to achieve a lower temperature and suiTable humidity rate than the outdoor climate.

Many academic studies conclude that passive cooling for buildings can be accomplished by three design steps: (1) preventing external heat gains; (2) modulating heat gains; and (3) eliminating internal heat from the building through natural ventilation or low-energy cooling technologies such as radiative cooling, evaporation cooling, or earth cooling (Algburi, 2018).

The passive cooling design is a collection of architectural design techniques used by architects to enhance a building's ability to react effectively to climatic conditions as well as other urban requirements (Ochoa, 2008). Because of the rise in high demands for daily comforts and energy efficiency, the passive architecture framework has grown in importance. As an architectural solution, a passive design intends to use specific building design criteria to reduce energy requirements to achieve an unusual state of thermal comfort (Al-Saffar, 2015). There are several variables that can affect passive design requirements, such as thermal comfort, air temperature, building opening, orientation, building form, selection of building materials, type of sunshade, etc. Any of these criteria may be used together or separately to achieve the goal of the passive design concept. In hot climates, passive techniques will reduce temperatures, resulting in reduced energy consumption and CO2 emissions. A greater degree of building efficiency can be achieved by combining many techniques (Ochoa, 2008). Passive cooling systems, according to (Taleb, 2014), use non-mechanical approaches to maintain a pleasant indoor temperature and are an important component in reducing the environmental effect of buildings. In a hot area, maintaining a pleasant interior atmosphere requires lowering the rate of heat gain into the building and increasing the rate of heat expulsion from the building. The basic rule for achieving ventilation in passive cooling ideas is to prevent heat from entering into the building or to evacuate it if it does (Kamal, 2012). This is dependent on two factors: the availability of a heat sink with a lower temperature than the indoor climate, and the progress of heat exchange into the sink. Environmental heat sinks, on the other hand, are classified into four categories (Figure 3.1);

1. Convectional heat transfer from ambient air.
2. Long-wave radiation transfers heat from the sky (upper atmosphere) to building structures, such as the roof.
3. Water, which evaporates inside and/or outside the building fabric to transfer heat.
4. Ground (below the surface soil), which is transferred into the building fabric by conduction (Kamal, 2012). Passive cooling techniques can reduce peak cooling loads in houses, reducing the energy consumption of mechanical air conditioning systems (Kamal, 2012).

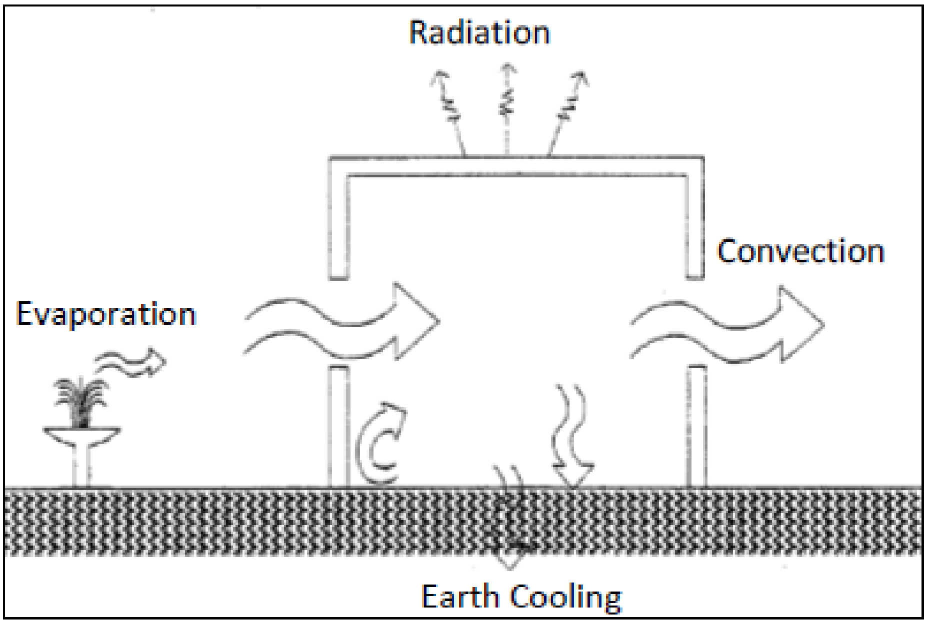


Figure 3.1. Heat exchange ways (Lechner, 2014)

Any of these natural heat sinks is a cooling source that can be used in a variety of ways and systems. For example, heat may be rejected or refused into these environmental heat sinks via natural means of heat transfer (natural cooling) such as conduction, evaporation, and radiation, or mechanical support via hybrid air cooling such as the use of fans or small power pumps (Samuel et al., 2013). Faster population and economic development in Khartoum, along with the scarcity of energy supplies, have had significant negative consequences for the environment and living beings. This building growth and expansion, along with active building constructions, ignores environmental needs such as wind and solar power. As a result, passive solar architecture techniques and concepts have become extremely necessary and urgent in order to minimize these detrimental impacts on both humans and the environment. Unfortunately, there is a significant difference between western building experience and passive architecture concepts in Sudan and other developed countries. As a result, the aim of this study is to illustrate the most appropriate architecture solutions based on passive design techniques and vernacular architecture design methods as a first step toward closing the gap. I assume that the city government, architects, engineering, building firms, and real-estate production should pay greater attention to clarifying and defining the existing energy use issues in order to identify appropriate architectural alternatives before it becomes more complex and perhaps more costly.

3.1. Design Strategies for Passive Cooling Techniques

The major design concepts of passive approaches necessitate designing the building based on how the planner should take advantage of natural wind and sunlight to evaluate the behavior of solar heat gain via the building envelope, especially windows, in order to reduce the need for artificial lighting and mechanical air conditioning. Furthermore, the primary goal of passive design methods is to adjust comfort conditions during the year. As a result, passive design methods can be achieved by optimizing the building's thermal efficiency, such as using external shade designs, natural ventilation, constructing the building envelope with energy-efficient codes and guidelines, insulation, and a variety of other techniques that correspond to specific climatic needs (Lechner, 2014). A study in Spain that looked at standard housing structures and found that using passive methods would solve cooling and heating loads while saving 18% of energy as compared to the actual house. using 350 mm lintel in window frames and Additional 200 mm insulation on the residential façade is used as passive approaches(Ruiz, 2011). However, When it comes to direction, aspects of land space, building shape, building structure, and distance between buildings, the responsiveness of passive residential architecture design is the only hope for sustainable housing in hot dry climate regions (Manioglu, 2008). According to (Ralegaonkar et al., 2010) Passive design strategies may result in significant reductions in artificial lighting energy waste, as well as cooling or heating loads. The two studies listed earlier confirmed that using passive architecture techniques reduced the amount of thermal discomfort in the buildings under study. The clever and efficient building envelop is one of the most important design features in the passive design solution in hot dry climates, because of its critical role in controlling the wind conditions and exterior solar before they enter the buildings (Figure 3.2 and 3.3), (Ochoa, 2008).

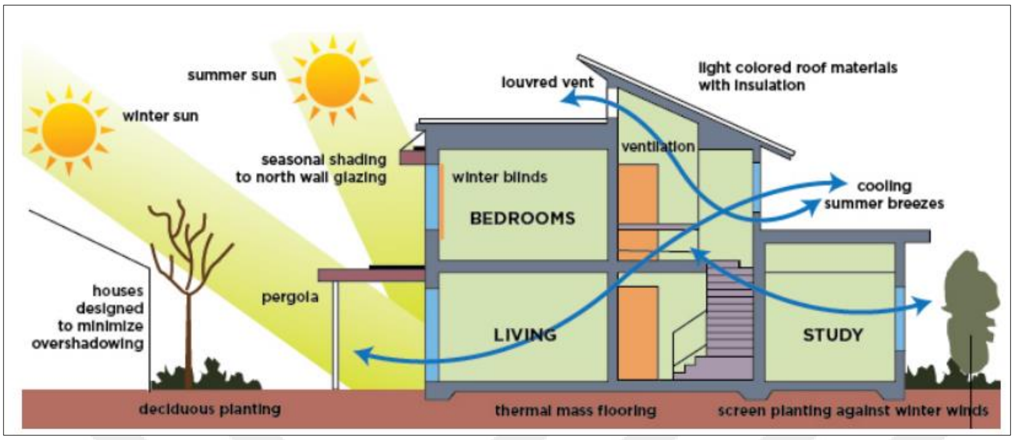


Figure 3.2. Passive cooling techniques (Internet: HMH Architecture + Interiors Passive Heating and cooling, 2021)

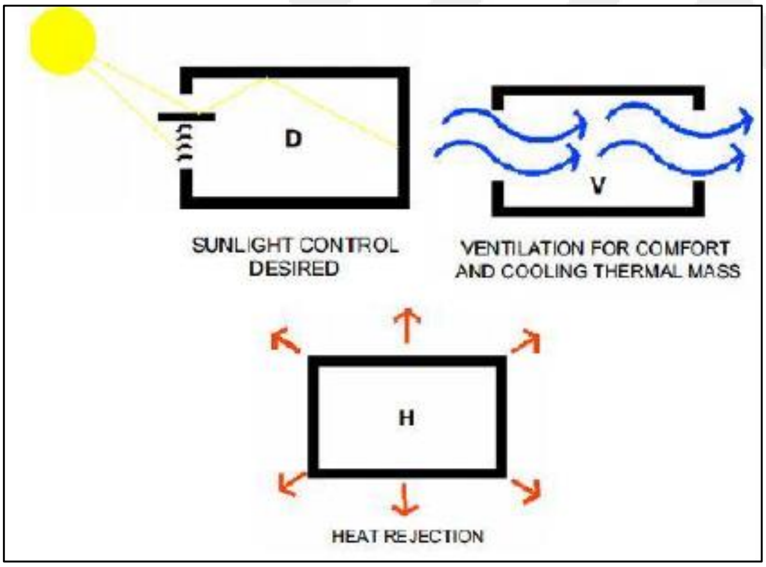


Figure 3.3. The main passive cooling methods for hot climate(Ochoa, 2008)

People's experience of sustainable buildings and low energy, including their importance for human life and effect on the built environment, is reflected in passive design approaches. This experience leads them to integrate passive strategies into the architecture, as well as combining a few developed technologies that assist in improving the urban environment as well as the condition of building users while using the least amount of energy possible. As a result, this has helped in the introduction of the principle of low-energy building evaluations (Mortada, 2016). Yet, all of the studies and observations listed above, point to the building's thermal efficiency improving, reducing energy waste, and lowering CO2 emissions. The purpose of this research is to find new ways to reduce the amount of cooling energy used by air conditioning systems. However, developing countries have faced a severe energy crisis in the last two decades according to the cooling load requirements of buildings Passive cooling methods should greatly reduce maximum cooling loads in buildings, reducing the duration of operation and the amount of air conditioning systems needed especially during the summer season (Kamal & Architecture, 2012). The building energy use is very high, and it is expected to continue to rise as people's lifestyles improve and the population grows. Electrical air conditioning systems only have recently entered the industry, but they have made a huge contribution to the rise in the highest energy use. (Santamouris, 2013) has mentioned that, to achieve suiTable indoor thermal conditions, a 'passive' solar design uses natural means such as conduction, convection, or radiation, rather than using any electrical device for heating or cooling. In the hot-dry climate zone, maintaining comforTable indoor environments requires reducing external heat gains and promoting the removal of interior heat (Kamal, 2012). Insulation methods, solar shading methods, forced ventilation methods, evaporative cooling, radiative cooling, desiccant cooling, and earth cooling are among the passive cooling methods investigated and prepared by Kamal (2012). (Geetha et al., 2012) study and investigate various passive cooling techniques for buildings and provide an application illustration for each technique, then they divided the techniques to three groups. The first group discusses microclimate parameters and solar control, as well as architectural design techniques to protect the building from solar heat. The solar control category includes the building envelope, surface properties of the building (color and texture), and solar shade, insulation, whereas the micro-climate control group includes the landscape design, vegetation, and outdoor water surface.

The heat modulation or amortization technique is discussed in the second group. An efficient solar system should be used to modify heat gains in order to achieve a balance between controlling solar pick-up and allowing enough light while maintaining the build envelope's design and basic requirements, furthermore, during the design stage, an appropriate amount of heat load should be enabled by modulating the necessary temperatures for various uses of inner spaces (Al-Obaidi et al., 2014). The heat modulation or amortization technique, which attempts to modulate heat gain by using night ventilation or convective heat, has a number of parameters. The third group of passive cooling techniques aims to minimize heat gain or eliminate heat from the interior by thermal transfer. The heat in the building's interior spaces could simply be reduced or transmitted by heat sinks through natural ventilation, air infiltration, or hybrid ventilation (Al-Obaidi et al., 2014). Passive cooling strategies for buildings, according to (Geetha et al., 2012), can be accomplished in three design steps: (1) removal of interior heat from the structure using natural ventilation or low-energy cooling techniques such as evaporative cooling or earth cooling, radiative cooling; (2) exterior heat gain prevention; (3) heat gain modulation.

Removal of interior heat from the structure

Quite sometimes, heat gains in the building can't be kept under regulation. A more advanced cooling technology combines heat isolation to heat sinks, such as the ambient sky, using natural heat exchange techniques (Sami A Al-Sanea et al., 2011). the climate of a building is significantly depends on its architecture and plan configuration the use of a PCM dependent design includes the use of natural ventilations and other natural heat dispersal surfaces, such as earth, for relieving the extra load of heat, along with the expectation of natural ventilation (Al-Obaidi et al., 2014). A research in Singapore showed that CO2 levels in air-conditioned rooms are much higher than those in naturally ventilated rooms. PPD (percentage of people dissatisfied) increases in air-conditioned buildings when it often results in an over cooled area, whereas the usage of only fans was found to be sufficient to provide thermal satisfaction in naturally ventilated buildings (Wong et al., 2004). Natural cooling ventilation, on the other hand, refers to methods that utilize mainly natural methods to cool buildings, such as natural ventilation, mixed-mode ventilation, and night ventilation. Natural ventilation utilizes hot, cold air from the outside to cool the house. Replacement air piped in and out from building openings is circulated to heat and then exhausted. As seen in (Figure.3.4), the air flow pathway defines the different ventilation methods: sub-slab distribution ventilation, stack ventilation, cross ventilation, single-sided ventilation, and (Zarandi, 2009). The author mentioned that even the natural ventilation cooling potential at some times cannot reach the necessary level of thermal comfort and is essentially dependent on outside air temperature. Consequently, naturally occurring airflow cannot deal with the internal heating gains in most and particularly the non-domestic buildings located on the urban heat-island where outside temperatures are higher than in rural areas. Therefore, it is one of the most important factors in naturally ventilated buildings is design a construction that allow the air to pass through. This makes natural ventilation unable to resolve internal heat gains, mainly and particularly in non-residential dwellings on the urban hot island, where outside temperatures are higher than in rural areas (Esfeh et al., 2013).

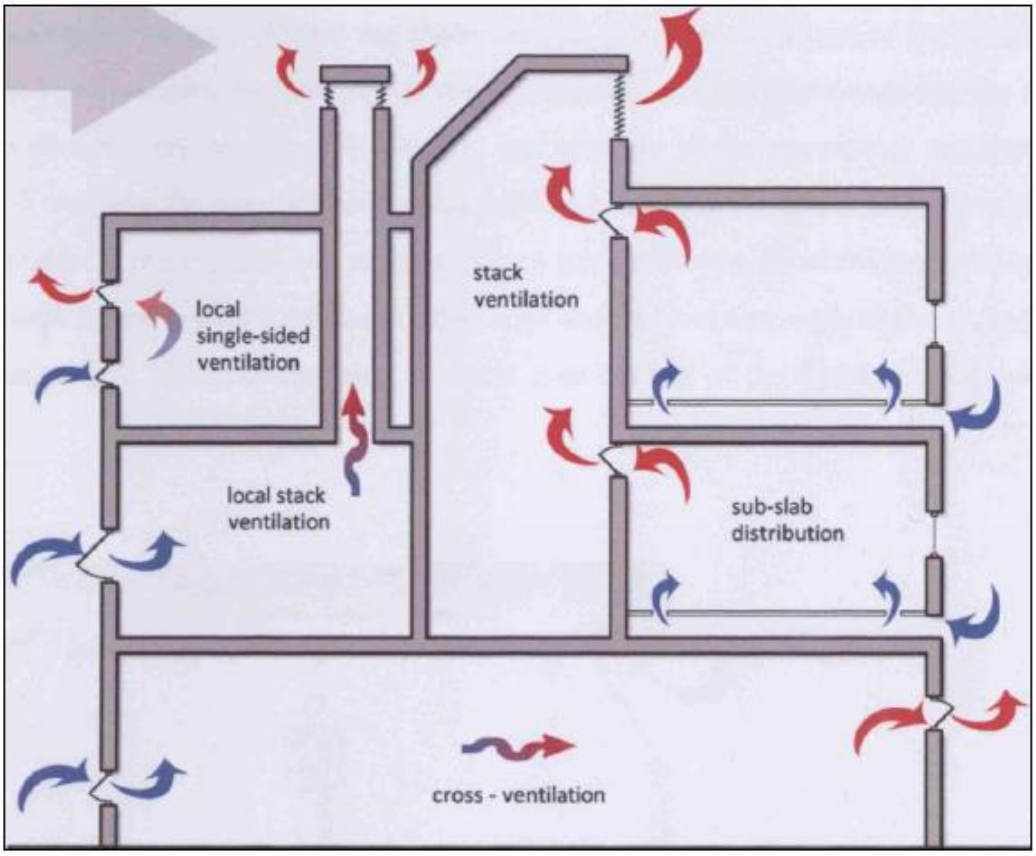


Figure 3.4. Different ventilation methods (Zarandi, 2009)

Heat gain prevention

According to (Venkiteswaran, 2017) Heat gains prevention is the first step to changing thermal comfort conditions in the building's interior and includes any measure which minimizes the thermal gains. The weather and micro climate of a building have to be changed. It is crucial to hold the building's internal heat steady in order to make passive strategies more efficient. Economic considerations, zoning controls, and units affect the design of the site, which may all interfere with the design of a building, in relation to the episode of solar radiation and available wind (Geetha et al., 2012). Vegetation may produce graceful outdoors and improve a building's micro-climate and reduce the amount of cooling. The important outline measure in terms of heat gain insurance is solar control. Solar rays affect the surfaces of the external building in specific, reflective, and diffuse modes. On a certain surface, the direction and surface edge of the solar radiation adjusts to the level plane. Solar lighting can cause problems in an indoor environment, for instance, increases indoor air temperatures, thermal and visual problems for residents, damages to objects and furniture. In this way, the regulation of solar radiation is crucially important (Al-Obaidi et al., 2014). A number of construction methods, including sun shielding for the building shell, building shape and morphology, external opening shade, surface properties, and heat isolation can be used to monitor solar heating as the color of the exterior surface determines the measure of recipient solar radiation (The decreased solar heat absorption is correlated with light colors)(Venkiteswaran, 2017). Blocking the entrance to the house and its interior by sun rays is an essential way of evading the inside of the building. While solar security is useful for the envelope, the shading of the windows must be important. This can be achieved either by building sunbath barriers (shading device) or by controlling the solar-operated features of the exposed area (Geetha et al., 2012).

Heat gain modulation

Modulated heat gain could be achieved by the use of construction materials with a high thermal mass or through a high building system heat storage capability. The air heating and the cooling of higher thermal mass materials including concrete blocks, bricks, and in general steelwork walls is a storage device for cold and heat. Two key strategies are usually employing either dense building materials or extra-energetic content for the construction process in the building envelope for obtaining thermal mass gain (Geetha et al., 2012).

3.2. Benefits of Passive Design Approach in Residential Buildings and Housing

The high temperature in hot weather imposes a great deal of responsibility on modern design and construction in hot climates; to address these challenges, it must be taken into account in the early design stages in order to minimize the reliance on active and mechanical energy systems. All of this leading to the value of using passive architecture techniques to achieve indoor thermal convenience in Sudan, as well as the reality that people do not design buildings passively, relies excessively on internal energy for comfort while considering the economic conditions, instability, and the greater impact of the greenhouse resulting from the generation of energy. Passive designs are used extensively for increasing indoor convenience and reducing energy consumptions in residential buildings by the usage of unique design standards for any environment, thus maintaining the building cold. One of the key factors behind implementing passive architecture techniques is to reduce maximum energy demand in peak hours, which combines decreasing the monthly bills while retaining desired indoor temperature with minimal interaction when active or mechanical systems.

After reviewing a significant number of publications and scientific study, the author found that six main passive cooling techniques can be used in Sudan, these passive cooling techniques are; (1) Natural Ventilation, (2) Shading Device, (3)Wind catcher, (4) Courtyard planning, (5) Earth air heat exchanger, (6) Evaporative cooling.

3.3. Thermal Comfort

The key problems relevant to thermal comfort are discussed in this part. The understanding of a person's thermal comfort comes from the basic requirement to keep the temperature of the innermost body segments within a range of 36-38 °C. In order to achieve this, it is important that the heat generated by our metabolism and our movement balances the heat emitted into the atmosphere (Butera, 1998). When we are cold, it means we are losing more heat than we are producing, and our bodies are cooling down; when we are warmer, it means we are producing more heat than we are losing, and our bodies are warming up. running, Walking, climbing, swimming, hitting, sawing, and other physical activities generate heat as well as mechanical activity (Carlucci, 2013). The metabolic rate is the overall amount of energy emitted. As a result, the body's energy balance can be listed as:

$M = W + Q$ where:

M = Metabolic rate,

W = Mechanical work,

Q = Heat loss, the metabolic rate is expressed in met or W per square meter of body

Surface area (1 met = 58.1 W/m2)(Butera, 1998).

One met is created by a seated human. With a surface area of 1.8 m2, the typical seated human produces slightly more than 100 W (Bessoudo, 2008).

Heat is exchanged between the human body and the atmosphere via (Figure 3.6);

1. Convection, which would be affected by the temperature of the skin, the temperature of the air, and the velocity of the air.
2. Radiative heat transfers, which are affected by the skin's temperature as well as the temperatures of the surrounding surfaces.
3. Transpiration (which may lead to sweating) and respiration, both of which result in the evaporation of water and the absorption of heat from the skin or lungs; relative humidity of the air is a factor.
4. Conduction occurs as a portion of the body comes into contact with a solid material; it is dependent on the temperature of the skin and the object, as well as the thermophysical properties of the object (Butera, 1998).

As a result, the heat loss (Q) is calculated as follows:

$Q = C + R + E + H$, where

C = heat loss/gain by convection

R = heat loss/gain by radiation

E = heat loss by evaporation;

H = heat loss/gain by conduction (Butera, 1998).

Naturally, the heat transfer between both the surface of the body and the atmosphere also depends on the clothes we are wearing since clothing is thermal insulation. Clothes are then determined by their thermal resistance and calculated by unit clo (1 clo = 0.155 m2K/W). The meaning of clo = 1 has been the traditional winter clothing also the lowest is clo = 0 (completely naked man), the value clo = 0,5 is just the kind of summer clothing and accessories. In conclusion, body heat equilibrium, and therefore thermal comfort, is influenced by six variables, two of which are personal and four of which are environmental. According to (Butera, 1998); The environmental variables are; air relative humidity, air relative velocity, air temperature, means radiant temperature, the personal variables are; clothing and activity. For the radiant heat, the apparent scale of every radiating surface should be taken into account, not just its temperature; the so-called view factor is used to calculate the apparent scale.

Air temperature

It is generally given in degrees Celsius (°C). Air temperature is the primary and direct effect on the thermal comfort, and despite a large number of effects, all of them revolve around the temperature of the air, so the body loses heat by interaction with the air through which the convection currents are produced as a result of the body's contact with it, and heat transmitted. The decrease in air temperature increases the rate of heat loss (Bessoudo, 2008).

Means radiant temperature

The exposure of the skin to receive or lose heat by sun rays has a direct effect on the feeling of heat regardless of the temperature of the air, feeling hot when exposed to the sun's rays, exposure to the sun's rays in winter, despite the cold weather, gives a direct feeling of comfort. The sun is not the only source of radiation, any object that stores some amount of heat radiates to the less hot object that is separated from it by a transparent medium such as air or glass. Hot walls radiate to the human body in whatever space it occupies. A distinction must be made between two types of radiation, short-wave radiation, which is radiation from a high-temperature object such as the sun, and long-wave radiation in the infrared range, which produces from buildings and human bodies in Low temperatures. It's necessary to remember that the mean radiant temperature is a function of the measurement location (Carlucci, 2013). In rooms with wide glazed surfaces, this is an especially important feature of thermal comfort to consider. Air temperature and mean radiant temperature are the only environmental variables that influence our heat balance, and therefore our comfort (Bessoudo, 2008).

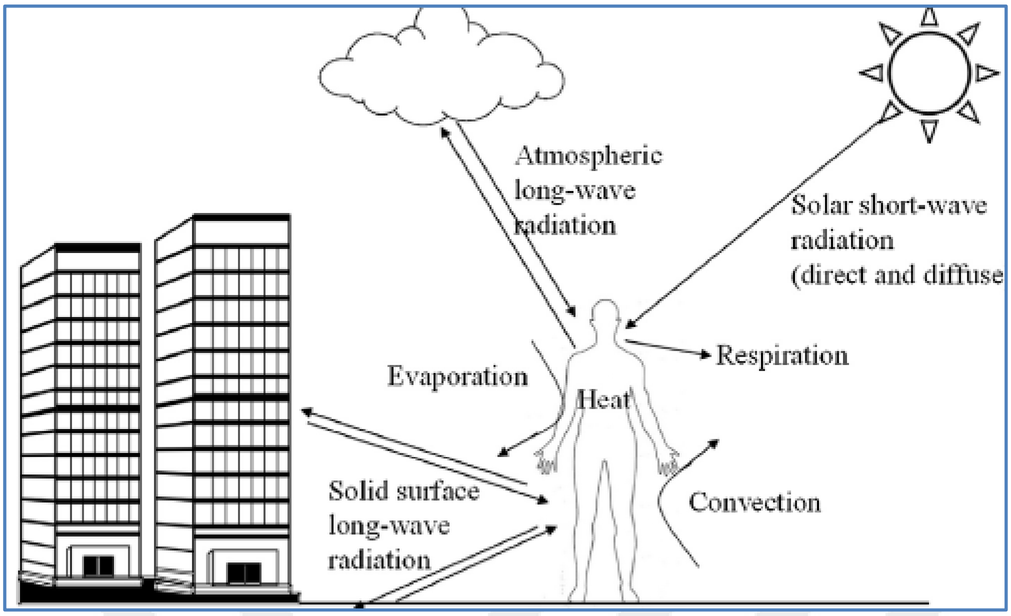


Figure 3.5. Heat is exchanged between the human body and the atmosphere (Lai et al., 2017)

Air relative humidity

Relative humidity affects the evaporation capacity in the air and then controls the degree of cooling that occurs when sweat evaporates from the surface of the skin, so it increases in the air and decreases with the increase in humidity in the air. In cold climates, low relative humidity increases the feeling of cold. Therefore, the feeling of thermal comfort in relation to the relative humidity is at (30%) to (50%) with a temperature ranging from (20 to 25 degrees Celsius). If exceeds (25) degrees Celsius, then the person feels the humidity in the surrounding atmosphere (Tanabe et al., 1994). According to (Jing et al., 2013) Humidity, around 40 percent to 70 percent may not have a significant effect on thermal comfort. In environments that are not air-conditioned or where outside weather conditions can affect the indoor air quality and thermal environment, relative humidity can be higher than 70 percent. Humidity indoor areas can differ considerably and can rely on whether or not there are drying operations (paper mills; laundry machines, etc.) where steam is expelled.

Air relative velocity

The average speed of the wind to which the skin is exposed, with respect to place and time is known as air velocity, The human body is very responsive to air movement, particularly in sections such as the neck, face, feet and it also depends on the sensitivity of the individual. If the air circulation velocity is too strong or irregular, discomfort occurs. It is also very important to control the speed of the air and the path of the air flow effectively (Ali-Toudert et al., 2005).

The operative temperature

Operative temperature is described as the mean between the air and the mean radiant temperature: if the area is air-conditioned and the ambient temperature is 26°C, the operating temperature in both situations is 26.5 and 27.5 degrees Celsius (Carlucci, 2013). Even if the air temperature remains the same, it is obvious that the individual who is closest to the glazed surface feels hotter than each other. The PMV (Predicted Mean Vote), according to ISO 7730, is a much more general index than the operative temperature since it is accurate for every value of environmental and personal variables. The PMV model is a thermal survey used on a vast population with the same temperature conditions (Bessoudo, 2008). The study focused on the seven-point scale from cold (-3) to hot (+3) of their thermal sensations. Empirical equations, capable of predicting the thermal sensation with regard to Predicted Mean Vote, PMV, were obtained from these surveys. An additional index, the PPD (predicted percentage of people who are dissatisfied), was created to estimate the number of people likely to experience discomfort in an environment (Kontes et al., 2017). It is difficult to achieve a thermal comfort that satisfies all due to human variations. There are still 5% disappointed, even with PMV none. In buildings without air condition, it is possible to apply the rules of adaptive comfort that take purely physiological factors into account but also psychological and behavioral factors into account. ANSI/ASHRAE standard 55-2004 (Figure 3.6) deals with the problem of adaptive comfort(Kontes et al., 2017). The norm applies the concepts of adaptive comfort in areas without climate control or where the machine is switched off and when the thermal conditions of the area are largely controlled by users via opening and closing windows (Carlucci, 2013).

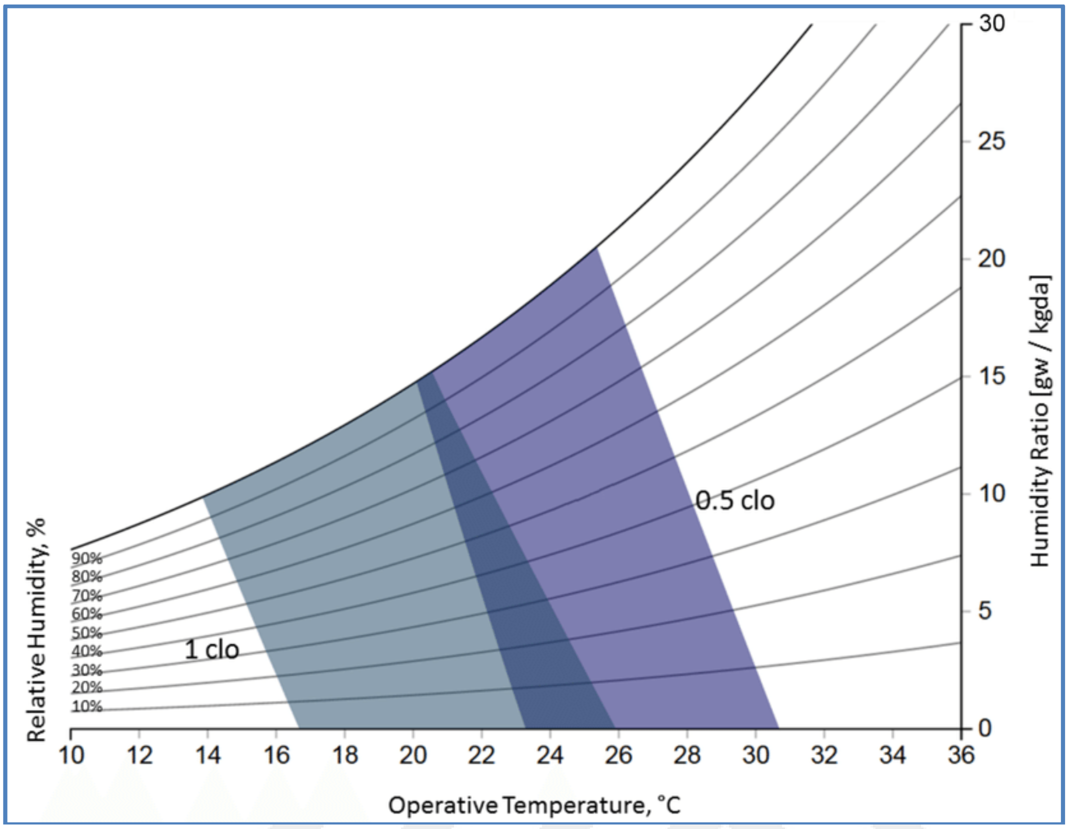


Figure 3.6. AccepTable domains of operative temperature and humidity rate based on ASHRAE Standard 55 (Kontes et al., 2017)

The operative air temperature at which the temperature is considered to be relatively comforTable in this situation is determined by the mean monthly outdoor air temperature. When internal operative temperatures are within the limits shown in (Figure 3.7), accepTable comfort conditions are achieved. One group of operative temperature limits is for 80 percent acceptability, while the other is for 90 percent acceptability. The acceptability limits of 80 percent are for normal applications, and the 90 percent limits will be used where a higher level of thermal comfort is required (Butera, 1998). The chart illustrates that comfort is reached in non-air conditioned spaces with temperatures greater than in air conditioned areas. In conclusion, thermal comfort is the key factor of energy use in buildings; more areas uncomforTable, lead to more energy used to keep it cool. For this purpose, understanding of the thermal comfort principles is essential to the design of energy efficient, and sustainable buildings (Carlucci, 2013).

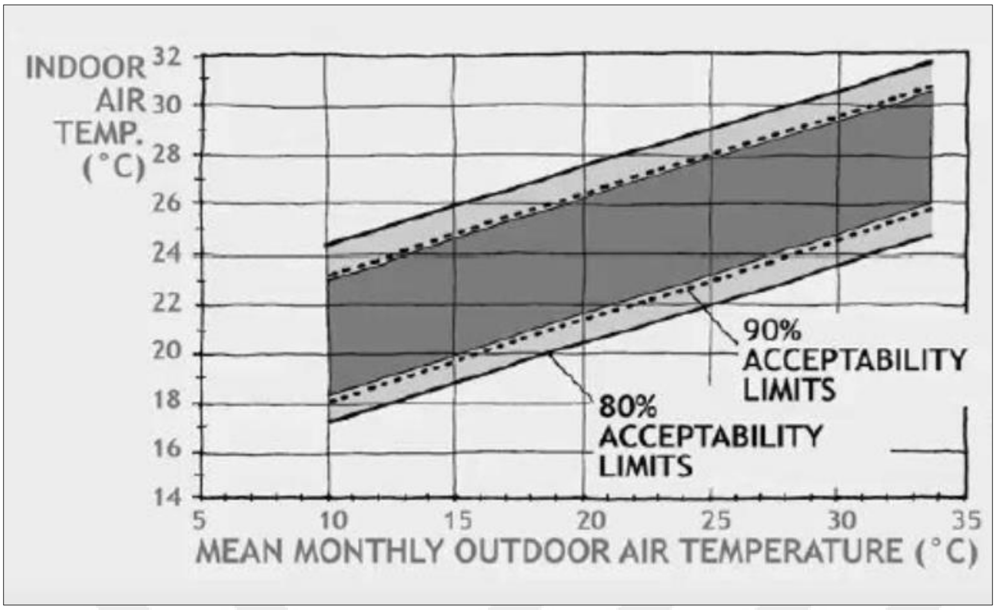


Figure 3.7. The values of operative temperature and thermal comfort in air-conditioned Space (Butera, 1998)

3.4. Traditional Architecture

The books of the pioneer are discussed and investigated in detail in research of traditional or Vernacular architecture such Amos Rapoport, Hassan Fathy, and Paul Oliver. The encyclopedia is written by the traditional architecture pioneers (Encyclopedia of Vernacular Architecture of the world), which is considered as a significant and important source of architectural study, It's been achieved over the last 3 decades, present in about 2500 pages (Algburi, 2018). Throughout the study, several good books are analyzed and reviewed with a view to the relation between vernacular architecture and its response to the local requirements for the climate. Bernard rudofsky defines architectural history and artwork as a universal phenomenon in those books (architecture without architects). He proposes architecture as a continuous practice carried out by residents on their own terms by presenting convenient and easy architecture solutions for residents to live comfortably in their surroundings. He appreciated the beauty of traditional houses in their traditional eco-friendly elements, like low-energy strategies designed to offer thermal comfort conditions, technologies that are fully incorporated into architectural design, construction orientation, and building materials derived from local resources. Vernacular is closely linked to social and cultural patterns. It responds to environmental factors and seems to be, in a way of natural development. It includes all structures, not only houses, and concerns about the climate and the resources available. It is designed to satisfy the basic requirements, while at the same time adapting the principles, economies, and forms of life of the societies that create them. Vernacular design is tailored to unique social and cultural environments (Oliver, 1997). Constructed areas are not random; they are the reflection of a reality that has been gradually developed over the years, carried out using local methods and tools, representing specific purposes and meeting physical, cultural, and economic requirements. Vernacular buildings seem to be the reaction to the environment and represent the relation between tradition, environment, materials, and weather. Over the years, each culture creates a design that leads to local demands and takes it on over generations. Vernacular structures express the tangible shape of ideals that local, peasant, and traditional communities have represented in various forms of residences (Oliver, 1997). It is structured to satisfy the basic requirements, while at the same time adapting the principles, economies, and forms of life of the societies that create them. Vernacular design is tailored to unique social and cultural environments. Amos Rapoport (1969) describes vernacular architecture as a social tradition that interprets the physical form of community, its needs, and values, as well as the wishes and desires of the general public. Dwellings have been directed by the environment of the region from the planning stage. Vernacular configurations show a variety of designs associated with the contexts that surround it, responding to the environment, history, descriptive interpretations, and the sense of comfort surrounding them (R. Y. Chow, 1998). In fact, vernacular architecture is indeed a manmade construct that arises from interrelationships within ecological, financial, material and cultural elements (Lanier, 2009). Throughout history, various vernacular strategies and materials shaped by the tradition, environment, and land of the community have been widely used. In addition, a large amount of those materials and methods have been utilized in different places with varying climatic requirements and social structures. For example, adobe design (clay or mud) has been used as the main building material in the construction of buildings in most of the inhabited districts around the world for thousands of years. In fact, a few examples of current adobe construction works can be identified in a number of countries with varying climates, A various vernacular strategies such as courtyards and wind catchers (towers) have also been used in modern designs for passive architecture (Asquith et al., 2006). Although there are several vernacular methods for cooling and day lighting in hot dry climates. The techniques are described by Asquith and Vellinga (2006) as; the wind catcher, domes, courtyards, badgers, plantation, towers of cooling, water walls, roof ponds, induction vents, mashrabiyas, and solar chimneys. Additionally, due to the specification of vernacular architecture structures, such as thermal mass wall construction techniques and local building materials, it was deemed a low-energy building.

3.4.1. Low energy techniques of traditional architecture

Energy management is now an interesting field of academic research. There are many explanations for the energy requirements, such as exponential development in the economy, an increase in population, a modern transport network, sophisticated technology systems and a new high quality of life. As a consequence, these influences may affect human activity and the climate, leading to the loss of non-renewable resources. Engineering, architecture, building production firms and scientific researchers are trying to explore low-energy technology that can reduce the problems of non-renewable energy use. One of the most effective low-energy construction strategies is to look at our traditional construction, which serves as environmentally sustainable and provides comfort conditions in many areas, such as climate, economic and social needs. Low energy construction architecture is required to be investigated and immediately used in new built surroundings to reduce negative environmental and human impact. Much of academic study and experimental research has been undertaken through exploring the linkage between traditional buildings and low energy technology. Because of its self-addictiveness to the natural atmosphere and compatibility with nature, they believe that vernacular architecture in several various climatic areas is an ecological system. In the twenty - first century a unique symbol emerged for architectural trends: the revival of the traditional cleverness exemplified in vernacular structures that require little equipment, technology, or ingenuity to enjoy comforTable indoor temperatures. Many thesis literatures and academic research articles now use words like low energy building, zero energy building, and energy-efficient architecture. All of these well-known titles have had the same goal in mind: to reduce the use of non - renewable energy in the buildings. Various methods, such as energy efficiency remodels, reduced cooling and heating loads, and energy protection programs may be used to reduce building energy use in new or remodeled buildings (Finnegan, 2017). Reduced electricity use allows meeting the building's energy requirements with renewable energy sources less complicated and more accessible (Toguyeni et al., 2012). In general, these principles seek to satisfy the needs of the inhabitants while reducing energy use and limiting the effect of energy usage on the climate. Few definitions may be provided to further distinguish them (Radhi, 2008).

Low energy constructions

Such buildings aim to achieve the lowest potential energy demands, using sustainability strategies to make reasonable usage of resources (Futcher et al., 2017).

Low energy buildings

These buildings use less electricity than conventional buildings with the usage of minimum energy requirements and systems including energy efficient windows, low air-infiltration levels, and high insulation levels, to reduce heating and cooling, they will also use technology for passive and active solar design and technology (Futcher et al., 2017).

Zero energy buildings

A revolutionary development of low-energy buildings was the idea of zero energy buildings. Zero energy buildings (ZEB) are commercial or residential buildings with significantly fewer energy requirements by means of efficiency gains, and renewable technology will provide the balance of energy requirements (Toguyeni et al., 2012).

Depending on the project priorities and the principles of the building designer and owner, the idea of ZEB can be approached from many angles. Owners, for example, are usually concerned with energy prices, so zero-cost energy buildings can be considered. Governments are obsessed with national energy statistics and are mostly interested in source resources, so zero source energy buildings are necessary (Radhi, 2008). A designer of construction may be concerned about the usage of electricity for energy needs at a site (zero site energy building), whereas the carbon reduction (zero emission energy building) of buildings worried with contamination from power plants and energy sources could be of consideration. The vision of ZEB may have a major effect on the architecture and features of zero power buildings (Toguyeni et al., 2012).

3.4.2. Passive cooling in traditional architecture

Passive cooling in traditional buildings is a part of traditional techniques within the natural environments of the city to increase indoor comfort. Although some of them are currently never functioning properly again due to changing living standards of the people, they are still ignored and unused in modern architectural projects (Foruzanmehr et al., 2008). Moreover, in Sudan, where the knowledge with vernacular or traditional buildings is not considered as helping to improve the process of development in new residential areas, the passive cooling technique will achieve its perfect implementation and possible benefit with a specific architecture context. In this way, the main test is to learn some basic concepts and principles of traditional buildings and to find methods for integrating such standards in the development of new structures or to redesign established ones. Lately, science has incorporated scientific approaches to analyze the efficiency of conventional strategies. In this context, qualitative research was devoted to the assessment of elements of passive cooling techniques, whereas the quantitative method involved studies to assess the actual efficiency of the thermal environment in the context of climate factors by field observation. Taylor et al. (2009) studied vernacular architecture in Oman's hot, desert environment. The results of the study showed that the vernacular architecture of the area offers suiTable ways, including climatically and culturally, to create comforTable conditions using only natural and sustainable energy sources. In terms of the value of combining qualitative and quantitative research, Foruzanmehr and Nicol (2014) fully investigate naturally ventilated buildings in Yazd, Iran, where the weather is hot and dry. The studies emphasized the validity and effectiveness of traditional Iranian architecture and design technologies in a modern context, and also their effectiveness in reducing the emission of carbon Dioxide and energy consumption(Algburi, 2018). Even so, in a comparative analysis, Meir and Roaf (2005) studied various construction methods and tools, as well as morphological, in arid conditions characteristic of the Middle East and Mediterranean climatic areas in order to provide sustainable buildings for the twenty-first century. Monitoring, modeling, and computational analysis were also included as part of the inquiry. Interestingly, local vernacular prototypes were designed with a large heat capacity and a minimal volume of fenestration that was mostly without glazed. These features render them very resistant to regular changes in the climate. As a consequence, the findings suggest that intense inertia is counter-productive since such structures are unable to take advantage of solar gains in the winter and night cooling through cross ventilation in the summer, owing to their small fenestration scale. The building technologies suited to climatic conditions, however, turned out it was cold in winter and hot in summer during most hours of the day. The thermal performance of such houses, on the other hand, was found to be higher in highland and mountainous areas than in the lowlands and also in more humid coastal areas (Algburi, 2018).

3.4.3. Climate responsiveness in vernacular architecture

Maria (2009) has performed an architectural typology and building materials research evaluation of a sustainable Greek traditional town and its scene. Sernikaki, a Greek traditional settlement that can be described as a living life type, was the subject of her investigation; it was also the result of hundreds of years of improvements in resource use, building methods, and environmental considerations. Her analysis along these lines evaluates specific traditional staying composes including their responses to climate in terms of inactive plan laws that could be tailored to exist compositional experience in the area to improve the relationship between location, construction, and weather. In her master thesis, Dabaieh (2011), performed a theoretical and practical analysis of the Balat town. She realized that traditional architecture was continuously a product of a typical cycle of sustainable construction norm to comprehend the importance of preserving desert vernacular architecture as an inspiring value for contemporary desert architecture.

People have acquired the traditional method of working from their precursors, and knowledge has been shared and produced over the years from age to age. Inhabitants respond to their environmental situation and the environment by experimenting in a way that suits their desires and expectations. This daily cycle would disappear because of the way the inhabitants leave their homes to break down or destroy them in order to build strong concrete houses today.

Shokouhian and Soflaee (2011) have carried out a large study of naturally refreshed frameworks in Iran's sustainable vernacular architecture that focuses on sustainability effects induced by natural refreshment frameworks in Iranian traditional hot-dry district architecture. They ensure that building biology is studied based on its potential to use environmental and climate criteria in a design, and thus develop spatial characteristics, such as comforTable. Help them explain that in Iran's traditional architecture there are different natural cooling techniques, such as Khan, Hozkhana, and wind catcher or Badger. In traditional architecture, in a hot and dry environment, and hot humid climates the wind tower or wind catcher is a construction element. It makes natural ventilation available and audiTable, a vital law for the protection of vitality. Usually, conventional construction methods are very much climate-adjusted and can be used for modern technology. Through analyzing them, they claim it is possible to identify the Iranian traditional architecture when indicated by a few elements. Iran's traditional design delicately influences the framing of the environment by climate forces and making it evident the climate has been perceived as a building condition. It is essential to use a renewable and inexhaustible source of vitality, such as wind structure and building type.

Many design features are influenced by conventional building these days, as many experienced people have contributed that local traditional types have been accredited to be energy effective and "sustainable," shaped by topography, local sources, and nature. in the academic study by Khoshsima et al (2011) examined the benefits from the past by doing a contextual study of the conventional architecture of Iran's southern shores of the Caspian Sea. Climate plays an important role in the design of buildings, according to the analysis. Currently, we face a range of environmental concerns, such as; ozone layer exhaustion, dangerous atmospheric deviation, and a shortage of non-renewable energy resources, all of which necessitate considering climate change while preparing a building project (Khoshsima et al., 2011). Conventional architecture has always been a good example of climate design and refers to the methods that our forefathers invented to improve their living standards. Traditional architecture can also be a source of inspiration for new architectural design since it can be used to gain inspiration and try to match modern buildings with the natural environment to a great extent. As a result of this investigation, the conventional architecture of Iran's southern Caspian Sea shores has been studied in order to identify the role of the environment in the construction of structures (Algburi, 2018).

Muhaisen (2006) conducted a simple analysis into the effect of rectangular courtyard extents on the shade and implementation conditions provided on the internal envelope of the form in four different regions, Rome, Cairo, Kuala Lumpur, Stockholm, and Kuala Lumpur are the regions in concern. The examination relies on the effect of climatic factors on suggested courtyard ratios and size in order to ensure a reasonable annual execution in the regions under investigation, it also explores the variation with in courtyard by the day shade including introduction exhibitions due to adjusting the latitude of the city and therefore the situation of the movement of the sun. In addition, the study proposes guidelines and general recommendations for a competent courtyard design for the climatic regions. In addition, it describes the ranges through which the dimensions of the structure can be modified with the minimum divergence from the perfect implementation. The analysis ends with the results showing that the shading conditions of the internal courtyard frame are completely subject to frame size, region latitude, and available environmental conditions.

An analysis study has done by Tavil (2004) to exploration of the thermal conductivity of the walls built from brick in Istanbul. This analysis depends on the thermal execution evaluation of the brick work divider design for comfort and energy efficiency with the DOE-2 program. The investigation contains a relation between the annual cooling and heating loads of the masonry wall choices of the example dwelling. In addition, the exterior and internal surface temperatures of the wall choices are processed in order to determine the variable temperature impacts on their thermal behavior during the cooling and heating seasons under the climatic conditions of the humid environment in Istanbul (Tavil, 2004).

3.4.4. Mashrabiya as a traditional cooling technique

Traditional architecture is fascinatingly widespread around the world, with pioneer design methods reflected in traditional dwellings that are used by the residents to protect themselves from the extreme weather conditions that they face (H. Fathy, 1986). Mashrabiya is a plain box that used to shade in the hot dry climate areas of Egypt, Syria, and Iraq, in their traditional buildings. It is a useful traditional technique because of all the functions it provides (Figure 3.8). For example, due to the grid openings on its surfaces, the passing of ambient air and natural light usually occurs to go through these openings, assisting in the decrease of indoor high temperatures while also controlling natural light.

In the past, privacy was another much more important function. Architect Hassan Fathy explains how several Mashrabiyan models were developed to achieve a number of functions in his book Natural Energy and Vernacular architecture (H. Fathy, 1986). The Shading is one of most efficient and necessary measures to ensure that solar radiation does not overheat. The starting point for a reduction in overheating is firmly assumed to be the shade of the structure, and therefore reducing the energy consumption for cooling the hot areas.

In recent years the design sense and style have changed considerably. One of the latest architectural developments in the area is, for example, the application of sustainability concepts in building architecture located in Arab cities (Abdelsalam et al., 2013). The Masdar City in the United Arab Emirates, which vernacular architectural elements are being used for passive cooling and has been considered the very first energy efficient city of Middle East, is also an obvious example of the application of vernacular architecture concepts in the region (Ibrahim, 2016).

Figure 3.8. Turned wood mashrabiya window, (Internet: A.allegretti, 2012)

3.4.5. Potentials of energy saving and thermal insulation

Significant quantities of energy are absorbed by air conditioning systems because of not really insulated building structures that cause the heat to be transferred into it. Preventing heat transfer across the building envelope by installing a thermal insulation sheet was therefore known to be one of the most efficient ways of saving electricity. So many researchers have studied the energy consumption or thermal insulation of the building structure (Macias et al., 2009). They have all come to realize that the elements of the building envelope are among the most efficient energy saving design factors.

Significant research has been carried out to test energy performance based on the location of the wall and roof insulation.

Ozel (2014) carried out an analysis in Turkey to examine the best isolation material position in three parts of the wall. According to the characteristics of the heat storage capacity (decrement factor and time lag) in the building structure component, the study concluded that the worst insulation was measured when the time lag was the shortest and the decrement factor was the highest, while the best insulation was observed when the time lag was the longest and the decrement factor was the minimum (Macias et al., 2009).

A further study examined the behavior of buildings' air-conditioning operating systems in order to determine the impact of an insulation layer applied to the exterior wall on energy consumption. The findings of that research indicate that air-conditioning irregular operation "on-off" control can save a significant amount of energy (Zhang et al., 2017).

Al-Sanea and Zedan (2011) performed academic research on the effect of thermal insulation layer position and thickness on 8 different wall parts with on-off air conditioning operation behavior, if the Air conditioning system is turned on and off on a regular basis, the research suggests installing a thermal insulation layer on the internal wall surface (Sami A Al-Sanea et al., 2011). Furthermore, Al-Sanea (2002) analyzed and compared the thermal performance of six structural elements commonly used in building projects of Suadi Arabian constructions. When compared to an un-insulated roof case, applying a thermal insulation surface to the inside layer of the roof section provides very little advantage on the heat-transfer load (Sami A Al-Sanea, 2002).

Using DesignBuilder hourly simulation modeling in a single-family house in Dubai, Friess et al (2012) investigated the impact of thermal bridging on six wall structure composition effects on the building's energy consumption. According to their simulation results, designing with suiTable external wall insulation should save up to 30% electricity (Friess et al., 2012). Many other research teams have looked into the relationship between traditional architecture as well as passive solar design, thermal comfort, energy-saving features, and low-energy techniques. After all, because the goal of this research is to use one of the passive cooling techniques (the wind catcher) to reduce cooling energy consumption and lower internal air temperature in residential buildings in hot climate areas, it's essential to keep the amount of heat transmitted through the building structure to a minimal level. The flat roof is the most exposed building elements to the influence of solar radiation in Sudan, making it one of the most difficult envelope components to protect against heat gain.

3.5. Hot Dry Climate Ventilation Methods

In the hot dry climate areas, old inhabitants have been adapted by themselves in the circumstance of the outdoor world. The temperature of the indoor air on a hot summer day would be extremely high due to various reasons, like the;

1. Solar heat comes into the building throws the glass.
2. Layers of the Building (roofs, walls) that absorbed solar radiation.
3. Heat transmitted by the adjacent building surfaces.(Dehghan, 2013)

The designer of conventional buildings depended on natural passive techniques to improve indoor air temperatures (Dehghan, 2013). For example, houses are usually built in near proximity to each other, or in the shape of collective buildings connected to each other by shared walls (Figure 3.9). Buildings that fall into a cluster or a similar group limit their total solar heat gain. The vernacular design in hot climatic zones often uses roofs, vaults, and domed to minimize heat absorbed from solar radiation. In order to provide building inhabitants with internal ventilation and convenient thermal living conditions, conventional buildings in hot areas have applied a number s of architectural elements. The Mashrabiya, and The wind tower or wind catcher are among these architectural elements or techniques.

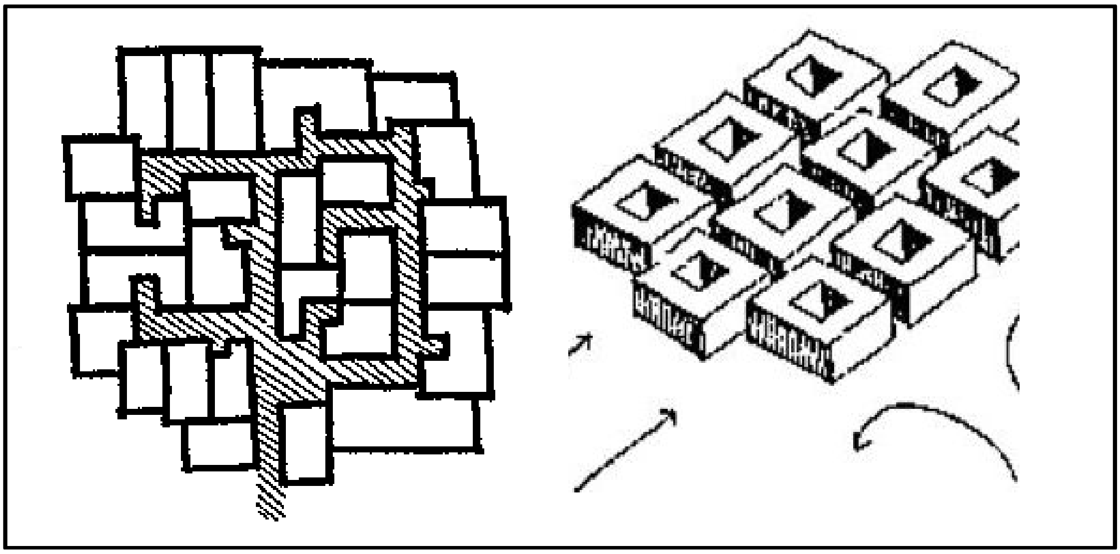


Figure 3.9. Urban constructions in arid and hot areas (Haas, 1993)

3.5.1. The courtyard

The courtyard is a common design feature tried out for many years, particularly in dwellings, and has become a zone of excitement for researchers' ongoing occasions. In all buildings of the tropical climates of the planet, the courtyard is one of several passive architectural elements. It consists of a totally inner enclosure and the half enclosure (Yakubu, 2019). In a hot and dry environment, the architecture of the courtyard shape has a massive effect on the shadows cast on the building structure, as well as the collected solar radiation or the building's cooling and heating loads, heating and cooling loads can also be determined for various courtyard forms. The form of the courtyard is based on the form factor (W/L). The shape component is the courtyard width ratio (W) to the courtyard length (L) (Manioğlu et al., 2015). According to a significant amount of research, courtyard buildings are more efficient at reducing cooling loads, especially in hotter climates. Compressed types of courtyards are arranged in this environment to reduce the area influenced by solar radiation. The shape of the courtyard has an effect on the energy loads of the building. As a result, different courtyard forms should have their cooling, and heating loads evaluated (Manioğlu et al., 2015). Muhaisen and Gadi investigate the shading efficiency of pentagonal, hexagonal, heptagonal, and octagonal polygonal courtyard shapes, (fig 3.11). The courtyard ratios and design have a significant impact on the shading efficiency of courtyard forms, according to this detailed empirical analysis conducted by the designed model (A. S. Muhaisen, Gadi, Mohamed B, 2006). Muhaisen's study continues with an examination of the impact of rectangular courtyard ratios mostly on shading and exposure conditions created on the form's internal envelope in hot dry, hot humid and cold climates. The position of the sun was discovered to have a direct connection with the produced shading cases in the types under examination. In hot humid climates, three-story courtyards perform best, two-story courtyards perform best in hot dry regions, and one-story courtyards perform best in cold climates (A. S. Muhaisen, 2006). Courtyard dwellings, on the other hand, have always been used in harsher climates.

The benefits that a courtyard provides are air movement, privacy, light, tranquility, and protection those benefits are almost always desired in human housing specifically in hot climate buildings (Yakubu, 2019).

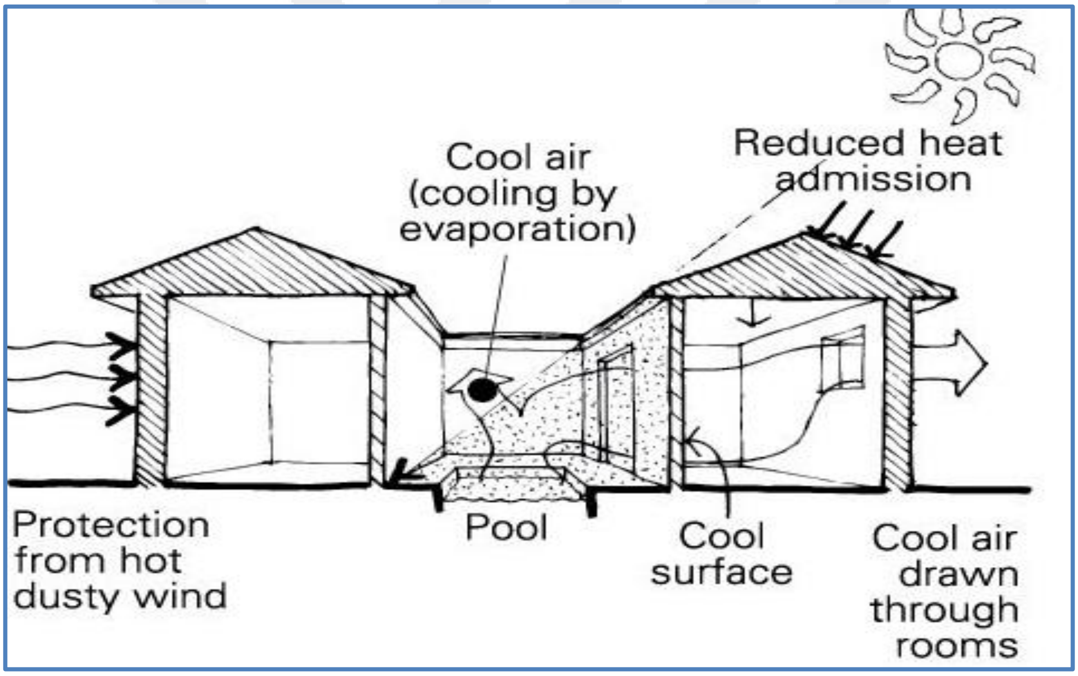


Figure 3.10. How air infiltrates the courtyard (Yakubu, 2019)

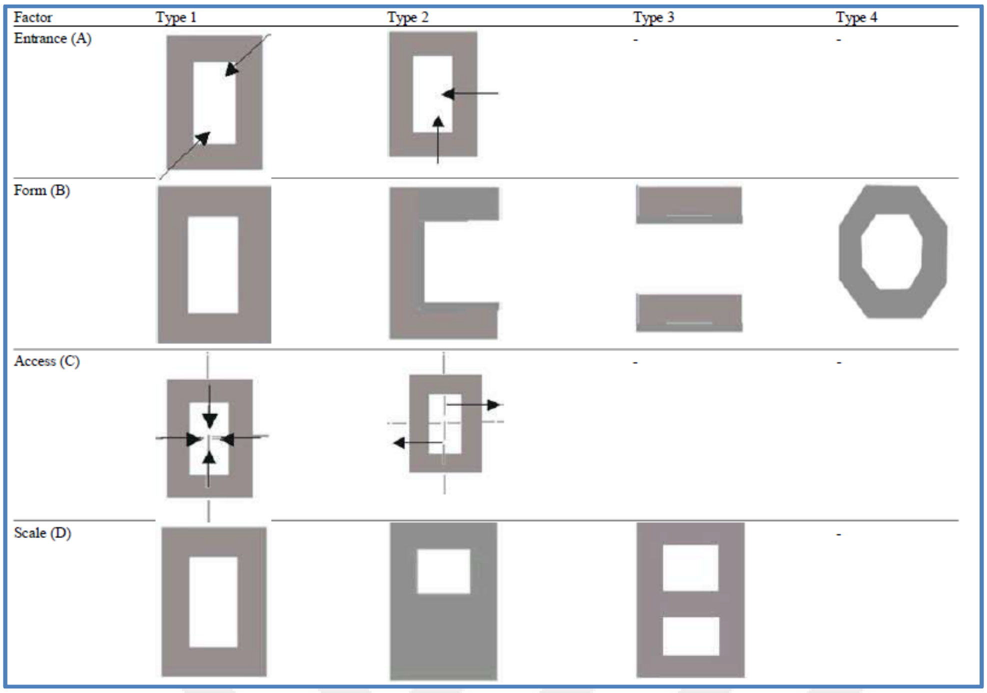


Figure 3.11. Different types of a central courtyard (Mahdavinejad et al., 2013)

3.5.2. The mashrabiya

Mashrabiya is derived from the Arabic term "drink" and refers to a spot where people may drink and relax. This area is a mesh-opening cantilevered space. Water pots were traditionally placed next to the mesh to be cooled by evaporation when outdoor air went through the mesh gaps. Mashrabiya is a common Arabic architectural feature that consists of a window surrounded by wooden latticework on the upper level (H. Fathy, 1986). (Figure 3.12&3.13) illustrates a Mashrabiya of a conventional Baghdad residence.

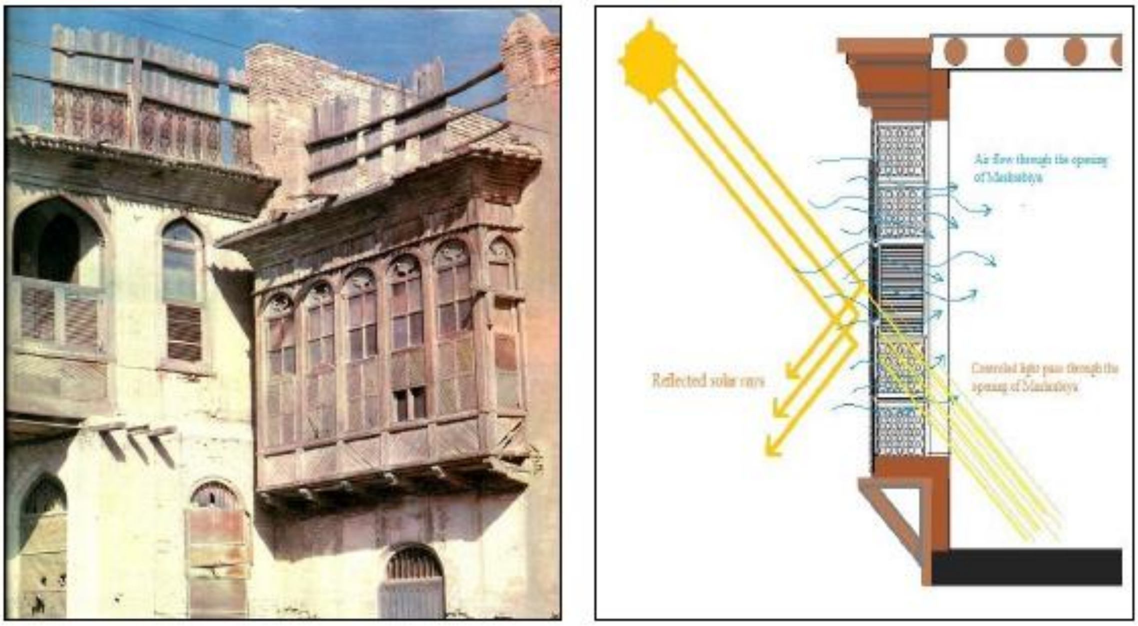


Figure 3.12. Mashrabiya of a traditional house (Algburi, 2018)

The mashrabiya, a typical architectural feature, serves five functions. Various patterns also have been created to meet a number of criteria that call for a focus on one or more of certain features. These functions are;

- Controlling the air circulation,
- Controlling the light that can pass,
- increasing the air current's moisture,
- Ensuring privacy,
- lowering the air current's temperature (H. Fathy, 1986).

As a result, the Mashrabiya element is made to perform almost all of these roles. That Mashrabiya, which is thought to have existed in Egypt since before the fourteenth century, is a traditional way of cooling water as well as an architectural feature that offered both privacy, and shade. Hassan Fathy, a contemporary architect, explains how the various models of mashrabiya were created to meet a variety of requirements or needs in his book Natural Energy and Vernacular Architecture (H. Fathy, 1986).

Figure 3.13. Mashrabiya in traditional house of old Cairo1865 (Internet: hosam, 2015)

The mashrabiya component has been used in a variety of hot climate areas, including Northern Africa and the Middle East, the Western and Southern of Asia especially India, south of Turkey and, and Spain, it is thought that the idea behind this system was used as a climate control feature. Mashrabiya's primary function will be to have privacy. It protects the house residents' privacy by allowing them to sit outside and observe the outdoors without being noticed Since it is made of mesh wood, air can flow freely through the interior space without affecting the privacy of the residents (Mohamed, 2015). It also provided shade from the scorching summer sun while enabling fresh air to circulate. Mohamed (2015) describes the social and religious aims of building the mashrabiya as a space for women to look through while staying unseen, a place where they can observe the activity of the road or the life of the patio without being noticed, in addition to its functional usage. The Mashrabiya's utility was not limited to individual houses, as Feeney (2009) points out in his article "The Magic of the Mashrabiyas." It was instead found in semi-public structures and mosques, Mashrabiya has been used on a much larger scale in that situation, but the intention of conditioning the environment for inhabitants or worshipers remained the same. The Mashrabiya's classification as a local architectural feature appears to introduce its usage as a flat wood box built in the upper floor for airflow. To summarize, the roles or purposes for which the mashrabiya was identified, as an area for cooling the water jars, provide home privacy, lookout the surrounding life, and control climate conditions in the dwelling, seem to be closely linked to this vernacular architecture element.

Traditional architectural types and materials, as noted by Feeney (2009), are a good way of conserving energy and enhancing material resources, which is exactly what the mashrabiya window has provided its residences, as well as public spaces, for centuries. In terms of usability and climate control, the element was effective, but it also performed a role in terms of artistic presentation, cultural, and social. The mashrabiya has fulfilled all cultural and environmental objectives for decades (Mohamed, 2015).

4. TRADITIONAL DWELLING IN SUDAN – KHARTOUM

Sudan is a complex country with over a hundred active languages and approximately 600 tribes. Until the division and creation of South Sudan, Sudan was known as "The Land of Million Square Mile." Sudan achieved independence from the United Kingdom state in 1956, and its climate, which differs from dry climate, arid-hot, in the north to rainy tropical climate in the south, is also another indication of the country's diversity. The major source of life in Sudan is the Nile. According to their position and construction, Sudanese soils are divided into six categories: semi-desert, desert, sand, ironstone plateau, alkaline catena, and alluvial. Because of irrigation problems, there are several local differences (Ali et al., 2019).

4.1. An Overview of Khartoum

Khartoum, the capital city of Sudan comprises, besides Tuti Island, three towns: Khartoum, Khartoum North, and Omdurman. They are determined by geography and landscape along the two distinct rivers: The White Nile and The Blue Nile. Its most significant physical feature, therefore, is the confluence of those two Niles where they form the great River Nile. Khartoum is situated on the left bank and Khartoum North on the right bank of the Blue Nile, while Omdurman is located on the left bank of the main Nile,(Figure 4.1) (Hamid, 2020). This may be regarded as the city's geographical structure. Even so, these three cities can be dated back to the sixteen century as small cities along with the Niles in terms of their growth as capitals throughout history. After the Turko- Egyptian invasion in 1821, their history of significant settlements began in the late nineteenth century (Ahmad, 2000). Khartoum city is a cultural melting pot of Africans, Arabs, and Muslims. Khartoum remained this way till the rebellion of Mohamed Ahmed AlMahdi, who crushed the occupiers, reclaimed Khartoum, and then somehow relocated the capital to Omdurman in 1885. Omdurman developed as a Mahdiist army base and it was later re-planned as a separate city with few large roads, a central marketplace, a mosque, discrete neighborhoods, and offices for the chief and his counselors. These neighborhoods, on the other hand, developed as intimate organic structures in the conventional informal type (Ahmad, 2000).

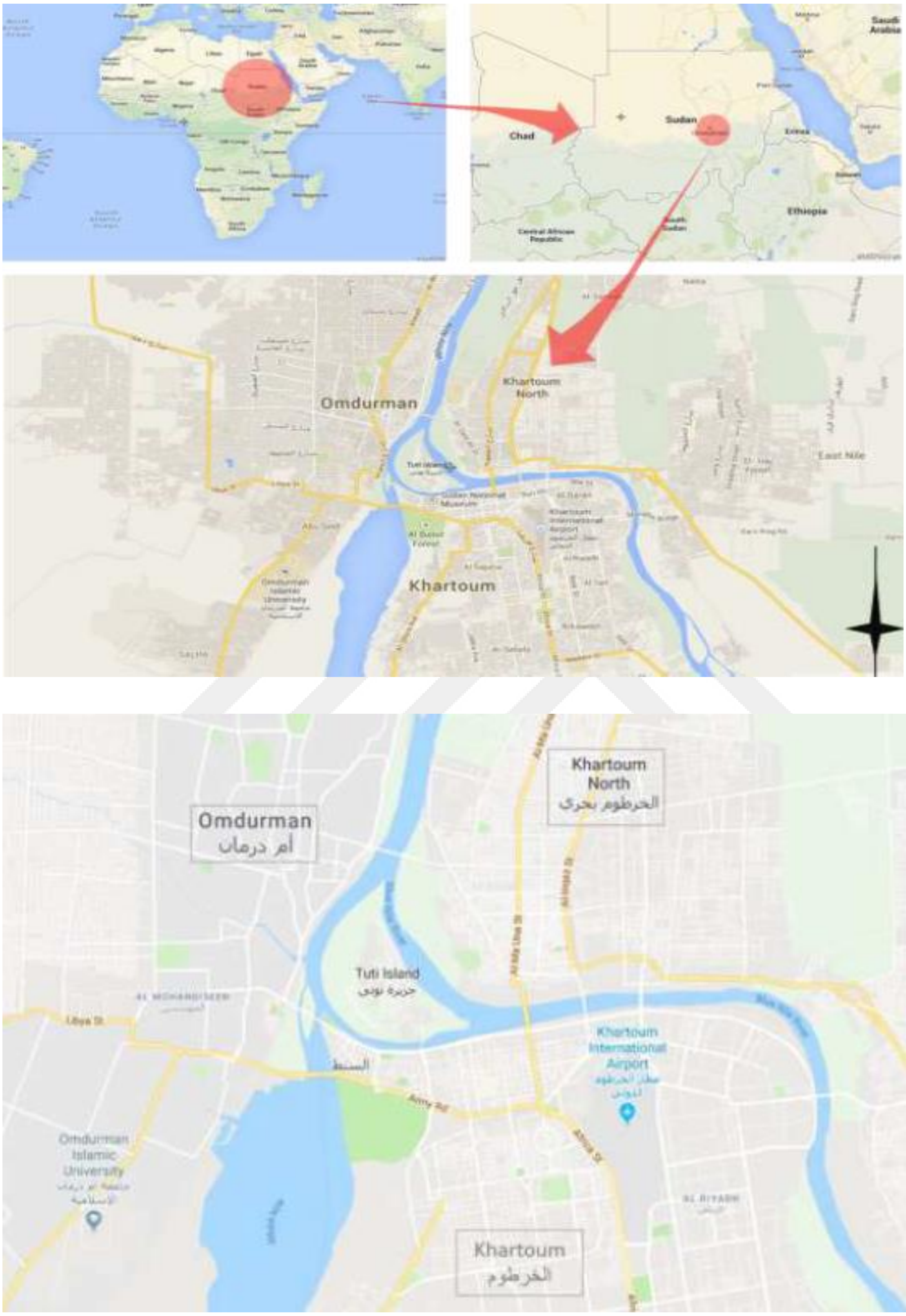


Figure 4.1. Sudan and Khartoum city (Internet: google map, 2020)

4.2. Climate of Khartoum-Sudan

Sudan's climate is desert in the north and along the Red Sea's coast, and semi-desert or semi-arid in the south, which is influenced by the summer monsoon. Khartoum is situated 400 meters above sea level where the White and Blue Niles meet (Figure 4.2).

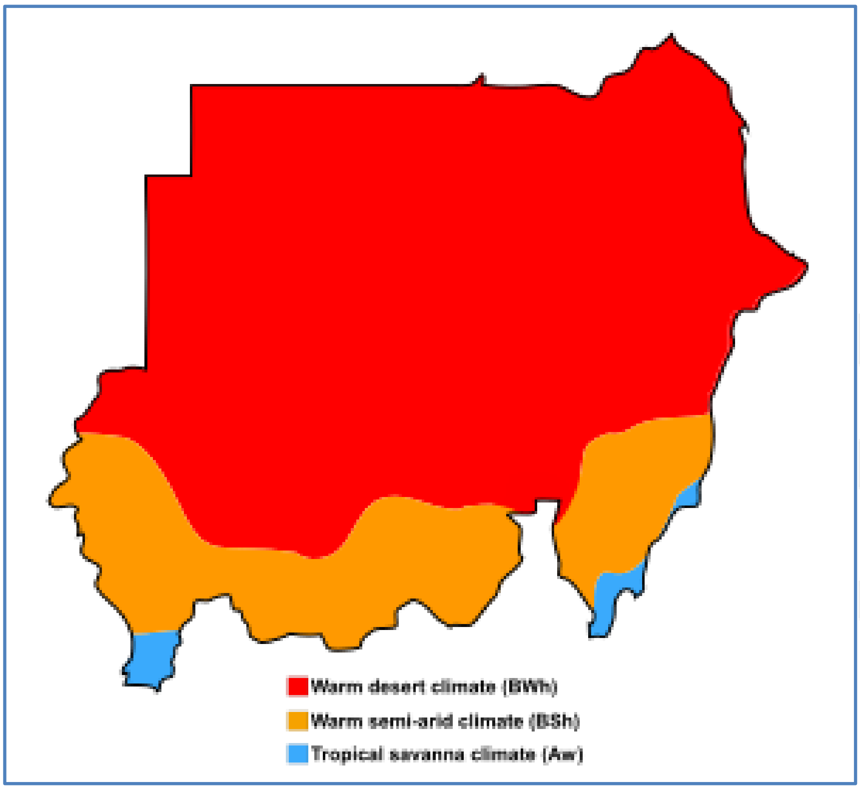


Figure 4.2. Sudan climate zones (Ali et al., 2019)

4.2.1. Air temperature

Khartoum it’s one of the world's hottest capitals. Khartoum's average annual temperature is 30 degrees Celsius. Even in the winter, it can be hot, with a maximum temperature around 31°C in January, but it can also be cold at night. Temperatures rise gradually in the spring, reaching 40°C as early as April; in April and May, temperatures have sometimes reached 47°C (Figure 4.3).

The weather is pleasant in the winter, which lasts from December to January, with temperatures falling in the morning before noon and after sunset. At this time, the temperature fluctuates between 32 and 28 degrees Celsius. When designing city structures, these climatic results must be taken into account.

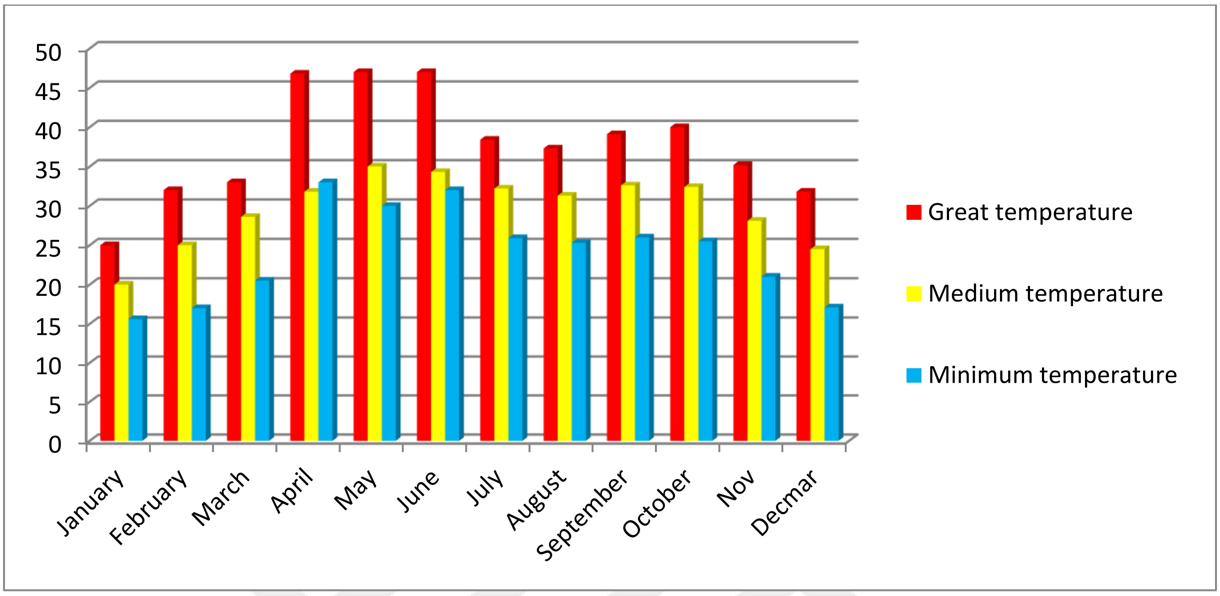


Figure 4.3. Average temperature Khartoum, Sudan (Internet: Wether Atlas, 2020)

4.2.2. Precipitation

Precipitation: The state of Khartoum experiences a rainy season from July to September, with an annual average of 162.2 mm and the highest amount of rain falling between 46 and 75 mm in July and August, (Figure 4.5 & 4.6). On 4/8/1988, Khartoum was recorded 5,200 mm in just one day. The rainy season is characterized by high humidity, and the prevailing winds from south to southwesterly are humid. Winds grab at the start of the rainy season, and the time from late June to early July is characterized by thunderstorms and dust, When a front of moist air from the south sweeps into Sudan's central region, it can cause a phenomenon known as Haboob, which is a sandstorm that moves like a wall with high of more than 100 meters and drastically reduces visibility, (Figure 4.4), (Vicki M. Giuggio, 2018).

Figure 4.4. Sand storms in Khartoum Sudan (Vicki M. Giuggio, 2018)

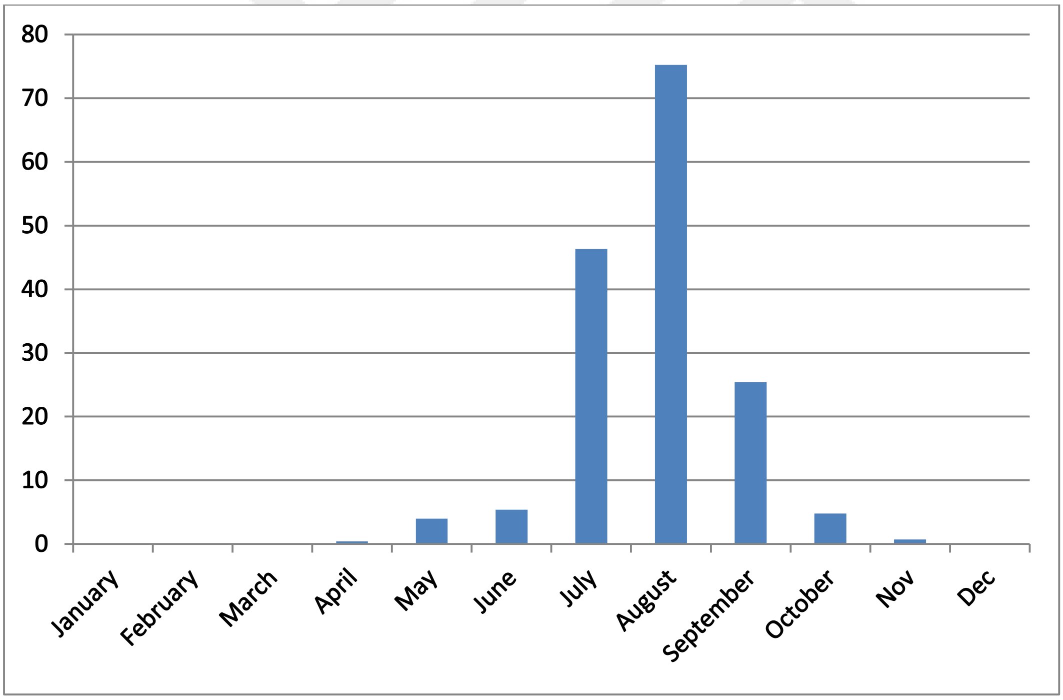


Figure 4.5. Average monthly rainfall by mm, in Khartoum state for the years from 1998-2008, (Internet: Sudanese Meteorological Authority, 2016)

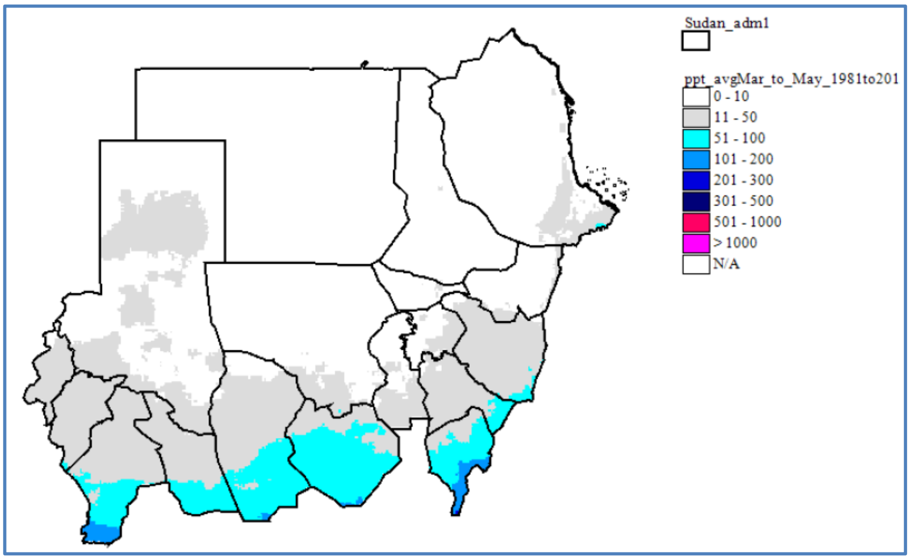


Figure 4.6. Average rainfall over Sudan during MAM from 1981 to 2010(Internet: Sudanese Meteorological Authority, 2016)

4.2.3. Relative humidity

During the year, it averages between 16 and 49 percent. The highest relative humidity in the early morning during the rainy season under the influence of the humid southern winds can reach more than 85%, while the minimum during the months of March-April under the influence of the Dry North and Northeast winds can drop to less than 10%, (Figure 4.7).

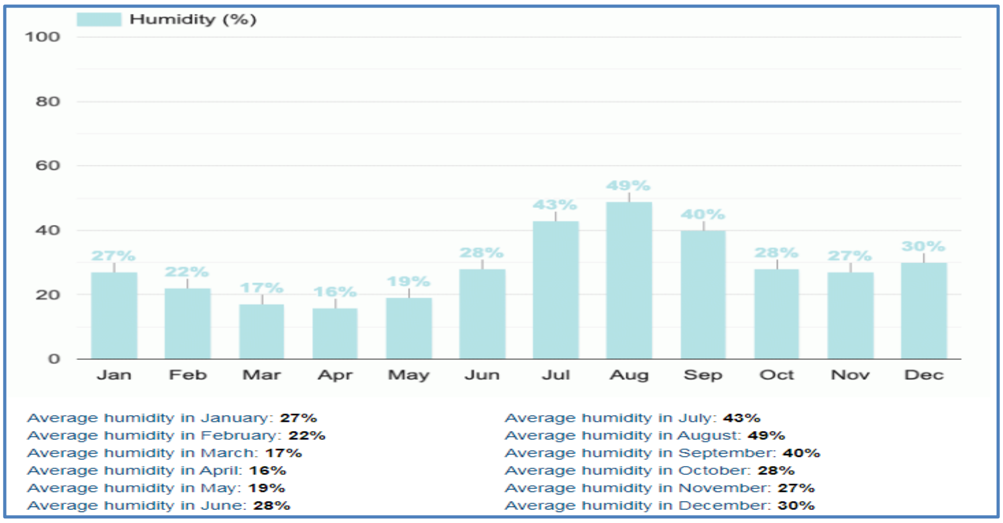


Figure 4.7. Average humidity Khartoum, Sudan (Internet: Wether Atlas, 2020)

4.2.4. The wind

The prevailing winds are mostly north-south (Figure 4.9), with speeds ranging between 14-17 km/hour and may increase to 45 km/hour when cold air fronts pass. During the rainy season that starts early in June and extends to September, the prevailing winds are south-easterly to south-westerly, where the speed ranges between 3-47 km /h, and the speed may sometimes reach 70 km / h when thunderstorms and dust storms occur, which may cause damage to the Electricity lines, communications, uprooting of trees, destruction of some homes, and transfer of waste from the southern outskirts to the center and north of the state (Figure4.8) (Internet: Wether Atlas, 2020).

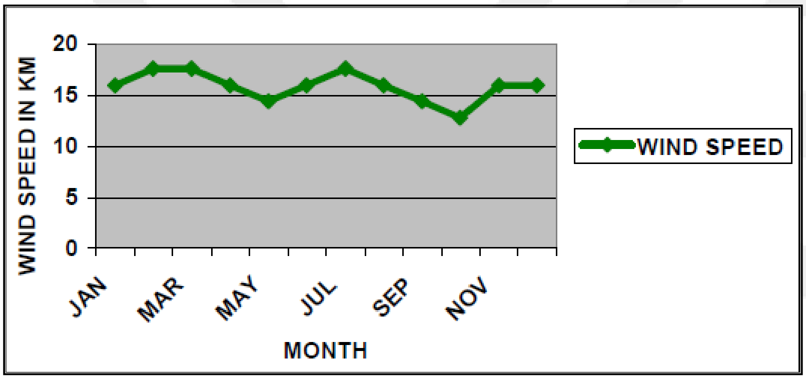


Figure 4.8. Khartoum wind speed (Internet: Wether Atlas, 2020)

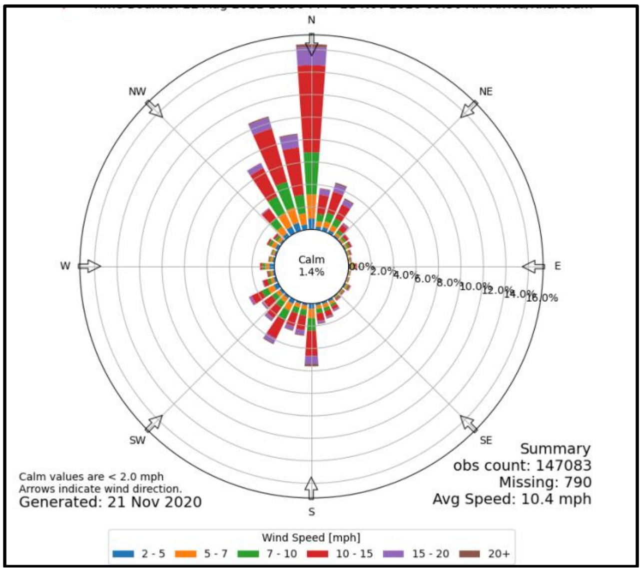


Figure 4.9. Khartoum wind direction (Internet: Iowa State University 2020)

4.2.5. Solar radiation

In the summer, solar radiation in Khartoum exceeds (1000 watts / m2) in horizontal spaces and fields, while the vertical field in the east and west can exceed (800 watts / m2), and the vertical field opposite the south side receives more than (500 watts / m2)(Abdallah et al., 2012)

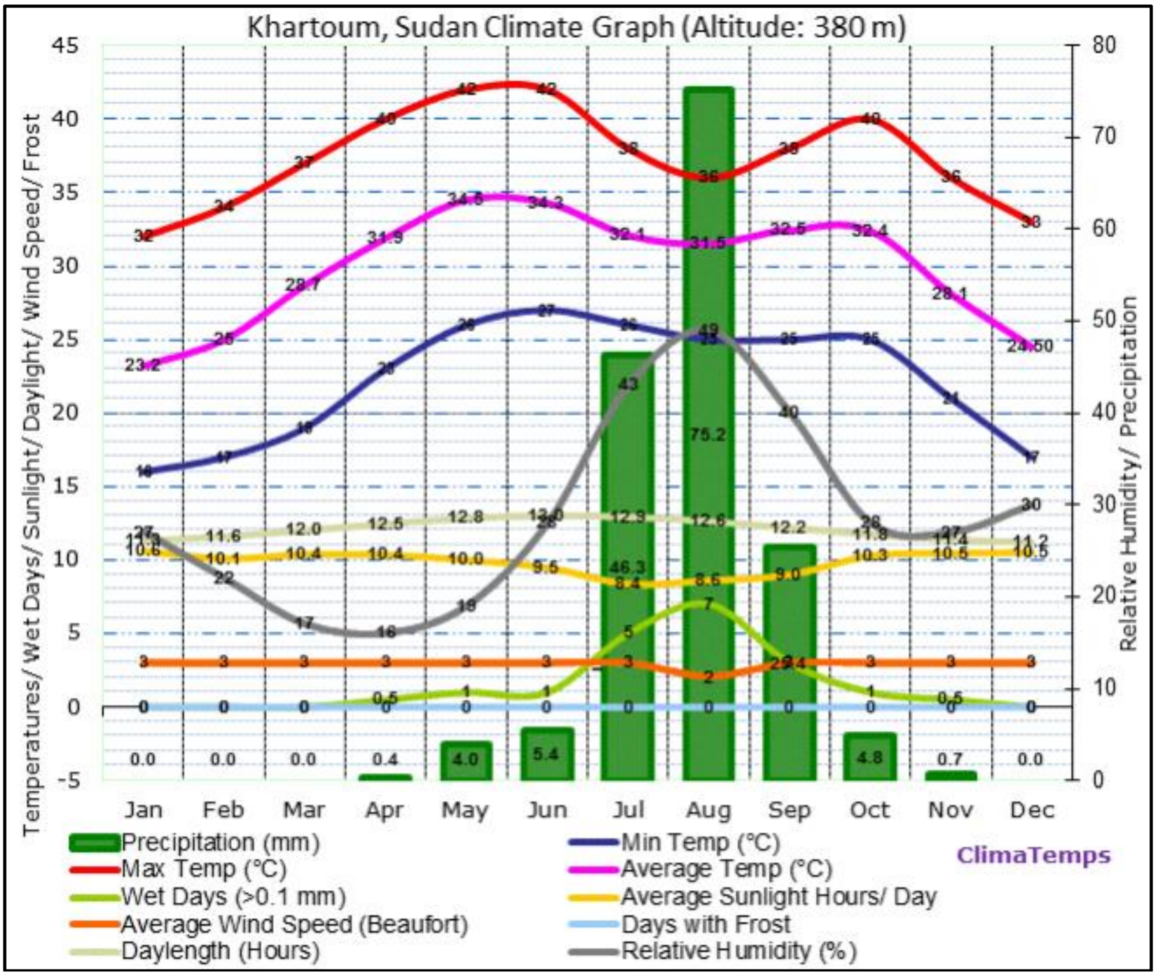


Figure 4.10. Khartoum, Sudan climate graph

4.3. Demographic of Sudan

Sudan's demographic has grown by 49.5 percent in the last 25 years, reached 41 511 526 million in 2018, with a 2.8 percent average growth rate. It is assumed that Sudan remains predominantly rural by an estimated one-third (34.6 percent) of the total. The population of Sudan might be double in 16 years if this rate of growth continues. Sudan's demographic pyramid is young and increasing, suggesting that it is of the expansive kind. Around 3% is over the age of 65, 41% of the population is under the age of 15, and 56% is between the ages of 15 and 64, according to the population distribution,(Figure 4.11), (Ali et al., 2019). Because of the health and economic systems, life expectancy is short. The bulk of the population lives in two climate regions. The hot dry region is home to 52 percent of the population, while the hot semi-arid region is home to 48 percent. The tropical savannah region is home to just 0.04 percent of the population (Ministry of Health – Sudan, 2017).

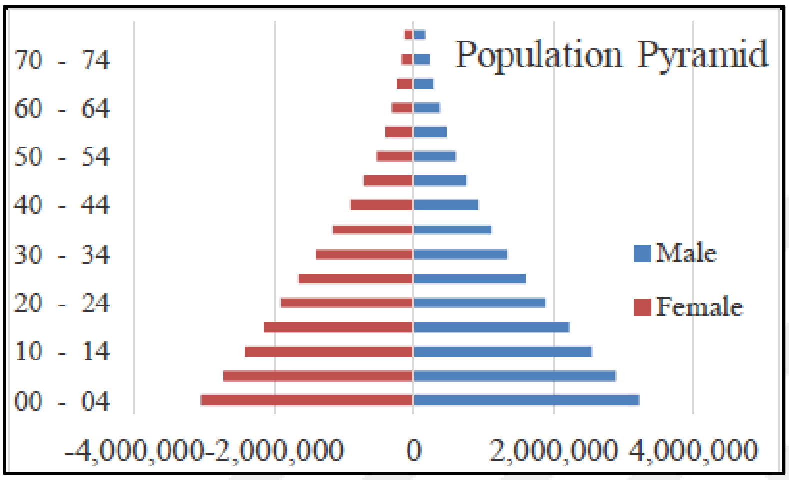


Figure 4.11. Sudan population pyramid (Ministry of Health – Sudan, 2017)

4.4. Dwellings' Tenure Classify in Sudan

Most of the Sudanese people either live in agricultural-scheme authorities or their own homes or rent from landlords. As seen in Figure 5, housing can be divided into four categories based on tenure status: free dwelling, rented, owned, provided as part of work. Figure 5 indicates that the overall of homes, around 86 percent, are owned, while accommodation offered as part of employment has the lowest value. The government isn't doing anything to help people find affordable homes.

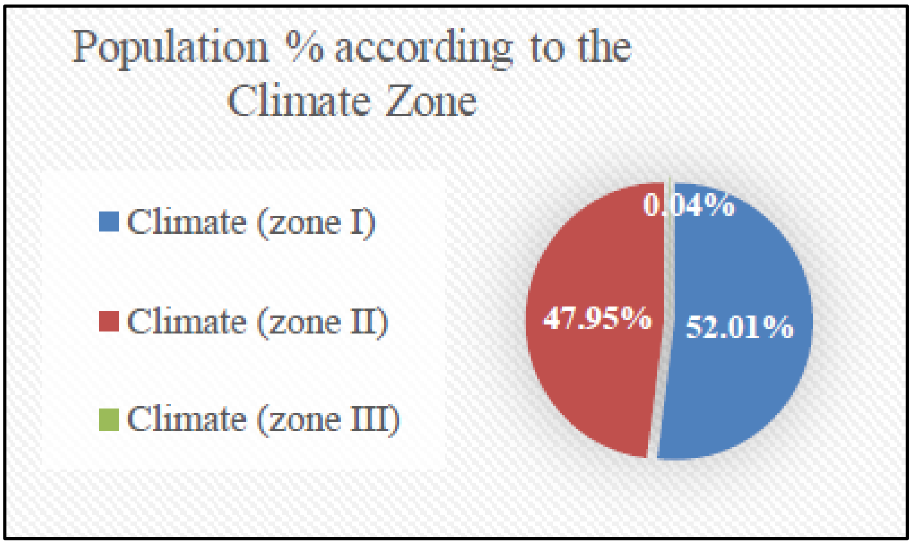


Figure 4.12. Population percentages according to the climate zone (Ministry of Health – Sudan, 2017)

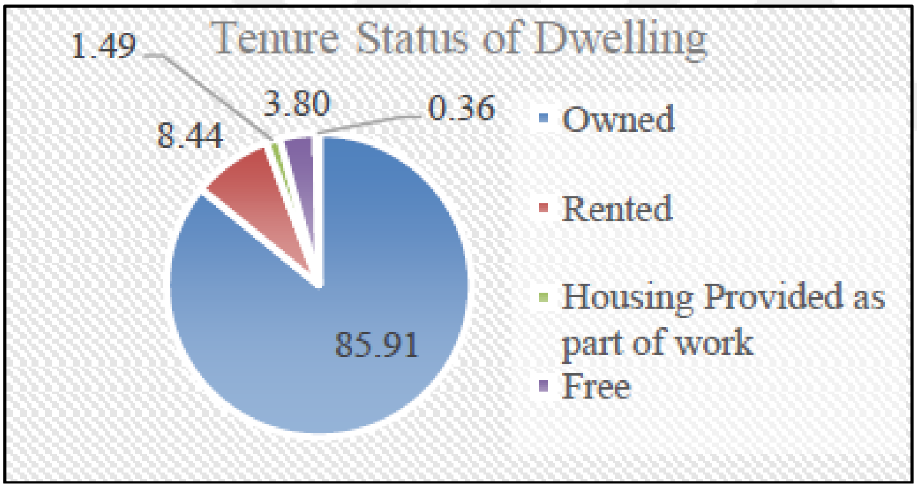


Figure 4.13. Dwellings' tenure classify in Sudan (Central Bureau of Statistics Census (CBS), 2008)

Table 4.1. Buildings types in Sudan (Ali et al., 2019)

Construction Time	Temporary	Single Family Dwelling Detached			Multi-family Dwelling
		Climate Zone I (warm desert climate)	Climate Zone II (warm semi – arid climate)	Climate Zone III (tropical savanna climate)	
Very old (1900-1950)[1,2]		 House of One Floor Mud (Adapted)		 Tukul/Gottiya Mud	
Old (1956-2000)[3]	 Tukul /Gottiya Sticks	 Tukul/ Gottiya Mud	 House of One Floor Brick/ Concrete	 Dwelling of Straw Mats  Wooden Dwelling	 Flat or Apartment
Modern (2000- till now)[4]	 Tent  Tukul /Gottiya Sticks	 House of One Floor Mud	 Villa		 Multi Storey House

[1] Early Colonial Architecture (1900–1920) [2] Late Colonial Architecture (1921–1956)
[3] The Post-Independence Era (1956–2000) [4] Architecture from 2000 onwards [19]

4.5. House Types and Dwelling Forms in Sudan

The main influence on the organizational arrangement of domestic space in a neighborhood or the individual houses is the social system. Various loci inside the houses have variable levels of priority allocated to them depending on similar roles. Dwellings have long been viewed as social models. They are often seen as transmitting social order from one generation to the next; they create boundaries and hierarchies that reinforce a culture's fundamental values. The value of each of these individuals, and therefore power relations, within a society, is maintained by house designs (A. Osman, 2005). There is a shortage of knowledge about traditional houses throughout history. The attention is often on royal accommodation, palaces, large public structures, and religious buildings, as is common in historical background and architectural historical writings. It seems that there was traditionally more variety and sub-division of usable space than there is in contemporary house styles, depending on what details may be collected, such as plans or images of houses that have not been evaluated or published. Shinnie defines a Meroitic house with a two room layout that repeats itself. The fireplace and cooking pots have often been located in the main room, indicating that almost all operations took place here anyway, the smaller room seems to have served as a shop. This feature was found in a number of buildings, leading to the conclusion that they were the dwellings of large extended families or small households. Housing became less compact as time progressed (Shinnie, 1967). This remains a feature of Sudanese towns and villages today, unfortunately. The House categories are categorized in accordance with socio-cultural patterns; historically, we can classify them into three categories;

- Conventional architecture,
- Colonial,
- Hybrid dwellings.

The conventional dwelling evolved as core units (People used to begin the construction of a house by constructing a room known as one core-room unit), from the Guttia (structure with a conical shape) to a square shape. To build the family house, additional rooms were added until it reached the forms which are already in use. The Rooms were traditionally arranged in a courtyard 'hosh' to form a structure that applied to the way of life and maintained socio-cultural values (Taha, 2005).

Much theoretical writing on rural housing makes the tacit inference that poverty and the fight for survival will mean that the poor's households, particularly those they have constructed for themselves, will respond primarily and also only to the fundamentals of shelters. In general, this poor home is the highest concentration of a community's power and culture. It is a location where a variety of life events take place that are both socially productive and meaningful. It is evident that the residents' simple spaces are filled with values and qualities that represent people as individuals as well as members of larger socio-cultural communities. Kellett also believes that anyone wanting to learn about either of these poor residences must first know the formation processes.

The vernacular traditional house in a Sudanese village takes multiple forms within the hoshes (courtyard), but housing development usually starts with a central unit. Each economic group of residents has its collection of forms. While the vernacular models of tradition begin with a central unit, the author is going to study the form of housing as a model for housing growth throughout the times, and the history of the government houses, which were profoundly influenced by the European people. The changes in space happen as a result of changing activity patterns (Taha, 2005). Physical changes are often related to the socio-cultural changes that have occurred in the villages, as evidenced by these design adjustments. Here, we'll focus at forms that have influenced conventional organic forms, such as Guttia from the east and west, mud houses from Sudan's north, and colonial housing.

4.5.1. Guttias form

As many African people migrated to the region after the agricultural scheme was established, the African Guttias (huts) had been commonly used. The rooms were usually constructed on a circular plan with thatch or mud walls and a conical thatched roof, with an internal diameter of three to five meters. The Guttia could also be constructed on a square base with a very pyramidal thatched roof. The Arabs in Eastern Sudan are familiar with this Guttia type. This form of Guttia is still used by the temporary farmer who comes for a short time, but they do so outside of the conventional village, generally on cultivated farms. Local materials like wood and even certain crop stems, particularly dura stems, were used by the residents. Houses in this form were constructed close to each other. Actually usually, the local farmer simply provides the straw, and then the residents start building the Guttia. The Guttia form was planned and constructed in a very simplified way. The use of basic local materials reflects its versatility and simplicity, as well as showing the culture of local building and materials. Thatch Guttia was built in a circle form with no threshold or foundations. A structure of divided acacia wood poles placed in the earth serves as the foundation. Foundation holes are dug in a basic way, 60cm depth and as wide as required to match the wood post, with the rest of the holes filled with earth. The platform's firmness was maintained by a framework of all posts that were linked together to form good stability. The horizontal and diagonal braces are then tied to the vertical pieces, ending in a very strong wall. The poles that support the roof are arranged asymmetrically around the structure. The bulk of their spacing seems to be practical. The various features and forms of the Guttia (hut) are depicted in (Figure4.14), (Taha, 2005). Mud Guttia were built from mud walls and a thatched roof with a conical shape. The foundations also were very simple, with trenches dug 60cm deep, and the thickness of the walls was generally equivalent to 35cm. The Guttias' floors were created from earth.

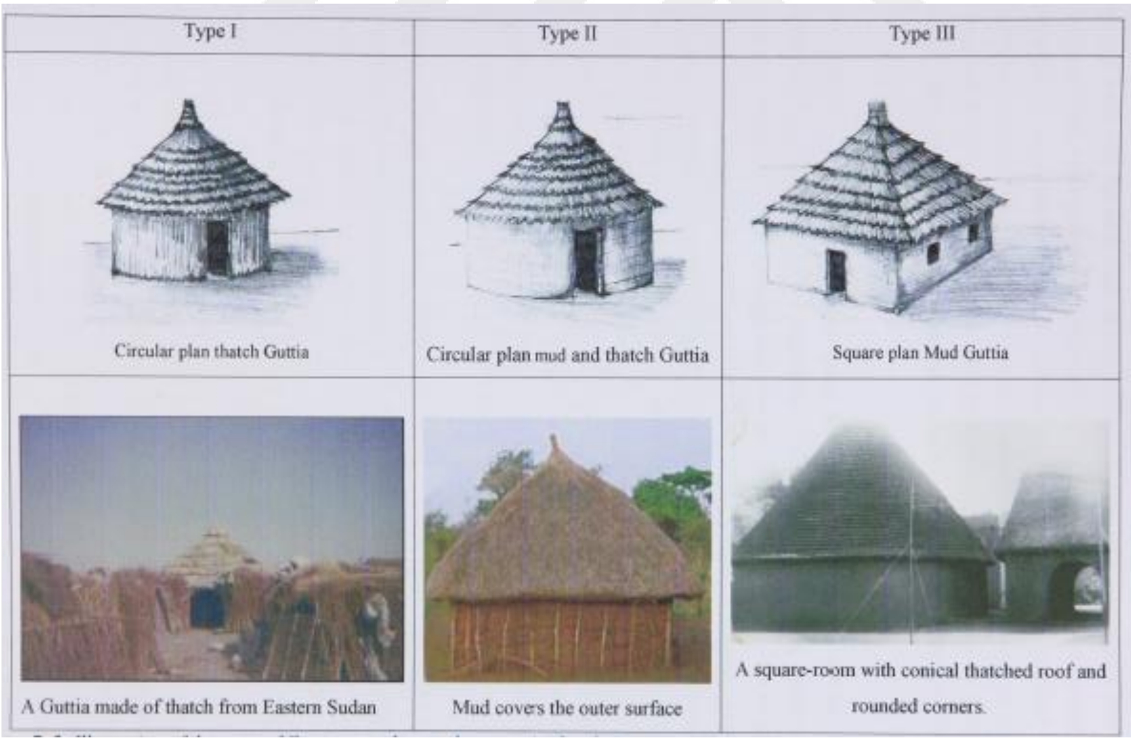


Figure 4.14. Various forms of the Guttia (Taha, 2005)

In most cases, the Guttia has only a single entrance. The squared plan shape is made up of four walls with ventilation windows on the north and south sides. The design of the Guttia had such a major impact on British designers who work for the Gezira Board; they used the same forms and redbrick materials to build huts for the Gezira Board's low-income staff.

4.5.2. Mud houses forms

The Mud houses are widespread in Sudan, and the term is used to refer to any structure with mud walls and flat roofs made of wood, thatch, and clay. The Mud buildings first were introduced along the Nile River in Sudan's Gezira district, in which there was a large Arab settlement. The circular plan form was overshadowed by a mud room unit with a flat roof and a square plan after irrigation was founded in 1925. The design of the mud house is identical to that of Arab houses along the Nile's banks. The mud houses might just be; a separate room, a room with a sunshade and storage, two rooms attached, or two rooms with a veranda.

Sun-shading techniques are still widely used. The Shaded areas are usually attached to the front of the dwelling, and a store is normally added to the back side. A slanting lean-to roof, sometimes in the shape of a wood roof or timber structure supporting straw, sorghum stems, or cotton stems, is usually added to the East end of a room, (Figure 4.15). Another way to provide shade is to build a rakoba, which is an isolated structure with mud columns supporting a cover of straw or cotton stems finished with clay, (Figure 4.16).

The square plan usually has one door and four windows and provides a space of approximately 4.6m2. In the 1940s, these rooms became extremely common, quickly displacing all circular-plan rooms. The mud walls are supported by thinner branches that contain a layer of earth and straw to shape the roof. There were also other room types, including the storage room (4.6m x 1.20m) usually linked to the western side of the room which serves a dual purpose as storing valuables, and protecting the west-end wall from the rays of the sun, which have been extremely hot in the daytime. Perhaps these types are replicated in one hosh (oppen area inside the house), as the family demands, and the financial situation consolidates them. The family's size had a huge effect on the unit’s number that extended family will need. That form of mud housing that remains amongst other houses has been transformed into a Gishra house (what is called here hybrid-dwellings). This transition is profoundly influenced by the position and scale of the family. This form of residence is often maintained within the new construction of a home. It can be noticed that was the traditional home form in Sudan villages, but now almost decreased, (Figure 4.15 &4.16).

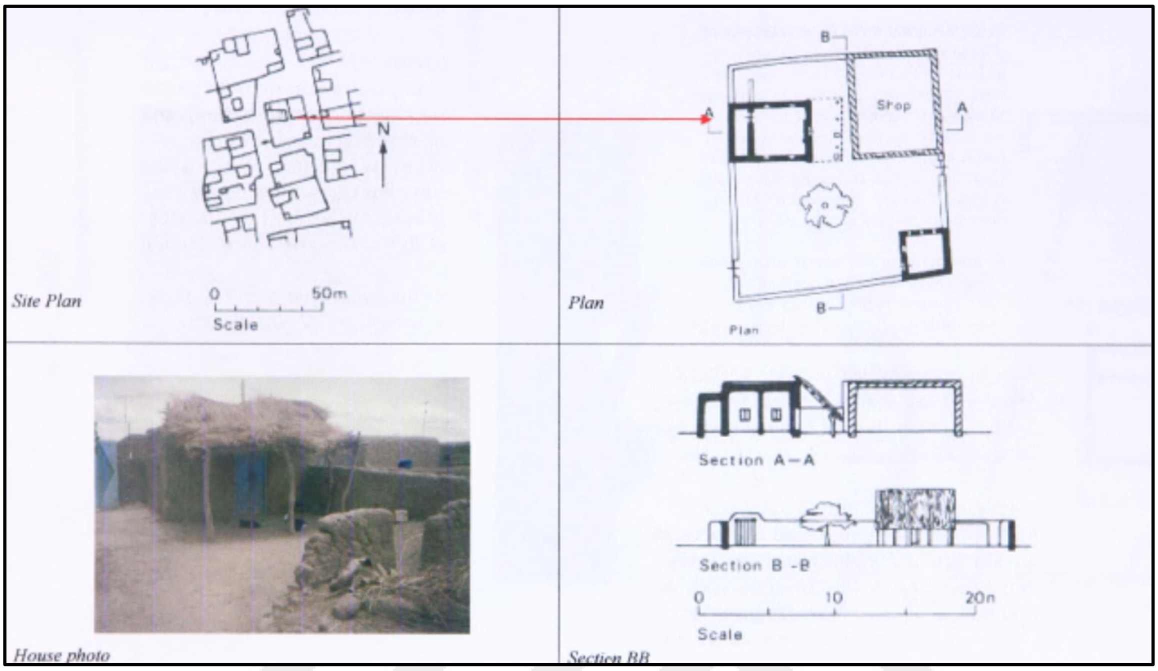


Figure 4.15. Traditional mud house form (Taha, 2005)

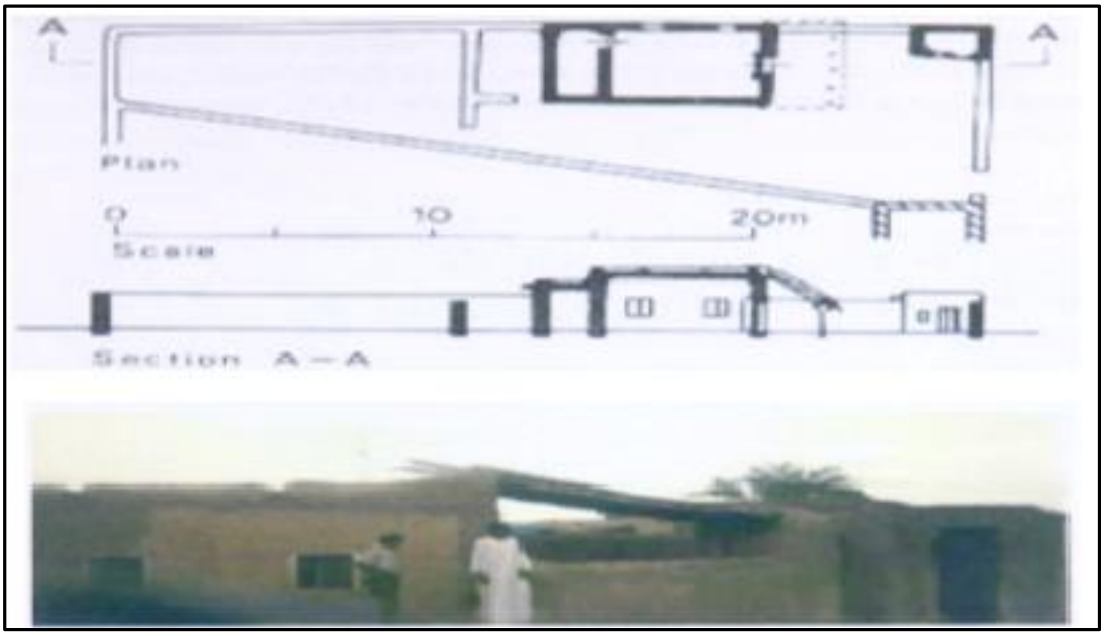


Figure 4.16. Section and view of a traditional mud house in Sudanese village (Taha, 2005)

4.5.3. The colonial house form

These houses are built by the local governments, especially for those impacted by the socio-cultural structure, and they contained of two different income group; low-Income group House forms, and other Income group House forms;

Low-Income group house forms

The staff' and lower rank officials' houses contain essentially circular rooms clustered around a patio or in the patio. The round unit was built and a smaller room and square kitchen house was then built for a small low-income family, and for larger families, four round rooms were built. The room was 3.6 square meters in diameter, and the kitchen area was 4 square meters in diameter (2x2m). The plot area was 196 square meters which is (18x12m). The bathroom or W.C seems to have been added to the family's house later.

There are three rooms facing the courtyard in the four-room houses. The fourth room (Figure4.17) is exposed to the outside, and it was used to ensure the privacy of the courtyard and in the same time used as a majlis (sitting room for men). The trenches are filled up to the depths of 60–80cm and the foundation is surrounded by a two-brick wall, then a brick wall (one and half) is built over the foundation, and the conical roof is made of cement mortar brick. Sand has been compacted to form the floor.

The Guttia provided the inspiration for the design. It reflects the colonial heritage and Guttias' association with conventional and international thought by using redbrick a conical roof and round walls made of red bricks instead of local wood and thatch walls and roofs.

The constructed areas appear to be limited in comparison to the size area of the plot; around a quarter of the total land area, that making the remainder open for people to expand on, but people's feelings of irresponsibility against the house prevent them from doing so. Because of the static shape and the rules preventing citizens from making major changes to the structure, the houses have preserved their natural structure.

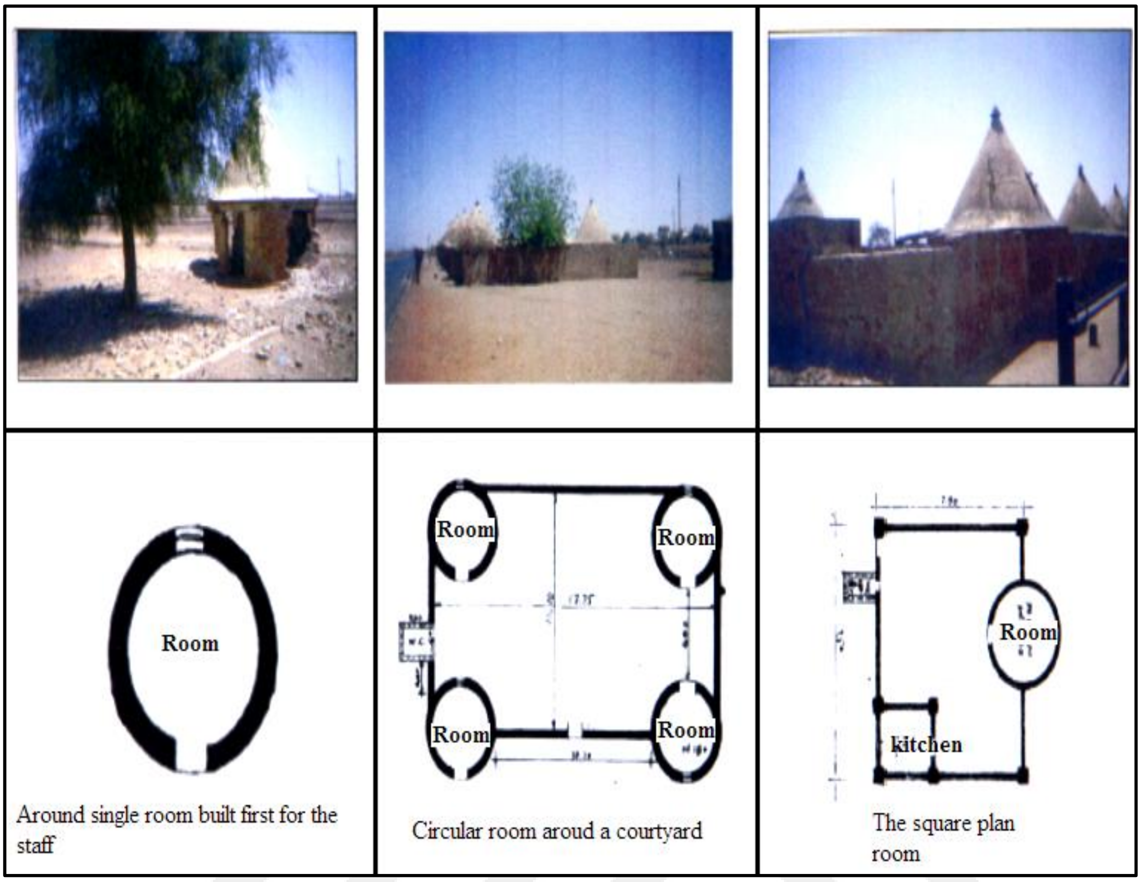


Figure 4.17. Different types of traditional houses that were built by the local governments for the low income groups in Sudanese villages (Taha, 2005)

<u>Other income group house forms</u>

At the launch of the Gezira agricultural scheme in 1925, the high and medium income community houses were mainly constructed for the British rulers. These houses consisted of square rooms framed by a wire-mesh veranda and are sometimes built on a large ranch the rooms are indeed open to each other. The dining room or sitting room was in the center of the building connected to two other bedrooms with two different toilets. The wire-mesh veranda helps to keep insects and flies out of the building while still allowing fresh air to circulate. The rooms were designed for family use in such colonial buildings with a different level of privacy (Figure.4.18). The floors are made of cement tiles, and the roofs of the two dwellings (Figure.4.18) are made of corrugated zinc sheets or roof tiles. To stabilize the slope to remove rainwater, the roof is made of a jack-arch system filled with sand mortar. The foundation trench is normally one meter deep, and 80cm wide, that foundation was built from concrete. Many houses were built with 1.5 redbrick walls. The roofs were constructed of wood panels with either clay tiles or slates. The dense trees that surround these buildings have a significant impact on the weather. These houses have windows that open north-south and make cross ventilation through their 80 cm x 150 cm windows. To keep insects away from the inside, a wire mesh framework is added to the outside windows' frames. The British model has been adjusted to fit the local officials' socio-cultural lifestyle. To offer the family some privacy, a patio (hosh) was attached to the back of the house. This desire for protection can also be seen in the turning of the fences to thick walls and the use of curtains to hide the interior of the wire-mesh system. The designs for houses constructed after independence show certain changes made to the traditional model of houses built before the independence of Sudan. The courtyard or hosh has been introduced to the layout of such homes to separate male visitors from the rest of the house, and to provide privacy for women, (Figure 4.19). Due to a higher number of visitors, the designated dining or sitting area has a dual purpose: it is used for family members as well for the frequent visitors. Two doors, one from the bathroom and the other directly from the dining or sitting area, link these rooms with the rest of the house. Bathrooms with two doors and two toilets were also designed to confirm the importance of separation. Traditional housing units, which offer more privacy and different divisions of the lineage, result in physical area transformations as a consequence of structuring sociocultural connectivity and communication, as well as building changes (Taha, 2005). The changed forms here may be any shape created by a community within a multinational environment, such as the Gezira district in Sudan. Those colonial buildings were changed either by construction in (Figure 4.19) or structural improvements such as the covering of wire mesh with cloths and the addition of boundary walls. In the Sudanese architecture Algezira settlements' ethnic intermingling produced an open ended design process; how the experience of these types changes conceptions of the type of house structure and influences social interaction should be of great importance to designers and planners. The traditional organic settlement of today is still formed by the method of adaptation and modification. The photos in (Figure 4.19) show the various types of housing that were constructed in the Farmhouses village in Sudan during the different generations of development. They display the various models that were created to accommodate two different income levels. They also illustrate the improvements made to both the colonial house and the architecture (Figure 4.19) designed by the Sudanese community, including curtains to the current building and the installation of walls.

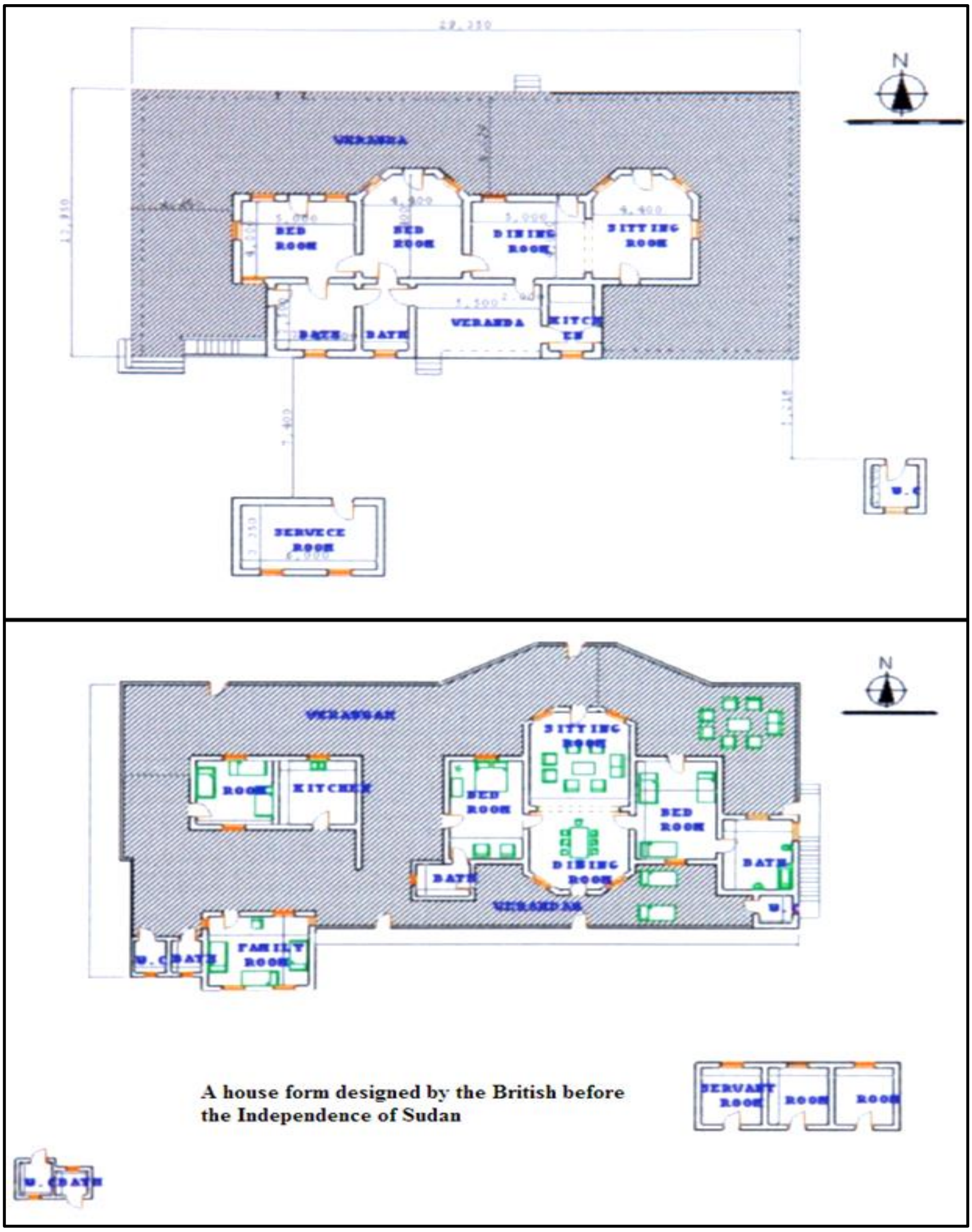


Figure 4.18. Various designs of traditional houses in Sudan: a small house for middle-income families and a big house for high-income families (Taha, 2005)

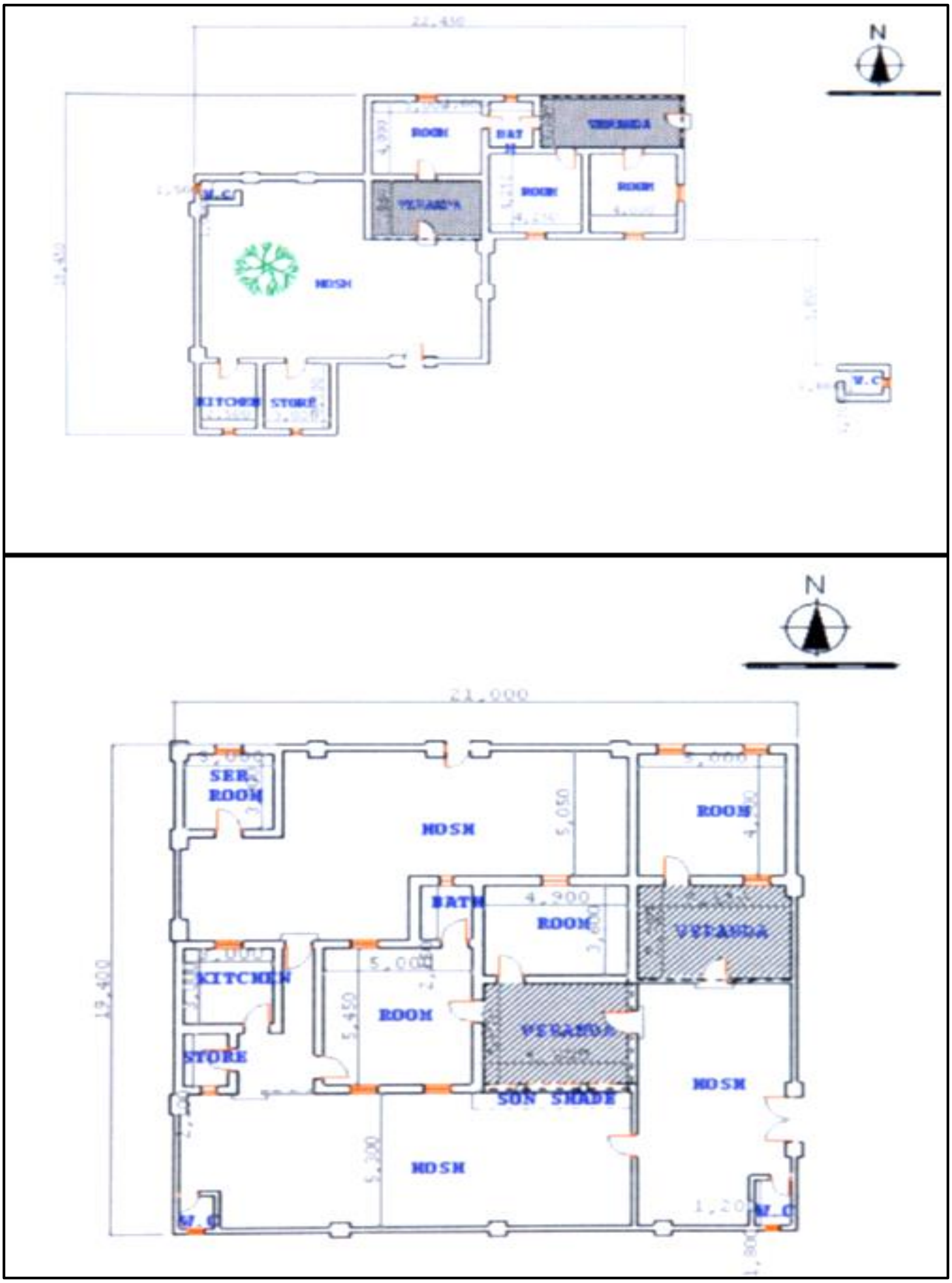


Figure 4.19. Two traditional houses after independence of Sudan: a small house for middle-income families and a big house for high-income families (Taha, 2005)

A large colonial house

A large colonial house

A medium colonial house

A medium Colonial house

A small Colonial house

A modified design for a colonial model

Figure 4.20. Different types of colonial housing (Taha, 2005)

4.6. Organization of Space

4.6.1. Size of the dwelling

The unit volume and the built-up floor area signify important aspects of the present housing phenomena including materials used, building costs, crowding at villages and residential levels, room understanding and usage, and also socio-cultural significance in general, are embedded in the elements of a dwelling (Awotona, 2018). The bulk of building sites in the traditional village and its expansion are over 500 square meters. Low income families have been allocated plots that vary in scale from 200 to 400 square meters. Due to the rise in population, the traditional village in Sudan was distinguished by the cramped existence of its dwellings. Each household had a small area. Since the hoshes were constantly split among the extended families, the residents had to stretch themselves inside these limited spaces. Families have nearly reached the necessary floor areas, with just a few spaces remaining for potential construction in small homes, as demonstrated by the characteristics of existing hoshes. Another aspect that affects the floor area is the family's financial condition. Building a diwan (big reception for the men), for example, is out of reach for low income families. About the fact that courtyards are necessary for some domestic operations, the relationship between socioeconomic factors and economic facilities continues to shape the shape of the hosh. Only through the family members and their financial capacity will the conventional households achieve their floor capacity. Weather has a major impact on the floor space and people's sleeping patterns. The hot dry climate, in particular in Sudan, tends to make intensive use of external spaces, especially at night-time, (Figure 4.21). A significant portion of the open area is normally allowed to do such domestic activities. Family home rooms are generally used in these situations, in the evening.

The residents end up using the verandas, shady areas, and, oftentimes, a shadow of a tree throughout the day. Compared with the sleeping habits of the British the colonial houses in the village of Farmhouses have certain features, although they prevail in the same condition. For sleeping at night and sitting during the day, the British used wire mesh covered roof terraces and wire mesh verandas, (Figure 4.21). The free space and floor area allocation have an influence on the building architecture. Air conditioning and cooling methods in Sudan's village housing have now been added. The cooling and air conditioning systems have now been added to Sudanese village dwellings.

Figure 4.21. Sudanese Hosh for night sleeping (left), veranda used for sleeping during the day-time (right), (Internet: Nazik Yosif, 2011)

4.6.2. The core room units

Within the hosh, the core room units were built, and then other units were added to form the appropriate home. In Sudanese villages, this form of housing construction through a core unit is still followed. People constructed their homes in steps, including in the recent expansion, for the following logistical reasons;

- This form corresponds to the family's requirements. They typically build housing extensions whenever a family needs additional space to accommodate the development of their family. Which demonstrates that the room and materials are handled with respect and meaning.
- This method often helps a family to configure their living room depending on abilities and their financial condition. Since the central government does not assist in housing provision or development, this form of planning has proven to be effective in providing residents with proper homes.
- Usually, individuals assist with the building process. When a family wants to build a home, they ask the villagers to help, and they agree on a date and how the construction will be done. As a consequence, social cooperation decreases construction costs. It appears that the core unit structure allows those who enter this process to schedule their time and select people with skills that complement the kind of work that needs to be completed.

That form of the building has recently been modified to a highly advanced technique that forces people to use other construction methods. (Figure 5.22) represent the steps and types of forms that evolved over the years in the Sudanese village and its expansion, which leads to the current organic forms and had an impact on colonial architects when they first suggested to provide homes for lower social class workers. They constructed round rooms to resemble Guttias (huts) with thatch and mud walls. The organic dwellings were created as a result of the core room units, which were characterized by their adjustment to the residents' socio-cultural behavior, and simplicity, in order to satisfy their daily needs. According to their financial capacity and the number of relatives who could assist, the residents normally began construction with one of the core room units shown on (Figure.4.22), first and second examples), then, as the family's needs increased, the dwellings expanded as well.

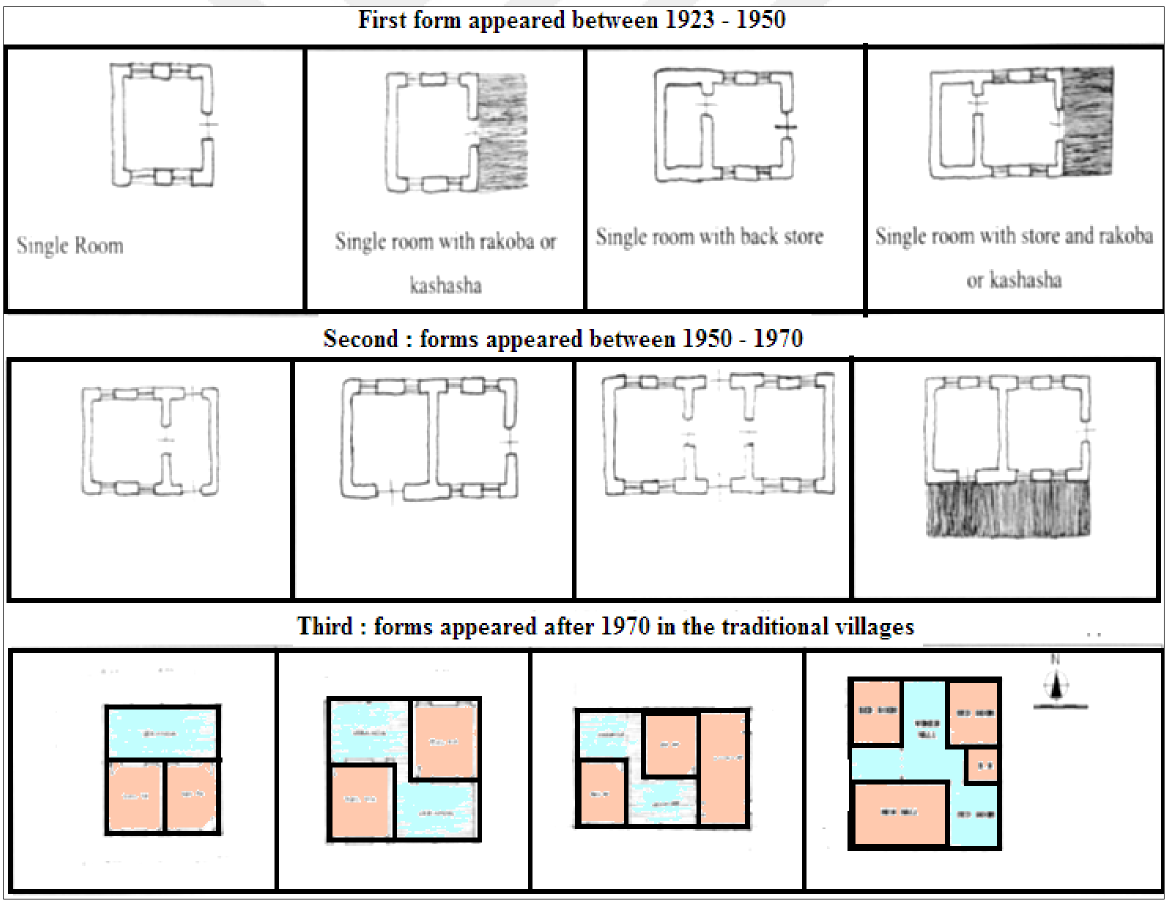


Figure 4.22. Tradition forms of core room units (Taha, 2005) edited by author

4.6.3. Traditional organic houses development

The conventional organic house typically goes through many stages of construction based on the family's requirements and financial condition. According to the space analysis of these dwellings, the homeowners begin with a core room unit and progressively raise the number of bedrooms as the family expands. (Figure.5.23) illustrates the various steps of construction of a traditional Sudanese village home, starting with two rooms with veranda, then adding more two rooms with veranda, and eventually reaching the step of the diwan (men’s reception room).

A piece of the land has been left empty for future expansion. This form of planning contains two features, first, it allows families to assist each other in the work of building a house, and secondly, it addresses the family's financial condition.

As previously mentioned the family's income is low and is dependent on fanning income, which often is not a primary influence in house building but does help it. In this case, sociocultural influences have a significant impact on home making by teamwork and financial help. As a result, there is a link between, economic, social, cultural, and architecture space development in Sudanese villages. To regulate construction in the traditional village, a system of building regulations and planning was introduced after 1970.

Building owners must submit the proposed design for their plots' expansion. Surveyors, architects, and other planners used to plan for the home owners. The housing ministry devised specific designs for residents to expand in steps, (Figure 4.23). In the villages, this form of construction has not been very effective.

There are very few such designs on the ground, considering the fact that there are so many on authorized papers. This indicates that the new type may not be a suiTable design for residents, despite architects' efforts to express the socio-cultural interpretation of the room central unit, which was widely used throughout the old houses. This further indicates that architects and designers have looked to conventional settings for solutions to modern issues. Although the facades are similar in terms of technical abilities, construction materials, scale and area, bedrooms, entrances, windows, etc, each village seems to have its own unique character.

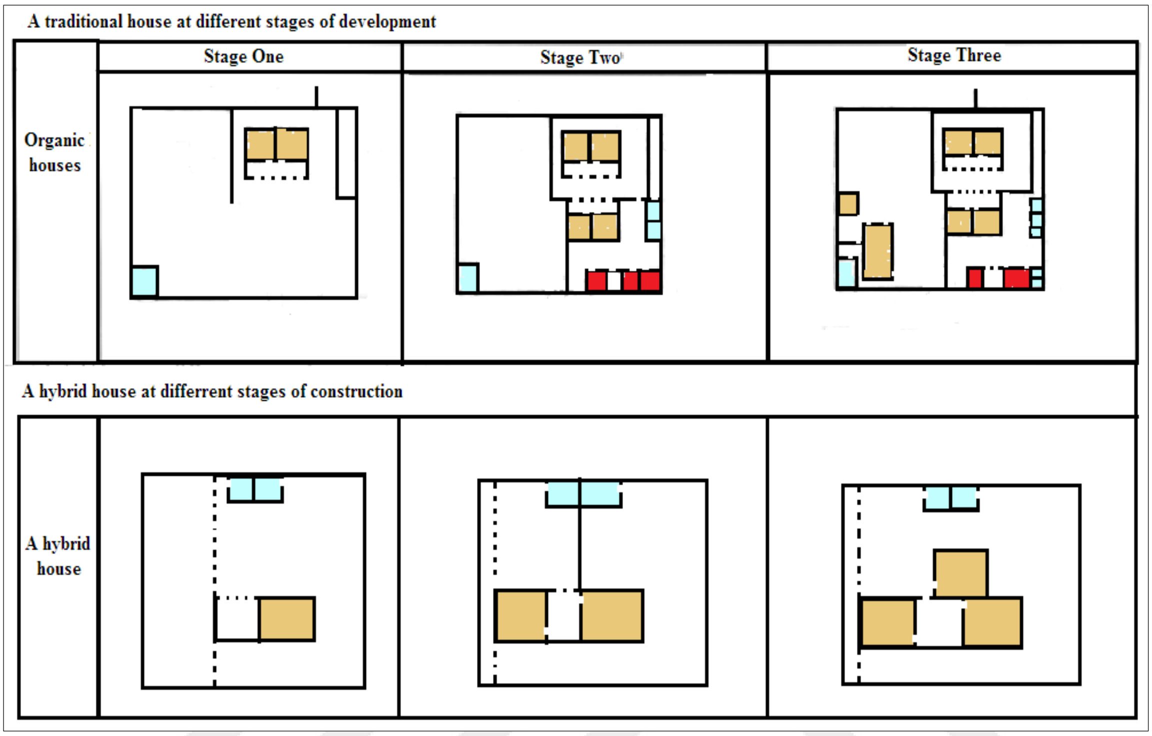


Figure 4.23. Traditional houses plans (Taha, 2005), edited by author

4.6.4. The diwan

The Diwan is an area designed as a reception of men, and it has been divided into compartments with guestrooms and separate facilities such as bathrooms and a water area. The diwan is also a room where the family lets the outside world enter. In this case, the house forms a barrier between the outside world and the family. As a result, the diwan provides the opportunity to demonstrate interconnectivity and to open itself. This is a space inside the home where the family's regular visitors are welcomed, so in the case of activities, it is the most effective opportunity for them to open their world to the visitors.

This Diwan was designed with the old conventional way, with a veranda and rooms, constructed with mud and bricks and supported by arches, (Figure 4.24). The veranda width is 3m, and normal measurements for rooms are 4.5m * 4.5m. The Diwan has been designated in a different area of 15mX15m (Taha, 2005).

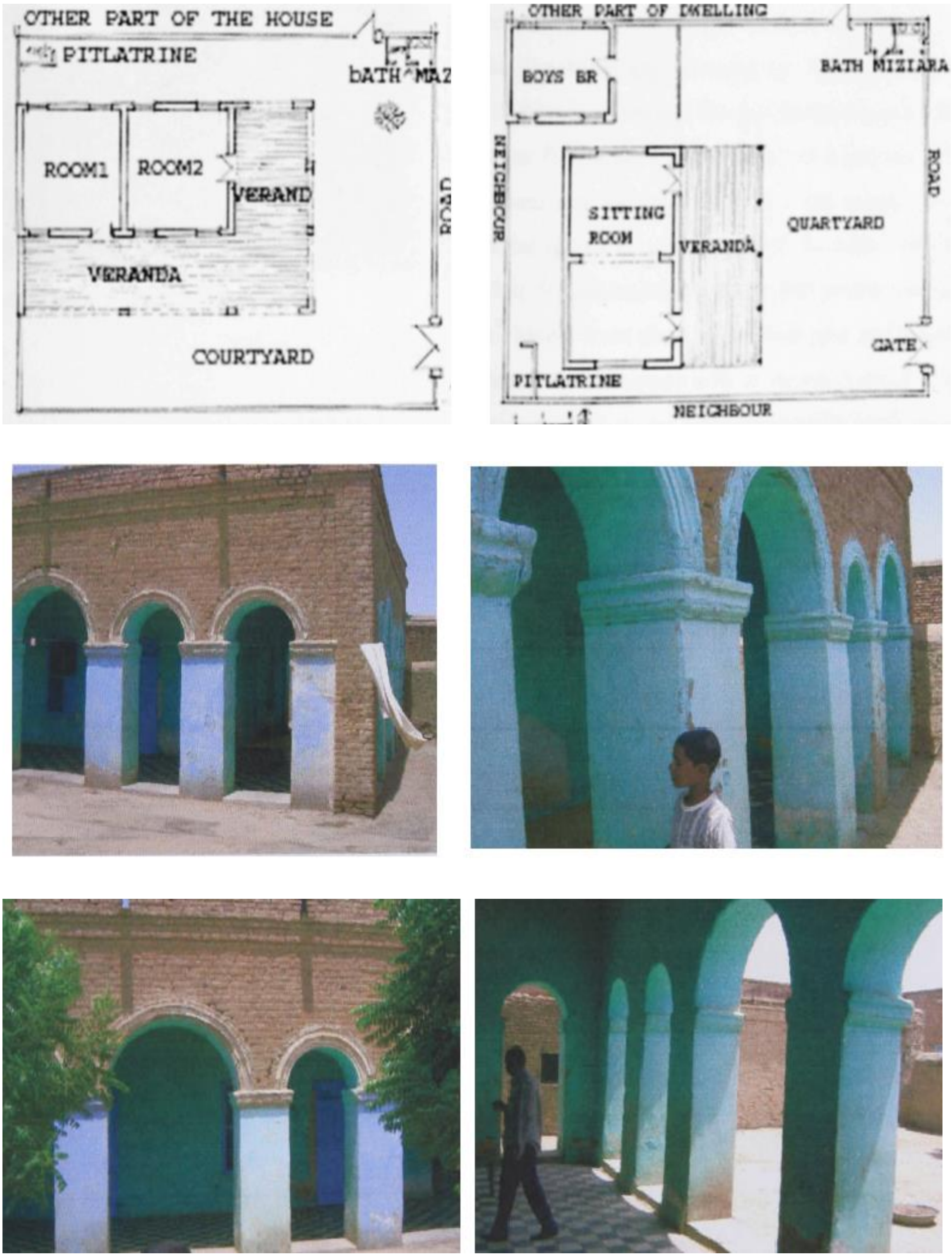


Figure 4.24. The diwan (Taha, 2005)

4.7. Spatial Organization of the Organic Traditional House

The first model of the organically home, which has been designed to house a standard family unit, could be seen in the traditional house of today in the villages or even cities of

Sudan, where the growth in residential areas corresponds to the growth of the family. Obviously, the hosh is divided into three main sections, each of which accommodates the family's household arrangement and social cultural practices.

As a consequence, there are three variables interacting within the house structure to integrate the lifestyle; social activities, the level of the room, family. When we look at the families inside these homes, we can see that each one has more than one family member. The bulk of the families were founded on patrilineal relationships.

The family unit, which consists of a male, his wife, and their own single children, was discovered to be the first stage in a development cycle that contributed to hybrid co-residential kinship communities. Each family grows into various kinship groups, which are prone to splitting into two or three independent units (Figure 4.25).

In order of importance, the main explanations for these splits are;

- The family moves to the city because of their educational success,
- The economic success of the household's leader,
- The death of the family's leader,
- Marriage of male ancestors,

The head or leader of the family is typically part of a co-residential kinship party that includes collateral agnates, and their children, and his married sons. This kinship community, of which the 'hosh head' is partially accounTable, gives a measure of economic and social stability to all of its members.

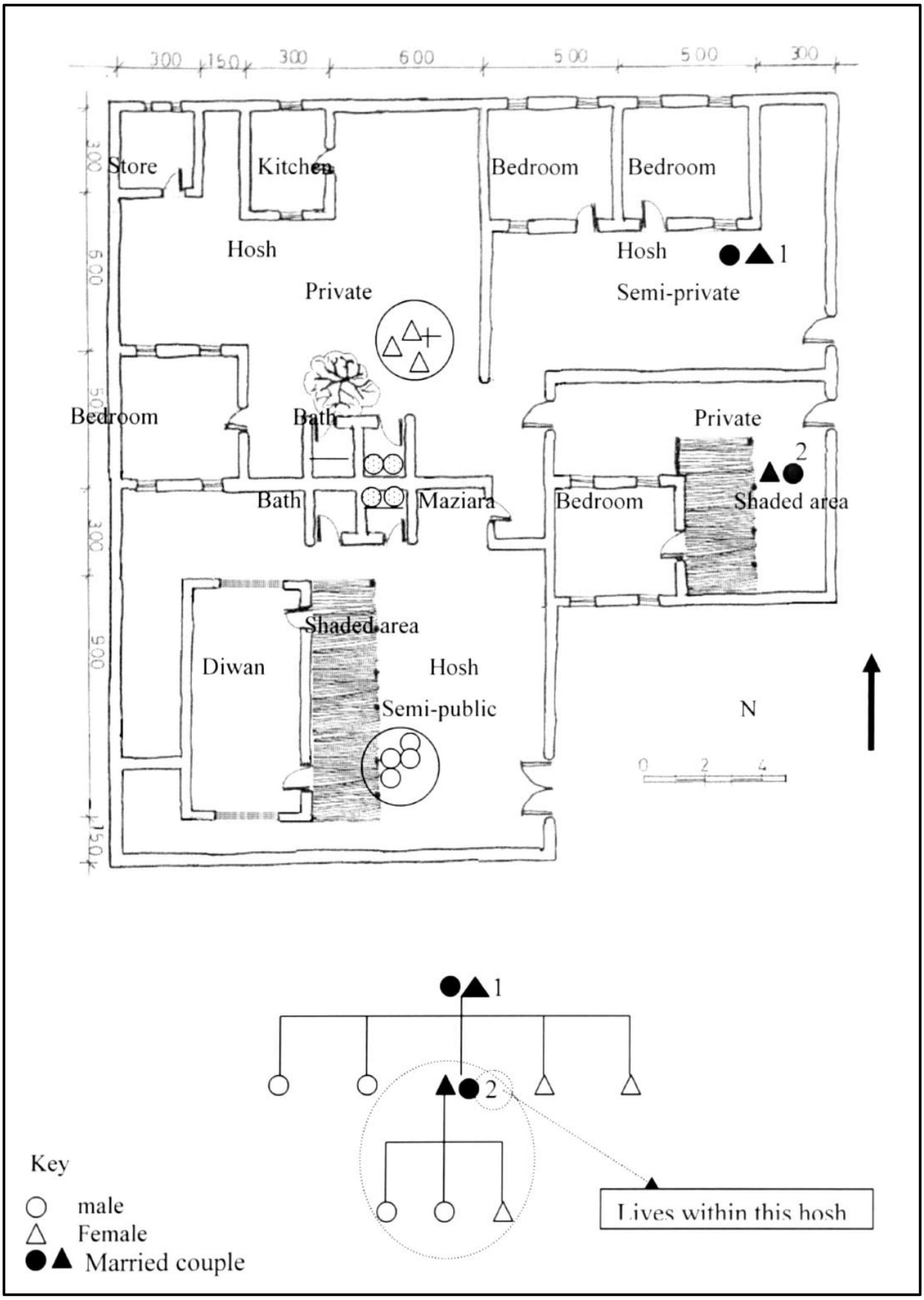


Figure 4.25. Spatial organization of the organic traditional house (Taha, 2005)

4.8. Classification of Khartoum Architecture

4.8.1. Traditional model / form

This model refers to the pre-colonial vernacular villages that were founded on Khartoum's land. On the banks of the Nile, these settlements were constructed out of clay and they remain in Khartoum till today, in areas like Khartoum North, the historic town of Omdurman, and Tuti Island. They are being absorbed into the city's urban system (Schulz, 1980). The overall physical patterns of conventional settlements, according to Ahmad describe, "Intimate organic patterns" are "their physical patterns show familiar twisting roads and alleyways of varying sizes, small open spaces and homogeneous clusters of low, relatively dense cubic mud dwellings" (Figure.4.26).

Figure 4.26. The traditional model in Tuti Island (Hamid, 2020)

Norberg-Schulz (1980), on the other hand, witnessed and described traditional architecture in Khartoum's three cities. He saw typical urban settlements as an organic collective made of three major interdependent factors: social structure, environment, and housing, He saw the dwelling as a living cell whose aggregation creates a tightly organized urban environment, and this urban environment stretches horizontally, with a clear hierarchy of urban spaces ranging from the private house to the semiprivate entrance road, and finally to the public street (Figure 4.26). The 'house' is the critical unit of this paradigm's architecture inside this specific urban context (Figure 4.27). While it has a simplistic cubist shape, it reflects a simple and conservative way of life. As a result, it carries significant symbolic, spiritual, and social values. As a consequence, both externally and internally on the immediate surrounding urban settlement, the spatial organization becomes more influenced by the society's cultural practices. The architecture of this model in Omdurman was widely researched by Osman and Suliman (1996), who observed that boundary walls are among the key features. Though boundary walls offer a physical distinction between home, and the street, and neighboring homes, they are wrongly stressed as a standard in Khartoum's neighborhoods (Hamid, 2020). This requirement for residence in a desert region is justified by Norberg Schulz (1980) which has given the neighborhood identity. As a consequence, an urban landscape with streets lined with high walls concealing the building from visitors emerges (K. M. Osman, Suliman, M, 1996). Norberg-Schulez (1980) emphasizes that the frontier wall as an architectural element has defined the core of conventional architecture and thus characterized old Omdurman and Tuti neighborhoods and today's residential areas in Khartoum, (Schulz, 1980).

Figure 4.27. Houses in Khartoum as basic cubic structures, the wall, and exterior space (Hamid, 2020)

Therefore the features of the standard traditional buildings can be described as follows based on the authors' findings and the analysis of Norberg-Schulz;

- A sustainable performance that benefits through the use of local materials with earthy colors. Examples of such materials usually involve is the clay, which can be produced on site, or the sun-dried mud bricks. They are also layered with an additional cement and sand layer (K. M. Osman, Suliman, M, 1996).

- Pure, simple types of architecture.
- The Rooms are either freestanding or are linked to the outer wall.
- The courtyard is enclosed by the boundary wall, It connects all of the rooms and creates a social meeting place for the family and their visitors.
- The subdivision of the dwelling into separate areas for women and men and in terms of spatial organization.
- Because of the organic nature of the construction materials, houses have rounded corners.
- The house's Roof is flat and built from corrugated galvanised iron sheets/zinc, or from timber.
- The primary feature of a dwelling is the boundary wall.
- Street is used as a secondary or tertiary interval.
- the Efficiency of traditional house and the human scale
- There are few and narrow windows.
- The ornately decorated doors.
- Most of the houses are one floor.
- the streets are Narrow with different width
- Units are gradually clustered.

Even so, since Sudan is a socially and culturally diverse nation, this diversity is reflected in its architectural design, leading to a rich traditional building with a variety of designs, functions, construction materials, and shapes, all over the country (Ali et al., 2019). Mostly with the colonial forces' formation of Khartoum, vernacular architecture didn't receive sufficient attention from colonialists and Sudanese intellectuals. As a result, the standard urban area was primitive, with no character development (Bahreldin et al., 2011). Vernacular architecture is built by laypeople or their architects using more strong construction materials in today's neighborhoods in Khartoum's three cities. Even so, since they are designed in a monotonous gridiron layout, these communities have lost their organic urban character, with all roads and that most of the dwellings appearing the same. As a result, the expression of tradition in the city is decreasing, and it has become more restricted to body objects, clothes, and practices that are not inherently bound to a certain location in Sudan.

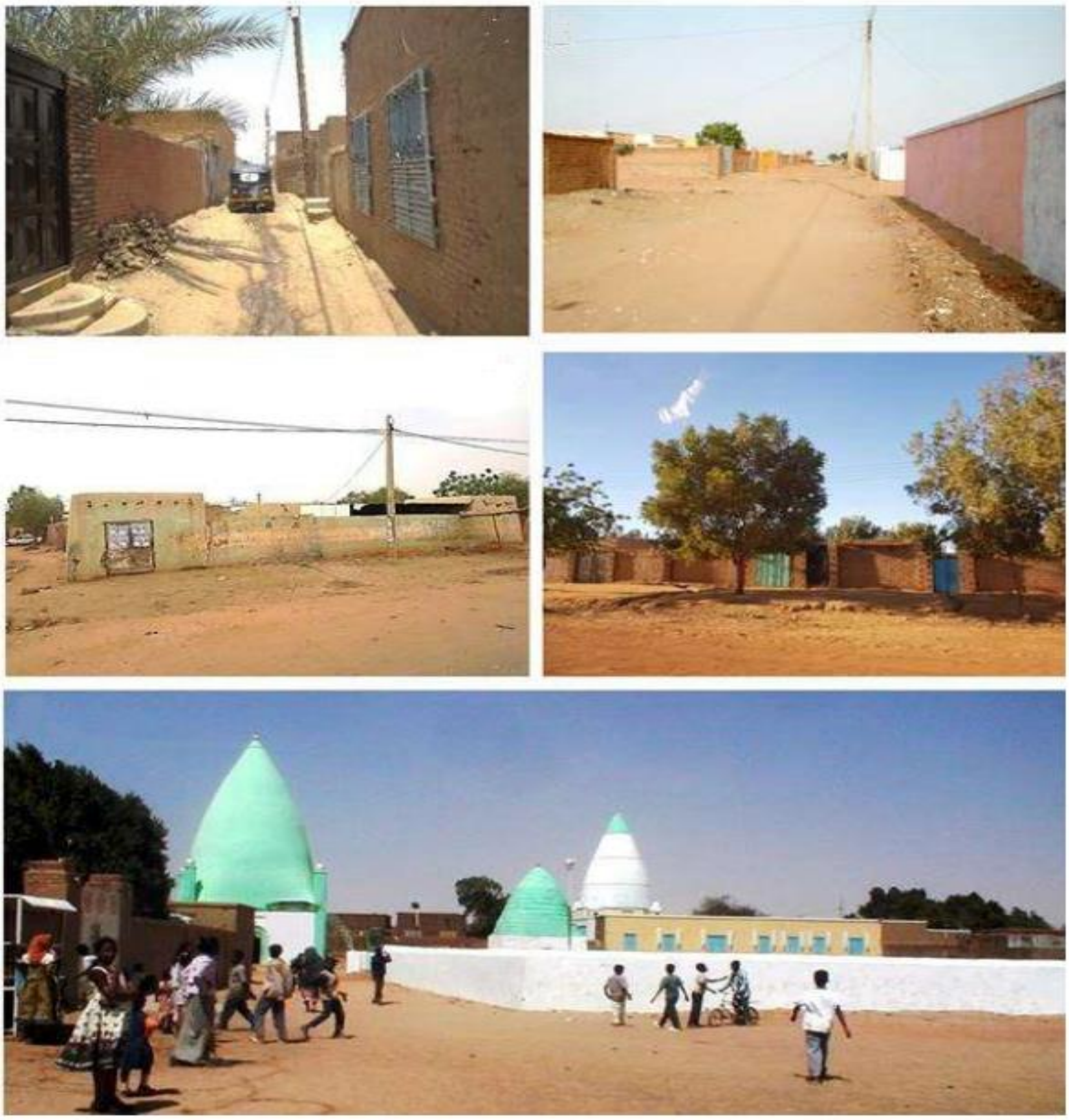


Figure 4.28. Traditional architecture in various towns in Khartoum(Hamid, 2020)

4.8.2. Colonial model

It may be claimed that the shocking events of 1898, which saw the harsh end of the Mahdia rule and the beginning of a new era of colonialism, traumatized Khartoum. The base of influence for the new colonization was actually moved to Khartoum City as a result of this switch in the Anglo-Egyptian colonialism period (O. S. Osman et al., 2011).

This time and its influence on architecture were defined as follows: Sudan was quite disconnected from the architectural trends of the rest of the world mostly by the end of the nineteenth century, and during the Mahdia rule. There was a decrease in the continuity of the beautiful traditional architectural heritage which was common in the country's earlier historical periods due to a variety of other influences, including; foreign colonization, religious changes, climate changes, political changes, and a lack of wealth and natural resources.

As a result, Khartoum City saw the advent of architectural style, which was adopted as an architecture it had never seen before, and the separation from conventional design started. Another explanation seems to be that the British did not think conventional architecture was appropriate for the required city housing facilities and edifices that met the requirements they were used to do in the United Kingdom (O. S. Osman et al., 2014).

As a result, they started to create a modern design that is different from Khartoum's architecture design. Those new updated architectural elements, although not completely Sudanese were still appropriate for the location and its surroundings. Institutional structures (including educational functions, industrial, economic, commercial, and governmental), as well as residential areas, were included. In Khartoum, this was the first time effective regulatory architecture was introduced as a new style of architecture. Which is gives Khartoum City its institutional or administrative feature, which it still has today. While this colonial section is still the heart of Metropolitan Khartoum, it no longer serves as a residential area or recreational.

However, for one or two commercial sites, this resulted in a location that is lively and colorful during the day. Even so, the newly adopted colonial design actually did would not have the same physical spatial structures as an urban culture but was a one-of-a-kind product that combined it with local design (King, 1977). Bay (2001) calls this a hybrid design, claiming that British colonial design in northern Africa took the best of local conventional architecture and applied it in a different manner, even though it wasn't clearly said (Bay, 2001). After all, Malinowski et al. (1961) disagree with Bay and King, believing that this is an entirely modern cultural development rather than a fusion of both cultures (Malinowski, 1976). With all that in the background, and based on author's findings and photographic evidence, the following features of residential colonial architecture may be somewhat actually listed (Figure 4.29).

Buildings and houses are more open to the surroundings than conventional houses, due to;

a) Verandas: that runs along the fronts of houses, creating a transitional area which connects the house's exterior and interior spaces. These verandas provide an area that is both connected to the natural world and much more environmentally sustainable than the outside courtyard throughout the day, especially in Sudan climate.
b) Thin fences; in contrast to the Conventional Model, here the wall is nearly transparent, or in some other causes, a translucent barrier is used in place of fairly rigid walls.
c) Windows those are large, which some time it's not suiTable in the climate of Sudan.

External courtyard: here the external courtyard has evolved from a central area which almost all bedrooms open into, to a very purely outer area the verandas serve as a bond between itself and the dwelling.

Similar characteristics may be attributed to northern locations, where residential design is characterized by flexibility and a close relationship with the environment. As a result, they gave colonial houses a modern semi-public identity for a dwelling that was new in town; as a consequence, residential design has shifted from being an introvert design in conventional architecture to one that is much more sociable. More architectural features from classical Architectural styles, like architraves and columns, were also included.

Such features are mostly used in residential design. Norberg-Schulz, on the other hand, came across bureaucratic public houses, which were not present in Khartoum's vernacular towns. As a result, he praised this form in his conceptual storytelling, partially because such institutional structures actually reminded him of those from his own community. These colonial structures were constructed of long-lasting materials which adapted to the local environment by offering adequate shade and protection from the heat in the hot dry summer and avoiding harm from the rainy season in the autumn months.

Whereas the form and features of colonial architecture were distinctive, they did not succeed in the autonomous post-colonial Khartoum. Even worse, colonial structures were not recognized as part of Khartoum's architectural form after independence; rather, they were not properly preserved, and in certain instances, they were misused and disrespected, resulting in rapid deterioration (Hamid, 2020).

Figure 4.29. Traditional house in colonial Khartoum (Hassan et al., 2017)

4.8.3. Modern model from 1960 to1970

That model's architecture marks the start of post-colonial design, which formed after the independence of Sudan. As a result, naming this model proved to be a challenging job. The term Modern was eventually selected because it signified a change in both colonial architecture and conventional Sudanese architecture, as well as the replacement of both with architectural design with new features (O. S. Osman et al., 2011). Through the view of the location, this model can be seen in Khartoum's downtown area and also the city's expansion to the south and north, and also in the recently developing mixed-use center in various styles of structures of dispersed residential design in Khartoum's three cities.

Via reinforced concrete structures, free plans, and free facades, this model's design followed the vocabulary of modernist design and also an architectural authenticity reflected by the purity of form and simplicity. This also expressed lightness and transparency through big windows, as well as revealing the structure (O. S. Osman et al., 2011). As a result, this model had a huge influence on Sudanese architecture, and it continues to have an impact today.

Osman et al. (2011, p.8) presented this model as architecture that is: pure, creative, transparent, ornamentation forms and functional were a source of admiration and inspiration for generations of architects. It is important to keep in mind, though, that creating this design was not a simple task. It occurred at a time when finances were limited, construction supplies were scarce, and professional labor was limited. This has prompted architects to adopt a more practical design style, resulting in projects that are perfectly suited to the New Movement's requirements.

In this model, the following architectural features of Khartoum after independence could be listed as;

- Rise of condo units and multi-functional projects with rental stores as apartment buildings.
- The Boundary walls that are less influential: unlike the two previous models, the boundary wall no longer seems to be a fence that only encloses a space outside the home, but rather appears to be incorporated with the structure as a single incorporated element.
- Adaptation to climate requirements and optimal orientation; to create environmentally friendly interior conditions and enhance air circulation. One of the key targets of this model tended to be the need for optimal shading.
- Clear facades and anti-ornamentations.
- The straightforwardness of plan shapes (Figure 4.30)
- The deep overhangs and façade’s layered vocabulary (Figure 4.31).

- The interaction between voids and solids (Figure 4.32).

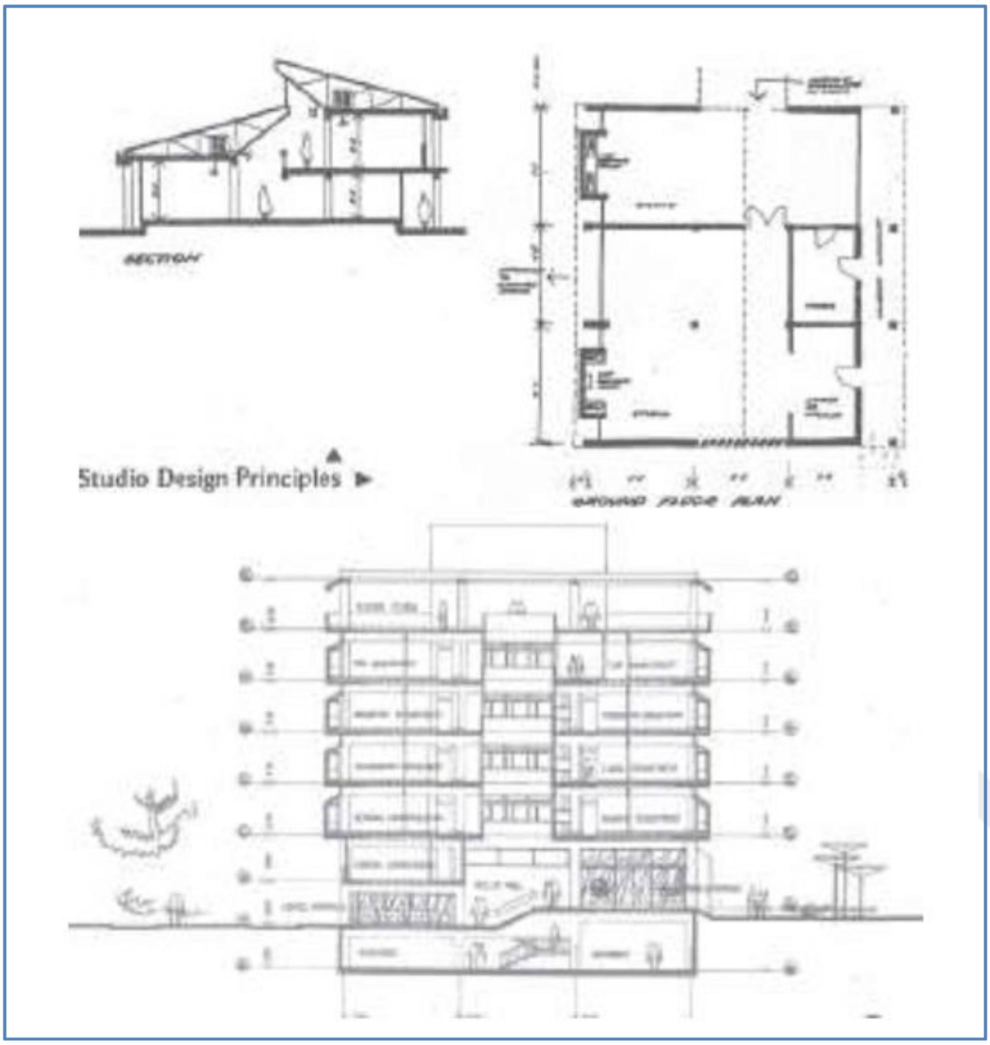


Figure 4.30. The straightforwardness of plan shapes in the architecture of the modern model (O. S. Osman et al., 2011)

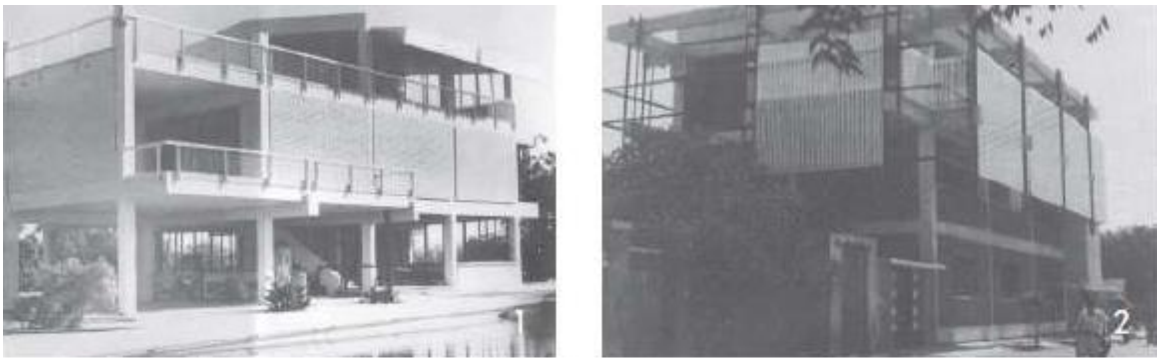


Figure 4.31. The deep overhangs and façade’s layered vocabulary (O. S. Osman et al., 2011)

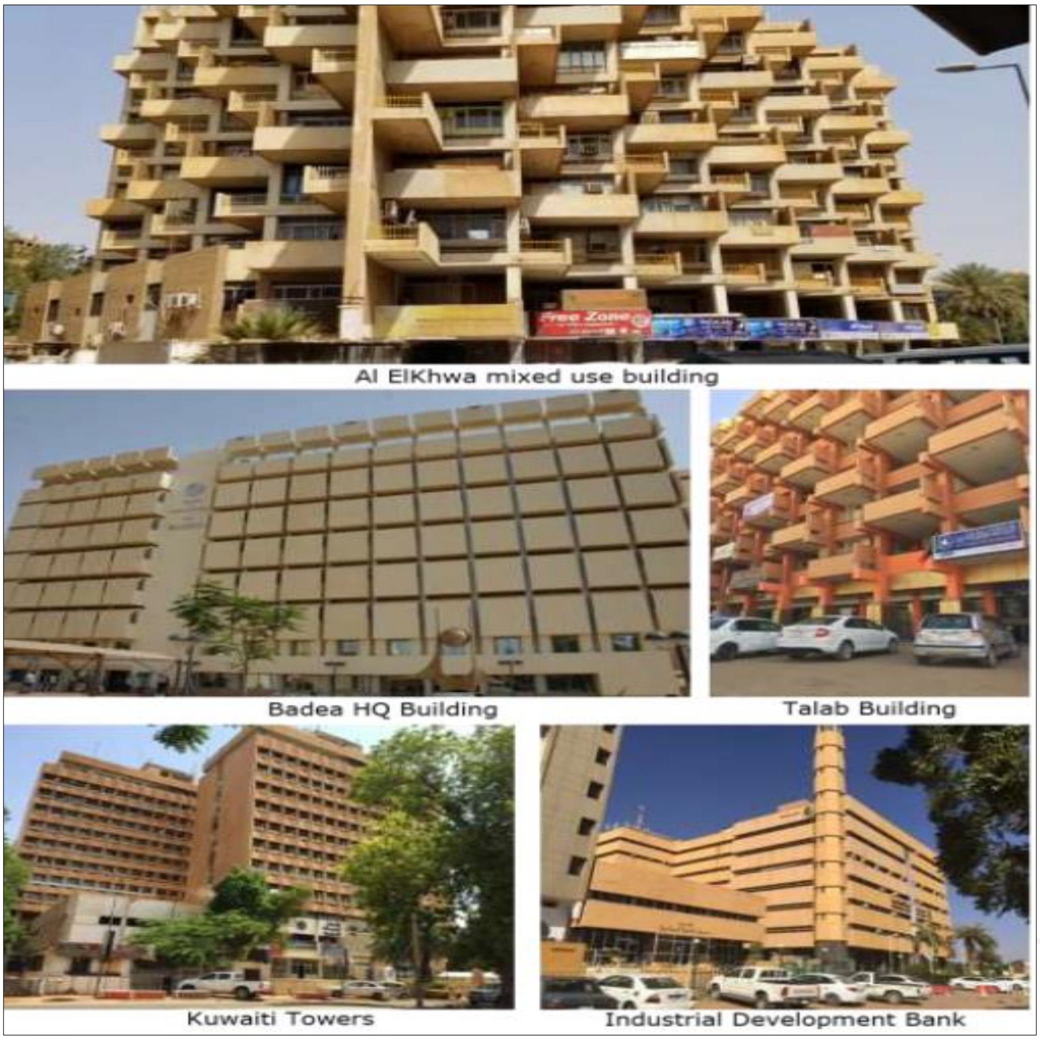


Figure 4.32. The interaction between voids and solids (Hamid, 2020)

4.8.4. Contemporary modern architecture in Khartoum 1960- 1990

The development of Khartoum's new residential architectural design made considerable strides during the 1960s decade. The very first huge housing project of its kind since independence, which was known as Al-Amaraat new expansion, boosted this in the early 1960s. In Al-Amaraat, three styles of house architecture emerged: the first is a short-lived built form of the early verandah house, with a first floor attached to load bearing walls and reinforced concrete confined to slabs. This style, known as Modern Vernacular, was clearly replaced by the Mediterranean villa in the late 1960s. So the second style or type is the Modern Mediterranean Villa, which is based on Stefanides' designs from the 1950s. As a result, Al-Amaraat marked the start of a modern period in which the Mediterranean villa began to supplant the traditional verandah home. The tropicalized version of Modernism, which incorporates features of Modern Architecture and expressions of tropical architecture, was the third house design style in Al-Amarat in the 1960s. (Bashier, 2007).

The career has been controlled by the private market since the early 1970s when the first wave of Sudanese designers came to fame. They were lucky to come in contact with an extraordinary collection of existing practices and experiences in architecture and building methods that evolved in the AL-Amarrat residential building in the 1960s. In the 1970s, Al-Amarrat provided a fantastic chance for Sudanese designers to interact with the traditional legacy of the sustainable development strategy that was the subject of interest in Khartoum's Modern Architecture (Bashier, 2007).

The house form-design from the 1970s till the 1980s in Khartoum

As mentioned before in the 1960s, three styles of home design were popular. The Mediterranean villa supplanted the neo-vernacular in the 1970s, and perhaps after the late 1960s. In the 1970s and 1980s, only two of the original three styles of house architecture remained; the first one, the Mediterranean style. The emergence of the Mediterranean villa, the forerunner of today's luxurious villa, was synonymous with a transition away from the traditional modern vocabulary of the 1960s and the emerging domination of Westernize life style in the 1970s. In the 1970s, the in-coming societies of modernization further elaborated the Mediterranean villa, which became the prototype for the luxurious villa that became the trend in the late 1980s. The second house design style is Tropical Modernism that was common in the 1960s and was revived on a smaller scale in the 1970s and 1980s. Tropical Modernism is represented by the designs of AbdelMoneim Mustafa (a Sudanese architect), whose abstract geometric shapes and abstract straightforward features show immense faith in Modernism's simplicity. The extensive use of overhang slabs, which offered significant shading of facades and linked the cultivated outdoors as well as the interior design through optimal shaded areas at patio level, was one of Mustafa's most distinguishing features (Figure 4.33).

Figure 4.33. Abd Elmoneim Mustafa designs (Internet: Arab center for architecture, 2014)

According to (Bashier, 2007), Kamal Abbas is a representative of Tropical Modernism, and he sometimes accepts Mustafa's influence on his design. Despite the fact that both designers conform to the sustainable design philosophy, and their styles seem to be somewhat close at first glance, they belong to entirely different architecture schools. Though Mustafa has the temperament of an abstract poet, Abbas shows exceptional craftsmanship. All his private projects lean toward ornamentation and styling, with an emphasis on the duplication of concrete fascia, columns, and beams (Figure 4.34).

Figure 4.34. Kamal Abbas design in Khartoum 1982 (Bashier, 2007)

Since the 1980s, Khartoum's Tropical Modernism has been increasingly dominated by the growing domination of the luxurious villa, and as a result, it has become so much less common. Despite its exorbitant valuation, the out-of-date luxury villa keeps going up unabated. It is now generally recognized as the ideal design for high and middle -income house buildings, so no one seems able to question or suggest a much more practical alternative for the Sudanese residential buildings.

4.9. Building Materials and Construction Methods in Sudan

In Sudan, there are different categories of building materials: (a) Traditional materials, such as thatch, mud, red bricks with the mud bricks for wall construction, mud construction for walls, and roofing made from sticks. (b) Modern materials, such as corrugated iron sheets, concrete, red brick with cement mortar, and cement bricks (Ali et al., 2019).

All of the materials for these traditional vernacular structures are sourced locally. Many of the materials and labor for the houses were local until the 1970s when window dressings and stone walls became popular. All construction was completed on site, with the exception of material collection and roof timber shaping. The work was done by relatives and neighbors; with no outside help was needed. However, in traditional buildings in Sudan there were different constriction methods it can be summarized as follows;

4.9.1. The earth model

Dwellings in vernacular communities were made of clay, which was used either in-site to build a uniform wall or in the form of hand-molded or sun-dried bricks bonded with earthen mortar. The traditional method, known as ‘jalous’ building (Figure.4.35 & 4.36), is increasingly being phased out in favor of mud bricks. Jalous walling is constructed in horizontal layers, each of which must completely dry before the next can be applied. Mud brick, from the other side, could be used constantly, minimizing the time taken for actual construction while requiring further prepping; the sun-drying process, and fermentation of clay with animal dung and molding. The supplies for mud building (mud, straw, and dung) actually came from local sources: dung from animal yards in the building or around the village, mud from pits on the site, or from fields that were not designated for agriculture, and straw from farms. These mud houses were usually constructed in 7 to 10 days, and when a person needed a house built, he informed his neighbors, whom all arrived at the scheduled date; some were preparing straw and dung to combine with it, some laid on clay, and some trod it. This was accomplished before the workers arrived to lay the wall courses. Making becomes expeditious and low-cost in this way, and that it must be recognized that they have sharpened the art of mud building to a degree of professionalism (Taha, 2005). As seen in (Figure.4.37) the basic design of enhanced mud house roof design; it appears that they are using reclaimed materials or imported wood for the windows and doors, and local materials for the building. The ground is formed of compacted earth or sand.

Figure 4.35. Jalous house in Sudan (Internet: gecko, 2015)

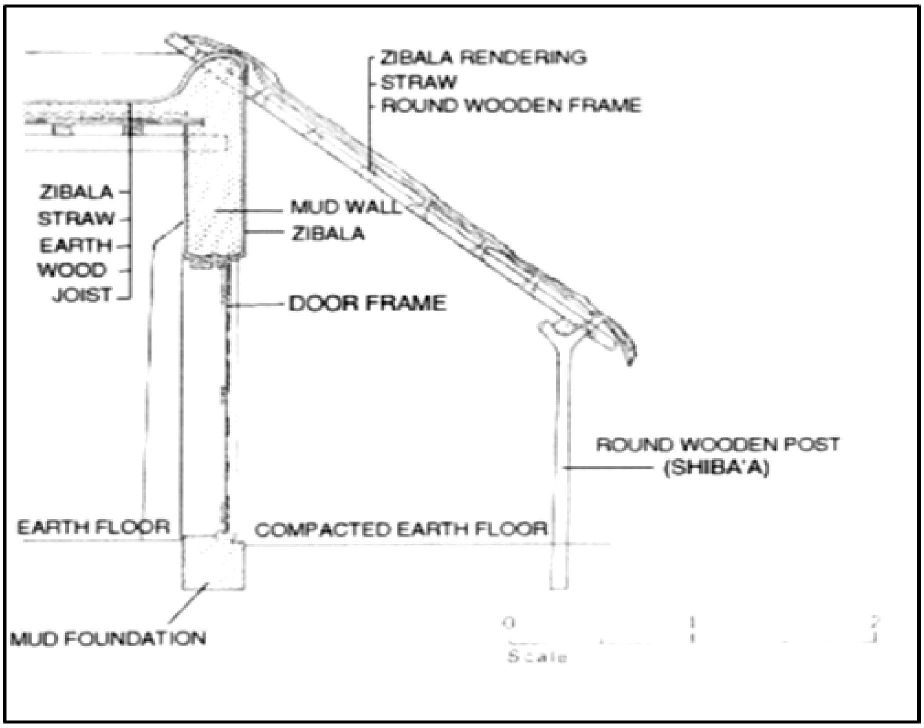
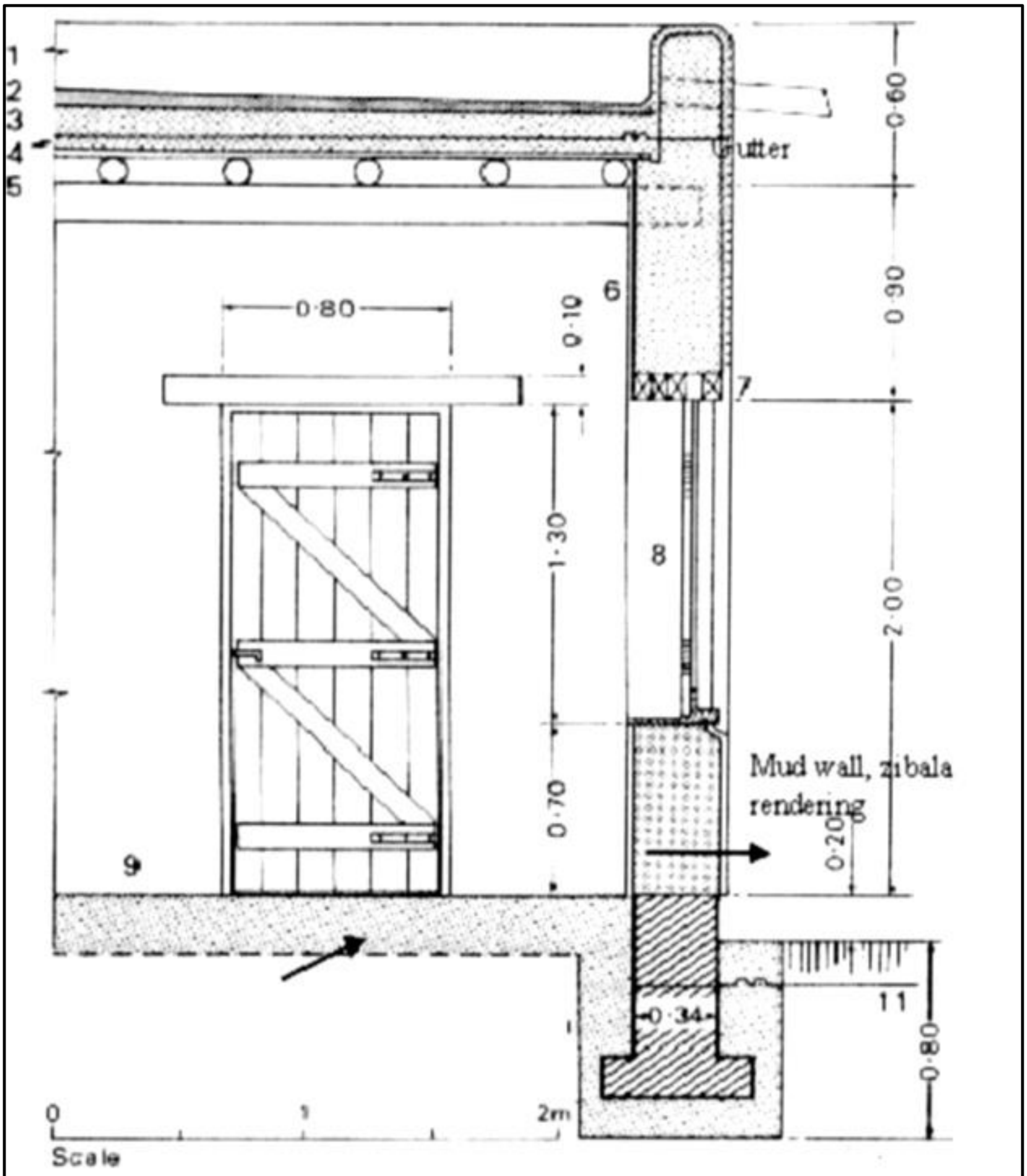


Figure 4.36. Traditional constructions (Taha, 2005)



Key:

1, mud brick parapet, 2, zibala roof finish, 3, earth/straw insulating layer, 4, polythene sheeting, bamboo, 5, local timber joists and beam, 6 mud wall rendered with zibala, 7 timber lintel , 8 window 'timber' 9, compacted sand floor, 10, Compacted sand , 11 compacted earth

Figure 4.37. Enhanced mud house construction (Taha, 2005)

4.9.2. The gishra model

Sudanese people have built Gishra Walls to increase the consistency of mud wall rendering. This may be a cross between vernacular buildings' mud walls and colonial housing's redbrick walls. Because of the types of materials being used, the layout, settlement, and house shape, were strongly influenced by the urban shape and structure after 1970, when planning involvement took a step forward. The colonial structure and elite planning interventions in the region culminated in the construction of many types of mud houses, rather than only one. This represents the intercultural interactions that exist in the field. In Sudan, there are also two types of red bricks: manufactured red bricks and locally burned bricks. Local bricks are made by hand from Blue Nile River clay, then stacked and burned in heaps covered by wood. Such thermal mass is both environmentally and financially costly. People are bringing wood from faraway forests, which have been impacted by irresponsible tree removal. The local government is fighting this, and several bills have been passed in an attempt to stop it, but to no end. That helps people to burn the clay carried in by canals, which costs the government to clear out, as well as the straw, which would be available in farm fields. From the other side, it instructed investors to improve redbrick production productivity for use in other parts of Sudan. The Gishra house is an example of how to improve mud building by using sun-dried bricks on the inside and red bricks on the outside.

4.9.3. Redbrick model

This style was already well-known in Sudanese cities, but it was brought to the Gezira Plain for the very first time only by the British with the establishment of the Gezira Project. It was also widely used within canal structures, as well as government buildings and homes. It is a more long-lasting form of build that prevents rain damage, but it is much more expensive than mud bricks or Gishra and jalous. Several brick factories were built in Suba settlement on the White Nile, where this clay is plentiful. It is important to research the redbrick type as well as its relation to the building and fabric in colonial buildings in order to better understand for efficiency of such a construction method and comparing that to other methods. The traditional village house has an outside dimension of 15m X 8m and is constructed on a two brick long strip base that is 1.50m high. Its walls 3.5m high so the walls were 0.35m thick and constructed with sand and red bricks, cement mortar, plastered and covered with manufactured emulsion. The rest of the dwellings are painted with cream or white. Many of the houses are surrounded by a veranda consisting of wire-mesh and timber frame facades. This is designed to shield the inhabitants from tropical flies and mosquitoes ant to shade the walls. There are doors in every room (1.20x2.10) and wide openings for windows (0.90x 1.80), which ensure that the walls are designed to withstand both environmental and health conditions. The larger windows allow more air to flow in. While air flow is important, thick walls are also important because they prevent heat storage and minimize solar heat gain throughout the day.

The Roofs; living room with traditional Roofs are unsuiTable to be used as a daytime living space during the summer months because they are exposed to the full effect of solar radiation at noon. The roof is clearly a determining factor in the overall design. Many different types of roofs were used in colonial housing to meet ecological sustainability. The brick walls are covered by a pitched roof constructed of slate tiles supported by a timber frame and a flat roof made of jack arches (Figure 4.38).

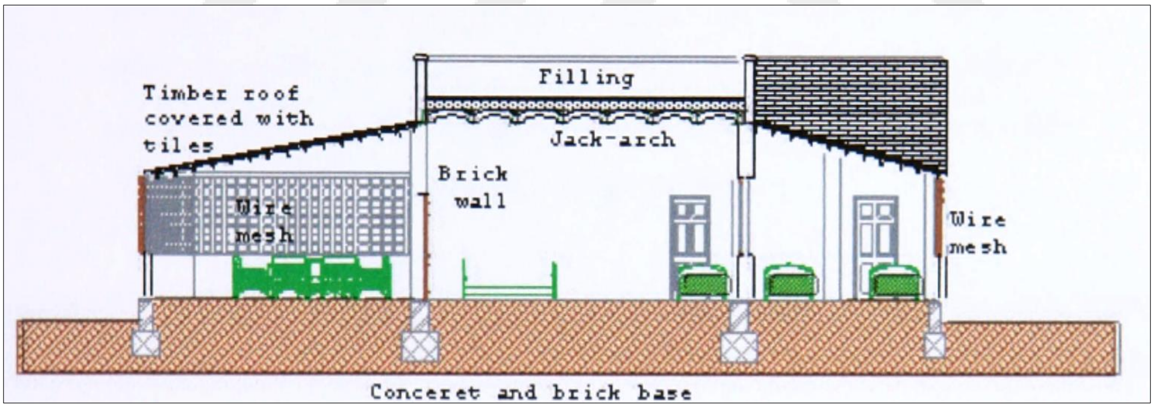
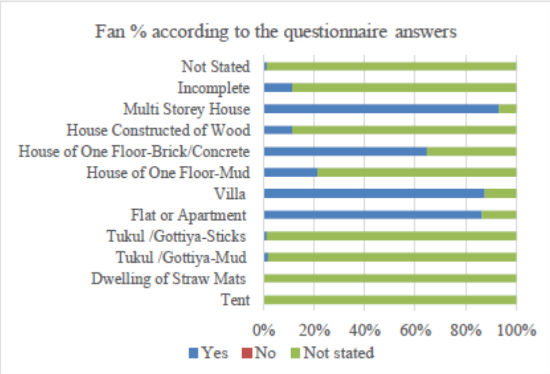


Figure 4.38. Section of a traditional house built with red brick in Sudanese village (Taha, 2005)

4.10. Heating and Cooling Devices in Sudan

Sudanese people use simple cooling machines like fans and air coolers. According to the information in (Ali et al., 2019) article; fans are used by 18.17 percent of the population, while air coolers are used by 3.94 percent. The majority of these machines are used by city dwellers rather than rural dwellers. Due to a wide number of unstated responses, the data in (Figure 4.39 and Table 4.2), could be inaccurate (Ali et al., 2019).



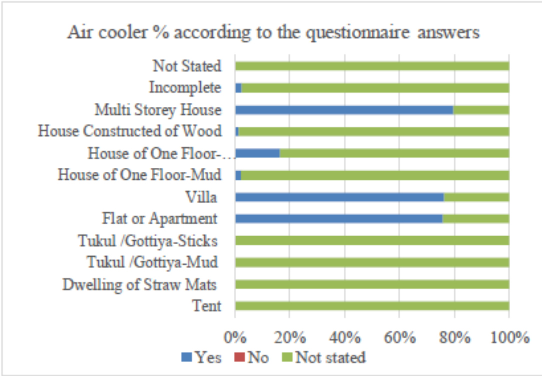


Figure 4.39. The ratio of air coolers and fans for various housing styles in Sudan (Central Bureau of Statistics Census (CBS), 2008)

Fans or air coolers are rarely used in conventional structures, temporary, and old buildings, although they are more popular in; one-story brick and concrete homes, apartments, and single or multi-story houses. Since concrete as a construction material is incompatible with the Sudanese climate, most modern houses made of reinforced concrete and bricks have either basic or advanced cooling systems. Except in a few houses in the north, where electrical heaters have been used for a few days during the winter, heating systems are not used in Sudan (Ali et al., 2019; Central Bureau of Statistics Census (CBS), 2008).

Table 4.2. Percentage of the overall population for air coolers and fans in Sudanese dwelling(Central Bureau of Statistics Census (CBS), 2008)

Item	Households%		
	Total %	Urban %	Rural %
Fan	18,17	40,22	9,3
Air Cooler	3,94	11,05	0,77

5. WIND CATCHER: PASSIVE AND LOW ENERGY COOLING SYSTEM

The environmentally sustainable features have become more common as a consequence of the negative impact of air conditioning systems on the environment. Renewable energy, such as solar power and wind, are used to make the system run, and to make the system more sustainable and more environmentally. The wind catcher is an example of a sustainable system. The Wind catchers are economically sustainable and long-lasting energy devices that have always been used for cooling and ventilation in the Middle East.

5.1. Purposes of Using Wind Catcher

To provide thermal comfort and fresh air, they depend entirely on natural forces (A'zami, 2005). Wind towers or wind catchers were used for four key purposes (Roaf, 2005);

1. To have evaporative cooling in hot and dry areas where indoor temperatures are more than 35°C.
2. To convective ventilation in buildings where the ambient temperature is about 25-35°C.
3. To have ventilation during the night.
4. To have Airflow and the supply of natural ventilation for indoor use.

The wind tower or catcher is a fixed chimney-shaped structure that can serve as an air inlet and outlet at the same time. Another benefit of wind catchers over more environmentally sustainable systems is that they can gain from both the stack effect and the wind (Soflaee et al., 2005).

5.2. History and Definition for Wind Catchers

The Wind catchers, also known as wind towers, are natural cooling ventilation methods. They have been used in many countries with hot, dry climates for decades, especially in the Middle East (Ghadiri et al., 2014). A traditional wind catcher includes a tower with a head that protrudes over the building's roof. Just one side of the tower head might have vents facing the prevailing wind stream (Mahyari, 1996). Two and four faces of the tower may, however, be open to allow wind from all paths. The tower should be split into two or three sets of shafts respectively. This subdivision causes air to flow up or down the tower in different directions at the same time, resulting in more surface space in touch with air (Amiri-Kordestani, 2014). As a result, the roof-top air is pulled and redirected to the summer living spaces, and exhausting the indoor air at the same time. The density of this structure would provide a microclimate inside the wind tower (Soflaee et al., 2005).

The Mochica Indians of Peru (200 BC - 700 AD) provide the simplest example of wind catchers (Figure 5.1). The Wind catchers were used to ventilate their structures, and It was interpreted from a pot that portrays a three-story building with many wind catchers on its roof pointing toward the sea. This case is sometimes mentioned as historical proof of wind catchers, but the absence of its continued usage in the Peruvian construction industry over time puts this claim into doubt. Wind catchers are represented in Egyptian paintings on papyrus from about 1500 BC. Two triangular-shaped wind catchers are portrayed in the illustrations (Figure 5.2), which represent the house of the rich in the New Kingdom (Mahyari, 1996). A new kind of wind catcher known as "badahanj" (Persian for "wind drawer") was brought from Iran to Egypt, according to literary facts. Several different types of "badahanj" were installed in Cairo dwellings, and they became recognized as "malqaf" in the fourteenth century (Roaf 1988). Also, they can be found on structures all over the world, from Pakistan to Egypt, in a variety of shapes and sizes, where the climate is hot dry, and even sometimes humid climate.

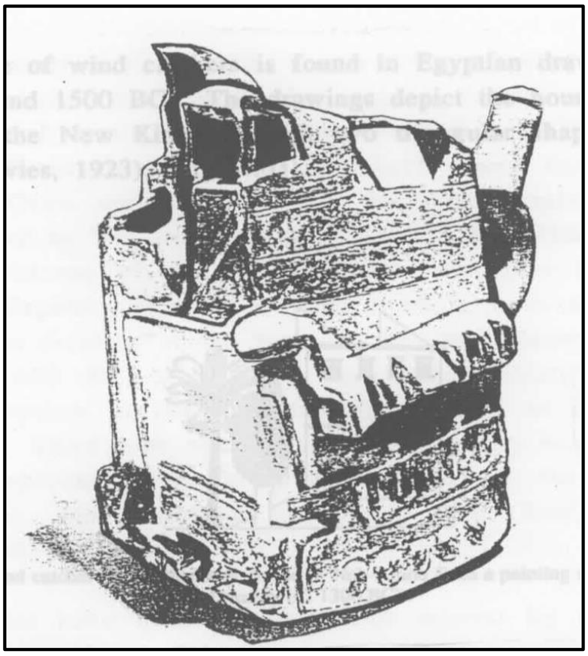


Figure 5.1. A pot representing a three-story house with wind catchers on the roof, made by the Mochica Indians of Peru (Mahyari, 1996) .

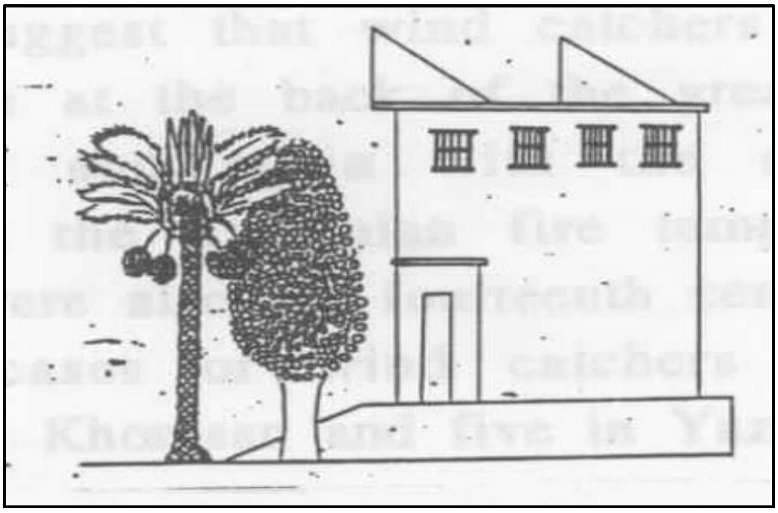


Figure 5.2. Wind catcher of the pharonic house of Neb-Amon from a painting on his tomb, Nineteen dynasty (C. 1300 BC)(Mahyari, 1996)

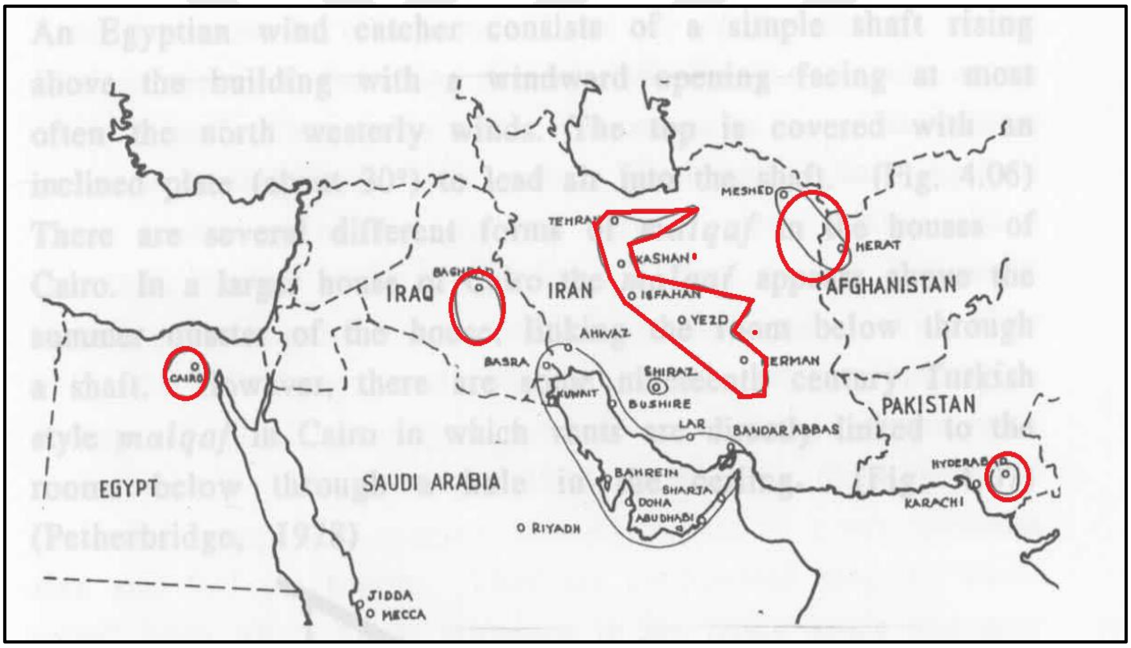


Figure 5.3. The location of countries of the Middle East in which wind catchers exist (Mehdi N Bahadori, 1994; Boloorchi, 2014)

5.3. Historical Types of Wind Catchers along the Middle East

About the border of the hot zone of the Middle East countries, there are many varieties of wind catchers. According to their source and general arrangement they may be divided into many major classes, for example, those linked with Iran's central cities (such as Ardakan and Yazd) are classified as "Ardakani type" and "Ardakani type". Similarly, wind catchers in Persian Gulf coastal areas such as Rarat in Afghanistan, Sind in Pakistan, Cairo in Egypt, and Baghdad in Iraq may be referred to it as "Bandar-e-Abbassi"(Roaf 1988).

5.3.1. Wind catchers of Egypt (malqaf)

The usage of wind towers (wind catchers) as a structure for buildings in various regions of various climates can be seen in traditional Egypt's design, which goes back several centuries. In the building of "Neb Amon," wind towers existed as an architectural feature of Pharaonic architecture. They also appeared in churches and cathedrals of Christian design in Egypt. Hospitals and most houses in Islamic architecture, especially during the Abbasid period, were built with wind catcher (wind tower). Islamic architecture recognized the climate and attempted to meet the requirements of the structures in the area. El-Saleh Talaea Mosque's wind tower is deemed one of the ancient wind catchers still existing. After that, the wind catchers are found at the El-Senary House, the El-Camilia School, and the Baibars Building (1209AJ/1794 AD). The wind catcher in El-Senary Building has been on the right side of the building, it was built to cool the interior of the building in the mornings when the air temperature is very high (Boloorchi, 2014). According to (roaf 1988), the Egyptian wind catcher consisting of a basic shaft rising above the buildings with a windward window facing the north westerly winds at most times, with angled plate (approximately 30°) covers the top to direct the air into the shaft, (Figure 5.4). Throughout history, many of these examples of wind towers were Refers to Egypt's architecture ideas. In Cairo, there are several early nineteenth century Turkish-style wind catcher with direct air vents to the rooms just below out of a hole in the roof, (Figure 5.5)

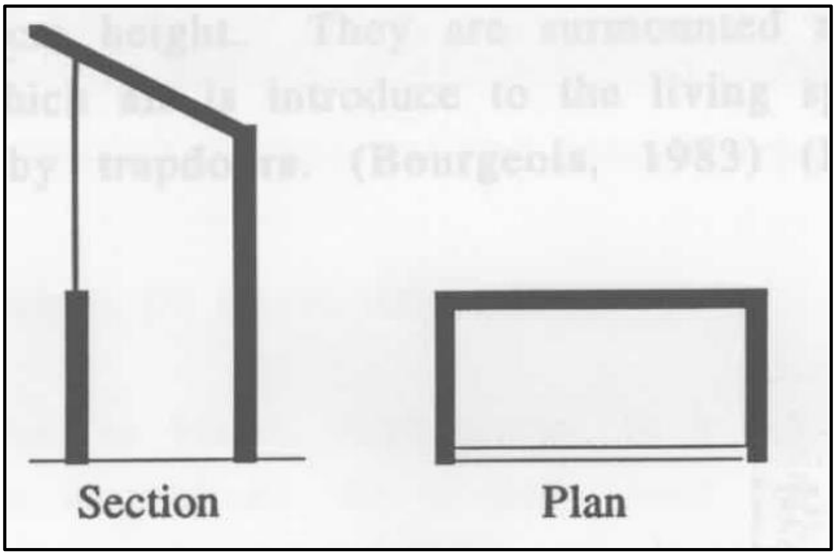


Figure 5.4. The Egyptian type of wind catcher with one-directional with angled plate (approximately 30°), (Roof, 1988)

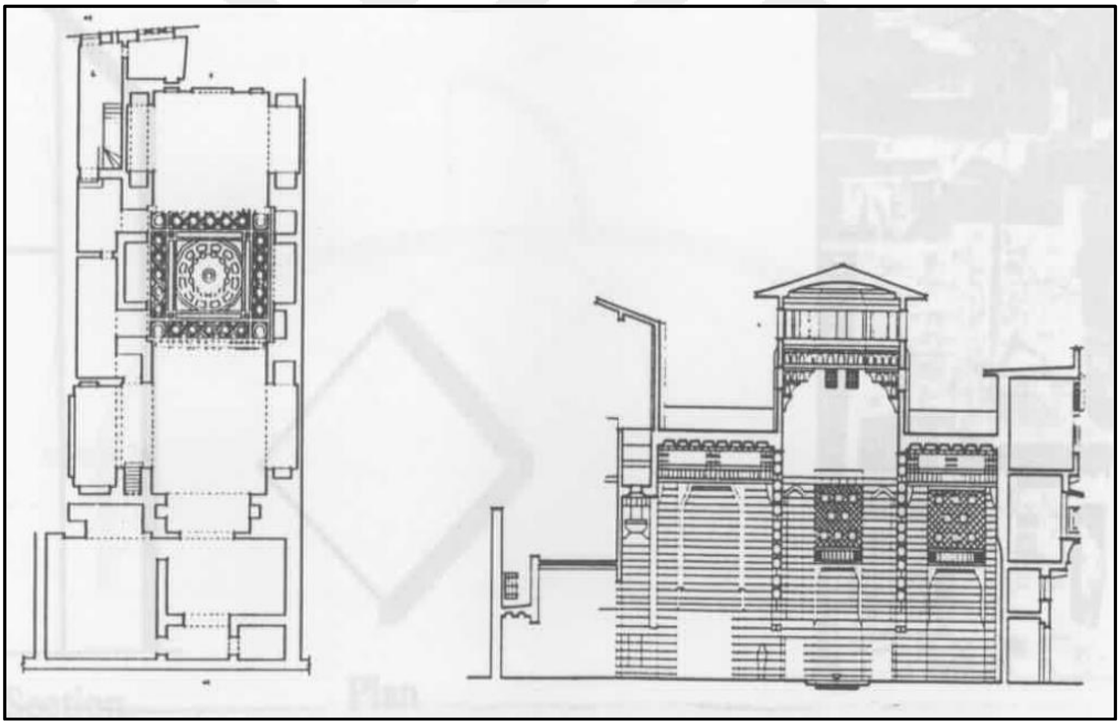


Figure 5.5. The Egyptian type of wind catcher of the Qaaof Muhib Ad-Din built in Cairo about 1970 (Fathy. 1986)

5.3.2. Wind catchers of Harat, Afghanistan

In Afghanistan, the wind catcher of Heart is a basic object that is usually located on the domed roofs of all rooms, with a maximum height of 1.5 m. it was constructed in the path of the prevailing air, which comes from the north. Their plan shapes are square with 1*1 m dimensions and slope roofs with almost 30 degree angles (Figure 5.6). Afghanistan's wind towers are quite close to the short and one-sided models that have been seen in Iran's southeastern and northern east (Aini et al., 2016).

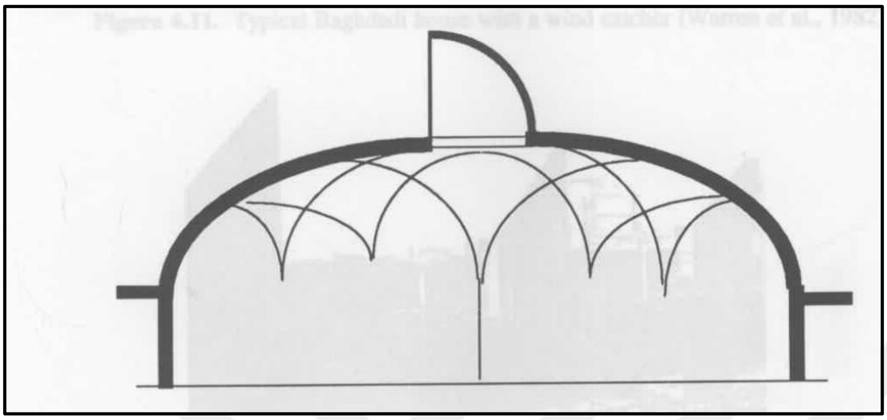


Figure 5.6 .Sketch of a typical wind catcher on top of a dome, Harat, Afganistan (Mahyari, 1996)

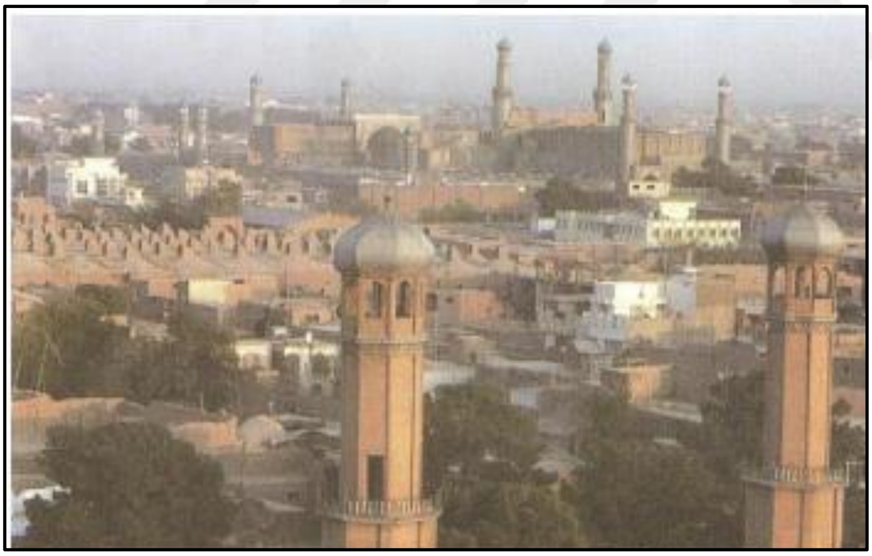


Figure 5.7. Short and one-sided wind catchers in Heart (Aini et al., 2016)

5.3.3. Wind catchers of Iraq

Wind catchers in Iraq are essentially an air channel constructed into the dense mud brick wall at the back of summer rooms heading North West in order to catch the wind and change the air temperature. Vertical shafts connect the roof vents to the basements via these structures, (Figure 5.8) (Goodwin, 1985). The basement walls are made up of multiple shafts, each of which serves as a wind tower with a width of 15-60 cm and a length of 50-120 cm. An angled plate at 45 degrees from the roof plane covers the tower head (Figure 5.9). In Iraq's inland areas, wind catchers often supply air to rooms on the ground and first floors (Goodwin, 1985).

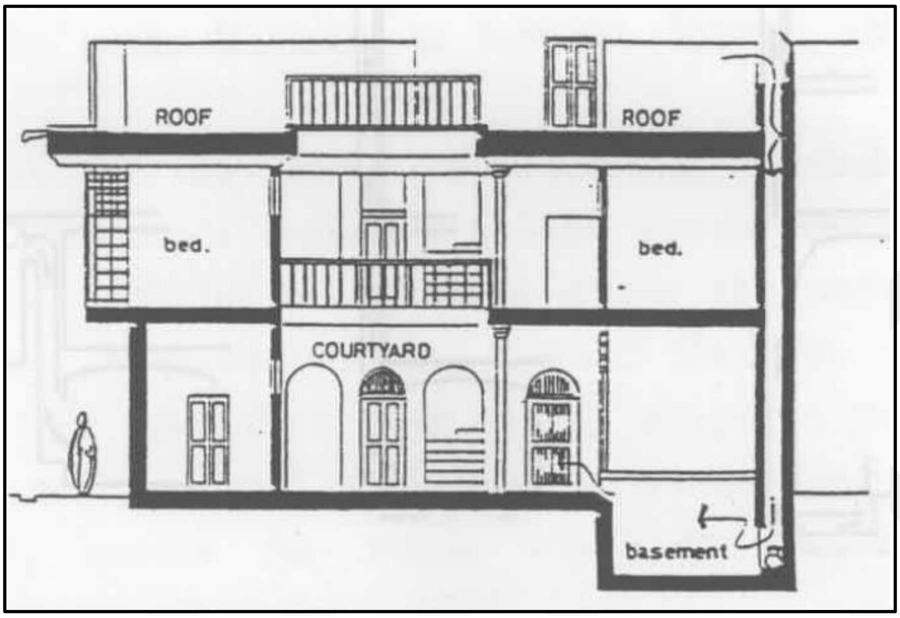


Figure 5.8. Typical Bagbdadi house with a wind catcher (Goodwin, 1985)

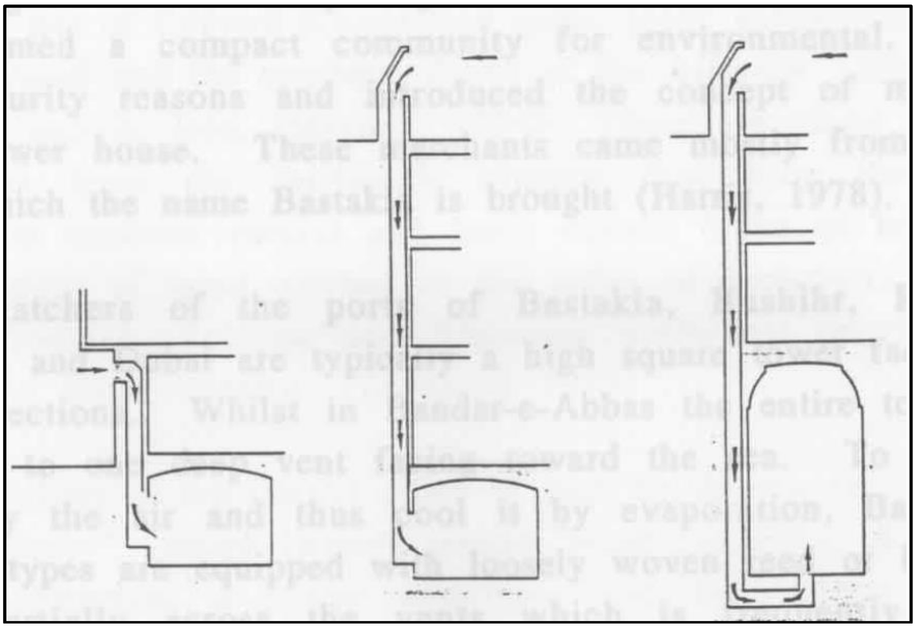


Figure 5.9. Circulation of wind through a typical wind catcher in Iraq (Goodwin, 1985)

5.3.4. Wind catchers or coastal cities of Persian Gulf

Wind tower or wind catcher on the Persian Gulf's south coast come in a variety of shapes and sizes and are constructed by Arab and Persian residents of the area. Each type tends to be similar to wind catchers from the other part of the Persian Gulf. For example, there is a direct connection between Bastakia's wind tower and Bushihr's wind catchers (Roaf 1988). This link may be traced all the way back to a historical incident throughout the nineteenth century when Persian traders were harassed by the national government. They moved to Dubai and developed a small society for environmental, social, and protection purposes, as well as introducing the masonry wind tower building design. These traders were mainly from Basta, which gave rise to the term Bastakia. Wind catchers are traditionally a large square tower facing four directions in the ports of Bastakia, Bushihr, Kuwait, Bahrain, and Dubai. In Bandar e-Abbas, the whole tower has been reduced to a single deep vent facing the coast. Bandar-eAbbasi varieties have loosely woven reed or bamboo mats partly over the vents, which are often wet on summer evenings, further to humidify the air and thus cool it through evaporation. In Gulf settlements where the climate is hot and humid, a kind of basic wind tower known as "badkesh" or "wall ventilator" is used. Badkesh is a short angled shaft installed into the wall to enable air passage across the wall while preventing clear solar radiation and obscuring the view into the building (Roaf 1988).

5.3.5. Wind catchers of Iran (badgirs)

Finding the background of the wind catcher in the projects that survive from Persian architecture is extremely complicated since the first steps of demolition require the removal of roofs and high volumes of houses, and the wind catcher is one of them. Wind catchers have been identified in Iran dating back to the eighth century (Branch, 2013; Rafooneh, 2013). The earliest record of the wind tower in Iran comes from the fourth century B.c. A Japanese exploration discovered a basic wind catcher in a building near Tappeh Chackmaq, about eight kilometers north of Shahrood, on the southern edge of the Alborze hills in the north eastern of Iran(Mehdi, 2013). There are various literary sources dating back to the thirteenth century that describe the wind catcher in Iran's north eastern and southern central towns. Wind catchers have been identified in the cities of Shiraz, Sirjan, Isphahan, Semnan, Khorasan, and Teheran in Iran's north-east area (Mahyari, 1996; Tavassoli, 1982). Wind catchers in Iran's major areas are classified as "Badgir or

Baudgeer," which means "wind catcher" in Persian. A traditional badgir is made up of a tower with one end in the summer house’s living rooms and the other rising from the roof. Internal partitions or shafts split the tower into many vertical air channels. These top shafts end in holes on the wind catcher head's edges. Within the badgir, the flow of the air is in two directions: up and down. When the wind comes from one side, the inlets are the windward openings, and the outlets are the leeward openings, and vise - versa. Badgirs can be found not only on the roofs of ordinary buildings, but also on the tops of mosques, water cisterns, and karvansarahs. The 'badgirs' spatial structure varies from one location to another. In some cases, the badgir is installed on top of a badgir room, while in others; the badgir is connected with a semi-open space known as "wan". In certain cases, the badgir is not strictly linked to the living quarters, in this case, the badgir is constructed away from the building, and an underground tunnel connects the badgir's foundation to the basement. Badgirs appear in a variety of shapes and sizes, for example, the plan of the wind tower can be rectangular, square, hexagonal, or octagonal, although square and rectangular are the most popular. The tallest tower in Yazd is 33-35 meters high and is built on the top of Bagh-e-Dowlatabad (Figure 5.10) (Mahyari, 1996).

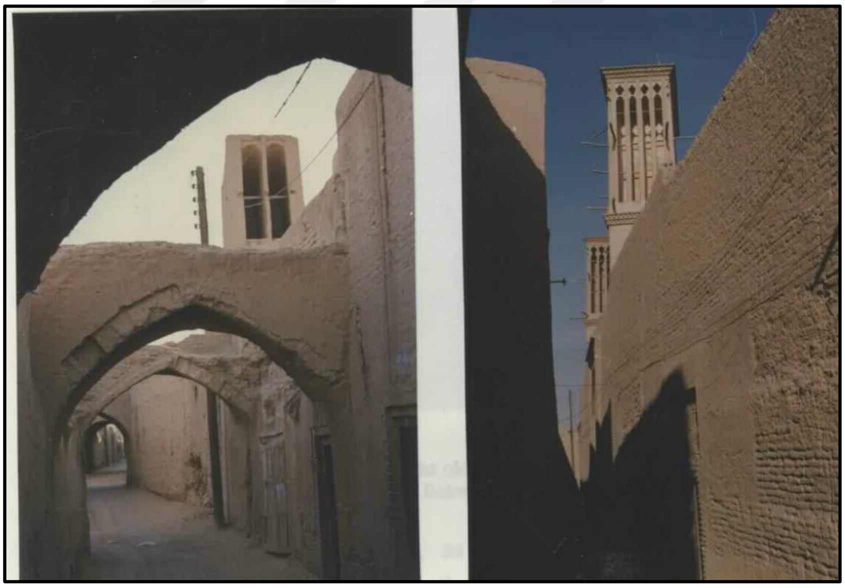
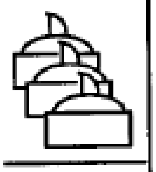
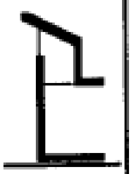
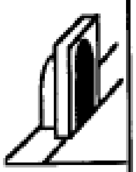
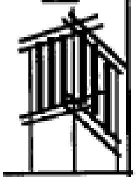
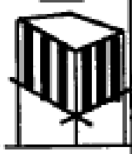
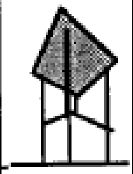


Figure 5.10. Left, an ordinary wind catcher Ardakan, Iran, right, a (four sided wind catcher in Yazd, Iranb Two types of wind catchers in the old quarter of the cities of central Iran. above, one directional towers in Ardakan, blow four directional towers in Yazd (Mahyari, 1996).

Figure 5.10. (continue) Left, an ordinary wind catcher Ardakan, Iran, right, a (four sided wind catcher in Yazd, Iranb Two types of wind catchers in the old quarter of the cities of central Iran. above, one directional towers in Ardakan, blow four directional towers in Yazd (Mahyari, 1996).

Table 5.1. includes a synopsis of the historical wind catcher types, as well as the specifications of each type of wind catcher, and also a summary of the climatic factors.

Table 5.1. Comparison between various types of the wind catchers with respect to climate in the Middle East (Mahyari, 1996)

	Afghanistan 	Egypt 	Iraq 	Iran 	Persian Gulf 	Pakistan 
Climate Region	Semi Hot-Arid	Hot-Arid	Hot-Arid	Hot-Arid	Hot-Humid	Hot-Humid
Wind direction	North	North-West	North-West	North-West North-East North	See Breeze	South-West
Cross Sectional Shape	Square	Rectangle	Rectangle	Rectangle Square Hexagonal	Square	Square
Dimensions (m) (Average)	1 x 1		0.5 x 0.15 1.20 x 0.60	0.5 x 0.8 0.7 x 1.1	1 x 1	1 x 1
Height (m)	1.5 Above the Roof	One story Above the Roof	1.80 - 2.10	1-5	1: -5	up to 5
Orientation with Respect to Wind	Normal	Normal	Normal	Diagonal	Diagonal	Diagonal
Top-End Shape	Inclined with 30°	Inclined with 30°	Inclined with 45°	Flat	Flat	Inclined with 45°
Space Vented by the Tower	All Rooms	Reception & Room	Basement Only	Reception & Basement	Reception & other Rooms	All Rooms
Concept of Flow	Uni-Direction	Uni-Direction	Multi-Direction	Multi-Direction	Multi-Direction	Uni-Direction
Use of evaporative Cooling	No	Sometimes	Sometimes	Sometimes	No	No

5.4. Climate Classification of the Wind Catcher

While the form of wind-catcher is determined by environmental and climatic factors, the basic idea is to capture wind and simultaneously removing indoor air from low pressure zone. The Two major categories of conventional wind catchers can be identified as follows;

1. Wind catcher in hot and humid regions.
2. Wind catcher in hot and dry regions.

5.4.1. The Wind catcher in hot and humid regions

Considering the low wind power in that climate, these forms of wind catchers have very big openings and short shafts. Normally each space has its own wind catcher to provide a suiTable indoor air temperature and comfort conditions. Wind-catchers, and most natural cooling systems, can offer indoor air circulation that can help evaporate moisture and helps to provide cool air for the users, particularly in hotter cities (Roaf, 2005). The mortar plaster, ashes, and also Plaster of lime, have been used in the hot and humid climate, and the color that has been used in the wind tower frame and the wind tower surface was white, which was aimed to reduce the radiation absorption and heat, (Figure 5.11). Furthermore, the materials used on the surface of the wind tower in the hot and humid regions assist in humidity resistance. The cross - section plan of such wind tower is typically square, with equal length and width (A’zami, 2005).

Figure 5.11. Wind-catcher in hot and humid area (Roaf, 2005)

5.4.2. Wind-catcher in hot and dry region

In this climate, the shaft height of the wind catchers is higher than the one in hot and humid climates. In the hot dry climate, the wind catcher's column descends to the ground floor, where the residents usually stay(A'zami, 2005). By changing the height of the shaft the air temperature drops as the distance from the earth increases, and the wind catcher is able to catch colder and cleaner air with higher speed and less dust at the higher area. Due to greater wind intensity in such a climate, the size of this kind is less than that of a wind-catcher in hot and humid regions, (Figure 5.12) (Narguess, 2009).

Figure 5.12. Traditional Wind Catcher in hot and arid area, Yazd, Iran (Narguess, 2009)

When the wind reaches a structure through the wind catcher, it usually flows over a fountain or a stone pool at the bottom of the structure, carrying the humidity and also the cold air into the structure. Hot weather improves evaporation and that will increases the cooling influence and relative humidity in these conditions, resulting in cooler temperatures and higher humidity levels (Ghaemmaghami et al., 2005). The materials that have been used in the wind tower are influenced by environmental standards and the available materials in hot and dry regions same as the materials that were used in other conventional buildings. The wind catchers or the wind towers are normally made of backed brick or mud brick that is plastered externally and internally with straw plaster and light paint to return solar radiation and to have a rough texture. Furthermore, mud brick has the ability to absorb heat in their construction throughout the day and avoid the heat at the evening (Narguess, 2009; Roaf 1988). It must be noted that wind catchers, like other natural ventilation systems, were used in hot and dry regions or hot and humid regions and that they, like other natural ventilation devices, are normally supplemented by other criteria to make the interior environment comforTable for the occupants, and this can have an effect on the overall use of the building or the house. According to the Roaf notebook, people who live and work in hot climates and building users who use wind catchers play a significant part in adapting and managing the indoor atmosphere (Narguess, 2009).

5.5. Wind Catcher's Function

Wind catchers work in the same way as most natural ventilation systems, relying on the wind and the so-called stack effect, which is caused by temperature variations. Specific ways of opening and closing are used in the wind catcher to optimize these features. Wind has a difficult time switching directions and entering a space through normal openings like windows; the wind tower is used to fix this issue (Figure 5.13). Vertical columns in wind catchers assist in changing the path of the wind and directing it down to the interior of a house (Li, 2007).

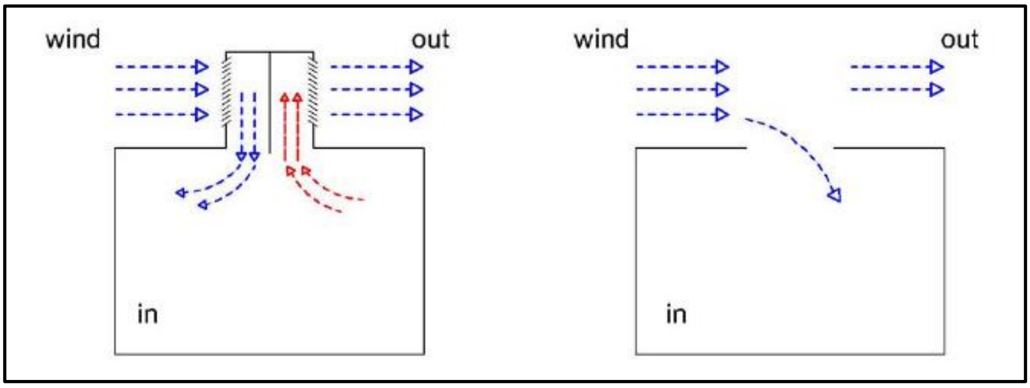


Figure 5.13. Air flow in a building with and without a wind catcher (Narguess, 2009)

5.5.1. The wind

Around a barrier, pressure variations are created by the wind. If the wind hits an object, (such as the wind tower), the air pressure in the windward zone will be increased in comparison to the leeward zone. As a consequence, positive pressure forms on the building's windward edge, while negative pressure occurs on the other part of the barrier (wind tower), so wind enters from the positive pressure zone then moves to the lower pressure area (Figure 5.14&15). Since the lower pressure area of a wind catcher is situated at the bottom of the shaft, fresh air enters the building space when the hot and dirty indoor air exhausts to the other part of the inlet with greater negative pressure (Mehdi N Bahadori, 1994). Evaporation could follow the cooling process in certain forms of wind catchers. The humidity is found at the bottom of the shaft in this kind of wind catcher, and as the wind passes through it, it supports evaporation and consumes air heat, which aids cooling cycles.

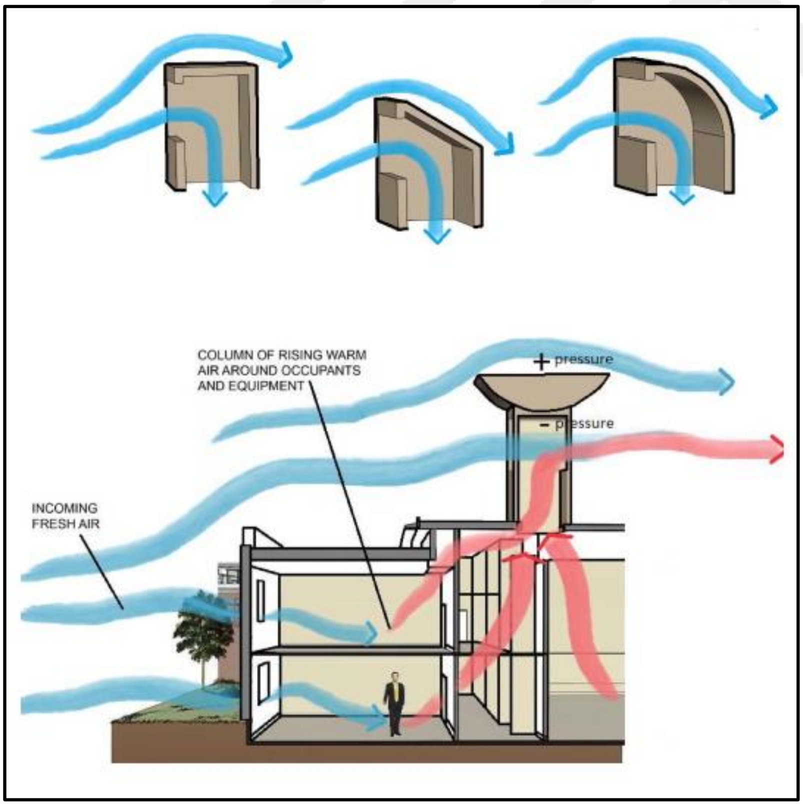


Figure 5.14. Natural ventilation in wind catcher (Jomehzadeh et al., 2020)

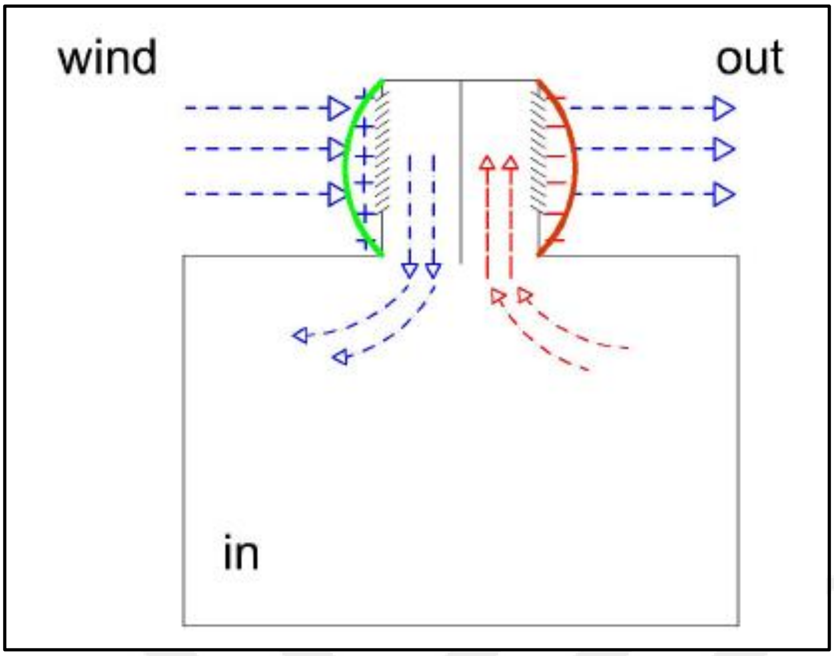


Figure 5.15. Pressure zones around a wind-catcher (Narguess, 2009)

5.5.2. Stack effect

Due to density variations in outdoor and indoor climates, the stack effect happens in wind catchers. A pressure differential forms between the top and bottom of the column whenever a breeze moves through the top of a wind catcher, even if it is not noticed at the bottom, which helps to introduce colder, denser air to the building and remove hotter and lighter air from the building. Moreover, since the lower floor of the building often has several windows, fresh air reaches the building through the openings, while hotter and lighter air depletes from the top of the building,(Figure 5.15) (Yaghoubi et al., 1991).

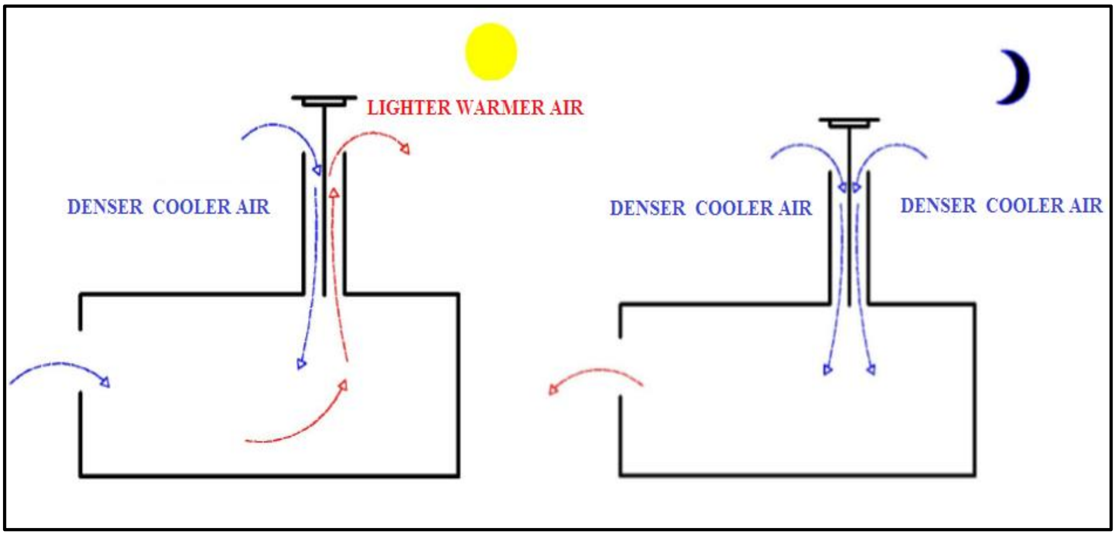


Figure 5.16. Function of wind catcher due to stack effect during day time and night (Narguess, 2009).

The temperature of the outside environment drops at night, allowing denser colder air to access the wind structure. The cooler, denser air in the structure is mixed with the warm air, which is absorbed between day time and night by the wind catcher and the building, So the cold air will be mixed with the hot air that has been absorbed by the building and the wind catcher's structure inside the building, this cycle will continue until the internal air temperature and the outside air temperature of the wind catcher becomes balanced. The cooler and higher density air that reaches the structure of the wind catcher gets combined with the hot air that has been absorbed by the wind catcher and building through the day and night, then mixed warmer air rises up from the structure or other window in the building and new cooler air is released to the indoor space, and this process repeats till the wind catcher or tower and the outside air temperature become commensurate, (Figure 5.16), (Narguess, 2009; Soflaee et al., 2005). As a result, wind catchers will advantage from such a function at night in areas where the accumulated impact throughout 24-hour duration is important (Elmualim et al., 2006). The weather catchers used as solar chimneys throughout the day when there is a Weak wind. Similarly to a solar chimney, the wind catcher enhances air exhaust by cooling the surface of the wind catcher. Moreover, although wind catchers create air circulation within the zone, and helps in the evaporation of sweat from skin surface, they provide a more comforTable atmosphere during the summer (Roaf 1988).

5.6. The Components of Wind Catcher

Wind catchers traditionally have an octagonal or rectangular or cross section with a chimney-shaped tower formed into multiple shafts by brick walls. At least one opening is visible on the top of this chimney-shaped structure. The elements or components of a wind catcher can be divided into three categories (Narguess, 2009) (Figure 5.17);

- The tower of the wind catcher,
- The opening or vent of the wind catcher,
- the partitions in the wind catcher,

5.6.1. The tower of the wind catcher

The tower is the key component of the wind catcher, and its height is defined by the place and the surrounding area. The openings and vents are located in the upper part of the tower, while the stalk is located in the lower part of the tower. The highest point of the wind catcher affects the height of the stalk, which may be designed for aesthetic purposes (Roaf 1988).

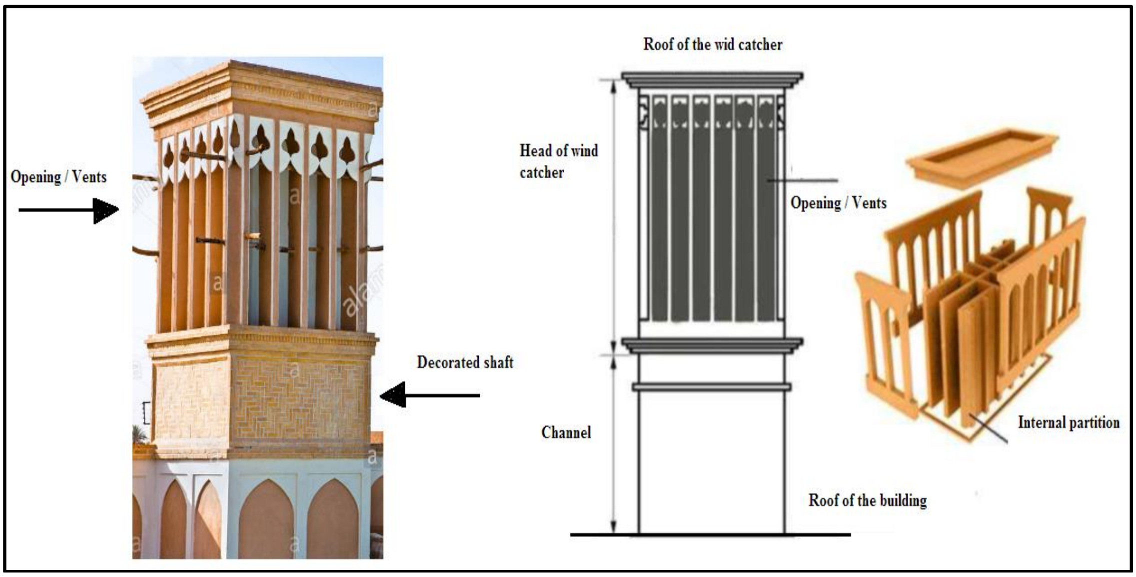


Figure 5.17. Components of traditional wind catcher (Jomehzadeh et al., 2017)

5.6.2. The opening or vents of the wind catcher

The fresh and clean air is captured and diverted back into the building through openings or vents in the highest section of the wind catchers' column. The amount of openings is decided by the position of the wind-catcher and its cross-sectional area. Wind catchers with rectangular, square, hexagonal, or octagonal cross sections are common. Circular plan wind catchers are sometimes documented in modern wind catcher architectural design;

- The Rectangular wind catchers are available in one, two, and four-sided models.
- The Square wind catchers have vents on two or four edges of the wind catcher, allowing it to receive wind from one, two, or four different ways.
- It's interesting to note that each side of the wind-catcher can have up to twelve separate vents.
- Hexagonal wind catchers normally have openings on six sides.
- Eight-sided wind catchers with eight vents at the top are known as octagonal wind catchers.
- Most circular wind catchers have four holes (Roaf 1988).

5.6.3. The partition

Partitions were used to split the tower of a wind catcher into many different shafts. Wind tower or catcher with multiple shafts can supply a building with fresh and cold air from one side while exhausting warm and used air from the other side, and partitions are needed for structural purposes. Generally, partitions were constructed of mud bricks, but new structures have replaced them with new materials. There are two main categories of partitions; main partition and secondary partition (Figure 5.18).

<u>Main partition</u>

Wind catchers are divided into two, four, six, or eight vertical shafts by main partitions that run through the middle of the tower. They often enable air to reach and leave the wind catcher at the same time. The primary partition may be in the form of “H”, diagonal, or vertical (Ghaemmaghami et al., 2005) (Figure 5.19).

<u>Secondary partitions</u>

Secondary partitions were used to either increase the efficiency of the wind catcher or to provide structural strength. The width of the secondary partition is the same as the width of the outer wall. If the wind approaches from a narrow zone, the air movement will improve, and the wind speed increases, then the air flow rate will change, (Ghaemmaghami et al., 2005; Narguess, 2009).

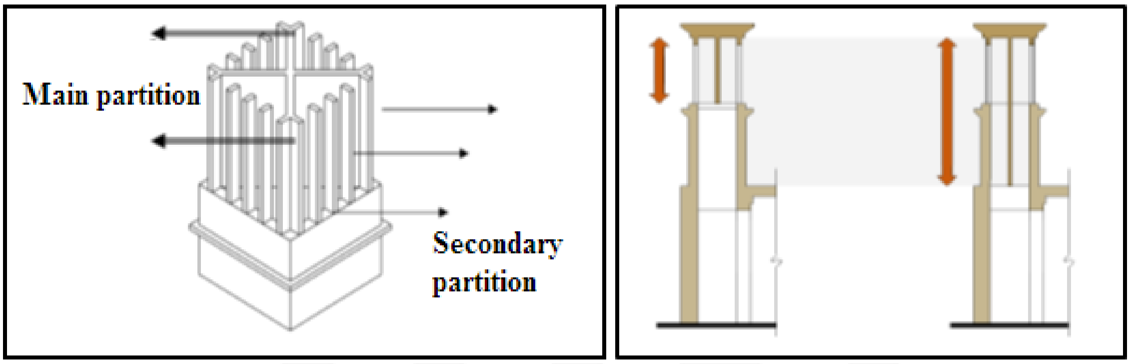


Figure 5.18. Partition categories (Roaf 1988; Vahdatpour, 2020)

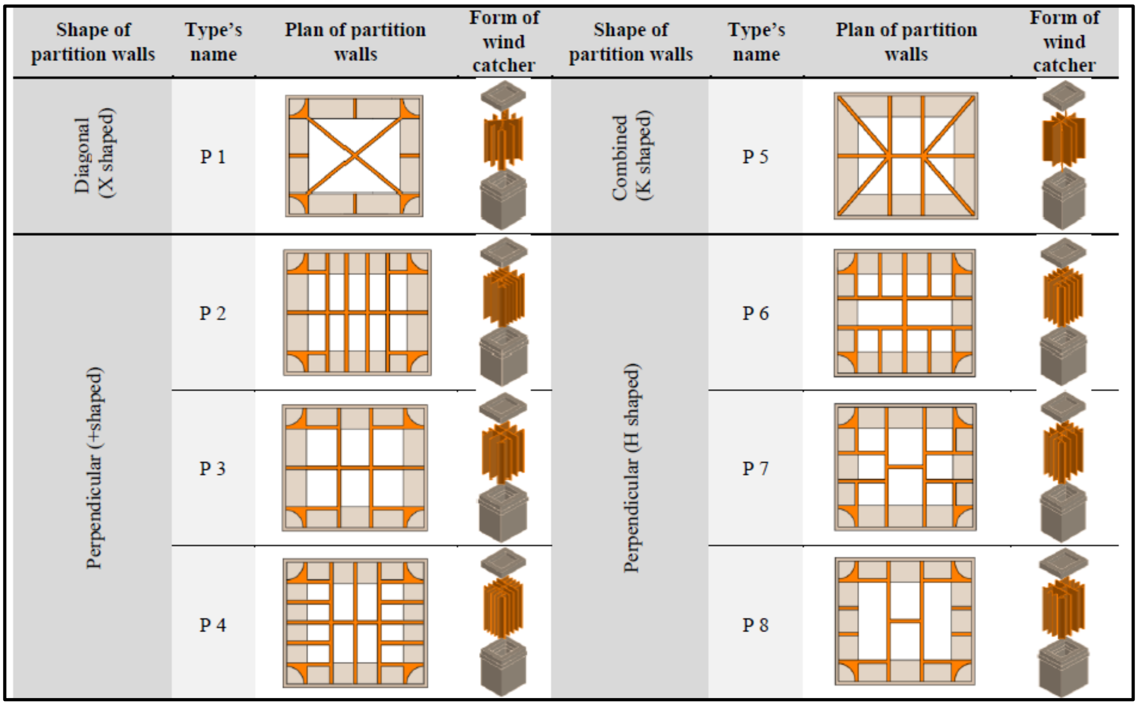


Figure 5.19. Partition wall arrangements in four sided wind catcher (Vahdatpour, 2020)

Furthermore, using secondary partitions during the day enhances the surface area in contact with the warm air. As a result, partitions have been constructed with heat-absorbing mud bricks, which absorb external heat throughout the day and release the accumulated hot air to the outside area at night, helping in the cooling of the area, (Figure 5.20), (Roaf 1988). Instead of vertical secondary partitions in conventional wind catchers, horizontal louvers have been used in new designs (Narguess, 2009).

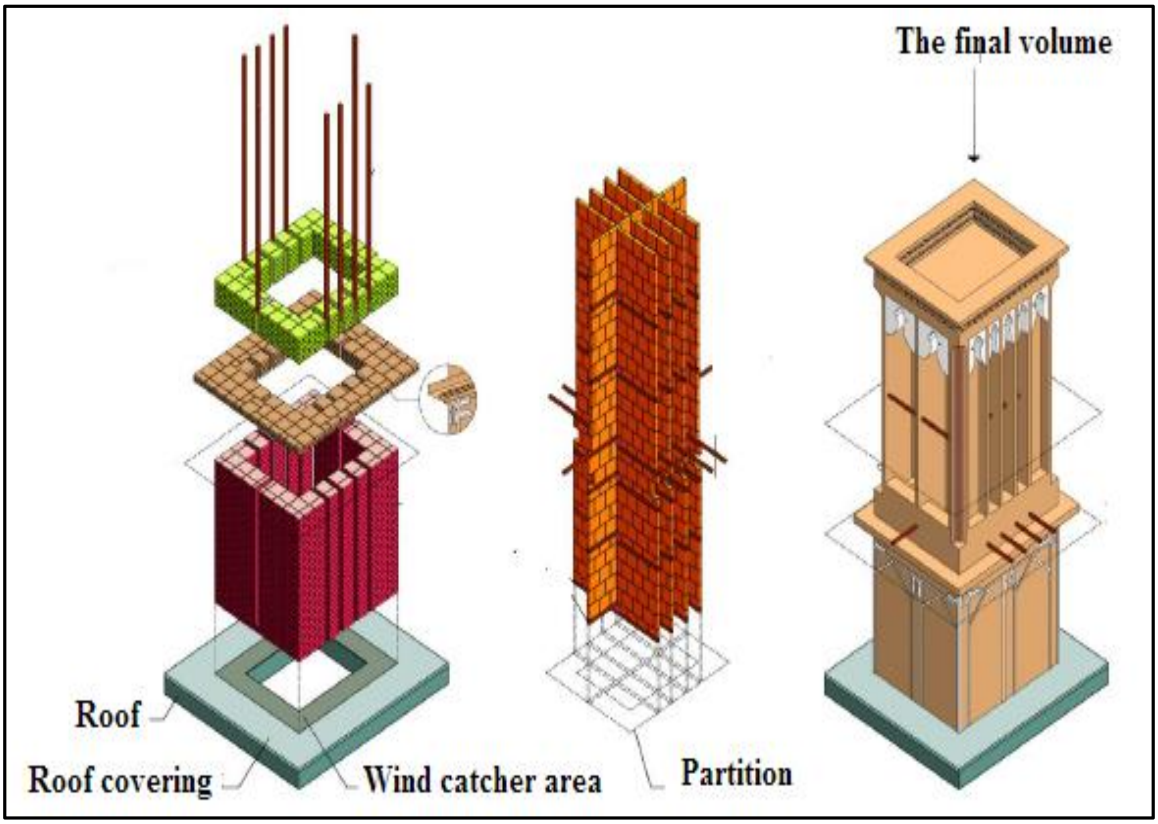


Figure 5.20. Wind catcher construction process (Vahdatpour, 2020)

5.7. Wind Catcher Structure

A wooden frame was historically used to construct a wind catcher, which then was covered with mud bricks. Bricked mud primary partitions were constructed within the entire length of the wind catcher's foundation to protect the structure. The horizontal wooden beams could be used at different levels of the wind catcher in addition to supporting the foundation of the wind catcher. (Figure 5.21) shows how beams protrude from the wind catcher to form a staircase that allows for better accessibility to the higher part of the wind catcher for maintenance, and construction (Ghaemmaghami et al., 2005). Furthermore, according to Roaf these beams improve the wind catcher's tower's shear resistance, which may impact the wind catcher's efficiency (Roaf 1988).

Figure 5.21. Beams come out from wind catcher tower (Internet: Kaushik 2005)

Vertical partitions (secondary partitions) are often used in higher parts to support the exposed space of wind catchers (vent). Various forms of arches may be used to decorate vents. These arch-shaped decorations aren't important for any structural or functional purposes. Finally, brick rows are added to the top of the wind catcher, which is constructed to provide shading for the wind catcher as well as rain coverage (Roaf 1988).

5.8. Wind Catcher’s Efficiency

Even though previously described, the effectiveness of a wind catcher is determined by the temperature differential and wind, so the wind tower or catcher's efficiency is determined by optimizing the differential pressure between both the outlet and inlet and the variation in temperature between the inside and outside of the tower's structure, as well as the inside and outside of the building. As a result, the following criteria may be used to determine the effectiveness of a wind catcher (Narguess, 2009);

- The cross sectional plan
- The height of the wind catcher
- The location of outlets and inlets
- The orientation of the tower

5.8.1. The cross sectional plan

The overall amount of air and the direction of wind coming down from the wind catcher are influenced by the size and shape of the cross - section plan of the wind tower. The size of the cross sectional areas of the shaft and the effectiveness of a wind catcher have a correlation. As the total opening area of the shaft increases, the total amount of air introduced to the building increases as well, helping in the operation of the system; on the other hand, as the amount of air continues to grow, the Bernoulli Effect slows the velocity of air traveling down, reducing the total airflow rate introduced to the building. As a consequence, if a wind catcher is built, these two criteria should be taken into account simultaneously. The cross-sectional design affects the number of openings in the wind catcher; the number of openings on different sides of the wind catcher allowed the wind catcher to capture air of various directions, therefore, the cross- sectional plan of the wind catcher or tower has an impact on the system's effectiveness. The number of openings is generally used to identify wind-catcher's type. The next wind catcher classification system is based on its cross - section plan (Montazeri et al., 2008).

<u>One-side wind catcher</u>

This type of wind catcher was used in many countries of the Middle East where the permanent winds are in one direction, but if the winds have different directions; this type of wind catcher will not work properly, whereas this types of wind catcher usually have openings in the north or north-west direction, with a sloping roof and one or two vents

(Figure 5.22). The wind enters the building from the opening in the wind catcher and passes via the living space, and going out from the exhaust vents, windows, and doors (Maleki, 2011).

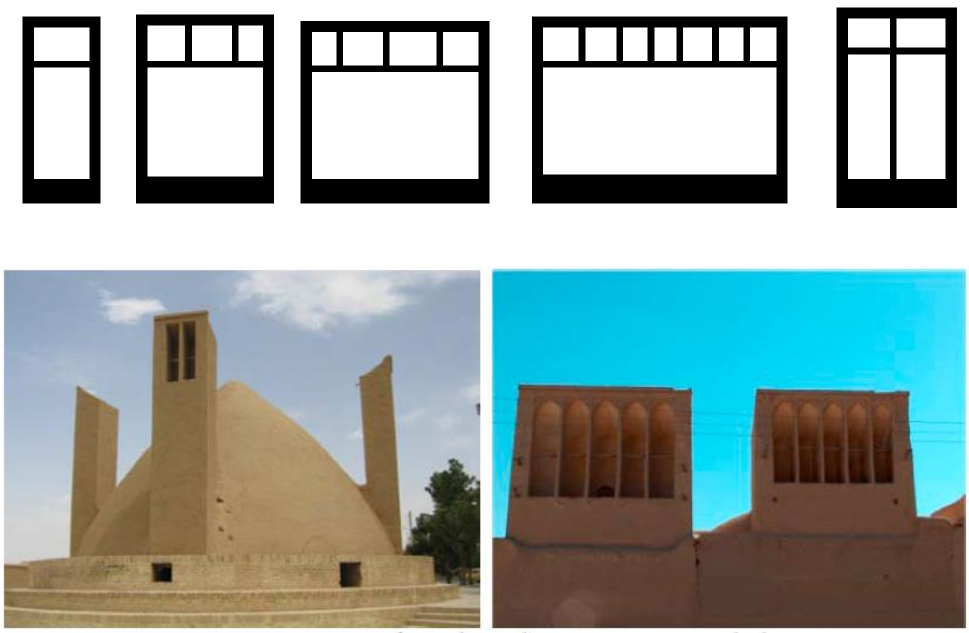


Figure 5.22. Typical plan of a one-directional wind catcher (Maleki, 2011)

The Two directional wind catchers

This type of wind catcher has been divided into two parts by using a partition made of bricks. They are oftentimes called by direction, such as the south-north wind catcher (Figure 5.23, and 5.24). Roaf's survey indicates that 17% of these types are made in traditional houses (Roaf 1988).

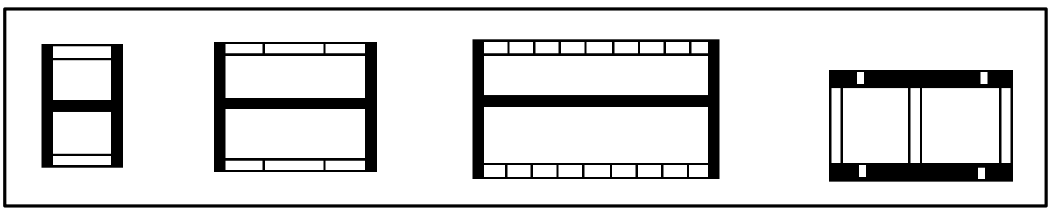


Figure 5.23. Typical plan of two-directional wind Catchers (Maleki, 2011)

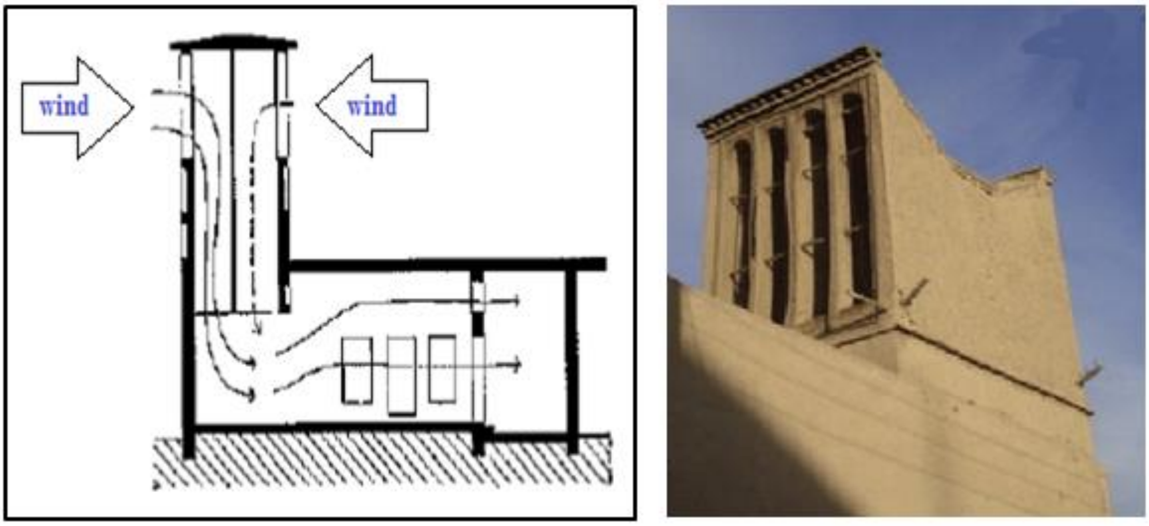


Figure 5.24. Two-directional wind catcher section and view (Montazeri et al., 2010)

The four directional wind catchers

Studies generally indicate that all of the wind catchers in the hot humid region are four directional types, and more than half of these types of wind catchers in the hot and dry region that has been used in Iran, (Figure 5.25). The most common wind catchers have four main vertical shafts split by partition (Ghaemmaghami et al., 2005). In the layout of rectangular wind catchers, the larger side faces the prevailing wind, and the width to length ratio is normally 1 to 2. If a square plan wind catcher is being used, the tower is normally separated into four different vertical columns by two major partitions. The size of the space and the owners' personal preferences influence whether they choose a wind catcher with a rectangular or square plan (A'zami, 2005; Roaf 1988). The total number of vents on each side of a four-sided square plan wind tower is estimated to be six, while the number of vents in a rectangular plan wind tower ranges from one to fifteen (Roaf 1988).

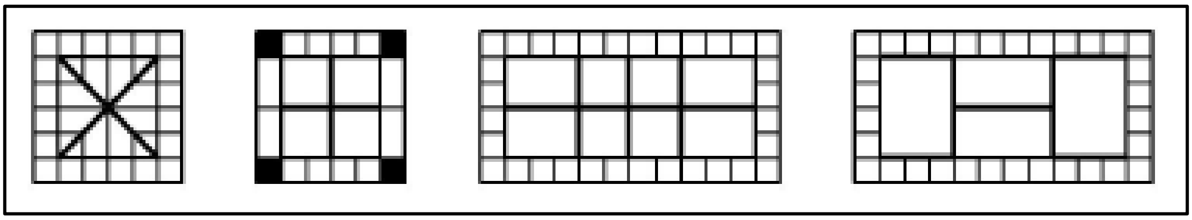


Figure 5.25. Four directional wind catchers (Roaf 1988)

Figure 5.26. Left; rectangular wind catcher, right; square wind catcher (Internet: Iran in depth, 2018)

The hexahedral and octahedral wind catchers

Only twenty multi-directional examples Out of seven hundred and thirteen wind catchers have been reported. The greatest badger on top of Khan's Pavilion at Bagh-e-Dowlatabad (Figure 5.27& 5.28), has an octagonal plan. While they are the most popular on-water cistern.

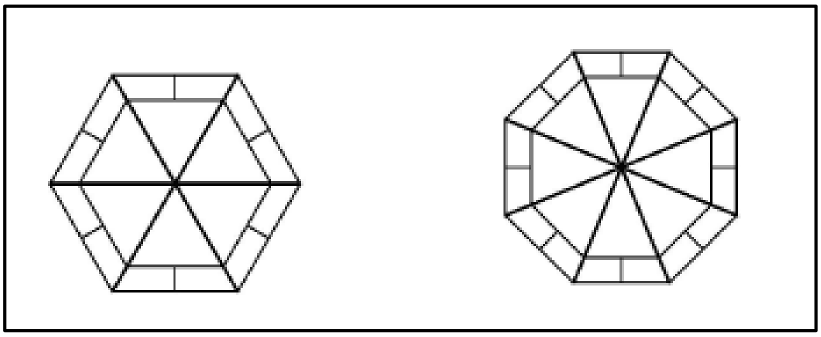


Figure 5.27. Typical plan of six and eight sided wind catcher (Roaf 1988)

Figure 5.28. Six and eight sided wind catcher (Internet: Iran in depth, 2018)

5.8.2. The height of the wind catcher

The height, wind direction, and air temperature both have a strong relationship. Wind resistance from the ground surface decreases as structure height increases; as a consequence, wind speeds in the upper zone increase. Furthermore, as a result of the distance between both the air around the upper part of the wind catcher and the hot air at the ground level, air temperature actually decreases in the upper zone. The wind strength and temperature brought into the building by the wind catcher's vents are influenced by the height of the wind catchers. Badran demonstrated in 2003 that the height of the wind catcher has a direct connection with its efficiency (Badran, 2003). Furthermore, the wind catcher may benefit from the better and cleaner air at a higher altitude. After all, since the internal partitions in the wind catcher are made of thicker brick that usually stands on the wind catcher's sides and is supported by timber frames, the wind-catcher structure's height is constricted. Standard wind catchers typically range in height from 1.5 to 32 meters above the earth, with 60% of wind tower are less than 3 meters high, and only 15% are higher than five meter (Montazeri et al., 2008; Narguess, 2009).

5.8.3. The location of outlets and inlets

The overall pressure variations between the inlet and outlet determine the efficacy of wind catchers, since when the inlet is situated in the highest pressure area and the outlet is situated in the lowest pressure area the wind catcher's output will increases (Narguess, 2009).

5.8.4. The orientation of the tower

Since the direction of the prevailing wind is affected by orientation, the direction of a wind catcher's tower has an impact on the effectiveness of wind catchers. As a consequence, the wind catcher's orientation is basically decided by the position of the prevailing winds; however, various places have different wind catcher orientations.

5.9. Traditional and Modern Wind Catcher

The new or modern wind catcher designs take conventional wind catcher principles but adjust and develop them to create modern wind catchers. The inlet and outlet have also been positioned in the very same design in both new and conventional wind catchers, allowing the wind catcher system to deliver fresh air and remove dirty and hot air at the very same period, (Figure 5.29) (Narguess, 2009).

Figure 5.29. Modern wind catchers (Internet: Alivia mondal, 2015)

As explanations for the variations between traditional and modern wind catchers, there are two major groups of differences that can be identified (Figure 5.30);

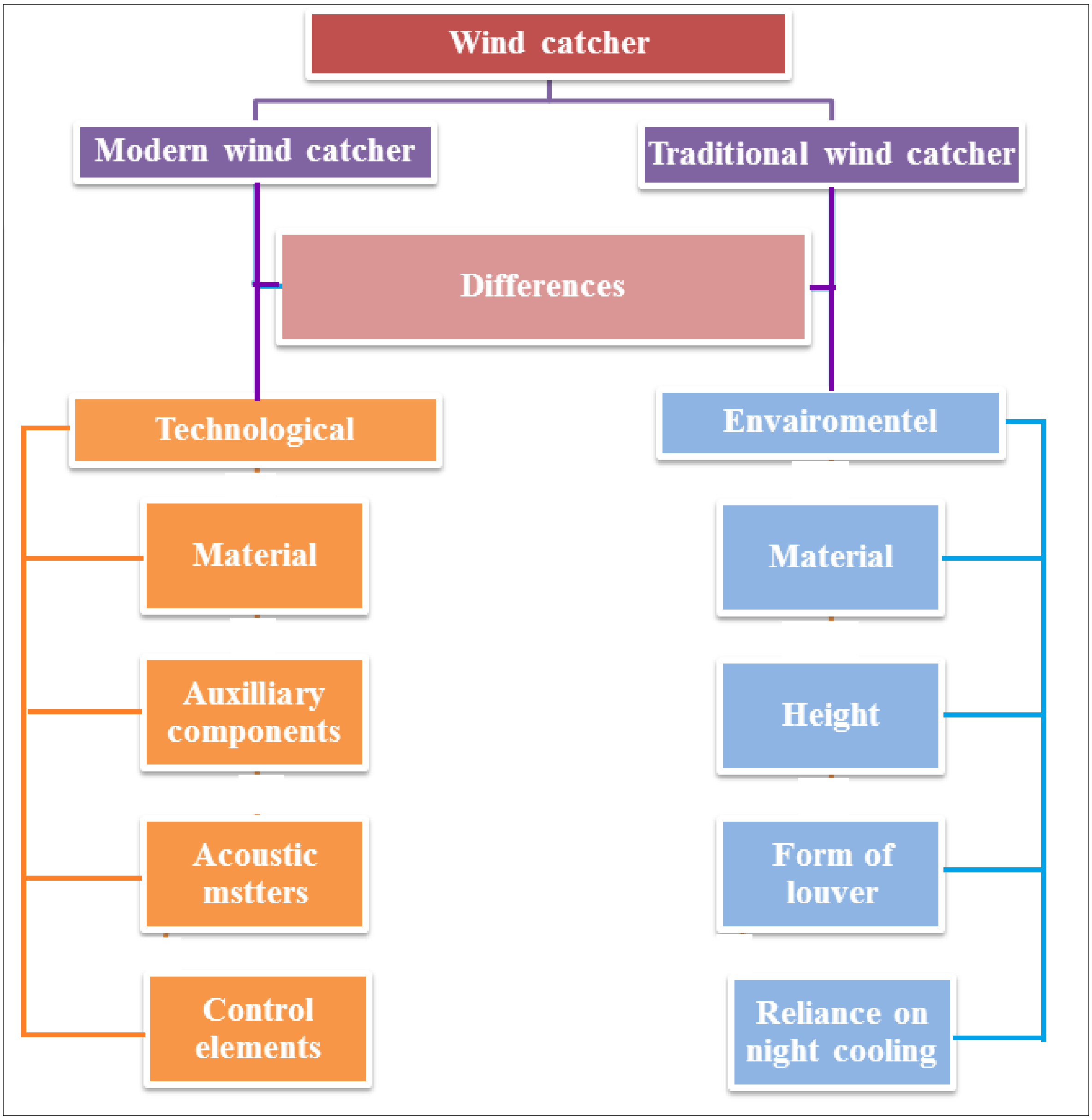


Figure 5.30. Differences between modern and traditional wind catcher

Technological availability is the first category of differences. The new techniques that have been established, like control systems or acoustic materials, did not exist during the time of conventional wind catchers, the first category of variations actually improve the conventional style, and the second category of variations, such as variations in height and the louvers, is the result of the differences in climate and temperature. The results of the second category may have an effect on how well wind catchers perform. The following are the differences between conventional and contemporary wind catchers;

5.9.1. The auxiliary tools

The new wind catchers systems are often supported by auxiliary equipment such as water supply or a fan to enhance the wind catchers' efficiency.

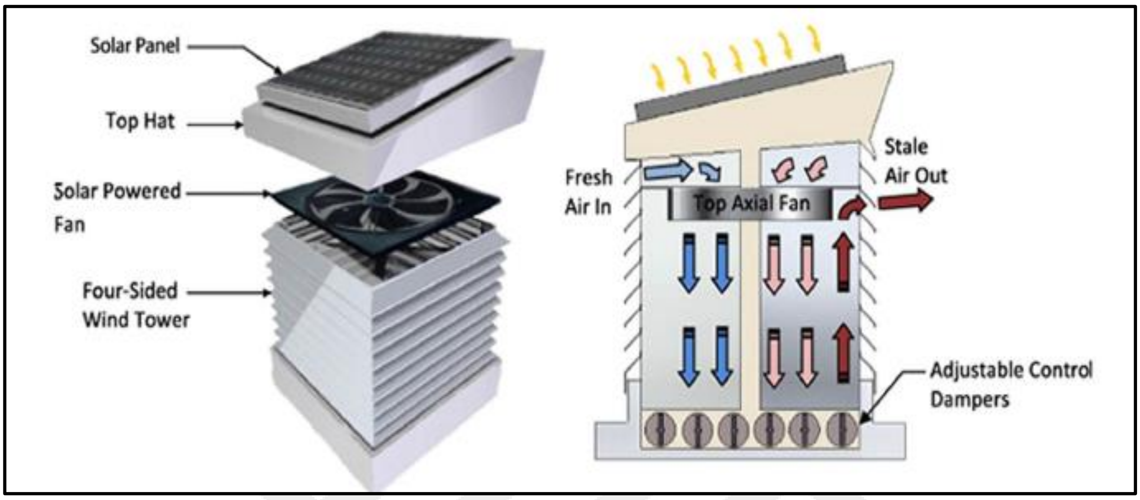


Figure 5.31. Modern wind catcher integrated with a solar powered fan (Hughes et al., 2012; Khatami, 2009)

5.9.2. Control devices

Traditional wind catcher's doors are the only control systems available to users, but new wind catcher modern designs provide to users more options for controlling their wind catchers. There are three types of control devices that have been used in modern systems (Narguess, 2009),

- Positioner control: By turning a dial, users can change the temperature of the air within their building, , for example when the dial is adjusted to 20°C, the damper automatically updates to let ventilation into the space until the indoor air temperature reaches 20°C.
- Manual control: Manual control devices work in the same ways as conventional control devices work. A damper is situated at the roof level which provides users with manual control.
- Automatic monitoring: such devices are sensitive to air temperature, relative humidity, and CO2, pollution levels, as well as the wind catcher control devices may be set according to the users' requirements

5.9.3. Noise transmission

Noise transfer happens while air from the outside is brought through natural ventilation systems. The openings in the wind catcher are normally situated at higher levels, making it less likely that vehicles or outside noise could reach the building. New wind catchers, on the other hand, are more insulated against outside noise than conventional wind catchers due to the use of acoustic lining in the air paths (Khatami, 2009; Narguess, 2009).

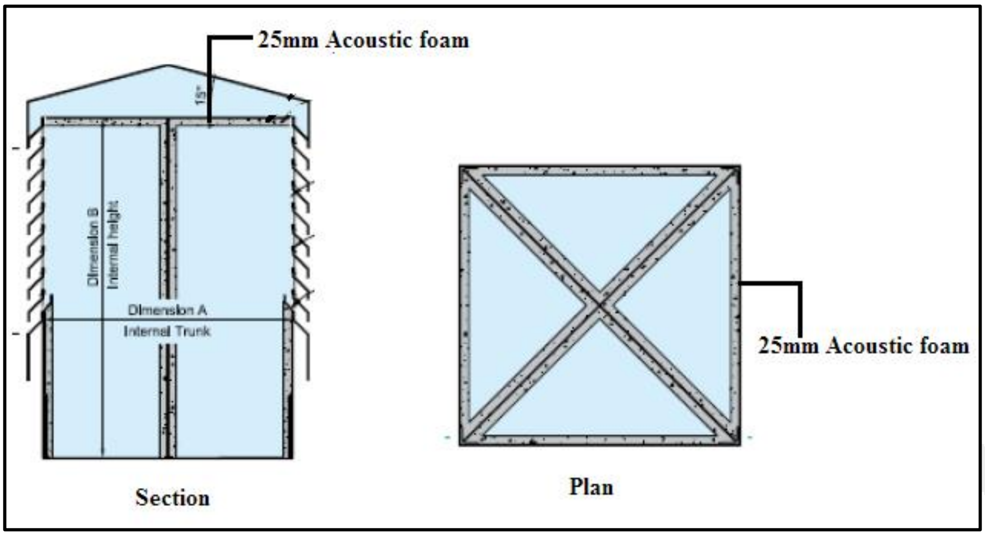


Figure 5.32. Acoustic isolation in new modern wind catcher (Internet: Monodraught Ltd, 2018)

5.9.4. Height

The height of new wind catchers in Europe is lower than the height of wind catchers in the Middle East for economic and aesthetic factors. As a consequence, they are less able to take full advantage of the stack effect. Furthermore, in modern cities, using low-level openings in noisy, crowded areas, and polluted areas is unfavorable, whereas in traditional buildings with wind catchers, using low-level openings such as doors or windows helps to optimize the stack effect (Harwood, 1998). As a direct result, in contrast to conventional wind catchers, shorter new wind catchers are less able to take full advantage of temperature variations.

5.9.5. Material

Small plastic and metal sheets are the components used in the new or modern design of wind catchers. new wind catcher components are thinner than conventional models, and in most modern projects, wind catchers were built with three layers of fiber glass and Class 0 fire resistant, because of that They have stronger fire resistance, (Figure 5.33). On the other hand, Traditional structures of wind catcher can absorb more heat during hot summer days due to the use of thicker brick with a higher thermal ability (Narguess, 2009).

5.9.6. Louvers form

The shape of the wind catcher's louvers is primarily affected by the weather. Wind catchers have large vertical vents in conventional designs of wind catcher, as they are typically used in dry and hot areas. However, rain has a major impact on architecture in Europe, so modern wind catchers in Europe have many oblique horizontal louvers, which can influence the wind catcher output. To maximize the overall volume of air introduced into the building, the number and size of wind catchers are usually increased in modern wind catchers. Since air reaches a wind catcher via louvers, the shape and size of the louvers also have a direct impact on the system's efficiency. As previously mentioned, one of the critical differences between conventional and modern wind catchers is the shape of the louvers. New wind catchers use louvers rather than vertical primary partitions in conventional models, (Figure 5.34). New horizontal louvers offer greater protection from dust, rain, birds and improve building safety but may have an effect on system performance (Narguess, 2009).

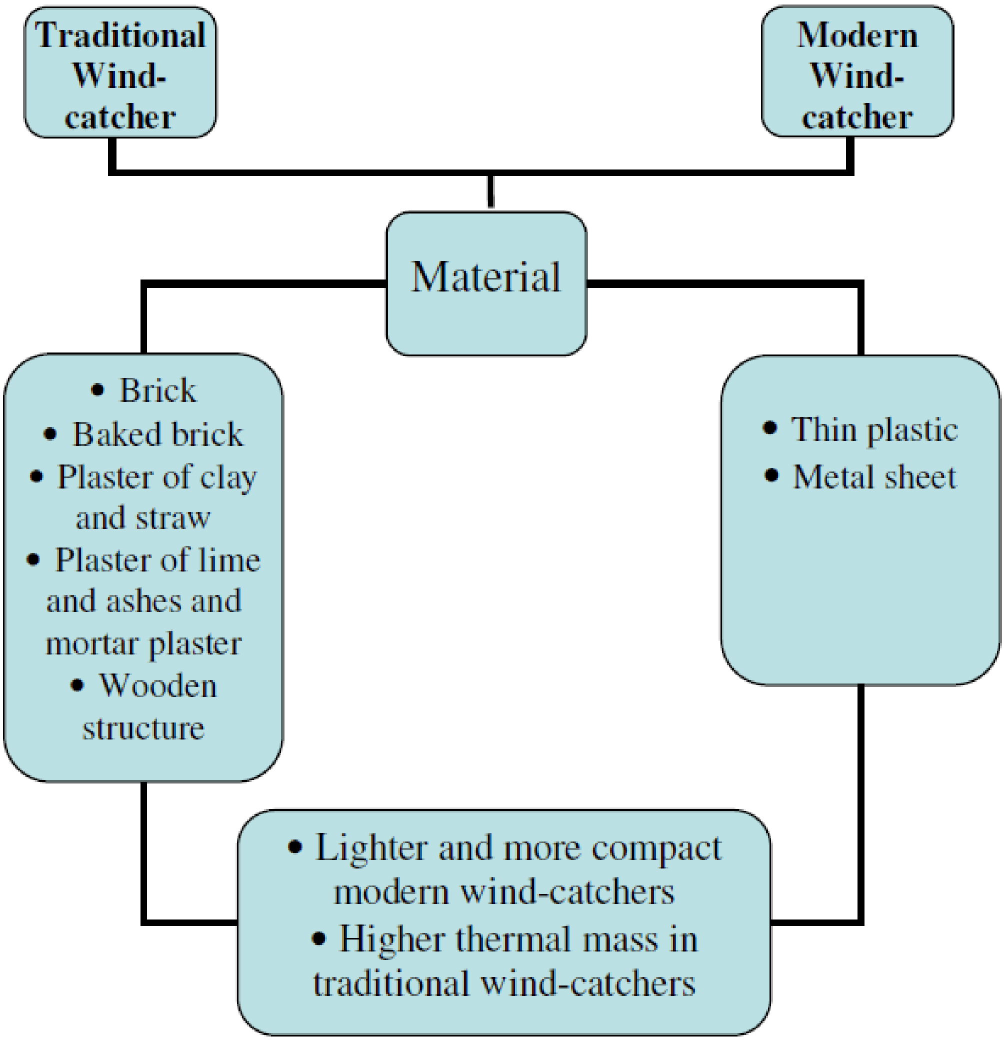


Figure 5.33. Compering between the materials used in modern wind catchers traditional (Narguess, 2009)

Figure 5.34. Modern wind catcher with lovers (Internet: Monodraught Ltd, 2018)

Figure 5.35. Different designs and styles of modern wind catchers (Internet: Monodraught Ltd, 2018)

Advantages of the modern wind catcher

- It delivers pure fresh air clear of dust and dirt.
- It provides a high level of airflow to the building without losing efficiency.
- This system is completely energy free in its natural state.

- There is no repair, nothing to break, nothing to patch, and the Wind catcher mechanism enclose any prevailing wind from the outside.
- It has been noted one of the key benefits of the wind catcher mechanism seems to be the night time cooling system, which still allows the colder night air to drop to floor level with the dampers fully open, somewhat pressurizing the building but still forcing dirt and dust out of another side of the Wind catcher structure.
- Another value to the Wind catcher method is that because all of the air is extracted from the roof, it is relatively free of dust and hot air.

5.10. Wind Catcher Cooling Techniques

Buildings that are naturally ventilated do not need any extra energy to move the ventilation inside the residential building. On the other hand, traditional wind catcher, have restricted cooling capability due to the structure's layout. As a result, cooling the air is important to increase the comfort conditions of the building's inhabitants (Mehdi N Bahadori, 1994). In This segment examines cooling methods that can be used to increase ventilation and thermal efficiency of a traditional wind catcher system. (Figure 5.36) illustrates a wind catcher structure with cooling equipment as a prototype design. A pump recirculates water over evaporation cooling pads at the high point of a wind catcher. The evaporation of water cools the hot air that passes through these pads. Since cool humid air has a higher density than surrounding air, it falls to the wind catcher and then into the enclosed area. Warm air must be released in order for cold air to move in. The solar chimney is positioned directly across from the wind catcher to provide efficient cross-flow ventilation and to exhaust the accumulated hot air utilizing neutrally buoyant powers (Hughes et al., 2012).

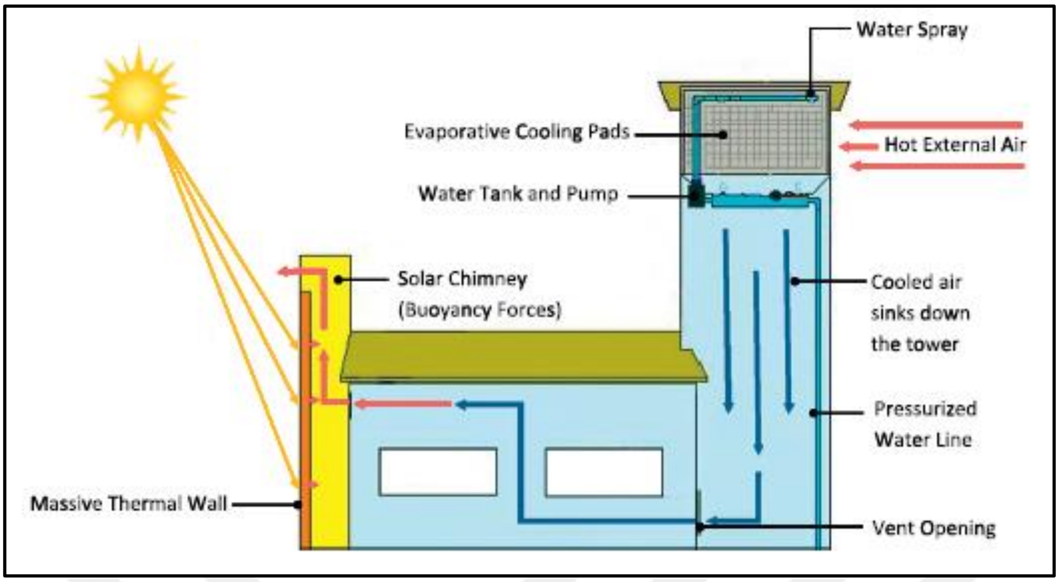


Figure 5.36. A model design for a passive wind catcher with multiple cooling systems (Hughes et al., 2012)

5.10.1. Evaporative cooling

A typical approach for improving natural ventilation and thermal efficiency in old Middle East buildings is passive evaporative cooling. This method of cooling is especially useful in climates that are both hot and dry (Bouchahm et al., 2011). Through saturating it with humidity, outside air is refreshed to its dew point temperature. Before reaching the building, the surrounding air flows by wet walls or underground channels. In summer, a wind catcher's evaporative cooling capacity and its higher air flow rate can be used to completely minimize the indoor temperature loads and provide residents with greater thermal comfort (Hughes et al., 2012).

Wind tower with wetted column and wetted surface

Wetted surfaces upon wind catcher increase the cooling and thermal efficiency of the passive system, overcoming the shortcomings of the traditional architecture. These towers may be used in hot, and dry climates to save a significant amount of electricity used for building cooling in the summer (Bahadori et al., 2008). External air is pre-cooled by evaporative cooling methods before being incorporated into the building. Cooled air is heavier than ambient air and drops to the bottom of the building. As a result, there would be less air loss from such wind catcher openings. Wind catchers with wetted columns are outfitted with fabric curtains or clay conduits that are spaced 5–10 cm apart and attach vertically within the column, as can be seen in (Figure. 5.37). Water is sprayed into a nozzle mechanism at the top of the structure to damp the curtains. Wind catcher with wetted roof has evaporative cooling pads installed at the wind catcher's entrance. Likewise, water is sprayed on top of the unit to damp the cooling pads. The cooling method is well suited to dry areas with strong wind speeds.

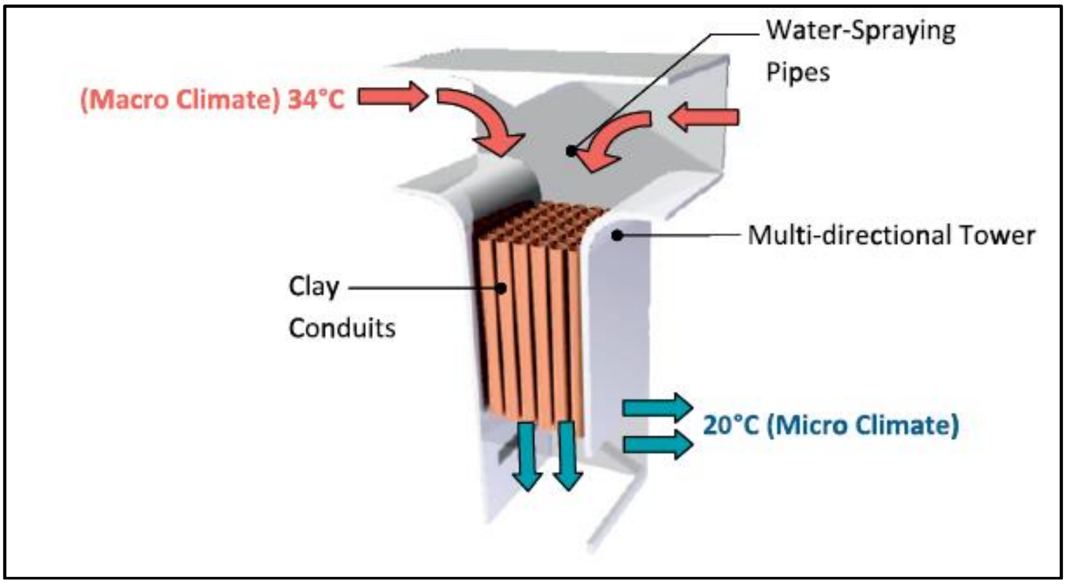


Figure 5.37 .Wind catcher integrated with wetted columns or clay conduits (Hughes et al., 2012)

Using analytical investigation, Bahadori tested the thermal efficiency of two different cooling wind catchers system. These two options were one with wetted columns and fabric curtains hanging in the wind catcher's structure, and the other with wetted panels and evaporative cooling pads just at the entry point. The analytical findings revealed that the air temperature accessing the living area via the wind catcher with evaporative cooling systems was considerably lower than the air temperature escaping the traditional wind catcher. The findings showed the wind catchers that have wetted surfaces performed better in low wind conditions, while the buildings that have wind catcher with wetted column performed better in high wind conditions (Bahadori et al., 2008). The study found that integrating a cooling device into a traditional wind catcher's system was effective, mostly with air leaving the wind catcher's structure at considerably lower temperatures than the surrounding air. Even so, there was a slight decrease in airflow velocity within the wind catcher. The evaporative cooling strategies investigated in the experiment are depicted in

(Figure. 5.38) the use of evaporative cooling pads in the wind catcher's system resulted in the greatest temperature reduction.

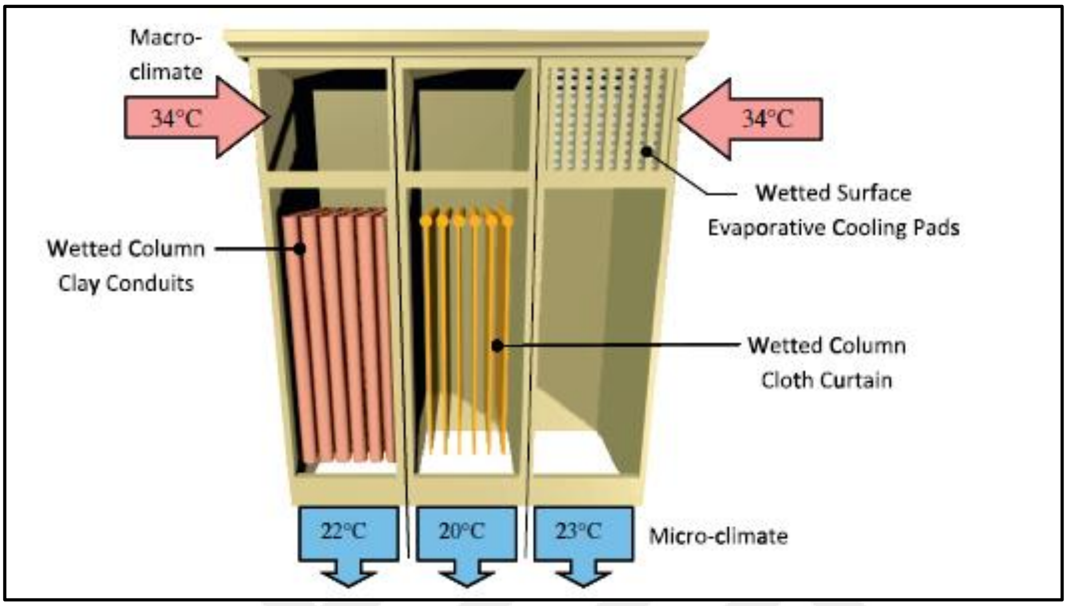


Figure 5.38. Thermal performance of a wind catcher incorporating evaporative cooling devices (Bahadori et al., 2008)

Da Silva assessed the effectiveness of passive evaporative cooling systems built into a lecture hall facility. To determine the relative humidity of the air and the air temperature entering and exiting the structure via the cooling towers, a theoretical model was developed. The model has also been used to identify the impacts of the cooling device's physical parameters on the thermal atmosphere inside the building. According to the findings, the output of the passive cooling device is primarily determined by the amount of cooling degree and the hours of evaporative cooling performance. The study emphasized that using passive cooling systems in the summer months is accepTable in order to reduce the use of traditional air conditioning and improve internal comfort conditions (Da Silva, 2005). Using experimental and theoretical methods of analysis, Bouchahm assessed the thermal efficiency and ventilation of a unidirectional wind catcher's structure integrated into a climatically adapTable building. The aim of this analysis was to examine the efficiency of evaporative cooling systems incorporated into a passive ventilation device. To improve mass and heat transfer, clay conduits were built within the shaft of the unidirectional wind catcher, and a water pool was placed at the wind catcher's floor to enhance the humidification operation. The analytical model has been validated toward experimental measurements, and there was close interaction between the results. The findings showed also that airflow produced by the 0.75 m * 0.70 m wind catcher has a significant impact on internal temperature reduction. It was discovered that increasing the amount of the small sized partitions was more effective than increasing the height of the cooling tower's wetted column. Depending on the diameter of the conduit partitions, height, and the environmental conditions, the cooling tower integrated with wetted interior surfaces was able to reduce the indoor temperature by up to 17.6 K. According to Bouchahm's analysis, wind catcher can improve thermal comfort for residents and provide a fresh supply of air regardless of the extreme external conditions. The study pointed out the importance of passive cooling towers and their potential as an alternative to mechanical ventilation systems, which are more commonly used (Bouchahm et al., 2011). Badran researched the efficiency of an evaporative cooling wind catcher system as well but preferred to test internal temperature and air flow (Saffari et al., 2009), levels for a multidirectional wind catcher. A mathematical theory was established to examine the state of air flowing via the wind catcher's evaporative cooling column under various external conditions. Equally, clay conduits were built within the wind catcher's channel to cool the moving air before it was pushed inside the building (Figure. 5.37). The air temperature coolness is kept in the conduits mass even during the evening so that it can operate throughout the day. According to the findings, 0.57 m x 0.57 m evaporative wind catcher with a vertical height of 4 m could even create an airflow of 0.3 m3/s as well as lower the internal air temperature by 11 K, which would be similar to the efficiency of a 1-ton cooling system (Badran, 2003). As a direct result, the author proposed that lowering the height of the wind catcher, which traditionally reached up to 15 m, would reduce construction costs without sacrificing efficiency. Even so, Safari and Hosseinnia investigated the thermal efficiency of modern wind catcher models under diverse environmental conditions and different architectural parameters by using analytical computational CFD modeling. The groundbreaking wind catcher architecture involves wetted curtains located within the cooling device's column, which are shaped as surfaces that spray water droplets at incredibly low speeds. The CFD multi-phase model dependent on the Lagrangian–Eulerian method was used to investigate the impact of temperature and injected water droplet diameter on device performance. The numerical findings revealed that perhaps the wetted columns with a height of 10 m were capable of lowering the ambient air temperature by 12 degrees Celsius and increasing the total humidity of the air by 22 percent. The analysis also discovered that when the diameter of the applied water droplets decreases, so wills the temperature of the air exiting the wetted columns (Saffari et al., 2009). Smaller droplets form a greater evaporation surface area, resulting in increased heat transfer. The author has concluded that the difference in air temperature at the wind catcher's inlet has a larger effect than the difference in humidity levels (Hughes et al., 2012).

Wind catcher integrated with ground cooling

Passive evaporative cooling is already a common technique for improving thermal efficiency and ventilation in old Middle Eastern old houses. The conventional Iranian wind catcher, which can be used in combination with an underground water system or qanat, is an explanation of this. The wind catcher is situated above the building, with the opening faced the predominant air flow path. That airflow over the vertical shaft decreases pressure on the building's leeward side. mostly as a consequence, cold air from the qanat tube or tunnel is pulled in to absorb the hot and dry air that has been emitted. The cold air from the qanat is pulled into the tunnel, which is located some distance from the building, (Figure.5.39). The hot air is passed through the cooled tunnel wall (several meters beneath the ground, the earth stays continuously cool) and water stream running through the qanat, giving up its latent heat of evaporation as water evaporates into the air (Bansal et al., 1993). As a result, when the air enters the spaces, it is colder, due to the water vapor from the underground water system or qanat.

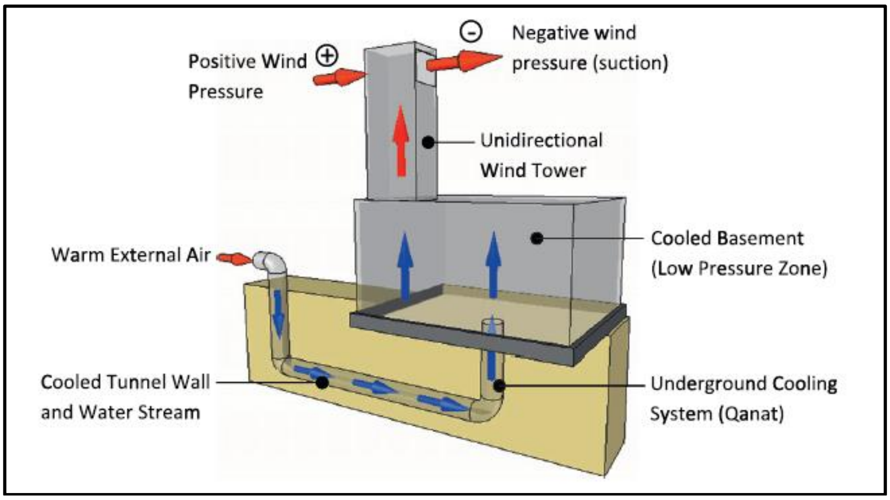


Figure 5.39. Wind catcher systems integrated with underground cooling, (Hughes et al., 2012)

Traditional Iranian houses were the subject of early cooling system research. The qanat with wind catcher, which dates from the tenth century, was mentioned in detail by Boustani (Boustani, 2008; Hughes et al., 2012). According to Boustani the integrated device will reduce the air temperature coming from the qanat by more than 15 Kelvin in hot dry climates. The inhabitants' thermal satisfaction is improved by circulating a combination of air from the basement cooling system and the wind catcher across the underground and into the buildings.

5.10.2. Structural night ventilation

Structural night ventilation, according to Hughes, is a passive cooling technique that depends entirely on buoyancy forces or wind. Thermal comfort is offered during the day by cooling the inner surface of the wind catcher channel at night, resulting in heat absorption during the day. The air created during the day is cooled by nighttime coolness contained in the partitions and wind catcher's walls, making it denser, and then sinking into the base of the wind catcher and into the structure. As the wind catcher cools the air going through it, the tower inevitably gets hot. Whenever the level of the thermal mass temperature reaches the same temperature as the surrounding atmosphere, the cooling effect of the wind catcher is actually lost. Wind catcher systems, according to Bahadori, could use shaft dividers that are arranged to have more and more surfaces in contact with the moving air, allowing the air to interact thermally with the heat contained in the shaft dividers mass (Bahadori et al., 2008). The shaft dividers used in traditional wind catcher were identified by Ghaemmaghami and Mahmoudi as thermal sinks built of mud bricks that operated like radiator fins, absorbing heat during the day and releasing it at nighttime (Ghaemmaghami et al., 2005). Most of the time, the ambient air is only sufficiently cool at night. Hollmuller suggested using a storage device to allow the ventilation mechanism to be used during the day while also retaining the coolness provided the night before. The amount of coolness deposited for use in balancing heat loads is proportional to the structure's storage space. The quantity of heat volume in a wind catcher determines how much cooling it can maintain and how quickly it gets hot the following day. Low thermal mass wind catcher can't store enough coolness and heat up easily since they have to avoid cooling morning air fast. The key drawback of structural night ventilation is the restricted controllability and sluggishness of the charge/discharge mechanism due to the reliance on natural convection for surface heat transfer (Hollmuller et al., 2007). Wang analyzed the viability of an office tower night ventilation management strategy. The EnergyPlus program was used to model the overall thermal conditions and energy usage in an office building that included night ventilation. The analysis also examined the factors that influence night-time ventilation efficiency, including thermal mass, weather conditions, and ventilation levels. The result shows that when the active cooling period is almost equal to the night ventilation operation time, the performance of the night ventilation technique is better. With night ventilation of 10 ACH, the air temperature of the interior spaces was decreased by up to 3.9 degrees Celsius (Wang et al., 2009a).

5.10.3. Wind catcher with solar chimney

Thermal or solar chimneys are used to promote natural ventilation by stack effects. The pressure difference between the inlet and exit, induced by thermal gradients (naturally-driven convection), and the incident wind (forced convection) also affect the air movement rate through the solar chimney. Buoyancy flow convection happens when the influence of a temperature gradient moves the air. The solar chimney wall is heated by the sun, as is the air inside. As a result, hot air rises to the top of the wind catcher and escapes, while cold air is pulled in via the vents or openings (Wang et al., 2009b). The solar collector layer, outlet-inlet openings, and ventilation shaft are the three important components of a solar chimney's system structure. The solar panel could be located at the top of the solar chimney or it can stretch the length of the shaft, (Figure 5.40).

For utilizing solar gains, harnessing, and storing, the thermal properties, collector's orientation, form of glazing, and insulation, are essential. The vertical shaft links the building's exterior and interior. The thermal properties, ventilation shaft height, and cross-sectional area can all influence the passive device's efficiency. Field research, experimental and, theoretical, and computational simulation has also been used to evaluate the ventilation and thermal efficiency of a solar chimney. The effect of wind and buoyancy mediated air flows on the ventilation efficiency of a building with a solar chimney was explored by Zamora and Kaiser. For different wind velocities (0–10 m/s), the analysis developed CFD model, and a mathematical, to evaluate the induced mass flow velocity, pressure coefficients, and average Nusselt amount of the air flow inside the updraft tower (Zamora, 2010). To simulate the heating conditions of the channel wall (uniform heat flux, and isothermal), different Rayleigh numbers were used. For this form of study, the Reynolds k–w turbulence model proved to be the most accurate.

The numerical findings indicated that the wind generated force was the primary driving force for the system at a positive flow speed of 2–3 m/s, resulting in marginally greater values of induced mass flow rate than buoyancy induced flow (Hughes et al., 2012).

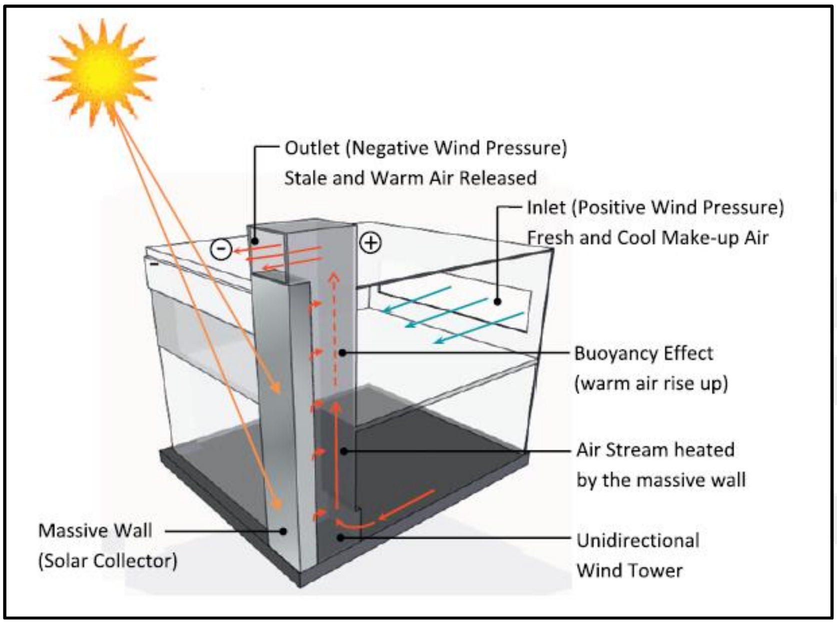


Figure 5.40. Solar-wind catcher system integrated into a naturally ventilated building (Hughes et al., 2012)

Inside the thermal chimney, however, a mixed buoyancy-wind mediated flow was found for lower values of wind velocity. The mass flow rate via the solar chimney becomes negative when the wind velocity is negative (leeward side facing the prevailing wind). As a result, external air travels from the chimney's upper opening, producing channels of reversed air flow at the top of the tower. The pressure analysis revealed that with positive values of flow speed, the chimney's outlet suction produces significant airflow compared to the air flow pressure, whereas for negative values of flow speed, overpressure was found. The average Nusselt number findings also indicated that the wind driving force was influential for wind speeds of 2–3 m/s, and that wind suction influence was significant at even low wind speeds. In recent years, there has been a lot of study into the use of solar chimneys and their possible advantages in terms of natural ventilation. Even so, the vast majority of experiments have focused on situations involving air flow triggered by buoyancy. A solar chimney combined with a wind catcher has been tested numerically and analytically in several works to induce natural ventilation.

So many researchers have examined the possibility of combining solar chimneys with wind catcher to improve thermal comfort. On warm or hot low wind days, wind catcher systems combined with solar chimneys will provide natural ventilation, and improve cross flow ventilation (Hughes et al., 2012).

5.10.4. Wind catcher integrated with courtyards

The typical style of the Middle East's vernacular architecture is primarily affected by the availability of building materials, local environment, and culture. Buildings were built tightly together with high walls, resulting in small alleys between the buildings that provide shade for the residents during the day. Locations of a courtyard, which allows free movement of wind through the building, are constructed in spaces with wide windows. The courtyard is subject to long hours of solar radiation. Therefore, due to flowing influences the air in the courtyard gets hotter and rises. To substitute it, cold air from the ground passes thru the openings, and the indoor ventilation is then established, (Figure 5.41, 5.43), (Hughes et al., 2012).

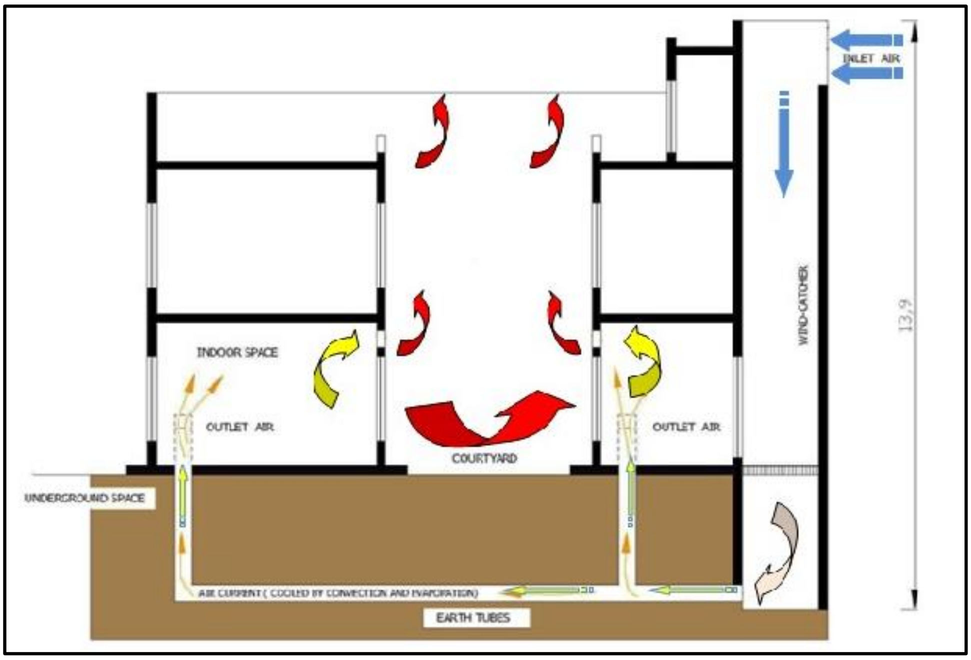


Figure 5.41. Traditional building integrated with a courtyard and wind catchers (Jassim, 2015)

The cooling mechanism is changed during the night time. Surface air cools and settles into the courtyard, entering the rooms from lower-level openings and exiting from higher-level openings. In hot climates, where daytime ventilation is unfavorable, such system could be efficient. As when the courtyard absorbs a lot of solar heat, even then, a lot of heat is produced and radiated into the living areas instead of the induced draft of air, which decreases the efficiency of the design specification considerably (Safarzadeh et al., 2005). Evaporative cooling wind catchers were also built into conventional courtyards, which helped to improve the thermal environment inside the courtyard and enclosed spaces substantially. Under extreme climatic conditions, this proved to be an important means of constructing an enclosed area with special environmental qualities. The courtyard has been transformed into a thermal sink that cools the rooms surrounding it while minimizing humidity (Edwards et al., 2006). Sharples and Bensalem examined the air flow patterns in an atrium building and a courtyard and in an urban environment. Different ventilation techniques resulting from the use of various atrium pressure structures (positive pressure and suction), and courtyard were investigated using experimental wind tunnel technology (Sharples, 2001). The model systems were observed in isolation as well as in simulated urban environments of differing community population densities. It also was noticed that the direction of the wind had an impact on ventilation efficiency. According to the findings, an open courtyard in an urban setting performs poorly in terms of airflow, whereas an atrium roof with windows that operate under negative pressure performs better.

5.10.5. Wind catcher integrated with curved roofs

Domed or Curved roofs are preferred over flat roofs in hot and dry climates. Domed roofs have a much wider surface area, allowing for more heat to be released. As a result, curved roofs cool even more easily than flat ones. In most cases, the passive roof is located in the center of the building; Warm air within the structure rises to the dome and escapes thru the curved roof vents. The colder air reaches the windows or wind catcher's openings as the air velocity increases over the curved roof, lowering the external pressure and drawing the hot air out of the dome. The curved roof or dome's structure is normally determined by the environmental condition it faces, such as wind direction. When the wind is coming from various directions, a dome roof with an opening at the top is much more efficient. During the hotter months, the curved roof and vault are more useful in places with a single prevailing wind (M. Bahadori et al., 1985). For decades, domed and curved roofs have been used in many Middle Eastern buildings. Suction ventilation may be improved by combining other natural ventilation devices such as wind catcher and windows with the dome. Wind catchers have been used for such passive ventilation roofs In most cases to increase ventilation. The role of local architectural components such as roofs and wind catchers seen in many forms of buildings in hot and dry areas has been illustrated by Fathy. On the top of a room on the structure's northern façade, wind catchers were built. Incident air reaches the wind catcher through the opening and slowly flows through the room before speeding up into the center of the structure (H. Fathy, 1986). A domed or curved roof with vents at its base encloses the central hall. Due to buoyancy, the hot air extends and rises to the domed roof. Via the exterior doors, the low-pressure air flow outside the dome forces the stale air collected inside the dome out, (Figure5.42), (Soflaee et al., 2005) . Asfour and Gadi investigated the impact of combining wind catcher with curved roofs using numerical CFD. For differing wind wind speeds and various angles (0, 45, and 90) , a scaled model was created and simulated. The research was using a passive ventilation system to increase air flow distribution and ventilation rates within buildings (downstream and upstream zones) with curved roofs (Asfour et al., 2006). The findings revealed that positioning the wind catcher in the center of the building's wind direction façade increases the ventilation efficiency of curved roofs by stimulating air by suction. Deep plan structures with suction wind catcher often allow air to efficiently infiltrate the structure's downstream part. The analysis found that the proposed design was effective in - air flow rates and enhancing air flow efficiency within the structure (Hughes et al., 2012).

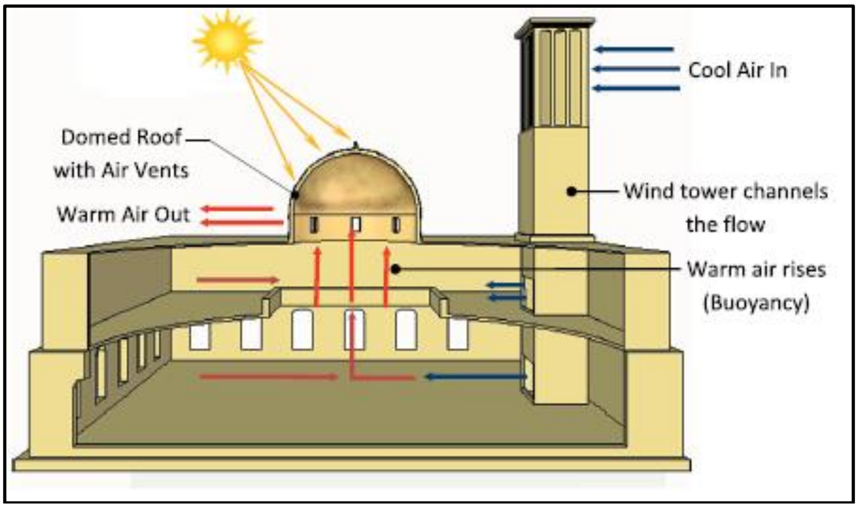


Figure 5.42. Traditional structures with wind catcher and curved roofs (Hughes et al., 2012)

Figure 5.43. wind catcher and courtyard (Internet: G&M Therin-Weise, 2019)

Table 5.2. Summarizing of wind catcher cooling techniques

Techniques for Ventilation	Constriction technique	Temperature reduction
Wetted columns	Clay conduits suspended vertically in the wind catcher channel, spaced 10 cm away. Water is sprayed on the tops of the curtains to dampen them. Low wind speeds improve efficiency.	Enhancing the internal temperature by 11 K and 15 K for a 1 m _ 1 m, and 0.4 m _ 0.4 m wind catcher.
Wetted surface (cooling pads)	A pump recirculates water over evaporative cooling pads at the top of a wind catcher. Water is sprayed on each of the pads to moisturize them. When there's a lot of wind, it's much more powerful.	The temperature of the indoor air was reduced by 7.8–12.9 K using a 1m*1m wind tower with wetted interior surfaces.
Qanat	The qanat's air is pulled into the tunnel at a distance from the structural system and cooled by interaction with the tunnel wall. Through ancient times, only the Middle East has used wind catcher with qanat cooling.	The integrated cooling system will provide up to a 15-degree drop in indoor air temperature in hot dry climates.

Table 5.2. (continue) Summarizing of wind catcher cooling techniques

Solar chimneys	Improve natural ventilation for exhaust systems at intentionally constructed exits by using stack effects, the impact of thermally induced ventilation in buildings, the structure is basic, and the cost of maintenance is minimal. In hotter climates, it works great.	The heat drop obtained primarily by the use of a solar chimney were reported to be in the range of 1–3.5 K. a shortage of observational data
Night ventilation	Material with a high thermal mass. On cold nights, warm systems lose heat to the atmosphere. The coolness of the surrounding atmosphere is retained in the wind catcher mass and then used to cold the morning air Traditionally used in sunny, hot dry summer areas with clear, cold nights.	With a night ventilation rate of Ten air changes per hour, the indoor temperature can be decreased by up to 3.9 K.
Wind catcher with courtyards	By enabling hot air to rise and escape from the Wind catcher, the courtyard provided air flow in the building. The courtyard acts as a heat sink, allowing the nearby rooms to stay cooler.	Highest temperature decrease of Eleven degrees Celsius in the courtyard and perhaps 7 degrees Celsius in the living areas.
Wind catcher with curved roofs	As a result, there is a wider surface area from which to release heat. For decades, curved roofs were used in many Middle Eastern homes to increase ventilation.	There is no information available.

6. BUILDING SIMULATION

This section's main focus is on exploring thermal dynamic modeling techniques for buildings and structures. In addition, the building performance system and the chosen simulation software were analyzed and introduced Hourly weather data is also given, as well as an overview of the modeling used in the simulation process.

The computational or a process that is run or managed by a computer model of a building or facility that focuses on energy consumption specific issues, life cycle values of various issues including; indoor natural ventilation, lighting, water heating, indoor air-conditioning, or other energy usage elements could be described as energy performance simulation and modeling (Jenkins et al., 2011). As a consequence, computer simulation and modeling are powerful methods for analyzing natural airflow in and around structures. For analog models, an analog has to be created among the characteristics of two variables in order to execute these techniques. An explicit mathematical model for the ventilation processes or direct correspondence between the two sets of variables may be able to establish these analogies. However, much of the time, the connection between real analog and phenomena isn't perfect.

6.1. The Approach of Building Simulation

Design modeling should help in the development of low-energy systems, reducing energy usage. Buildings environment modeling seemed to have started in the 19th century when a team of scientists developed evaluation systems methods, which are a collection of equations that were refined in the 19th century (Glotzer, 2011). From the 1960s to the 1970s, the engineers of heating, ventilation, and air conditioning (HVAC) have used certain equations to measure the maximum cooling loads. Mostly by the early 1970s the civil defense agency, now named as Federal Emergency Management Agency, has been involved in preparing for cooling needs in thermonuclear radioactive material containers. The Japanese scientist Kusuda studied the impact of weather and sunlight in a single room, bringing this method to the next level. Going on to the twenty-first century, we are seeing building information modeling (BIM) firms buying sustainable building modeling firms, and they are starting to combine energy modeling with building information modeling. The Scientists expected a significant increase in building energy modeling in the future in the order of the creation of stricter building standards. Also, the carbon taxes and carbon credits were witnessing huge increases in manufacturing and building technologies (Jenkins et al., 2011). After all, in order to achieve a much more successful architectural design, it is necessary to consider all environmental problems that affect the structure's behavior in conjunction with its surroundings. Building thermal modeling, on the other hand, has assisted engineers and architects in building architecture as well as additional assistance in other areas such as building evaluation prior to construction in recent years.

Generally, the architectural design process may be conceived of as a system and an arrangement of arranging ideas, including unique improvements and criteria, and then reviewing the structure or building's performance as well as many other implementation concerns within a specific design environment. Simulation and Building modeling are also commonly used in a large number of building projects in collaboration with architects and engineers in order to achieve efficiency in the buildings (Hien et al., 2003).

Generating characteristic results, on the other hand, provides general notations to the construction planner, whereas simulation systems have developed in importance, assisting in the consideration of various area examinations and estimations in building construction execution, and as a consequence, delivering ideal designs or generating optimal or correctly computed models (Hensen et al., 2004).

The simulation programs are an amazing development to analyze and identify the degree of interaction between issues of civil engineering, architecture, and mechanical engineering in building structures. Interacting on a true digital model of a structure is easy due to simulation. Computer modeling, unlike physical modelings, such as creating a scale model of a house or building, is simulating and utilizes equations and algorithms.

Simulation tools create a dynamic ecosystem for analyzing computational models as they're operating, with the option of viewing them in two and three dimensions. Simulation technology is a method of resolving actual issues in a sTable and effective way. It offers a valuable form of research that is easy to validate, interact with, and understand. Simulation modeling provides interesting solutions within building industries and the different sectors by offering simple insights into dynamic processes.

6.2. DesignBuilder as a Simulation Program

As previously stated in this section, building energy simulation engineers are tools that are mostly used during the planning phase of a project that can be used to predict and improve energy efficiency in buildings, including measuring comfort conditions in different types of buildings and structures. Even so, since there are several modeling programs, this research focuses on natural ventilation and thermal comfort measurement, as well as a system analysis of thermal behavior. Crawley et al (2001) performed a systematic review of available energy simulators, which included a variety of large building simulation systems that were compared and analyzed separately for implementation, functions, and capabilities.

The following software (BLAST, e QUEST, EnergyPlus, Energy Express, IES (VE), ECOTECT, DeST, BSim, DOE-2, HAP, HEED, eQUEST, ESP-r, DeST, BSim, PowerDomus, Energy-10, TRACE, TAS, SUNREL, BLAST, ESP-r, and TRNSYS), are among the building simulation programs reviewed by the researcher. The information and expertise provided by the energy simulation program engineers in the areas of building modeling highlights, walls, infiltration, architecture, daylighting, natural ventilation, zone airflow, and cooling and heating loads are relied upon in this article. Crawley et al choose the EnergyPlus simulation tool because it has an excellent ability as compared to several other simulation systems. EnergyPlus is a provided energy simulation platform for structures, according to the developers, based on the efficiency and qualities of BLAST programs and DOE (Crawley et al., 2001).

DesignBuilder is a computer simulation application for energy efficiency that has now been commonly used by academic researchers and engineers. DesignBuilder has a wide range of capabilities, particularly for assisting engineers and architects in analyzing alternative design scenarios and advising them to the better energy efficient design choice (Hensen et al., 2004). DesignBuilder is a powerful modeling application with a user-friendly GUI. From idea to construction, the entire architecture team will use the same tools to create convenient and energy-efficient building designs.

According to Saif et al (2020) DesignBuilder is a graphical user interface for the EnergyPlus energy simulation engine. Instead of coding in a text format, as in EnergyPlus, the interface allows for simpler modeling of the building geometry with a user-friendly graphical interface. Having access to the metrological database enables you to use weather data from all around the globe. The cooling loads can be modeled using the EnergyPlus simulation to allow complex fluctuations due to diurnal or monthly climate variations. In addition, DesignBuilder has a built-in library of numerous HVAC units, making evaporator modeling dependable and powerful (Saif, 2020). DesignBuilder is a perfect match for this project since it is built on the well-known EnergyPlus simulation engine for building thermal modeling. The DesignBulder passive and active Breakdown chart allows us to evaluate the percentage of any benefits and losses from; internal loads, solar radiation, and infiltration. Energy distribution patterns can be observed in particular zones, and all these patterns can be followed throughout the year (EnergyPlus2020).

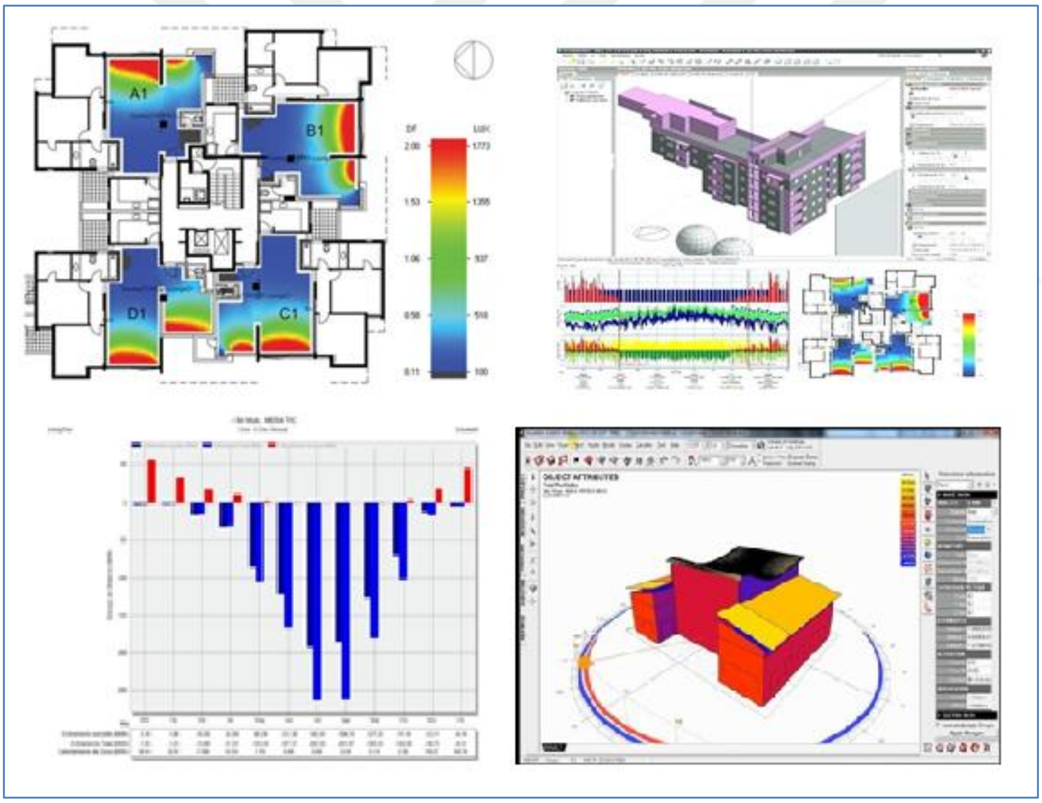


Figure 6.1. DesignBuilder simulation program

Even so, data input in DesignBuilder should always be specifically specified as; real outdoor weather or climate data (EPW format) with region and location selection, the geometry of buildings and thermal sites that, building specifications, building materials, as well as other important input information (Hensen et al., 2004).

6.3. Hourly Weather Data

In the weather simulation header of the DesignBuilder software, the hourly climatological sets of data are loaded on the site. The hourly weather file for Energy Simulation is one of the highest complex data criteria. For outdoor conditions during simulation, DesignBuilder utilizes EnergyPlus data formats every hour for the weather. Every geographical region will have its weather file that tracks atmospheric conditions, exterior temperatures, and solar transmission, for every hour of the year (Garg et al., 2020). In DesignBuilder program, the weather data file includes regularly typical data collected from hourly observations at a given position by a climatological office (Pyrgou, 2017).

By choosing the site data selection at the site level, the Simulations screen shows a weather data diagram. The hourly values of main climate data such as; outside dew point temperature, outside dry bulb temperature, wind direction, wind speed, solar azimuth, solar attitude, solar azimuth, direct normal solar, and atmospheric pressure, are shown in those diagrams (Vuong et al., 2015). Energy plus uses the EPW file extension to store hourly weather information. While DesignBuilder comes with a huge global database of climate data details, it only loads the data files for the default location initially. The user can choose a template of weather files for the nearest locations from DesignBuilder's comprehensive collection of weather (Garg et al., 2020).

6.4. Description of Simulation Modeling

This section of the study evaluates the proposed wind catcher and passive cooling methods for analysis by utilizing a cooling and natural ventilation wind catcher system. The modeling process created to develop a natural ventilation wind catcher in the test room model, and the output results have been used after being developed and modified in the actual house simulation model. The house chosen for modeling is conventional, one of the standard single-family houses seen in Khartoum's residential area.

6.4.1. The test room model

This case study was chosen as a small experimental room representing a suburban thermal area and in weather conditions of Khartoum City. A comparative simulation method has been used for various rooms with different types of wind catchers, simulated to represent the best option before applying certain types and after applying it in this test room. Indoor operative temperature and cooling loads are the main key parameters of the simulation to be compared before and after applying the different types of wind catchers in the test room.

The following details provide a short overview of the basic parameters that were used in the simulation;

- For this simulation, the room was built with two 0.5 m * 1.5 m windows on the south wall and two 0.5 m * 0.5 m windows on the north wall.
- The windows in the north wall were located on a high level of the wall, whereas the two windows on the south wall have been located in the middle of the wall.
- The simulated room has a south-north direction and 3.5 m high with a total area of 20 m^2 which is 6 m x 4 m (Figure. 6.2).
- A square wind catcher model with a dimension of 1.5m x 1.5m and with a height of 8.5m is connected to the 6m x4m room.
- The only variable was the opening direction of the wind catcher. The geometry of these models was generated by design builder software and simulated.

6.4.2. Material of the traditional room and wind catcher

- For the wall: 300mm of mud brick, with thermal conductivity about 0.7500 (W/m.k) and specific heat about 0.880 (J/k-k)
- For the roof: 150mm of concert slap +.0100 bitumen emulsion for insulation
- For the Ground floor: 150 mm concrete slap (Dens) + emulsion for insulation + ceramic tiles
- For Windows: Double glazing 1.5 m * 0.5 m reflective, with shading over each window, and wood window frame.

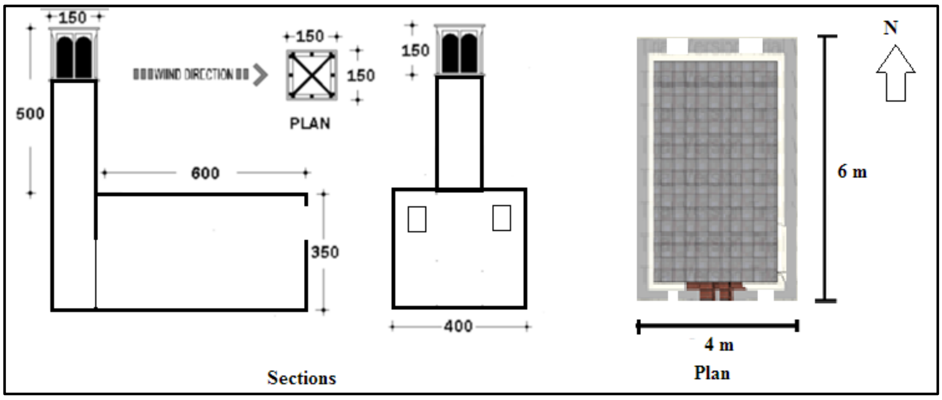
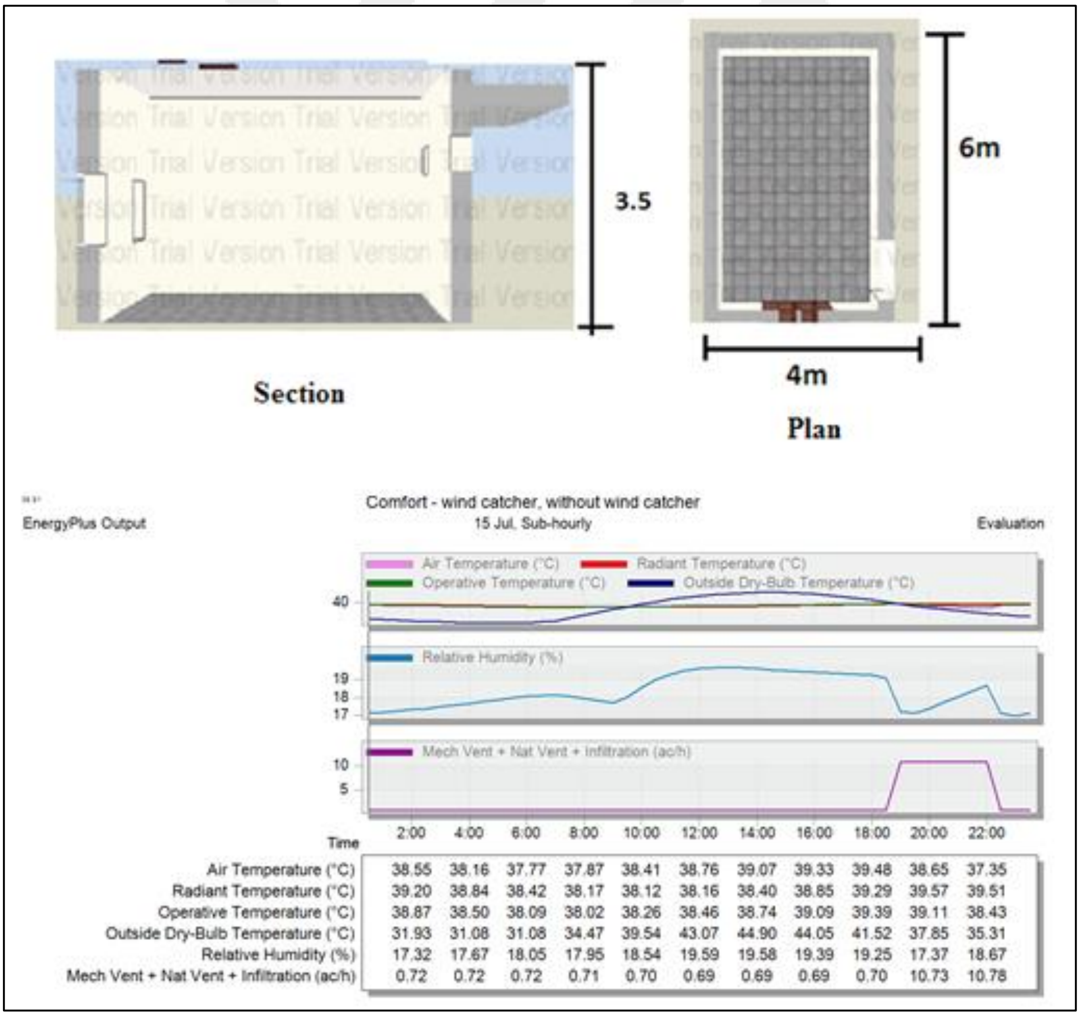


Figure 6.2. Simulated test room

6.5. Test Room Simulation Cases

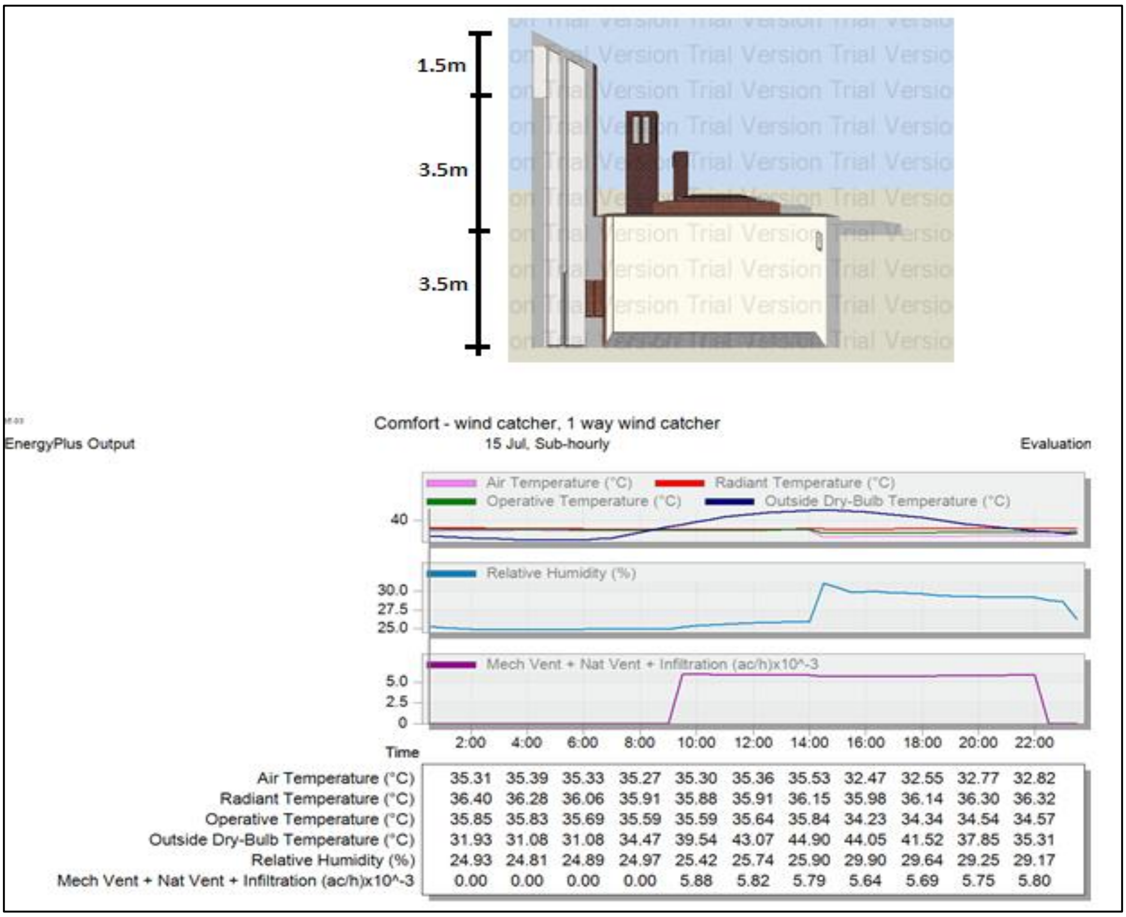
6.5.1. Case one; simulation house without wind catcher



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	38.55	38.16	37.77	37.87	38.41	38.76	39.07	39.33	39.48	38.65	37.35
Radiant Temperature (°C)	39.20	38.84	38.42	38.17	38.12	38.16	38.40	38.85	39.29	39.57	39.51
Operative Temperature (°C)	38.87	38.50	38.09	38.02	38.26	38.46	38.74	39.09	39.39	39.11	38.43
Outside Dry-Bulb Temperature (°C)	31.93	31.08	31.08	34.47	39.54	43.07	44.90	44.05	41.52	37.85	35.31
Relative Humidity (%)	17.32	17.67	18.05	17.95	18.54	19.59	19.58	19.39	19.25	17.37	18.67
Mech Vent + Nat Vent + Infiltration (ac/h)	0.72	0.72	0.72	0.71	0.70	0.69	0.69	0.69	0.70	10.73	10.78

Figure 6.3. Case one; simulation house without wind catcher

6.5.2. Case tow; simulation house with one way wind catcher

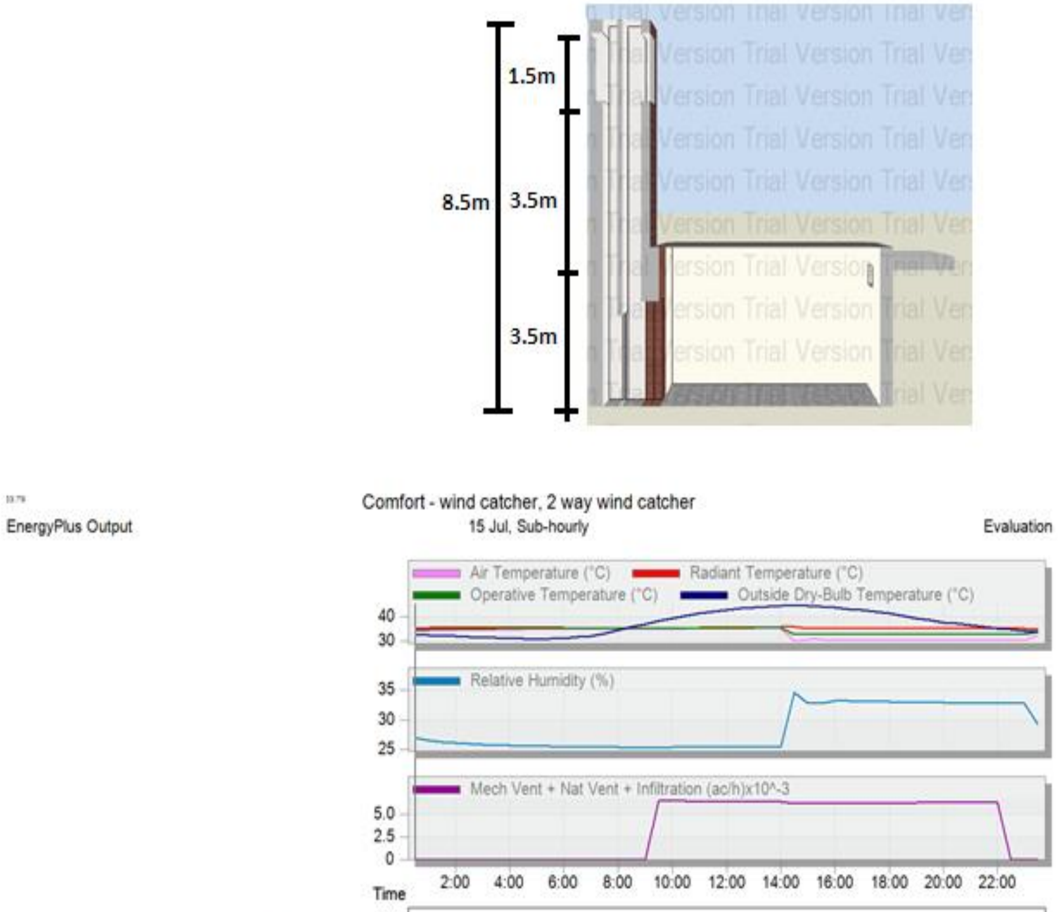


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	35.31	35.39	35.33	35.27	35.30	35.36	35.53	32.47	32.55	32.77	32.82
Radiant Temperature (°C)	36.40	36.28	36.06	35.91	35.88	35.91	36.15	35.98	36.14	36.30	36.32
Operative Temperature (°C)	35.85	35.83	35.69	35.59	35.59	35.64	35.84	34.23	34.34	34.54	34.57
Outside Dry-Bulb Temperature (°C)	31.93	31.08	31.08	34.47	39.54	43.07	44.90	44.05	41.52	37.85	35.31
Relative Humidity (%)	24.93	24.81	24.89	24.97	25.42	25.74	25.90	29.90	29.64	29.25	29.17
Mech Vent + Nat Vent + Infiltration (ac/h)x10^-3	0.00	0.00	0.00	0.00	5.88	5.82	5.79	5.64	5.69	5.75	5.80

Figure 6.4. Case two; simulation house with one way wind catcher

.

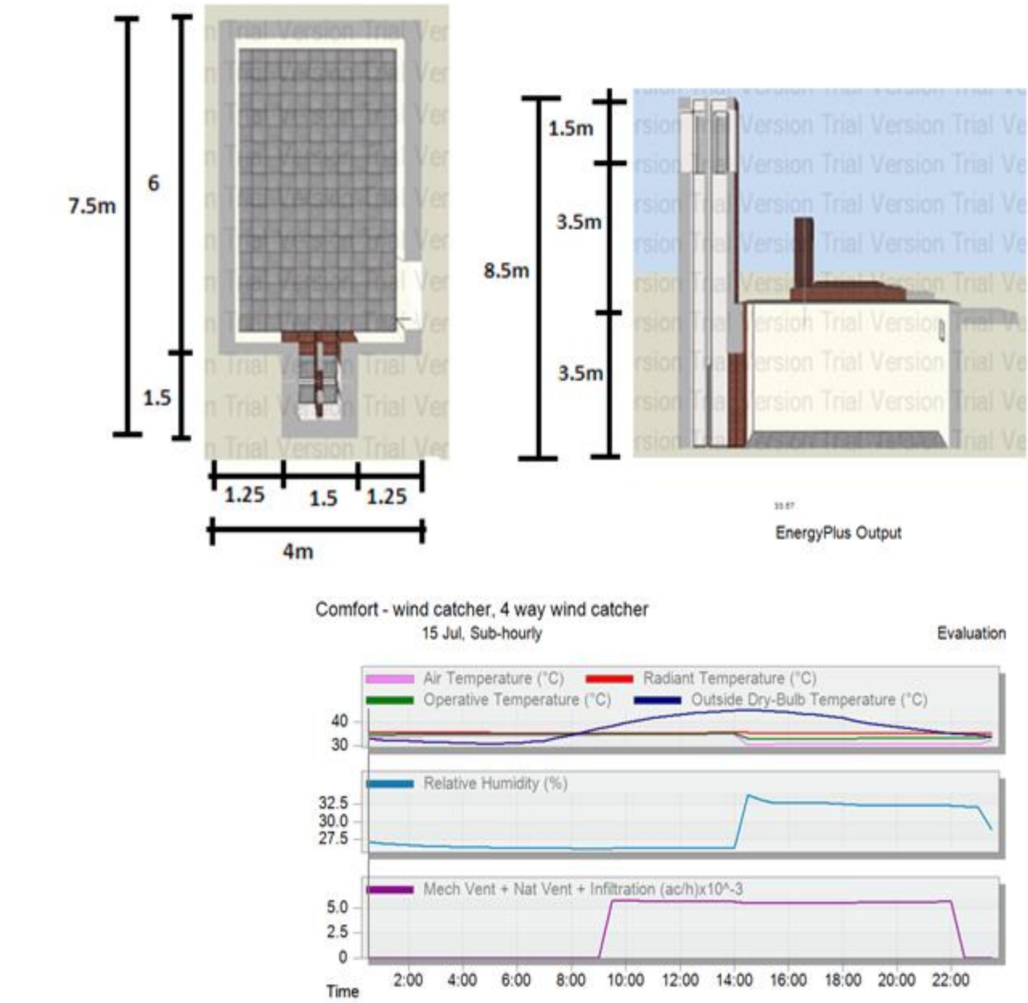
6.5.3. Case three; simulation houses with tow way wind catcher



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.34	34.65	34.78	34.85	35.02	35.16	35.34	30.30	30.30	30.41	30.40
Radiant Temperature (°C)	35.55	35.55	35.42	35.35	35.37	35.47	35.75	35.22	35.20	35.26	35.20
Operative Temperature (°C)	34.95	35.10	35.10	35.10	35.20	35.31	35.55	32.76	32.75	32.83	32.80
Outside Dry-Bulb Temperature (°C)	31.93	31.08	31.08	34.47	39.54	43.07	44.90	44.05	41.52	37.85	35.31
Relative Humidity (%)	26.08	25.65	25.46	25.35	25.34	25.38	25.35	33.21	33.12	32.89	32.90
Mech Vent + Nat Vent + Infiltration (ac/h)x10^-3	0.00	0.00	0.00	0.00	6.53	6.46	6.43	6.24	6.29	6.36	6.41

Figure 6.5. Case three; simulation houses with tow way wind catcher

6.5.4. Case four simulation houses with four way wind catcher



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.92	34.13	34.20	34.24	34.41	34.56	34.77	30.58	30.59	30.73	30.74
Radiant Temperature (°C)	35.47	35.41	35.24	35.15	35.16	35.24	35.52	35.14	35.20	35.30	35.26
Operative Temperature (°C)	34.69	34.77	34.72	34.69	34.78	34.90	35.14	32.86	32.90	33.01	33.00
Outside Dry-Bulb Temperature (°C)	31.93	31.08	31.08	34.47	39.54	43.07	44.90	44.05	41.52	37.85	35.31
Relative Humidity (%)	26.70	26.39	26.29	26.23	26.23	26.27	26.23	32.69	32.57	32.30	32.28
Mech Vent + Nat Vent + Infiltration (ac/h)x10^-3	0.00	0.00	0.00	0.00	5.75	5.69	5.67	5.51	5.56	5.62	5.67

Figure 6.6. Case four simulation houses with four way wind catcher

6.6. General Results from the Test Room Simulation

6.6.1. Air temperature

When comparing the four simulation cases, it was observed that the rooms constructed with a wind catcher had a more comforTable inside air temperature and more natural ventilation than the rooms constructed without one. When comparing wind catchers with one or two-way directions with wind catchers with four-way directions, it can be noticed that the internal air temperature of the room with four-way wind catcher decreases by about 4 degrees Celsius from the outside temperature at 10 am, 10 degrees Celsius from the outside temperature at 2 pm, and 3 degrees Celsius from the outside temperature at 10 p.m. As a result, the simulation results showed that the four-way wind catcher is more effective than the other types of wind catchers as can be seen in (Table 6.1).

Table 6.1. Simulation results for the test room

Case No	Time	Outside temp	Inside temp	Nat vent (AC/h)
1 without	10 Am 2 Pm 10 Pm	39.5 44.9 35.3	38.2 38.7 38.4	.7 .7 10.7
2 one way	10 Am 2 Pm 10 Pm	39.5 44.9 35.3	35.5 35.8 34.5	5.8 5.8 5.8
3 Two way	10 Am 2 Pm 10 Pm	39.5 44.9 35.3	35.2 35.5 32.8	6.5 6.4 6.4
4 Four way	10 Am 2 Pm 10 Pm	39.5 44.9 35.3	34.7 35.1 33	5.7 5.7 5.7

6.6.2. Air changes per hour

After comparing between the four cases it can be observed that the amount of air changes in one hour in a room without wind catcher is less than a room that builds with wind catcher in the morning and afternoon, while that amount of air becomes high in the evening. If the inside air temperature and the amount of air changes every hour are taken into consideration, case number four seems to be the optimal choice in this test room simulation.

7. TRADITIONAL BUILDING SIMULATION ANALYSIS AND RESULT

The aim of this whole doctoral thesis is to explore completely natural ways to minimize potential energy use in a traditional house in Khartoum- Sudan. After reviewing several academic research studies focused on the most efficient methods to reduce reliance on simple or complex mechanical air conditioners, this study discovered that passive cooling strategies provide better thermal comfort while considerably reducing the energy consumption and helping the environment and the building to be more sustainable.

One of these passive cooling strategies was the wind catcher. analytical studies of wind catchers morphology and statistical analysis on its different criteria, such as the size of the openings, the number of vents, and the cross-section composition, in addition to the different heights of the wind catcher were been conducted by many types of research and studies. Based on these studied and recommended criteria, the scope to work on was determined to test the influence of these criteria on thermal comfort when designing a wind catcher in Khartoum-Sudan. It is possible to obtain different kinds of results to calculate parameters whenever a measurement is needed by a physical or a virtual model. Via the building simulation method, the impact of building orientation, sunshine, wind behavior, etc. can be measured. The task of defining variables such as DBT (Dry Bulb Temperature), WBT (Wet Bulb Temperature), humidity levels inside the spaces, and so on, is simplified by the simulation Software ‘DesignBuilders’. During the analysis process, the parameters, the equations for various probabilities can be adjusted, thereby conclude the best choice for execution into the particular construction configuration of the respective location.

7.1. Simulation Method

In this study, 47 simulations have been performed using the design-builder program. In each simulation, the effect of the different criteria affecting the designs of the wind catchers have been tested, and determine how they affect the internal air temperature of the living room, taking into consideration that area is the most commonly used during the day.

The criteria that affect the design of the wind catcher are

1. The dimension of the wind catcher,
2. The height of the wind catcher,
3. The opening direction in the wind catcher,
4. The Number of the vent in the wind catcher,
5. The partition in the wind catcher,
6. The dimensions of the room in the target area,
7. The Living room Windows Location,
8. The Living room Windows Design.

To identify the criteria that may reduce the air temperature inside the living room in Khartoum climate, three variables were been tested for each one of the eight criteria that affecting on the design of the wind catcher, this has been performed by fixing the seven criteria and testing three variables in the eighth criteria. Changing between the criteria each time can determine which of these eight criteria is the most influential when designing a wind catcher and leads to reduce the air temperature inside the living room. Three different times during the day were selected to take temperature readings,

- 4 am: where external temperatures are lowest,
- 2 pm: where external temperatures are highest,
- 10 pm: where outside temperatures start decreasing significantly.

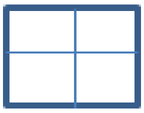
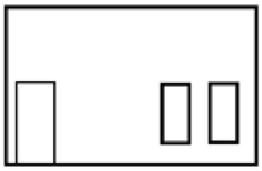
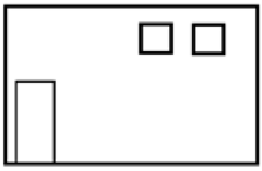
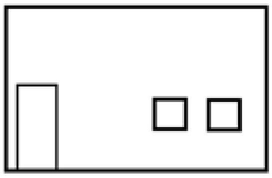
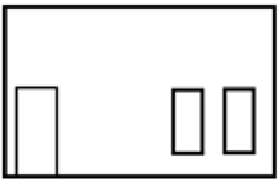
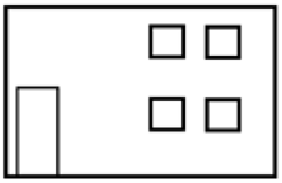
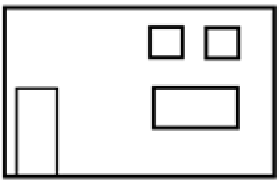
The best values and results from these three criteria were selected and combined in a new design and simulated again. In the last simulation, the Water spray is added for testing the effect of evaporation cooling on the windcatcher.

Simulation keys

BS = building simulation number, BS0 = building without wind catcher, SBS1= selective design 1, SBS2= selective design 2, DW= dimensions of wind catcher FD = form dimension, H = height of the wind catcher, OD = opening direction, NV = number of vent, P = partition type, R d= room dimension, WL= windows location, WD= windows design, AT = air temperature, AC/h = air changing /hour, CFD = Computational fluid dynamics.

7.2. The Variables of the Simulated Elements in the Windcatcher

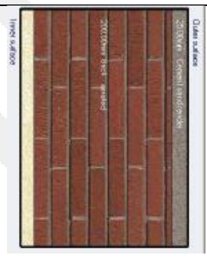
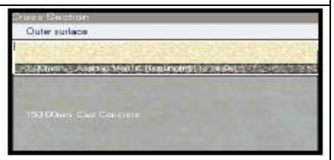
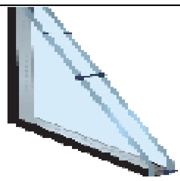
Table 7.1. Variables of the simulated criteria in the Windcatcher

Criteria	Variables of Simulated criteria		
The dimension of the wind catcher (DW)	1.5 m * 1.5 m	2 m * 2 m	3 m * 3 m
The height of the wind catcher (H)	6m	8m	10m
The opening direction in the wind catcher (OD)	One-way wind catcher,	two-way wind catcher	four-way wind catcher
The Number of the vents in the wind catcher (NV)	1	3	5
The partition in the wind catcher (P)	 Type (a)	 Type (b)	 Type (c)
The dimension of the rooms in the target area (RD)	4m*6m	5m*6m	6m*6m
The Living room Windows location (WL)	 Type (a)	 Type (b)	 Type (c)
The Living room Windows Design (WD)	 Type (a)	 Type (b)	 Type (c)

7.3. Construction Data Details and Thermal Properties of the Traditional Building and Wind Catcher

The simulation model in this phase is intended to choosing the optimum residential building materials for traditional residential buildings in Sudan in terms of thermal efficiency. In all the hypothetical trials, the much more widely used construction materials in Sudan were simulated, whereas the insulation layer and the final finishing building materials were set. The building materials mentioned in Table 7.2 are used in the construction of numerous houses in the area for years that have different thermal efficiency characteristics.

Table 7.2. Material used in the traditional building and wind catcher

Simulation Templates		Building material	Thickness	U value (W/m^2K)	Material section and insulation layer position
Construction	wall	Mud brick + Interior plaster render25mm	300mm	0.7500	
	Roof	Concrete slap +0100 bitumen emulsion for insulation	150mm	1.8	
	Ground floor	Concrete slap + water insulation + ceramic tiles	150mm	0.566	
	Window with shading	Double Clear Glass 6mm/13mm Air	50mm	2.511	

7.4. Simulation Model Design

This case study was selected as a traditional house in Khartoum city. The configuration of the simulated traditional building model for this study included two bedrooms, a living or sitting room, a men's reception (saloon), one toilet, and a wind catcher in the north part of the building connected to the living room, as can be seen in the diagram (Figure 7.1).

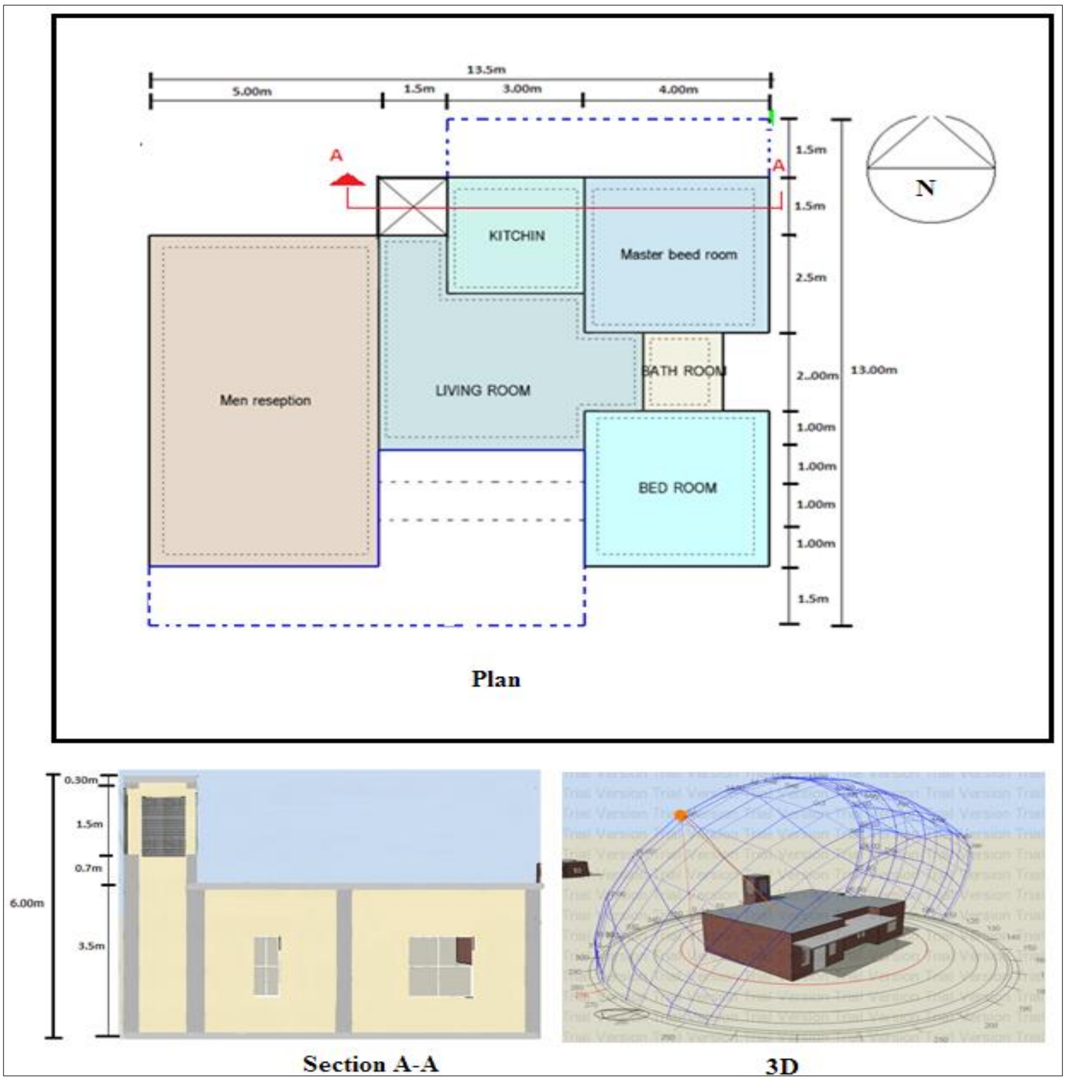


Figure 7.1. Design of the simulation traditional buildings' model

7.5. Characterizations of Variables in the Simulation Criteria

In order to identify and evaluate the influence of each variable in the criteria that will be simulated with the different models of the traditional building with wind catcher, the following Table has been designed;

Table 7.3. Simulation table

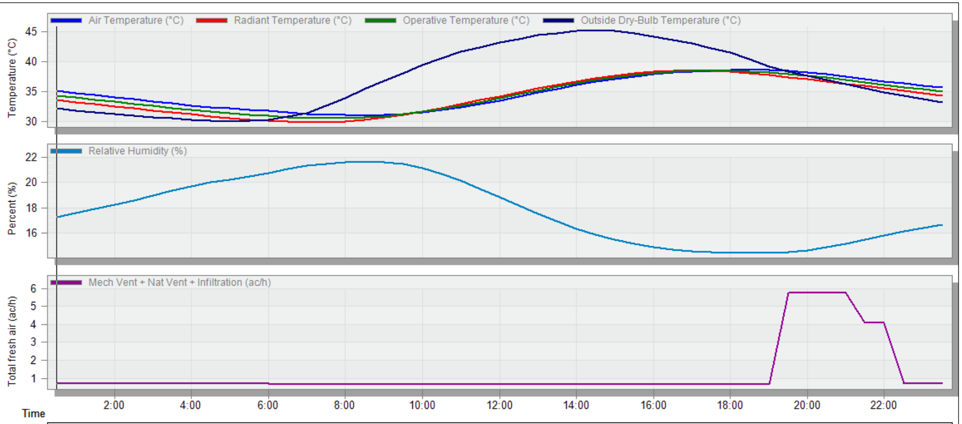
BSN	Dimensions of Wind catcher (DW)	High (H)	Opening Direction (OD)	number of the vents (NV)	partition type (P)	Room Dimension RD	Windo-ws location (WL)	Window s Design (WD)
BS1	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS2	DW(1.5m*1.5m)	H(8m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS3	DW(1.5m*1.5m)	H(10m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS4	DW(1.5m*1.5m)	H(6m)	OD(S-N)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS5	DW(1.5m*1.5m)	H(8m)	OD(S-N-E-W)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS6	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(3)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS7	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(5)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS8	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(B)	RD(4m*6m)	WL(a)	WD(a)
BS9	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(C)	RD(4m*6m)	WL(a)	WD(a)
BS10	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(5m*6m)	WL(a)	WD(a)
BS11	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(6m*6m)	WL(a)	WD(a)
BS12	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(b)	WD(a)
BS13	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(c)	WD(a)
BS14	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(b)
BS15	DW(1.5m*1.5m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(c)
BS16	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS17	DW(2m*2m)	H(8m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS18	DW(2m*2m)	H(10m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS19	DW(2m*2m)	H(6m)	OD(S-N)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS20	DW(2m*2m)	H(6m)	OD(S-N-E-W)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS21	DW(2m*2m)	H(6m)	OD(S)	NV(3)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS22	DW(2m*2m)	H(6m)	OD(S)	NV(5)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS23	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(B)	RD(4m*6m)	WL(a)	WD(a)
BS24	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(C)	RD(4m*6m)	WL(a)	WD(a)
BS25	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(5m*6m)	WL(a)	WD(a)
BS26	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(6m*6m)	WL(a)	WD(a)

Table 7.3. (continue) Simulation table

BS27	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(b)	WD(a)
BS28	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(c)	WD(a)
BS29	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(b)
BS30	DW(2m*2m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(c)
BSS31	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS32	DW(3m*3m)	H(8m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS33	DW(3m*3m)	H(10m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS34	DW(3m*3m)	H(6m)	OD(S-N)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS35	DW(3m*3m)	H(6m)	OD(S-N-E-W)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS36	DW(3m*3m)	H(6m)	OD(S)	NV(3)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS37	DW(3m*3m)	H(6m)	OD(S)	NV(5)	P(A)	RD(4m*6m)	WL(a)	WD(a)
BS38	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(B)	RD(4m*6m)	WL(a)	WD(a)
BS39	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(C)	RD(4m*6m)	WL(a)	WD(a)
BS40	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(5m*6m)	WL(a)	WD(a)
BS41	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(6m*6m)	WL(a)	WD(a)
BS42	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(b)	WD(a)
BS43	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(c)	WD(a)
BS44	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(b)
BS45	DW(3m*3m)	H(6m)	OD(S)	NV(1)	P(A)	RD(4m*6m)	WL(a)	WD(c)
SBS(1)	DW(1.5m*1.5m)	H(6m)	OD(S-N-E-W)	NV(1)	P(A)	RD(6m*6m)	WL(b)	WD(b)
SBS(2) +water spray	DW(1.5m*1.5m)	H(6m)	OD(S-N-E-W	NV(1)	P(A)	RD(6m*6m)	WL(b)	WD(b)

7.6. Simulation Results

BS0/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.07	32.66	31.76	31.05	31.51	33.55	36.12	37.97	38.60	38.29	36.71
Radiant Temperature (°C)	32.56	31.22	30.10	30.06	31.70	34.22	36.68	38.30	38.35	37.09	35.57
Operative Temperature (°C)	33.31	31.94	30.93	30.55	31.61	33.88	36.40	38.14	38.48	37.69	36.14
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.24	19.70	20.71	21.59	21.10	18.85	16.38	14.89	14.47	14.67	15.83
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.70	0.69	0.68	0.68	0.68	0.69	0.69	5.72	4.06

Figure 7.2. BS0 simulation charts

See the rest of the simulation result charts in the appendices.

Table 7.4. Simulation results table

BSN	4 am	2 pm	10pm	(Outside) – (inside)at 2pm	enhancing in the performance according to 45.2°	(BSN at 2pm) – (36.40°)	enhancing in the performance according to 36.4°
Outside temperature	30.30°C	45.20°C	34.86°C	——	——	——	——
BS0	31.94°	36.40°	36.14°	8.8°	19.46%	0°	0%
BS1	32.14°	33.14°	34.15°	12.06°	26.68%	3.26°	8.95%
BS2	32.40°	33.40°	34.36°	11.8°	26.10%	3°	8.24%
BS3	32.63°	34.62°	34.55°	10.58°	23.40%	1.78°	4.89%
BS4	32.11°	33.12°	34.14°	12.08°	26.72%	3.28°	9.01%
BS5	32.03°	33.06°	34.09°	12.14°	26.85%	3.34°	9.17%
BS6	32.14°	33.14°	34.15°	12.06°	26.68%	3.26°	8.95%
BS7	32.14°	33.14°	34.15°	12.06°	26.68%	3.26°	8.95%
BS8	32.14°	33.15°	34.10°	12.05°	26.65%	3.25°	8.92%
BS9	32.07°	33.16°	34.07°	12.04°	26.63%	3.24°	8.90%
BS10	31.28°	32.77°	33.74°	12.43°	27.50%	3.63°	9.97%
BS11	31.06°	32.64°	33.62°	12.56°	27.78%	3.76°	10.32%
BS12	32.14°	33.05°	34.12°	12.15°	26.88%	3.35°	9.20%
BS13	32.14°	33.05°	34.12°	12.15°	26.88%	3.35°	9.20%
BS14	31.83°	32.66°	33.75°	12.54°	27.74%	3.74°	10.27%
BS15	32.16°	32.98°	34.08°	12.22°	27.03%	3.42°	9.39%
BS16	31.88°	34.02°	33.25°	11.18°	24.73%	2.38°	6.53%
BS17	32.55	33.55°	34.49°	11.65°	25.77%	2.85°	7.82%
BS18	32.82°	33.81°	34.70°	11.39°	25.19%	2.59°	7.11%
BS19	32.22°	33.24°	34.24°	11.96°	26.46%	3.16°	8.68%
BS20	32.10°	33.16°	34.17°	12.04°	26.63%	3.24°	8.90%
BS21	32.25°	33.25°	34.25°	11.95°	26.43%	3.15°	8.65%
BS22	32.25°	33.25°	34.25°	11.95°	26.43%	3.15°	8.65%
BS23	31.87°	33.27°	34.67°	11.18°	24.73%	2.38°	6.53%
BS24	32.18°	33.27°	34.12°	11.93°	26.39%	3.13°	8.59%
BS25	31.36°	32.88°	33.84°	12.32°	27.25%	3.52°	9.67%
BS26	31.15°	32.76°	33.72°	12.44°	27.52%	3.64°	10%
BS27	32.25	33.16°	34.22°	12.04°	26.63%	3.24°	8.90%
BS28	32.25	33.16°	34.22°	12.04°	26.63%	3.24°	8.90%
BS29	31.93	32.78°	33.85°	12.42°	27.47%	3.62°	9.94%
BS30	32.28	33.10°	34.18°	12.1°	26.76%	3.3°	9.06%
BS31	32.36°	33.42°	34.41°	11.78°	26.06%	2.98°	8.18%
BS32	32.71°	33.77°	34.68°	11.43°	25.28%	2.63°	7.22%
BS33	33.0°	34.06°	34.90°	11.14°	24.64%	2.34°	6.42%
BS34	32.51°	33.69°	34.79°	11.51°	25.46%	2.7°	7.41%
BS35	32.17°	33.30°	34.31°	11.9°	26.32%	3.1°	8.51%
BS36	32.36°	33.42°	34.41°	11.78°	26.06%	2.98°	8.18%
BS37	32.36°	33.42°	34.41°	11.78°	26.06%	2.98°	8.18%

Table 7.4. (continue) Simulation results table

BS38	31.93°	33.03°	34.0°	12.17°	26.92%	3.37°	9.25%
BS39	31.93°	33.03°	34.0°	12.17°	26.92%	3.37°	9.25%
BS40	31.46°	33.07°	34.01°	12.13°	26.83%	3.33°	9.14%
BS41	31.24°	32.93°	33.89°	12.27°	27.14%	3.47°	9.53%
BS42	32.37°	33.34°	34.39°	11.86°	26.23%	3.06°	8.40%
BS43	32.61°	33.79°	34.93°	11.41°	25.24%	2.61°	7.17%
BS44	32.05°	32.95°	34.03°	12.25°	27.10%	3.45°	9.47%
BS45	32.40°	33.27°	34.35°	11.93°	26.39%	3.13°	8.59%
SBS1	31.04°	32.46°	33.51°	12.74°	28.18%	3.94°	10.82%
SBS2 + water spray	27.78	29.21°	29.59°	15.99°	35.37%	7.19°	19.75%

7.7. Building Simulation Results Analysis

7.7.1. Simulation analysis of the criterion variables in the wind catcher

The changing in height (H6, H8, H10) of the wind catcher when the wind catcher dimension is (1.5 m * 1.5 m)

The Altitudes that have been tested are 6m, 8m, and 10m. When the building height is 3m, and the height of the windcatcher was changed, the air temperature in the living room at 2 pm was being increased with the increase of the height. The air temperature was increased from 33.14 celsius in (BS1) to 34.62 celsius in (BS3), Which means the air temperature of the living room has been increased 1.5 Celsius at a height of 10 meters (Figure 7.3).

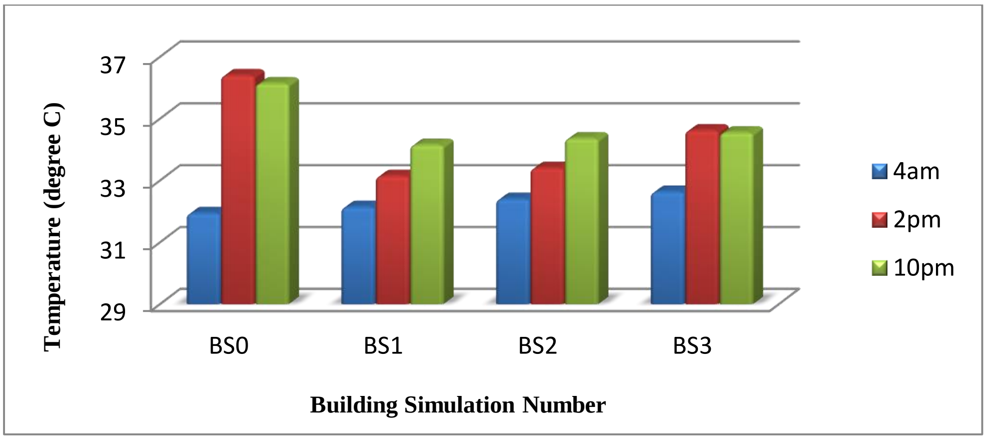


Figure 7.3. Changing in the height of the wind catcher when the wind catcher dimension is (1.5 m * 1.5 m)

<u>The changing in the opening direction (OD(s-n), OD(n-s-e-w)) of the wind catcher when the wind catcher dimension is (1.5 m * 1.5 m)</u>

The opening directions that were been tested are, north, south, and north-south-east-west. After the direction of the windcatcher openings were been changed from only north or south to north –south –east –west (four-way directions), the air temperature has been decreased from 33.12 celsius (BS4) to 33 celsius (BS5), hence the best thermal performance has been achieved when using the four-way windcatcher in the living room (Figure 7.4).

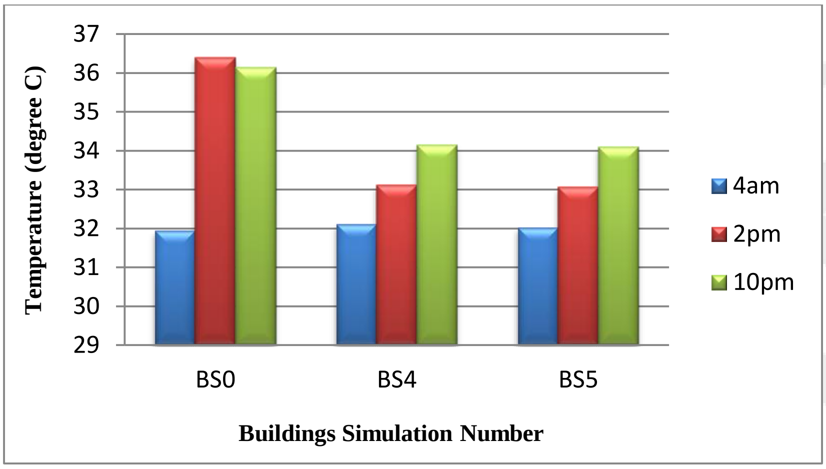


Figure 7.4. Changing in the opening direction of the wind catcher when the wind catcher dimension is (1.5 m * 1.5 m)

<u>The changing in the number of the vent (NV3, NV5) in the wind catcher when the wind catcher dimension is (1.5m*1.5m)</u>

It can be observed that changing the number of vent in the wind catcher from 3 vents to 5 vents doesn’t have a considerable effect on the internal thermal performance in the living room as seen in BS6 and BS7 (Figure7.5), whereas the air temperature in the living room at 2 pm was 33.14 Celsius.

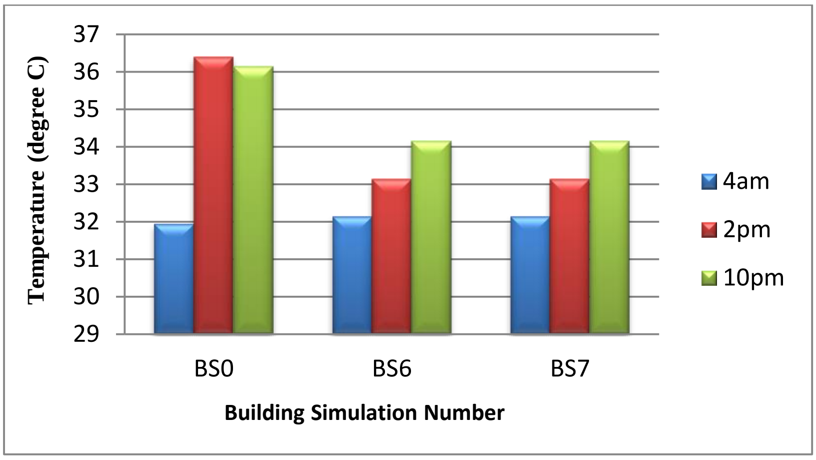


Figure 7.5. Changing in the number of vents in the wind catcher when the wind catcher dimension is (1.5 m * 1.5 m)

<u>Changing the partition type in the wind catcher (Pb, Pc) when the wind catcher dimension is (1.5 m * 1.5 m)</u>

Changing the partition types' in the wind catcher from partition type (b) to partition type (c), doesn't have a considerable effect on the internal thermal performance in the living room as seen in BS8 and BS9 (7.6), whereas the air temperature in the living room at 2 pm when partition type (b) was used is 33.15 Celsius, and 33.16 Celsius when partition type (c) was used.

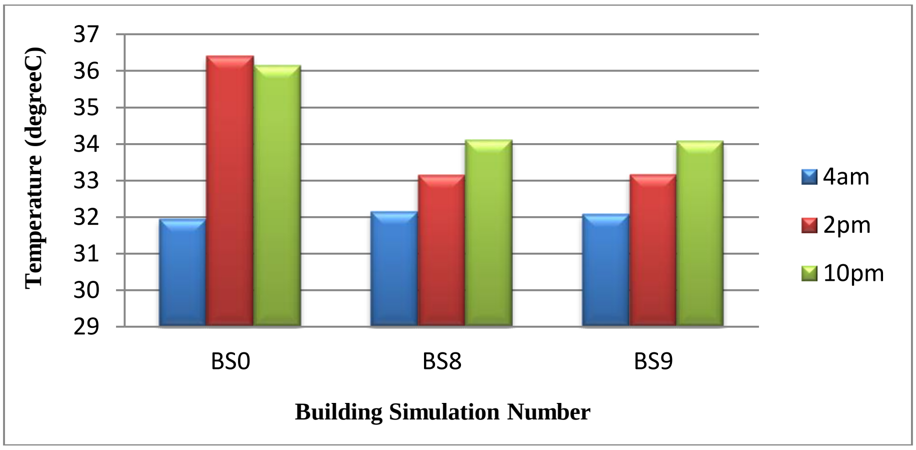


Figure 7.6. Changing partition types in the wind catcher when the wind catcher dimension is (1.5 m * 1.5 m)

Changing the living room dimension (RD 5m*6m, RD 6m*6m) when the wind catcher dimension is (1.5 m * 1.5 m)

The living room dimensions that were been tested are: (4m*6m), (5m*6m), (6m*6m). Changing the room dimensions from larger to smaller has been lead to better thermal performance during the day and night periods. The air temperature has been decreased by about 0.5 celsius at night, and 0.2 celsius during the day in (BS11). Hence the dimension of (6m*6m) had a better thermal performance than the room with the dimension of (5m*6m), and the dimension of (5 m * 6 m) is better than (4 m * 6 m) Figure.(7.7),

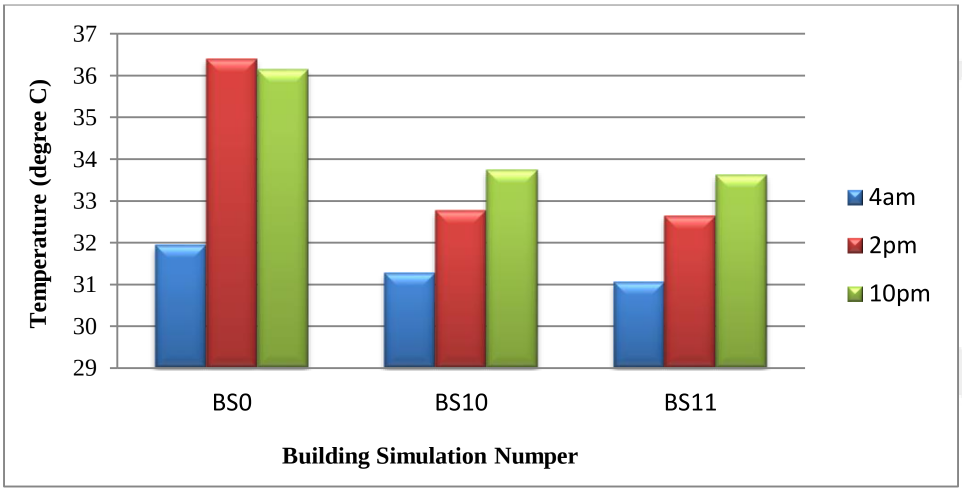


Figure 7.7. Changing the room dimension (living room) when the wind catcher dimension is (1.5 m * 1.5m)

Changing the living room windows locations WL (b), WL(c) when the wind catcher dimension is (1.5 m * 1.5 m)

The result that has been obtained when changing the locations of the living room windows from type (b) to type (c) was similar as seen in SB12, and SB13, whereas lead to a decrease in the temperature of the living room by about 3.35 Celsius in both types. (Figure.7.8).

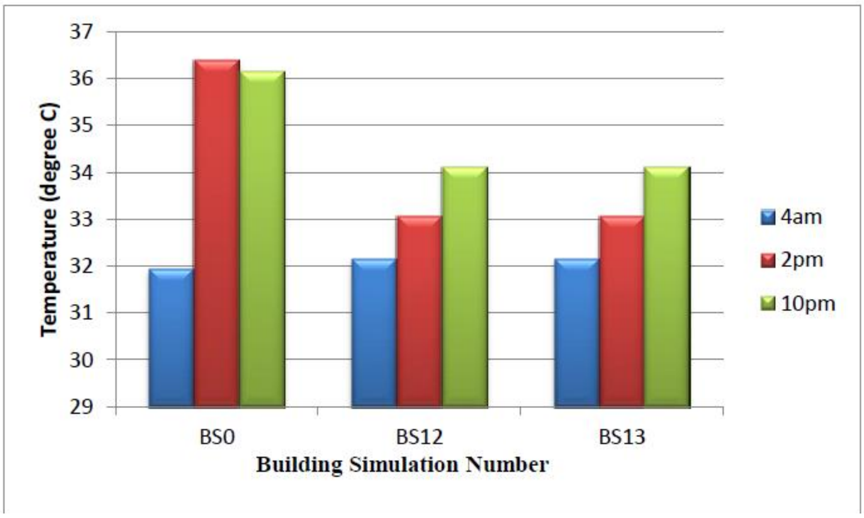


Figure 7.8. Changing the living room Windows Locations WL (b), WL(c) when the wind catcher dimension is (1.5 m * 1.5 m)

<u>Changing the Living room windows design WL(b), WL(c) when the wind catcher dimension is (1.5 m * 1.5 m)</u>

Changing the Living room Windows design from type (b) to type (c) leads to a decrease in the temperature of the living room by about 3.75 Degree Celsius in type (b) as seen in SB14, while leading to a decrease in the temperature of the living room by about 3.42 Celsius in type (c) as seen in SB15, hence the using of windows design type (b) was giving a better thermal performance (Figure 7.9).

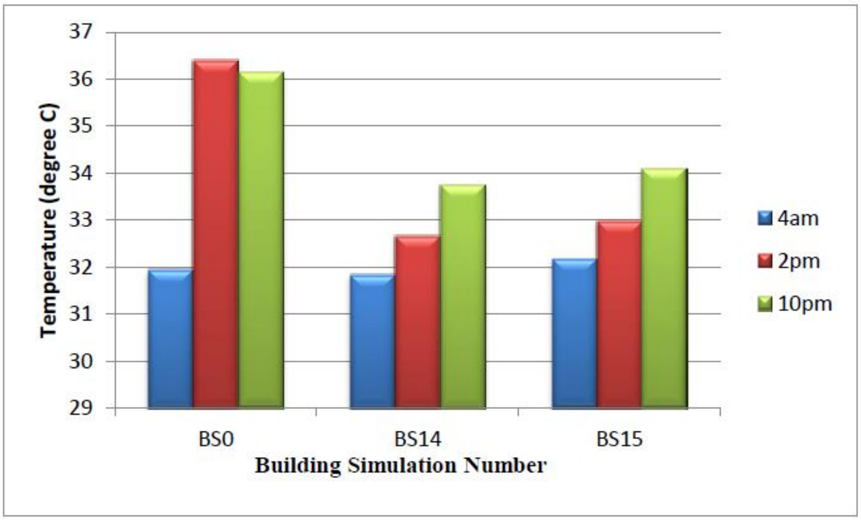


Figure 7.9. Changing the Living room Windows design WL (b), WL(c) when the wind catcher dimension is (1.5 m * 1.5 m)

Changing the height of the wind catcher (H6, H8, H10) when the wind catcher dimension is (2 m * 2 m)

By changing the height when the wind catcher dimension is (2m*2m) the best thermal performance in the living room at 4 am is in BS12 when the height is 6m, while the best thermal performance in the living room at 2 pm was in BS13 when the height is 8m as shown in (Figure 7.10). In the case of comparison with BS1, BS2, and BS3 in terms of thermal performance, It can observe that there is a slight rise in the temperature of the living room by about 0.15 Celsius.

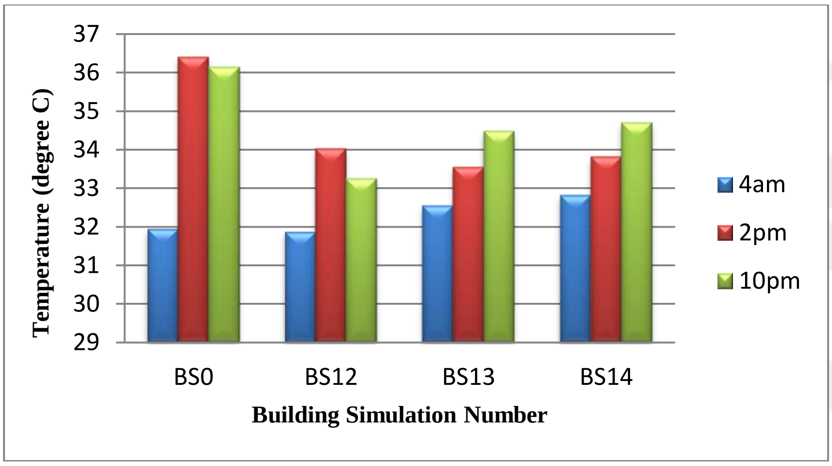


Figure 7.10. Changing the height of the wind catcher (H6, H8, H10) when the wind catcher dimension is (2 m * 2 m)

Changing the opening direction of the wind catcher, OD(s-n), OD (s-n-e-w), when the wind catcher dimension is (2 m * 2 m)

Change the direction of the openings in the wind catcher in BS15 and BS16 from (s-n) to (s-n-e-w), was led to a decrease in the internal temperature in the living room, while the best thermal performance was when using the four-way wind catcher as seen in BS16. In the case of comparison with BS4 and BS5 in terms of thermal performance, It can be observed that there is a slight rise in temperature of the living room by about 0.12 Celsius as shown in (Figure 7.11).

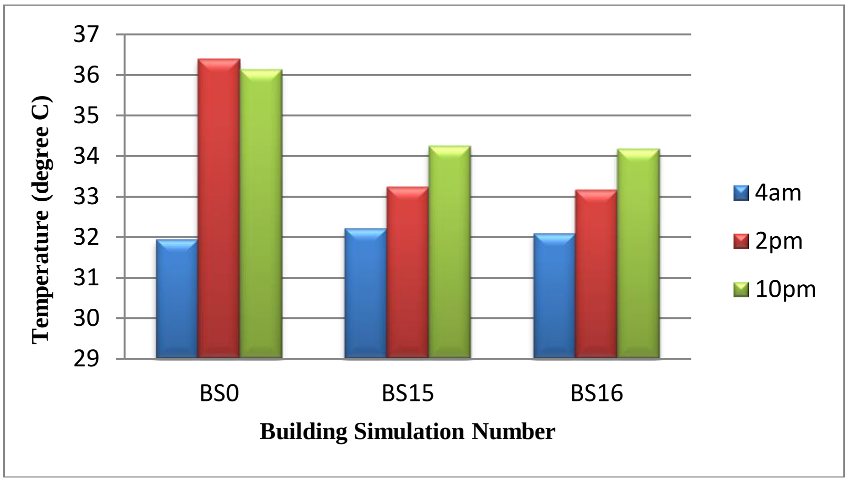


Figure 7.11. Changing the opening direction of the wind catcher when the wind catcher dimension is (2m*2m)

<u>Changing the number of the vent (NV3, NV5) in the wind catcher when the wind catcher dimension is (2 m * 2 m)</u>

Changing the number of vent in the wind catcher doesn’t have a noticeable effect on the internal thermal performance in the living room as seen in BS17 and BS18 (Figure7.59) In the case of comparison with BS6 and BS7 in terms of thermal performance, It can observe that there is a slight rise in temperature of the living room by about 0.11 Celsius as shown in (Figure 7.12).

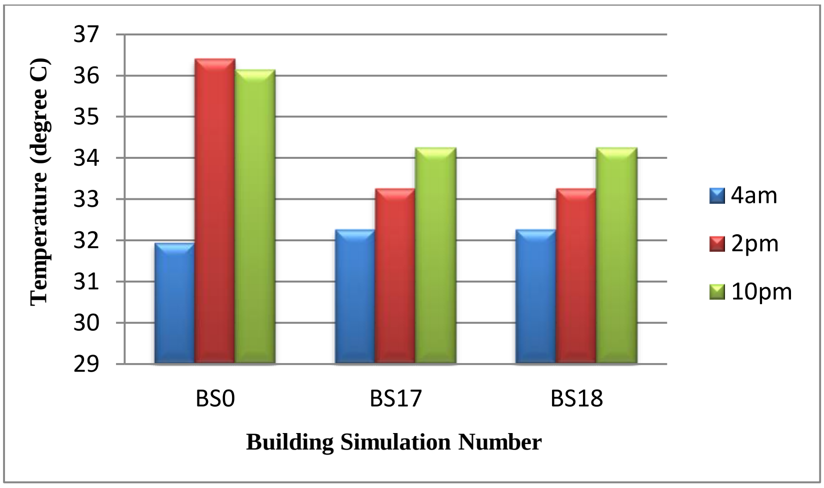


Figure 7.12. Changing the number of vent in the wind catcher when the wind catcher dimension is (2 m * 2m)

Changing the partition type (Pb, Pc) in the wind catcher when the wind catcher dimension is (2 m * 2 m)

Changing the partition type in the wind catcher from partition type (b) to partition type (c), doesn’t have a considerable effect on the internal thermal performance in the living room at 2 pm, but a slight change in night temperatures occurs inside the living room as seen in BS19 (Figure 7.13). In the case of comparison with BS8 and BS9 in terms of thermal performance, the temperature of the living room has been increased by about 0.07 Celsius as shown in (Figure 7.13).

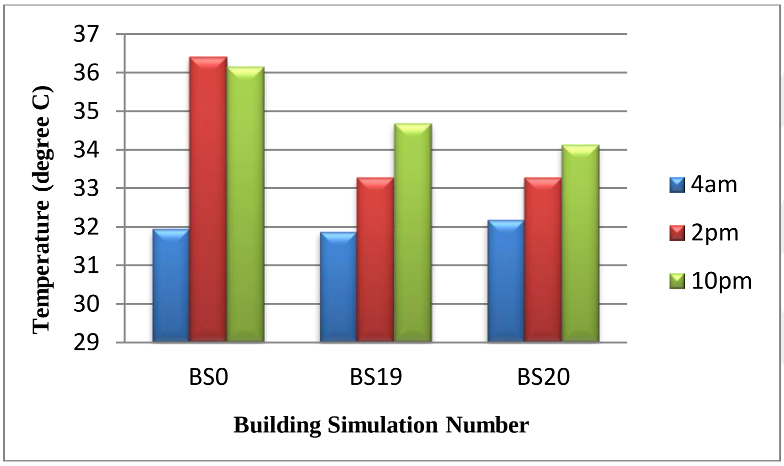


Figure 7.13. Changing the partition type in the wind catcher when the wind catcher dimension is (2 m * 2 m)

Changing the room dimension (RD 5m*6m, RD 6m*6m) when the wind catcher dimension is (2 m * 2 m)

Changing the room dimension leads to better thermal performance during the day and night periods as seen in the BS21 and BS22 Figure (Figure 7.14). In the case of comparison with BS10 and BS11 in terms of thermal performance, the temperature of the living room was increased by about 0.10 Celsius as shown in (Figure 7.14).

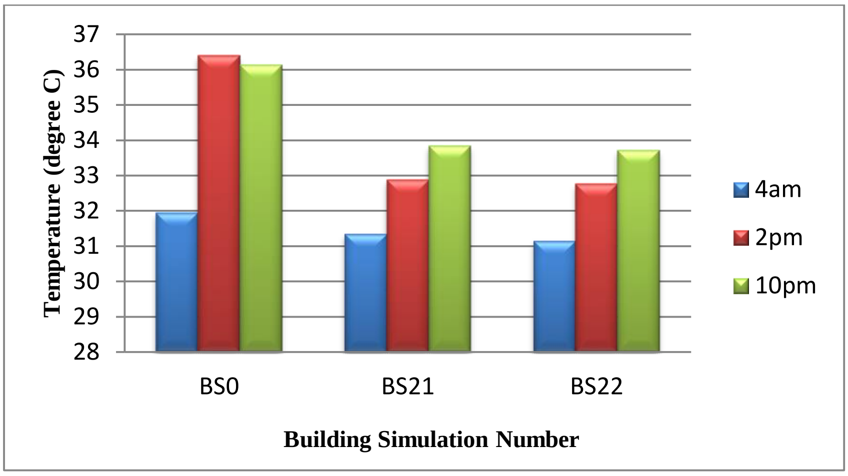


Figure 7.14. Changing the room dimension (living room) when the wind catcher dimension is (2 m * 2 m)

Changing the height of the wind catcher (H 6, H8, H10) when the wind catcher dimension is (3 m * 3 m)

By changing the height when the wind catcher dimension is (3m*3m) the best thermal performance for the living room during the day is in BS23 when the height is 6m, In the case of comparison with BS1, BS2, and BS3 in terms of thermal performance, It can be observed that there is a slight rise in temperature of the living room by about 0.5 Celsius, and about 0.25 Celsius In the case of comparison with BS12 and BS13 and BS14 as shown in (Figure 7.15).

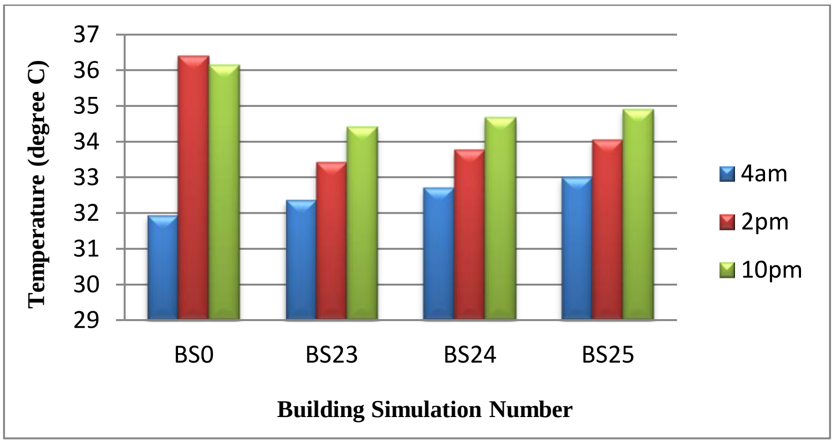


Figure 7.15. Changing the height of the wind catcher when the wind catcher dimension is (3 m * 3 m)

<u>Changing the opening direction OD (s-n), OD (s-n-e-w) of the wind catcher when the wind catcher dimension is (3 m * 3 m)</u>

Change the direction of the openings in the wind catcher in BS26 and BS27 is also leading to a decrease in the internal temperature in the living room, while the best thermal performance was when using the four-way (s-n-e-w) wind catcher as seen in BS27 (Figure.7.16). In the case of comparison with BS4 and BS5 in terms of thermal performance, It can be observed that there is a slight rise in temperature of the living room by about 0.57 Celsius, and about 0.35 Celsius In the case of comparison with BS15 and BS16 as shown in (Figure 7.16).

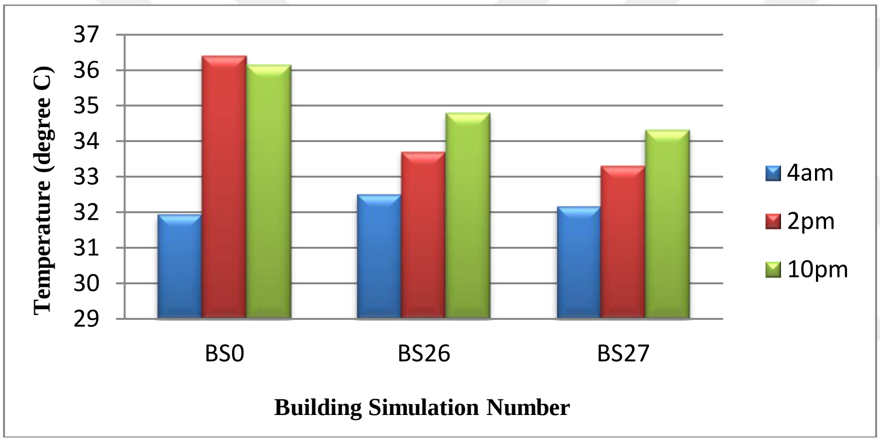


Figure 7.16. Changing the opening direction of the wind catcher when the wind catcher dimension is (3 m * 3 m)

<u>Changing the number of the vent (NV3, NV5) in the wind catcher when the wind catcher dimension is (3m*3m)</u>

Changing the number of vents in the wind catcher doesn't have a noticeable effect on the internal thermal performance in the living room as seen in BS17 and BS18. In the case of comparison with BS6 and BS7 in terms of thermal performance, the temperature of the living room has been increased by about 0.28 Celsius and about 0.17 Celsius In the case of comparison with BS17 and BS18 as shown in (Figure 7.17).

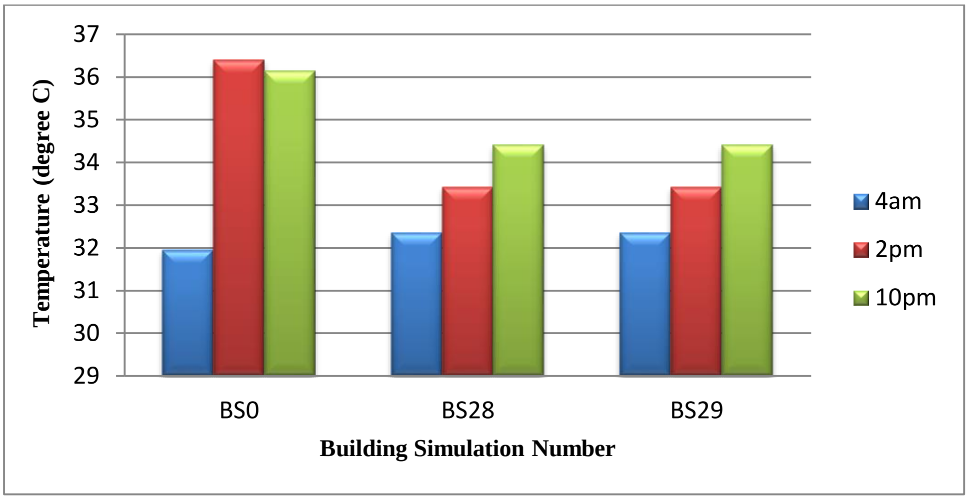


Figure 7.17. Changing the number of vent in the wind catcher when the wind catcher dimension is (3 m * 3 m)

Changing the partition type (Pb, Pc) in the wind catcher when the wind catcher dimension is (3 m * 3 m)

changing the partition type in the wind catcher doesn’t affect the internal thermal performance in the living room. In the case of comparison with BS8 and BS9 in terms of thermal performance, the temperature of the living room was increased by about 0.25 Celsius and about 0.13 Celsius In the case of comparison with BS19 and BS20 as shown in (Figure 7.18).

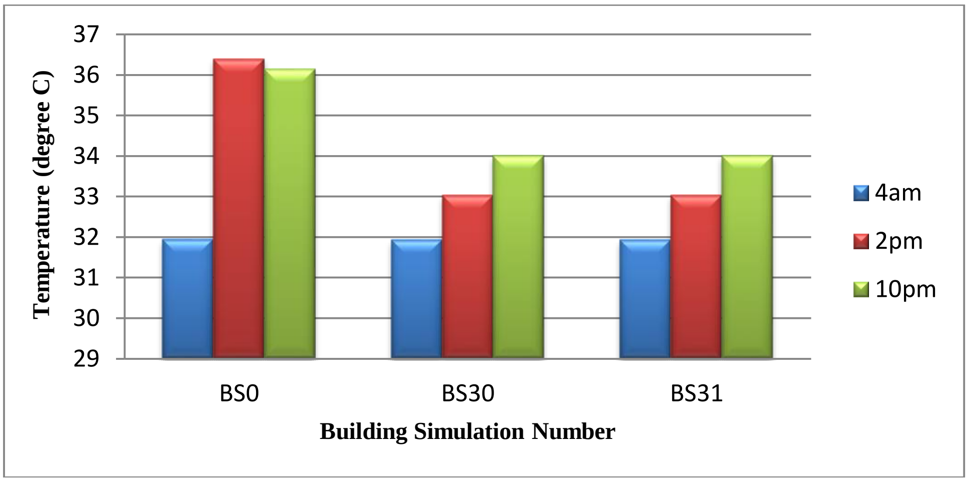


Figure 7.18. Changing the partition type in the wind catcher when the wind catcher dimension is (3 m * 3 m)

Changing the room dimension (RD (5m*6m), (6m*6m)) when the wind catcher dimension is (3 m * 3 m)

Changing the room dimension leads to better thermal performance during the day and night periods as seen in BS32 and BS33, In the case of comparison with BS10 and BS11 in terms of thermal performance, It can be observed that the air temperature of the living room increased by about 0.3degree and about 0.15 Celsius In the case of comparison with BS21 and BS22 as shown in (Figure 7.19).

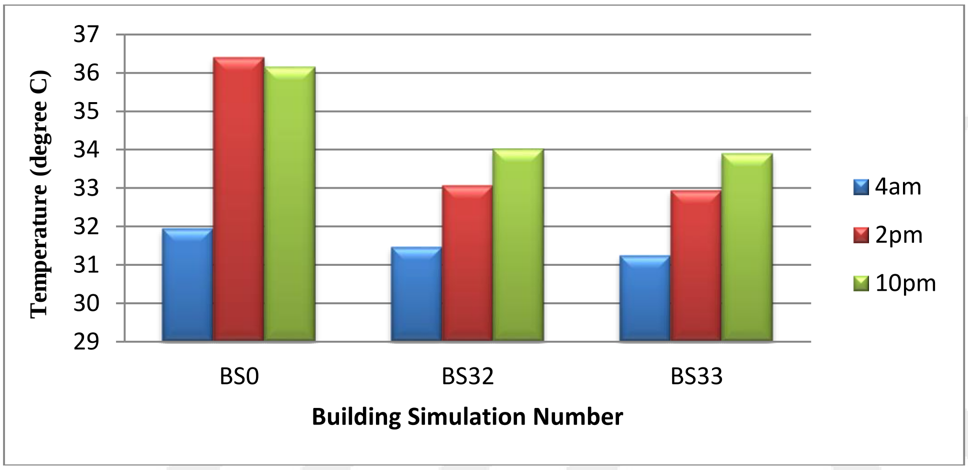


Figure 7.19. Changing the room dimension (living room) when the wind catcher dimension is (3 m * 3 m)

7.7.2. Selective design simulation analysis (SBS1, SBS2)

The best values and results from these eight criteria were selected and combined in one design and simulated again as SBS1. In SBS2 the water spray has been added for testing the effect of evaporation cooling on the wind catcher. When adding the water spray in SBS2 the internal air temperature for the living room was decreased by almost 4 ^{o}C at 2 pm and enhancing the internal air temperature as shown in (Figure 7.20).

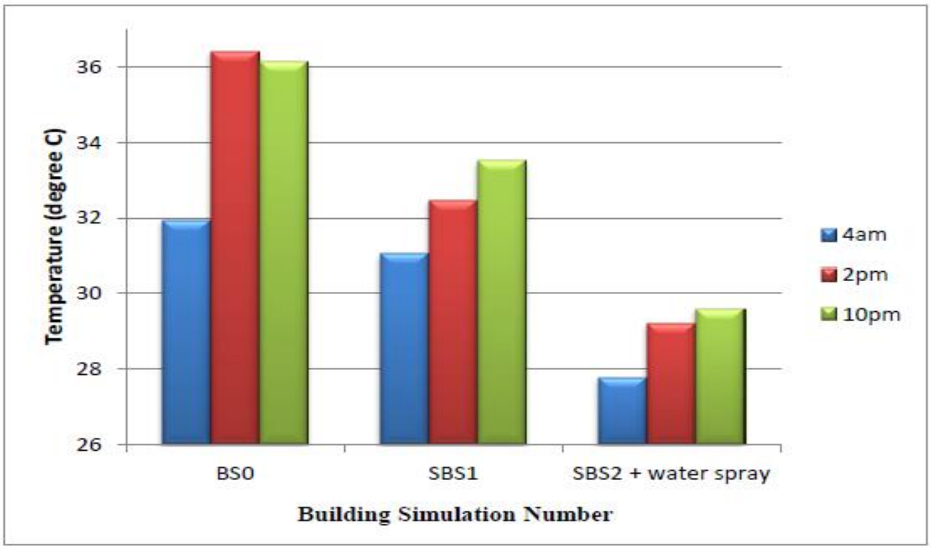


Figure 7.20. Comparing between SS1and SS2

The chart in (Figure 7.20) showing the deference's in thermal performance during the day. The best thermal performance and the best air temperatures are in SBS2. Also, It can be observed that in figure (Figure 7.20), the percentages of improvement are noticeably increased in SBS2.

Adding the Water Spray to the wind catcher

The best values and results from these three elements have been selected and combined in a new design and simulated again. In the last simulation, water spray has been added for testing the effect of evaporation cooling on the windcatcher (Figure 7.21). The results show that the use of the water spray has lead to a decrease in the temperature of the living room by 35.37% which 15.99°C (Figure 7.22).

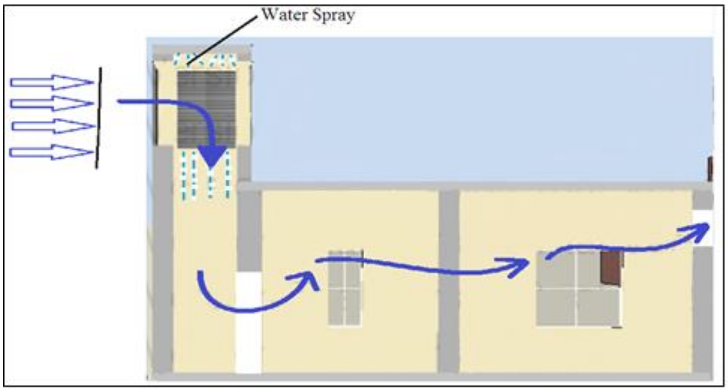


Figure 7.21. Water sprays in the wind catcher

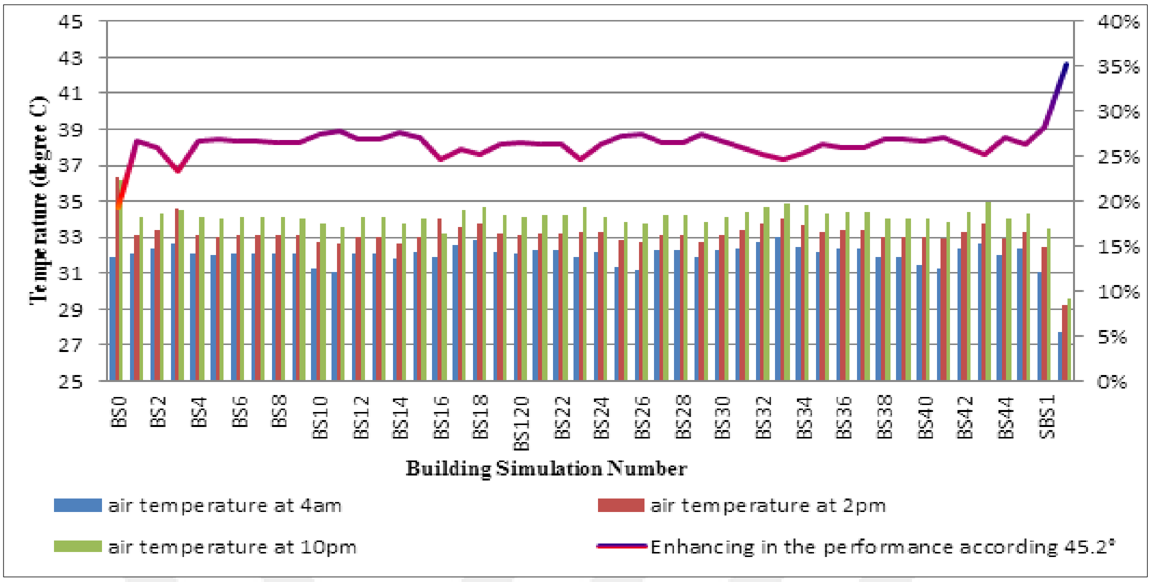


Figure 7.22. The deferences between thermal performance during the day in all simulation model

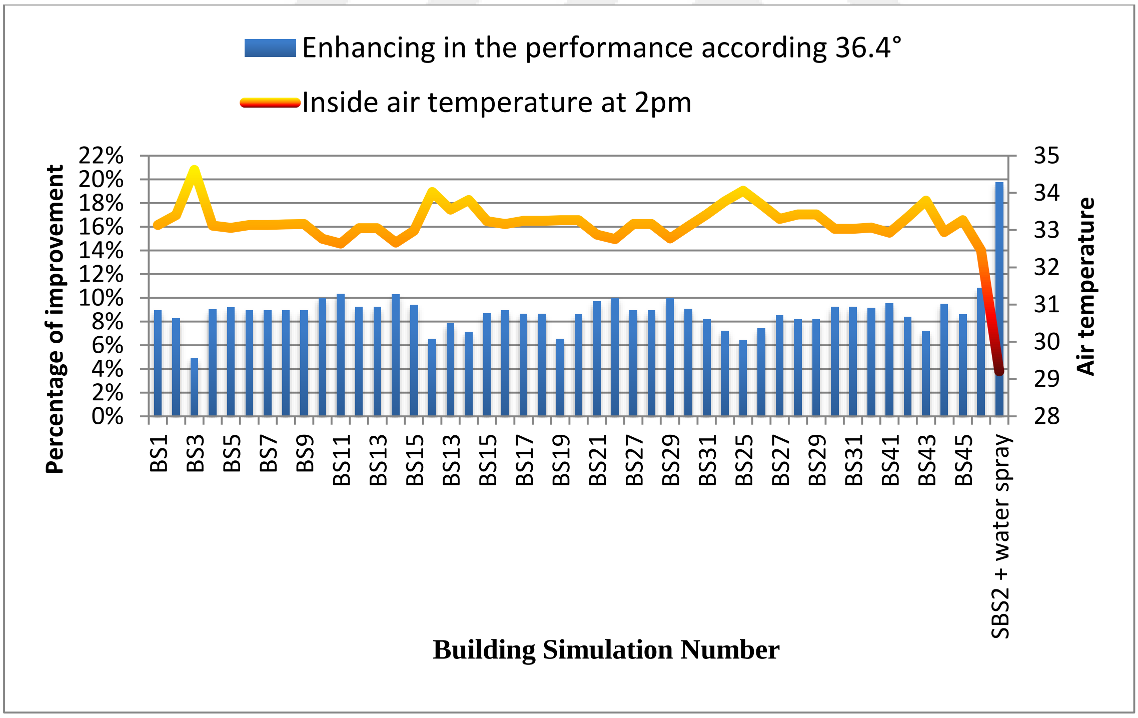


Figure 7.23. Enhancing in the performance according to the building without wind catcher (36.4°C)

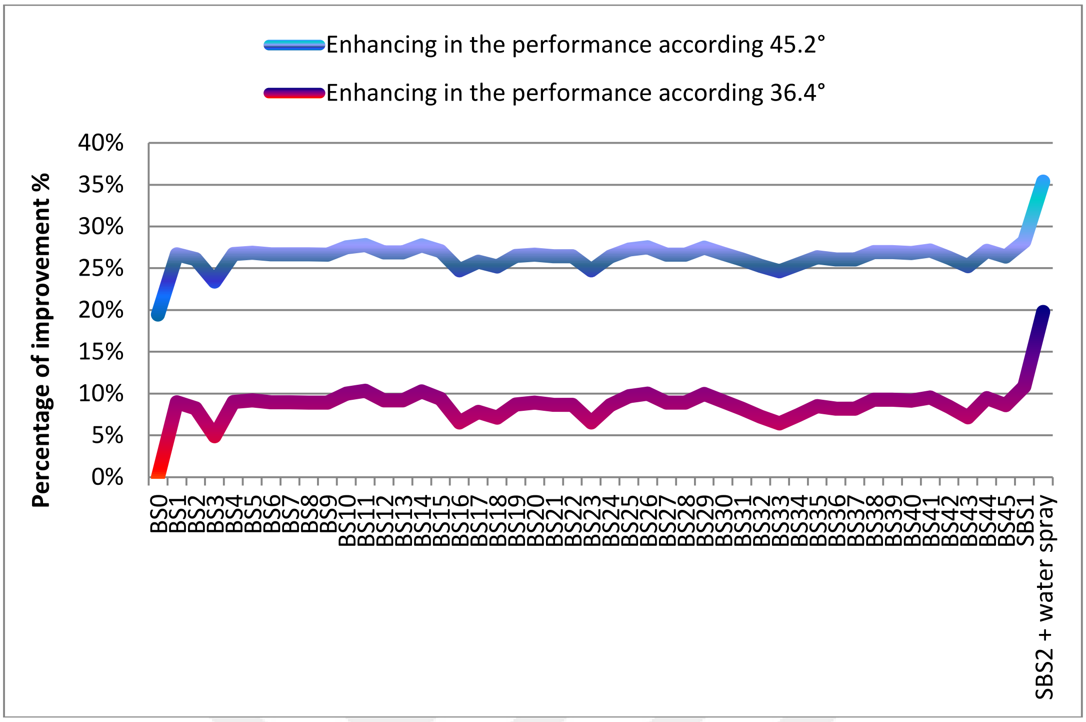


Figure 7.24. Enhancing of the performance according to 45.2°C, and 36.4°C

7.7.3. Comparing between the Designs (with the and without Wind Catcher) in term of natural ventilation

by looking to the heat balances charts and cumbering between the buildings with wind catcher and the building without wind catcher, It can be noticed that the internal natural ventilation inside the living room during the noon time is increased and the size of internal natural ventilation in the living room at the same time in the building without wind catcher is decreased. Also in the total fresh air charts it can be observed that the air movement inside the living room in the building with wind catcher is better than the air movement inside the living room in the building without wind catcher as can be seen in (Figure 7.25&7.26).

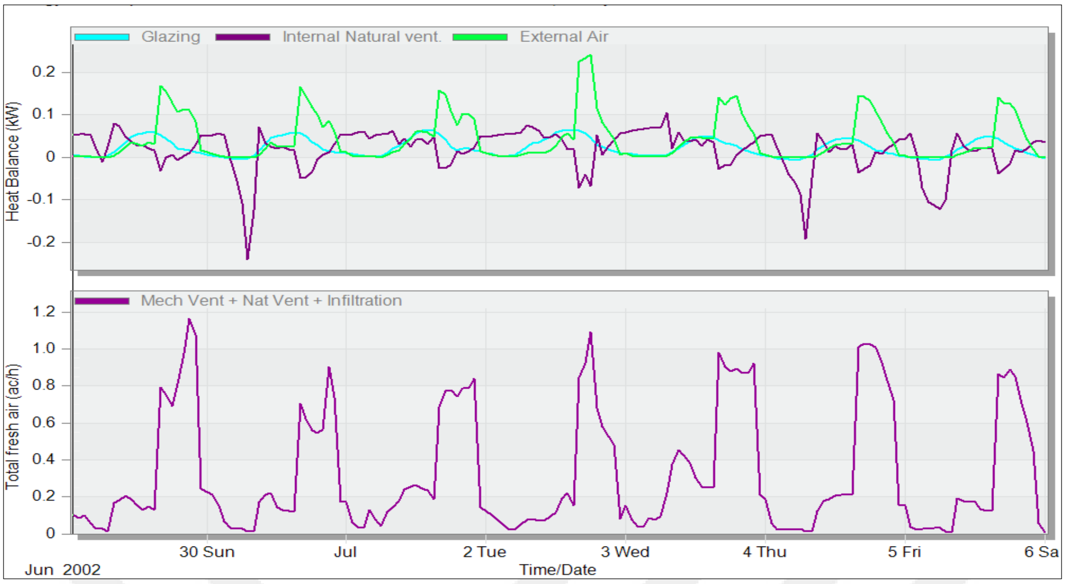


Figure 7.25. Ventilation without wind catcher

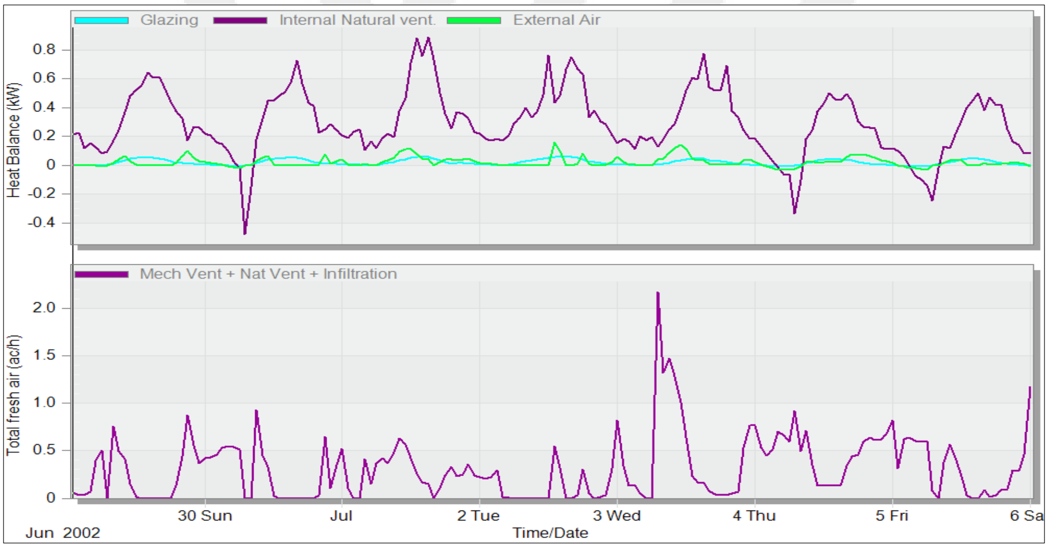


Figure 7.26. Ventilation with wind catcher

7.7.4. CFD analysis

<u>Building without wind catcher</u>

In (Figure 7.27) It can observe that, the effect of the hot wind coming from outside in the living room and the movement of the hot air, where it starts to spread out across the living room gradually from the windows and getting out after gaining heat from the living room.

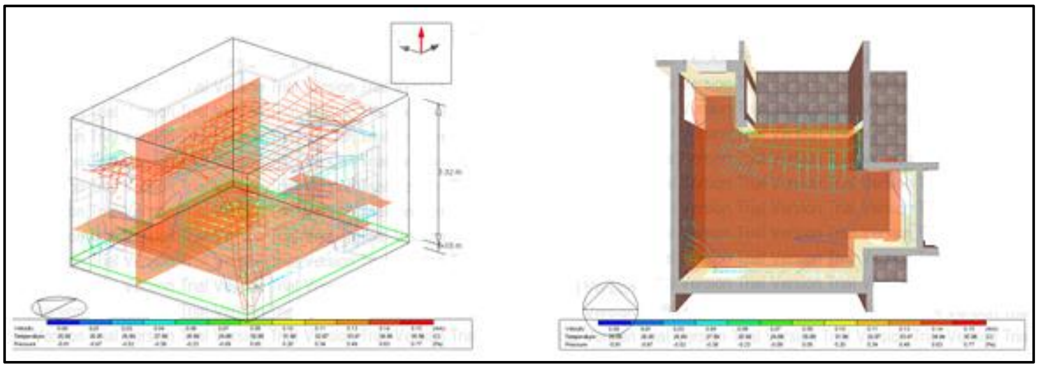


Figure 7.27. CFD analysis for the building without wind catcher

Building with wind catcher

In (Figure.7.29) it can be seen the effect of the windcatcher on the living room and the movement of cold air that comes from the outside and gets colder when mixed with water coming from the water spray inside the windcatcher. it starts to spread out across the living room gradually from the air inlet in the windcatcher until reaches the windows and getting out after gaining heat from the living room.

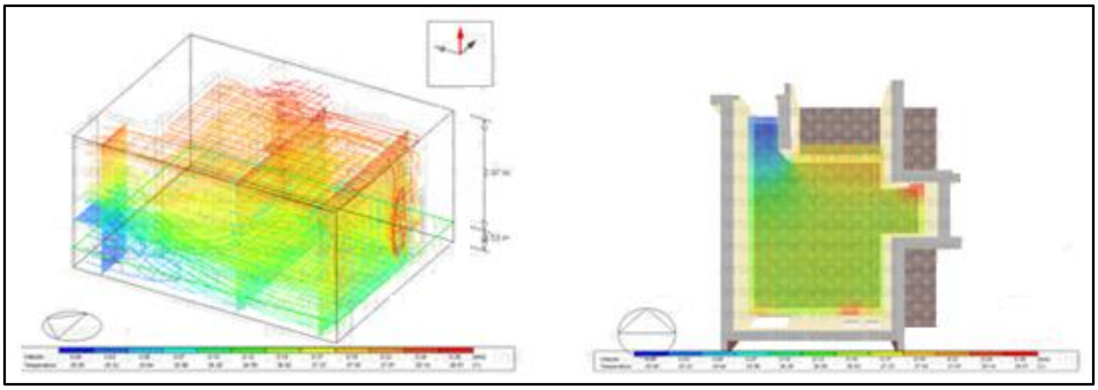


Figure 7.29. CFD analysis for the building with wind catcher

8. CONCLUSION AND RECOMMENDATIONS

When analyzing the literature, it becomes obvious that the ideas offered by centuries of established communities can be incredibly useful in developing good technology and development fields. The methods were largely based on innovative architectural systems that utilized natural ventilation to provide thermal comfort. To minimize the overall exposure to direct solar radiation obtained by each building, a system of compact clusters of house design in the form of a heavy mass of cells, shared walls, and alleyways were created. For a hot dry climate, the typical courtyard house design has been the most comforTable and reasonable design. Such architecture, and also features such as wind catchers, thick walls, demonstrates a clear view of how to live in harmony with nature. a concentration on the courtyard and good roof material use appear to be basic but successful alternatives to the conditions of such a hot and dry climate.

In reality, the courtyard house uses low-cost natural energy to maintain the house's environment to a modest degree. The availability of openings on exterior walls was not ideal or possible in such a design, and indeed the wind catcher has been the most efficient way to promote natural ventilation and thermal comfort.

Among a variety of elements and passive cooling techniques, the wind catcher is also a necessary part of the home. This research also came to the fact that a greater knowledge of this component will result in a better analysis of the overall ventilation system. The main goal was to examine the benefits of having a wind catcher in the modernist design of Khartoum's houses, Sudan. This thesis offered a reasonable viewpoint of a wind catcher by targeting certain things that were either ignored or overlooked through a literature analysis of the conventional building in Sudan, thermal comfort, passive cooling techniques, and natural ventilation systems, and simulation of different criteria that could have many variables. Table 7-5 presents an outline of the findings, which will be covered later in this chapter as the main result of this research.

Conclusion regarding the literature review and evaluation of the research's aims and limits

Because of low external wind speeds, and the extreme air temperatures in the hot dry climate, introducing natural ventilation systems to enhance indoor thermal comfort is very complex, especially during the summer season. Natural ventilation systems are also unpredicTable. Even so, since most building inhabitants favor natural ventilation mechanisms over artificial ones, wind catcher ventilation mechanisms have been a center of attention for many researchers. In addition, wind catcher natural ventilation systems use less energy and have greater benefits. All of this has been undertaken to evaluate the current experience in order to help within the development of a natural ventilation system for a typical Sudanese home. According to the literature review in chapter two, air ventilation systems such as modern advanced wind catcher, and wing walls, in combination with formed roofs, are capable of providing high speed indoor air flow, which is needed to producing a cooling effect, and therefore internal comfort conditions in hot places.

The literature review in chapter three was undertaken to determine how passive design strategies in the domestic construction field minimize energy consumption for cooling systems. Concerning energy-efficient houses, several architects and planners have decided to adjust their methods for cooling the building from modern air-condition or mechanical cooling systems to energy efficient passive cooling techniques in a modern manner. In order to reassess and analyze strategies to apply passive cooling to traditional residential buildings, a literature review has been conducted on natural ventilation systems, energy efficient and common vernacular, passive cooling techniques. From the literature review, the study found these passive cooling techniques could be used in a traditional building in Khartoum to improve the internal environment in the houses. Some of these strategies were been used during the development of the simulation model that used in the main house with wind catcher. The major elements of both conventional organic and modern structured dwelling conditions were outlined in chapter four, with an attempt to connect an overview to the utilizes or activities that occur inside both forms. We've seen how even the most basic of residences can be loaded with sense and extremely reflective of societal values. The observation of humans in the structures they produce and use provides another unique and interesting viewpoint. As a result, the house is a symbol that suggests and justifies ideas, relationships, and cultural divisions. People are expressing their self as human beings associated with particular social groups by the structures of residential houses.

The wind catcher design proposed in this study is based on previous studies contained throughout the literature review in the fifth chapter. For the wind catcher, guidelines from previous researches were used to create a single column with four inlets, form a rectangular shape. This study has also included; optimization of the wind catcher height to reduce energy consumption while maximizing thermal comfort and indoor air quality, partitioning of the column, changes to the shape, placement of the wind catcher on the building, and different position and designs of the windows in the living room area.

The key goal of this research was to establish a natural good ventilation strategy plan for conventional houses in Sudan's hot dry climate, which provides sufficient comfort conditions and increased indoor environmental quality while remaining energy efficient. Chapters 6 and 7 provided the modeling of the various parameters considered in this study in order to achieve this aim. The results of each criteria are then presented in detail to show the expected output in terms of thermal comfort, indoor air temperature in comparison to outdoor air temperature at various times of the day, and the percentage of the change or improvement in indoor air temperature.

Conclusion regarding the simulation

The simulation aimed to improve the efficiency of wind catchers on a technical level. The overall aim was to increase the structure's efficiency by adjusting some of the important criteria. The quality of wind catcher performance with the following points was the basis for improvement;

- The wind catcher's flow has been enhanced in structure. This included the enhancement of the wind catcher's form and details in terms of aerodynamic efficiency.
- By using the pressure effect on the leeward side of the wind catcher and dividing the outlet and inlet, the air movement across the living room was increased.
- For the effect of evaporative cooling, a water spray was provided at the top of the wind catcher, and preliminary evaluation indicated that direct contact between water and air may decrease the air temperature.

Traditional wind catchers' physical and visual features were simplified to increase efficiency; however, the basic architecture wasn't ignored. Furthermore, the proposed designs are typically recognizable easy and adapTable, the patterns and air quality are much more predicTable. All of this will allow designers and developers to control them to fit a specific need.

The DesignBuilder software's limited capabilities for CFD analysis were used in this research. Although the aim of this project was to consider variable indicators at the building level and air temperature, a true understanding of airflow variance at the zone level and the comfort variation that results from it necessarily require the use of advanced CFD instruments. Even so, because the conventional house's design and scale of the project were simple, the DesignBuilder CFD technology was deemed sufficient for this design.

The influences of design criteria; dimension of the wind catcher, the height of the wind catcher, opening direction in the wind catcher, the number of vent in the wind catcher, partition in the wind catcher, the dimension of the living room, living room Windows location, living room Windows Design, on the windcatcher performance in Khartoum houses have been investigated and the finding was as the following;

- Changing the wind catcher dimensions from (3 m * 3 m) to (1.5 m * 1.5 m), increases the performance of the wind catcher by 26 % which is about 12 °C.
- Changing the height of the wind catcher from 10m to 6m when building height is 3m increases the performance of the wind catcher by 26.68% in the living room which is about 12.06 °C.
- Changing the opening direction in the wind catcher from one-way to four-way direction increases the performance of the wind catcher by 26.85% which is about 12.14°C.
- Changing the number of vents in the wind catcher from 1 to 5, increases the performance of the wind catcher by 26.68. % which is about 12.06 °C.
- The use of wind catcher with one partition (type (b)) increases the performance of the wind catcher by 26.68. % which is about 12.06 °C.
- Changing the living room dimensions in the wind catcher from (4 m * 6 m) to (6 m*6 m) increases the performance of the wind catcher by 27.78%, which is about 12.56 °C.

- Using small windows with dimensions of 50 cm * 50 cm located at a high level (type (b)) of the living room increases the performance of the wind catcher by 26.88%, which is about 12.15 °C.
- The use of four small windows design (type (b)) with dimensions of 50 cm * 50 increases the performance of the wind catcher by 27.74%, which is about 12.54 °C.
- The combination of the best results that have been obtained from the simulation criteria of the wind catcher increases the performance of the wind catcher by 28.18%, which is about 12.74 °C.
- Adding water spray to the windcatcher increases the relative humidity and decreases the air temperature of the living room, and the thermal performance of the building will be increased by 35.37% which means the air temperatures will be decreased by about 15.99°C according to outside air temperature.
- The windcatcher with the suggested criteria and water spray provides more pleasant conditions and thermal comfort in the hot dry climate of Khartoum.

All the simulation findings have been summarized in Table 8.1

Table 8.1. Comparative analysis of all criteria according to outside air temperature (45ºC)

Criteria	Criteria Change s	Enhancing in the performance according to (45ºC)
The dimension of the wind catcher (DW)	from 1.5mx1.5m to 3mx3m	23 % - 26 %
The height of the wind catcher (H)	from 6m to 10m	23.40 % - 26.68 %
The opening direction in the wind catcher (OD)	from 1 way to 4 way	26.72 % - 26.85 %
The Number of the vent in the wind catcher (NV)	from 1 to 5	26.64 %
The partition in the wind catcher (P)	from type (a) to type (c)	26.63 % - 26.65 %
The dimension of the rooms in the target area (RD)	from 4mx6 to 6mx6m	27.50 % - 27.78 %
The Living room Windows location(WL)	from type (a) to type (c)	26.88 %
The Living room Windows Design(WD)	from type (a) to type (c)	27.03 % - 27.74 %
SBS1 and SBS2	With water spray	28.18 % - 35.37 %

Recommendations for further research

While some useful results have been made in this research, some limitations should be described;

1. The study examined the effect of only wind catcher on traditional house , therefore further study on specific aspects such as, glazing, shading of windows, building materials are needed to investigate.
2. Since any climate is unique, and has its characteristics, more studies or research papers are required to; check the right orientations based on the climate characteristics in various cities and climates, determine appropriate sizes, and enhance a systematic model of use.
3. This research indicates that it is better to study characteristics of wind under such weather conditions, such as during the hours of the day when everyone requires cooling instead of using standard or annual mean velocities of the books.
4. according to this research, The wind catchers should be analyzed more using the CFD system, and the calculated outcomes can be compared to the findings of this research.
5. The construction of the building in this research was assumed to be a one-story individual residential building with adjacent buildings of the same scale. This hypothesis may affect the outcome, therefore Further studies should be performed to assess the effects of other nearby, high-rise buildings or commercial structures on wind catcher systems and the prevailing winds.

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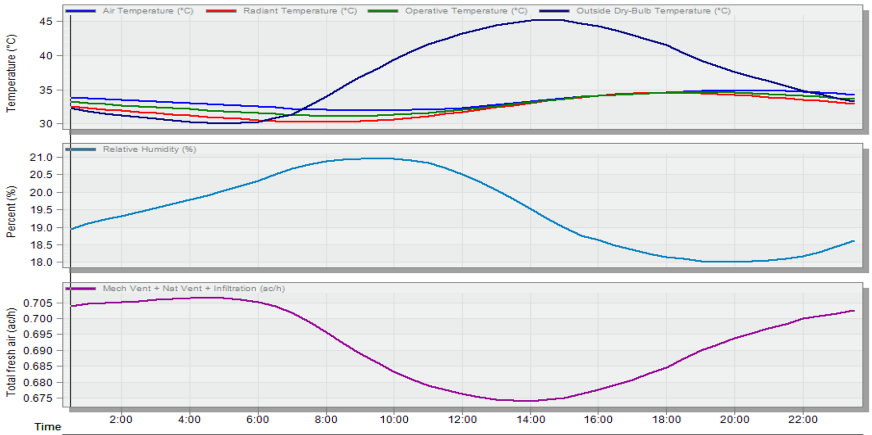
APPENDICES

APPENDIX-1. Simulation results charts

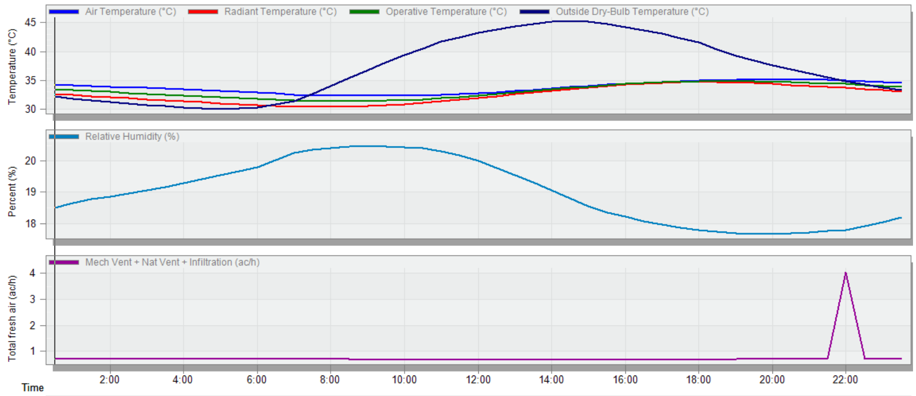
<u>BS1/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (4*6)</u>



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.52	33.08	32.58	32.02	31.98	32.36	33.23	34.09	34.62	34.85	34.75
Radiant Temperature (°C)	31.92	31.20	30.56	30.22	30.67	31.75	33.04	34.14	34.54	34.22	33.56
Operative Temperature (°C)	32.72	32.14	31.57	31.12	31.32	32.05	33.14	34.11	34.58	34.54	34.15
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.32	19.78	20.31	20.89	20.95	20.51	19.53	18.63	18.16	18.00	18.16
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 1. BS1 simulation charts

<u>BS2/ DW (1.5*1.5) H (8) OD(S) NV (1) P (A) RD (4*6)</u>

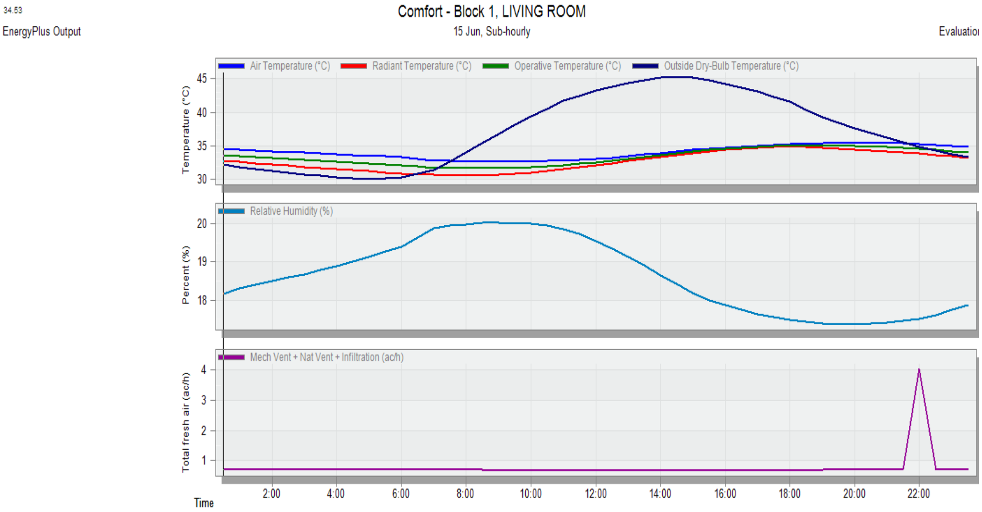


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.87	33.44	32.95	32.33	32.33	32.73	33.59	34.42	34.92	35.13	35.02
Radiant Temperature (°C)	32.08	31.37	30.74	30.39	30.83	31.91	33.20	34.29	34.69	34.36	33.70
Operative Temperature (°C)	32.97	32.40	31.84	31.36	31.58	32.32	33.40	34.36	34.80	34.75	34.36
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.86	19.28	19.79	20.42	20.44	19.99	19.05	18.22	17.79	17.66	17.78
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 2. BS2 simulation charts

APPENDIX-1. (continue) Simulation results charts

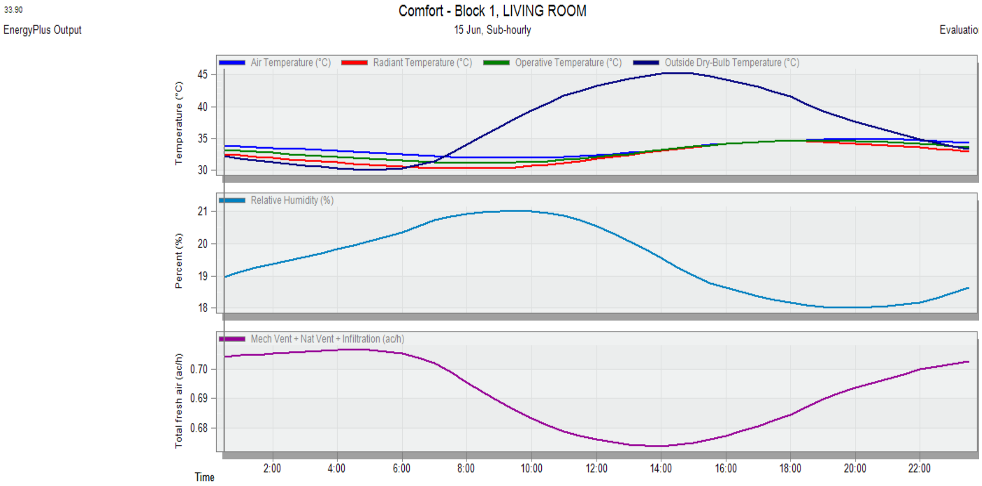
BS3/ DW (1.5*1.5) H (10) OD(S) NV (1) P (A) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.17	33.76	33.27	32.65	32.66	33.06	33.90	34.70	35.18	35.39	35.27
Radiant Temperature (°C)	32.21	31.50	30.88	30.53	30.97	32.05	33.34	34.43	34.82	34.49	33.83
Operative Temperature (°C)	33.19	32.63	32.08	31.59	31.82	32.56	33.62	34.56	35.00	34.94	34.55
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.49	18.90	19.39	19.98	19.99	19.55	18.66	17.88	17.48	17.36	17.50
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.68	0.68	0.69	0.69	4.04

Figure 3. BS3 simulation charts

BS4/ DW (1.5*1.5) H (6) OD (S-N) NV (1) P (A) RD (4*6)

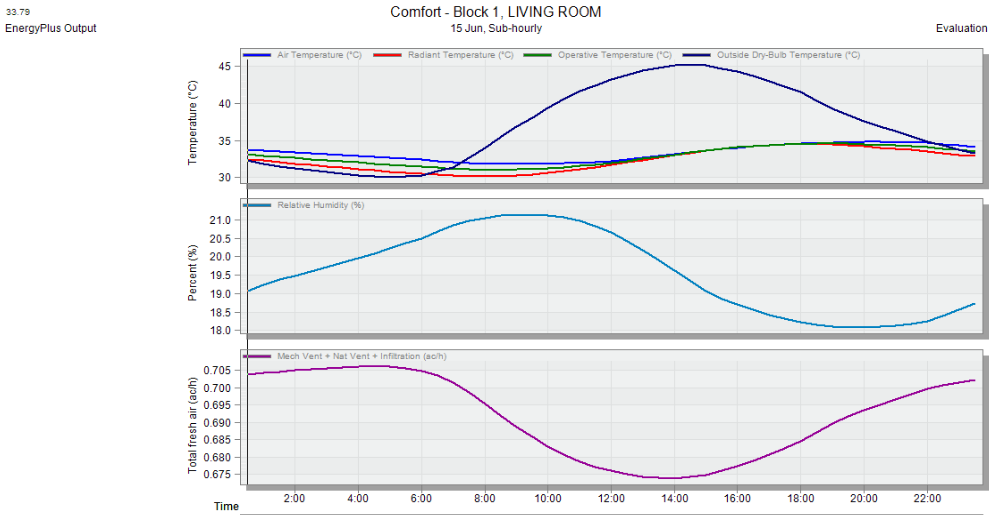


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.49	33.04	32.54	31.99	31.95	32.33	33.21	34.08	34.61	34.84	34.73
Radiant Temperature (°C)	31.91	31.19	30.55	30.21	30.66	31.73	33.03	34.13	34.53	34.21	33.55
Operative Temperature (°C)	32.70	32.11	31.54	31.10	31.30	32.03	33.12	34.10	34.57	34.53	34.14
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.36	19.82	20.36	20.92	20.99	20.54	19.55	18.64	18.16	18.01	18.18
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 4. BS4 simulation charts

APPENDIX-1. (continue) Simulation results charts

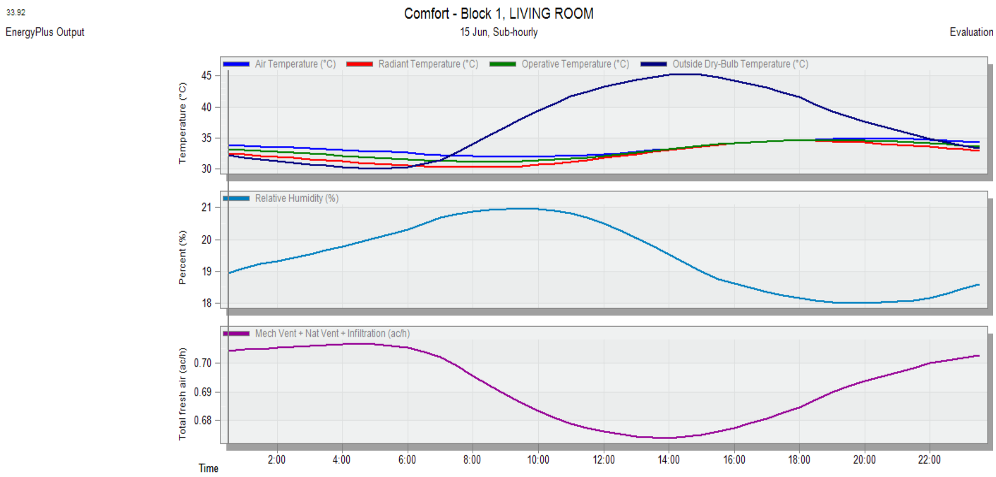
BS5/ DW (1.5*1.5) H (6) OD (S-N-E-W) NV (1) P (a) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.38	32.92	32.41	31.88	31.85	32.24	33.14	34.02	34.56	34.78	34.66
Radiant Temperature (°C)	31.87	31.14	30.50	30.16	30.61	31.69	32.99	34.09	34.50	34.18	33.52
Operative Temperature (°C)	32.62	32.03	31.46	31.02	31.23	31.97	33.06	34.06	34.53	34.48	34.09
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.48	19.96	20.50	21.06	21.11	20.65	19.64	18.71	18.22	18.08	18.26
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.71	0.70	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 5. BS5 simulation charts

BS6/ DW (1.5*1.5) H (6) OD(S) NV (3) P (A) RD (4*6)

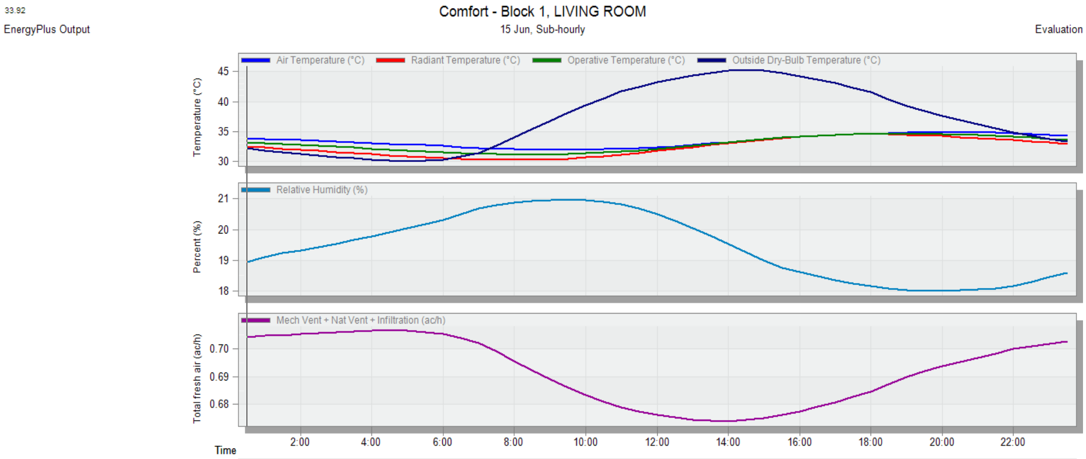


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.52	33.08	32.58	32.03	31.98	32.36	33.23	34.09	34.62	34.85	34.75
Radiant Temperature (°C)	31.92	31.20	30.56	30.23	30.67	31.75	33.04	34.14	34.54	34.22	33.56
Operative Temperature (°C)	32.72	32.14	31.57	31.13	31.33	32.05	33.14	34.11	34.58	34.54	34.15
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.32	19.78	20.31	20.88	20.95	20.51	19.52	18.63	18.16	18.00	18.16
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 6. BS6 simulation charts

APPENDIX-1. (continue) Simulation results charts

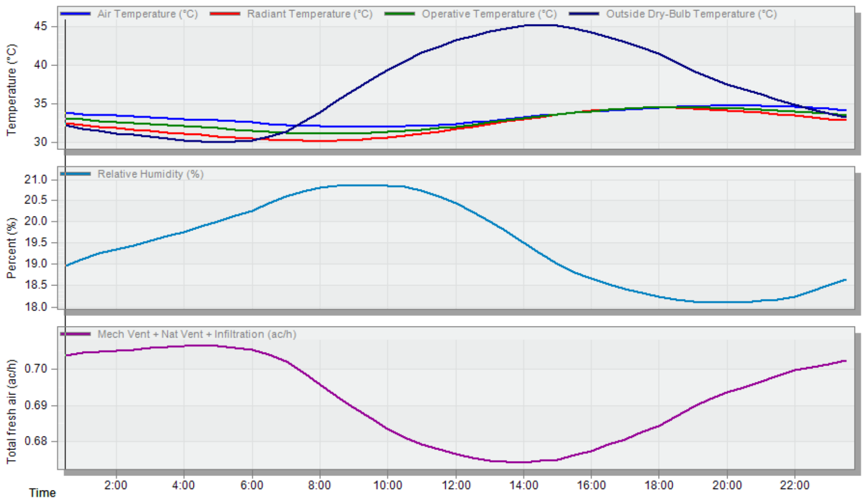
<u>BS7/ DW (1.5*1.5) H (6) OD(S) NV (5) P (A) RD (4*6)</u>



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.52	33.08	32.58	32.03	31.98	32.36	33.23	34.09	34.62	34.85	34.75
Radiant Temperature (°C)	31.92	31.20	30.56	30.23	30.67	31.75	33.04	34.14	34.54	34.22	33.56
Operative Temperature (°C)	32.72	32.14	31.57	31.13	31.33	32.05	33.14	34.11	34.58	34.54	34.15
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.32	19.78	20.31	20.88	20.95	20.51	19.52	18.63	18.16	18.00	18.16
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 7. BS7simulation charts

<u>BS8/ DW (1.5*1.5) H (6) OD(S) NV (1) P (B) RD (4*6)</u>

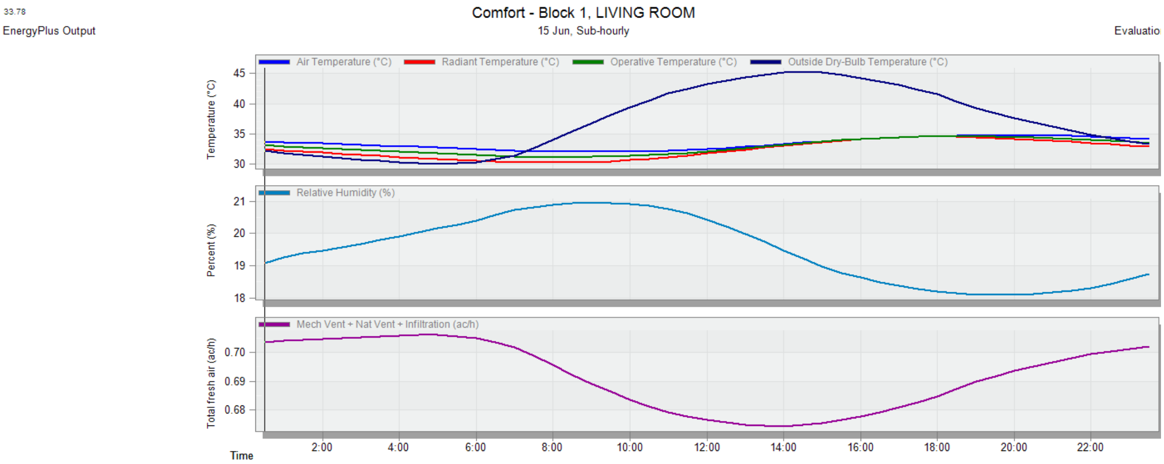


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.51	33.10	32.64	32.13	32.10	32.45	33.26	34.06	34.55	34.76	34.66
Radiant Temperature (°C)	31.90	31.19	30.56	30.23	30.68	31.76	33.05	34.14	34.53	34.20	33.53
Operative Temperature (°C)	32.71	32.14	31.60	31.18	31.39	32.11	33.15	34.10	34.54	34.48	34.10
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.33	19.76	20.25	20.79	20.83	20.42	19.51	18.68	18.24	18.10	18.24
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 8. BS8 simulation charts.

APPENDIX-1. (continue) Simulation results charts

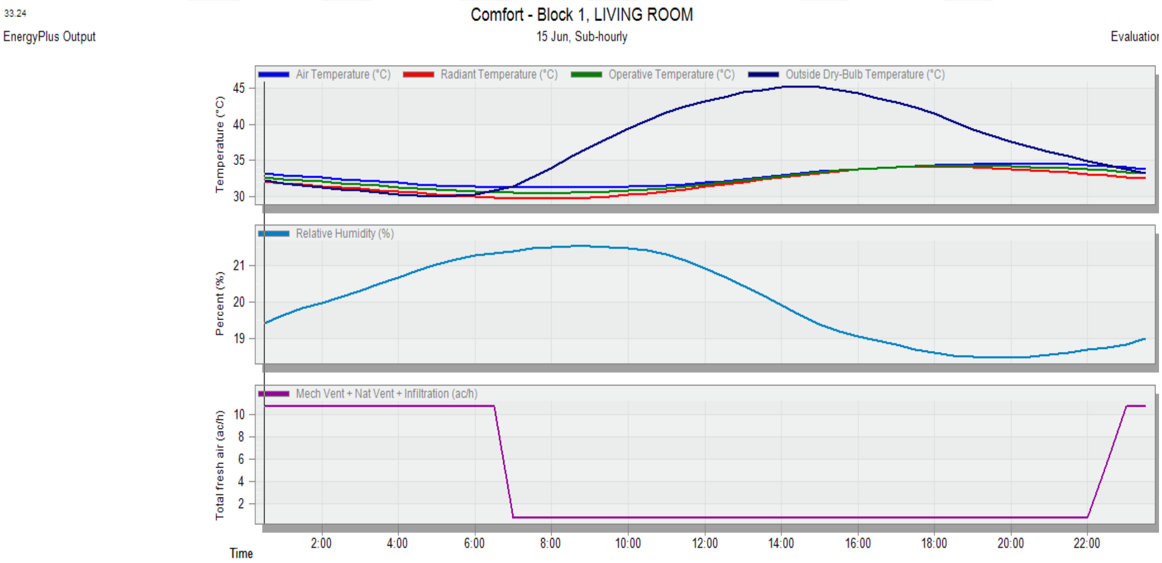
BS9/ DW (1.5*1.5) H (6) OD (S) NV (1) P (C) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.39	32.97	32.51	32.04	32.04	32.44	33.29	34.11	34.59	34.77	34.63
Radiant Temperature (°C)	31.88	31.16	30.53	30.21	30.67	31.75	33.03	34.12	34.52	34.19	33.52
Operative Temperature (°C)	32.63	32.07	31.52	31.12	31.35	32.09	33.16	34.12	34.56	34.48	34.07
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.47	19.91	20.40	20.90	20.91	20.44	19.48	18.64	18.21	18.10	18.29
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 9. BS9 simulation charts

BS10/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (5*6)

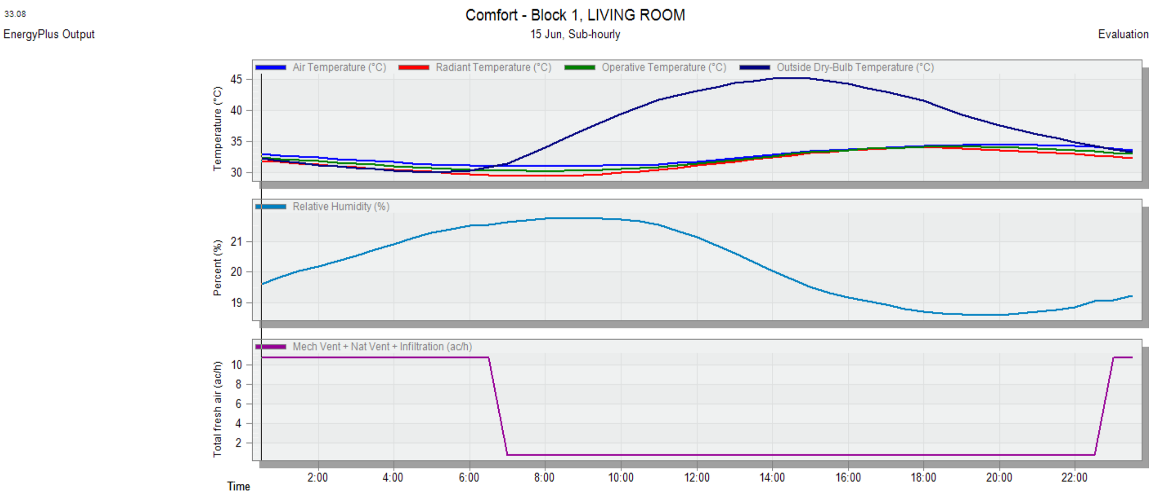


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.59	31.89	31.32	31.20	31.32	31.89	32.90	33.78	34.28	34.50	34.38
Radiant Temperature (°C)	31.43	30.67	29.98	29.68	30.17	31.30	32.64	33.71	34.12	33.78	33.11
Operative Temperature (°C)	32.01	31.28	30.65	30.44	30.75	31.60	32.77	33.75	34.20	34.14	33.74
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.96	20.67	21.27	21.50	21.46	20.92	19.90	19.06	18.61	18.47	18.68
Mech Vent + Nat Vent + Infiltration (ac/h)	10.75	10.76	10.74	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 10. BS10 simulation charts

APPENDIX-1. (continue) Simulation results charts

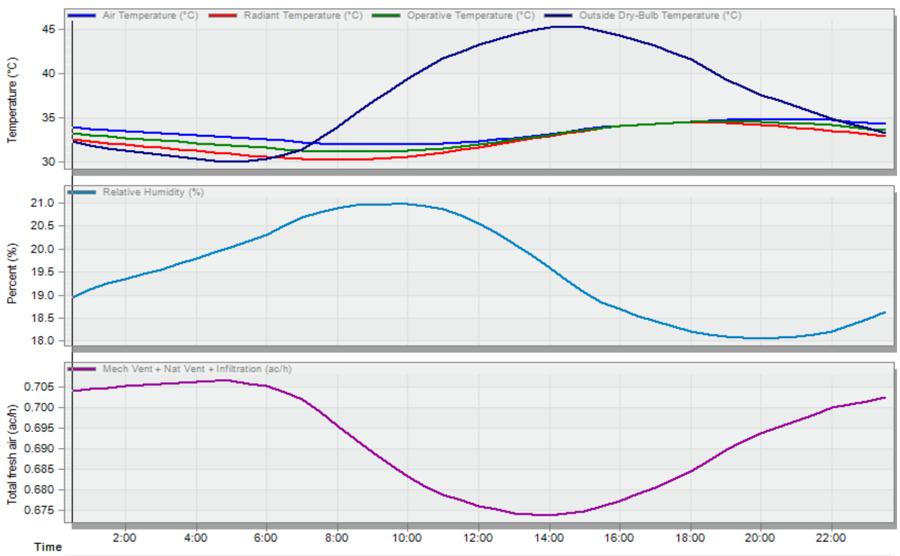
BS11/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (6*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.40	31.68	31.10	31.00	31.13	31.74	32.81	33.72	34.24	34.44	34.28
Radiant Temperature (°C)	31.23	30.44	29.74	29.43	29.93	31.09	32.47	33.57	34.00	33.65	32.96
Operative Temperature (°C)	31.82	31.06	30.42	30.21	30.53	31.42	32.64	33.65	34.12	34.05	33.62
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	20.18	20.91	21.51	21.74	21.71	21.12	20.05	19.18	18.72	18.61	18.86
Mech Vent + Nat Vent + Infiltration (ac/h)	10.74	10.75	10.73	0.69	0.68	0.67	0.67	0.68	0.68	0.69	0.70

Figure 11. BS11 simulation charts

BS12/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (4*6) WL (b) WD (a)

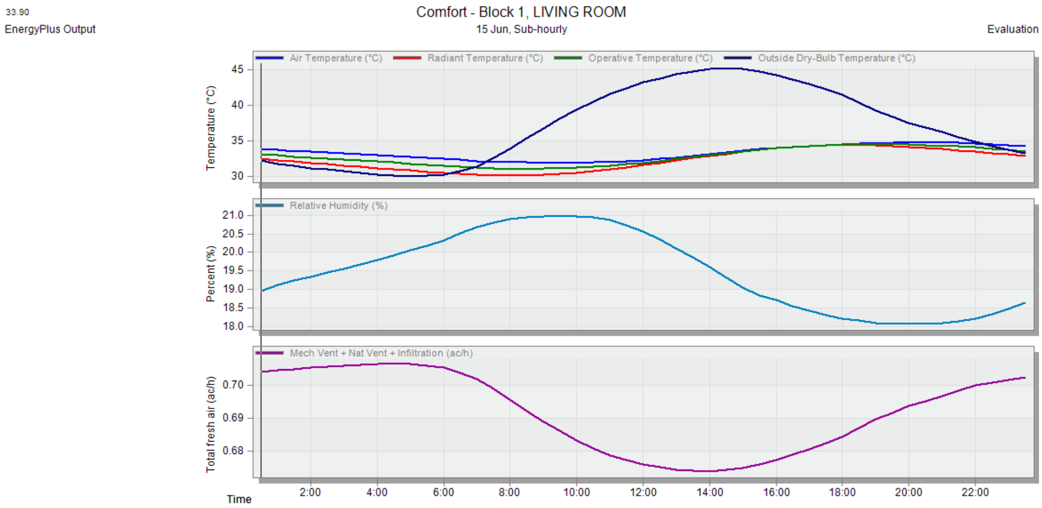


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.51	33.07	32.57	32.01	31.96	32.32	33.17	34.02	34.56	34.80	34.71
Radiant Temperature (°C)	31.93	31.22	30.57	30.20	30.61	31.65	32.92	34.03	34.47	34.17	33.53
Operative Temperature (°C)	32.72	32.14	31.57	31.11	31.28	31.98	33.05	34.02	34.51	34.49	34.12
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.34	19.79	20.32	20.90	20.98	20.56	19.59	18.70	18.22	18.05	18.20
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 12. BS12 simulation charts

APPENDIX-1. (continue) Simulation results charts

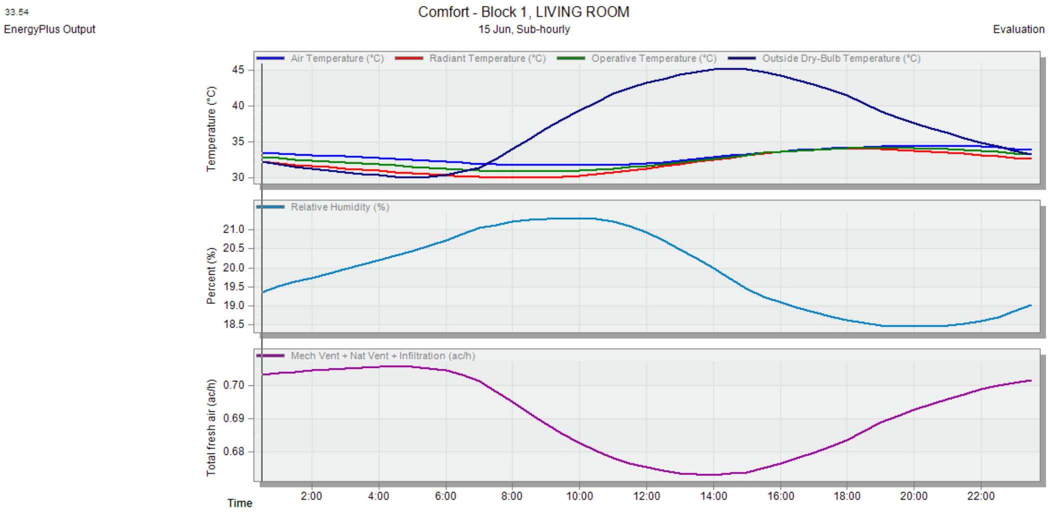
8.6.14 BS13/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (4*6) WL (c) WD (a)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.51	33.07	32.57	32.01	31.96	32.32	33.17	34.02	34.56	34.80	34.71
Radiant Temperature (°C)	31.93	31.22	30.57	30.20	30.61	31.65	32.92	34.03	34.47	34.17	33.53
Operative Temperature (°C)	32.72	32.14	31.57	31.11	31.28	31.98	33.05	34.02	34.51	34.49	34.12
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.34	19.79	20.32	20.90	20.98	20.56	19.59	18.70	18.22	18.05	18.20
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 13. BS13 simulation charts

BS14/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (4*6) WL (a) WD (b)

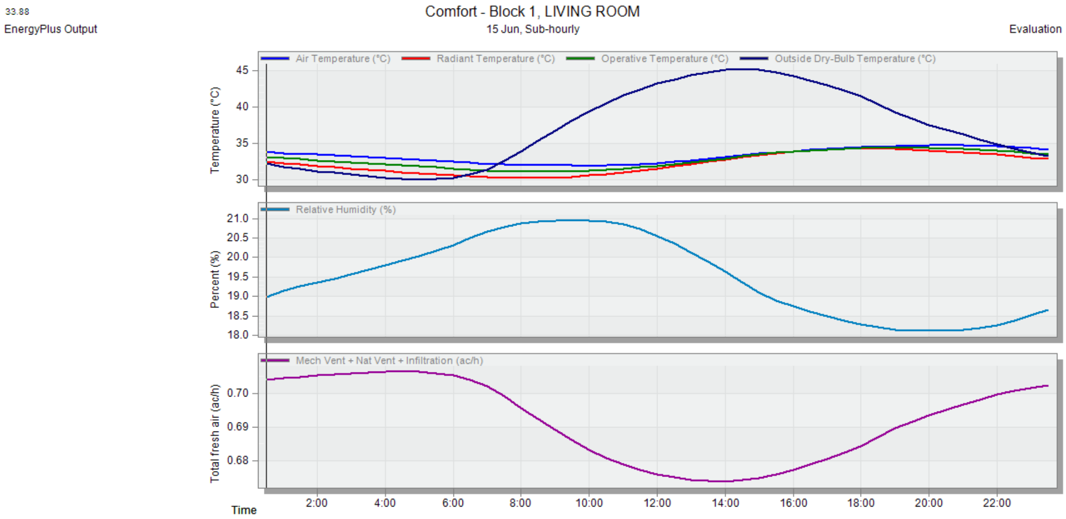


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.15	32.72	32.24	31.78	31.69	32.01	32.83	33.65	34.17	34.41	34.34
Radiant Temperature (°C)	31.62	30.93	30.31	29.94	30.30	31.28	32.50	33.57	34.02	33.76	33.16
Operative Temperature (°C)	32.39	31.83	31.27	30.86	30.99	31.65	32.66	33.61	34.09	34.09	33.75
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.74	20.19	20.71	21.22	21.32	20.93	19.98	19.10	18.62	18.45	18.59
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.71	0.70	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 14. BS14 simulation charts

APPENDIX-1. (continue) Simulation results charts

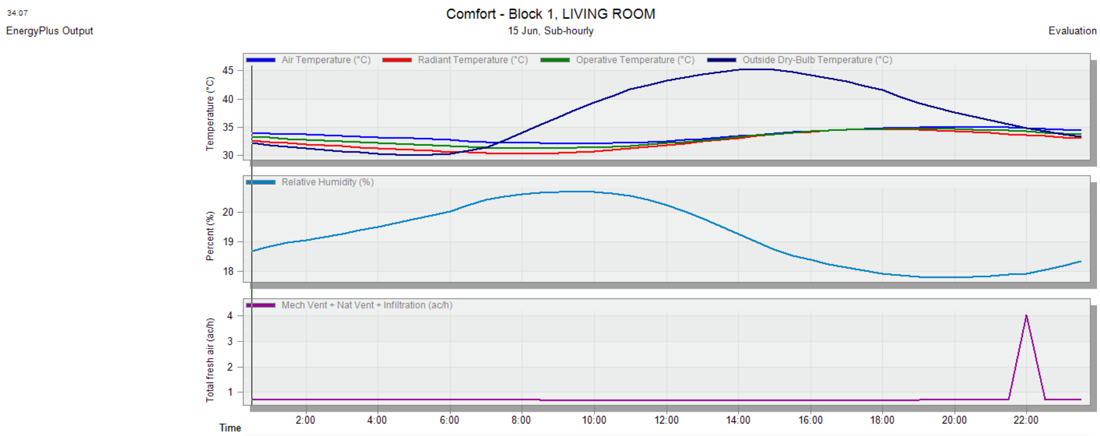
BS15/ DW (1.5*1.5) H (6) OD(S) NV (1) P (A) RD (4*6) WL (a) WD (c)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.49	33.06	32.58	32.03	31.98	32.31	33.14	33.97	34.49	34.74	34.66
Radiant Temperature (°C)	31.96	31.27	30.64	30.26	30.61	31.59	32.82	33.89	34.34	34.09	33.49
Operative Temperature (°C)	32.73	32.16	31.61	31.15	31.29	31.95	32.98	33.93	34.41	34.41	34.08
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.35	19.79	20.30	20.87	20.95	20.56	19.63	18.76	18.28	18.11	18.25
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 15. BS15 simulation charts

BS16/ DW (2*2) H (6) OD(S) NV (1) P (A) RD (4*6)

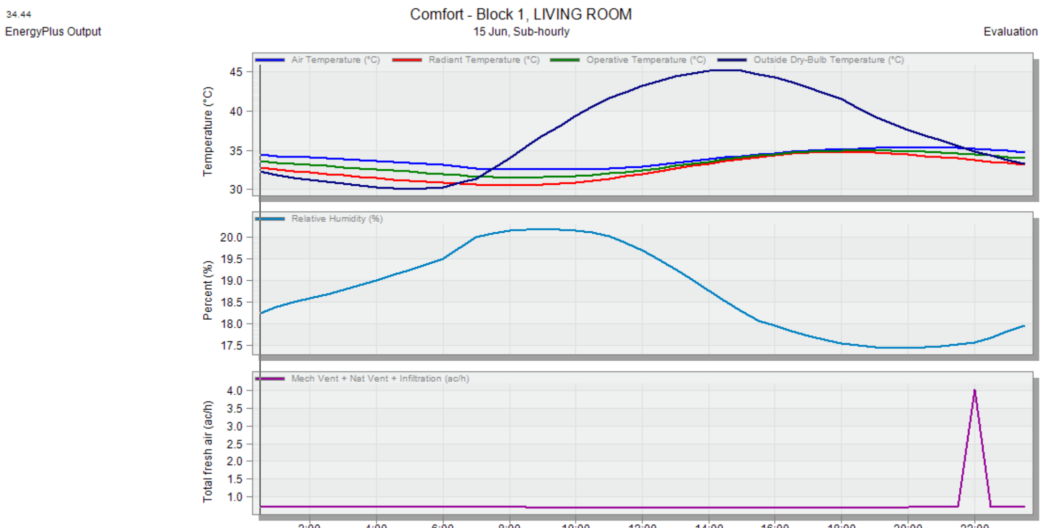


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.67	33.23	32.73	32.17	32.13	32.52	33.40	34.25	34.77	35.00	34.89
Radiant Temperature (°C)	31.98	31.26	30.62	30.28	30.73	31.81	33.10	34.20	34.60	34.27	33.62
Operative Temperature (°C)	32.83	32.24	31.67	31.22	31.43	32.16	33.25	34.23	34.69	34.64	34.25
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.06	19.51	20.03	20.62	20.68	20.23	19.26	18.39	17.93	17.79	17.92
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	4.03

Figure 16. BS16 simulation charts

APPENDIX-1. (continue) Simulation results charts

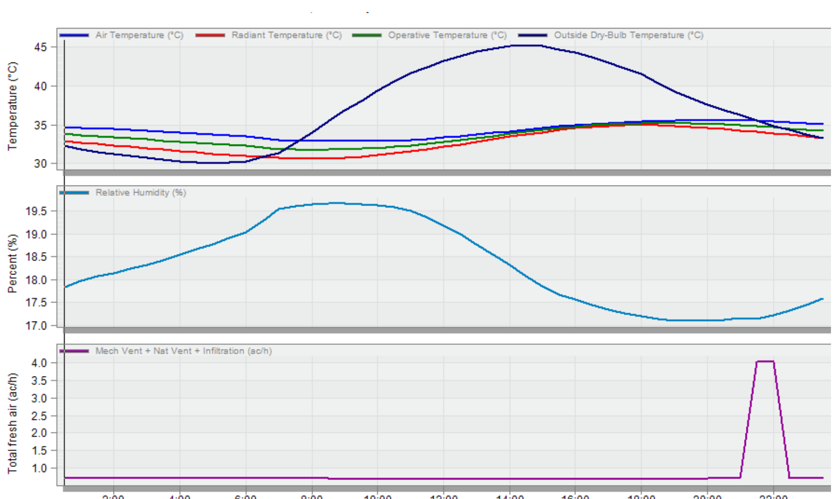
<u>BS17/ DW (2.2) H (8) OD(S) NV (1) P (A) RD (4*6)</u>



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.07	33.65	33.16	32.53	32.54	32.95	33.81	34.63	35.11	35.32	35.20
Radiant Temperature (°C)	32.16	31.45	30.82	30.47	30.91	31.99	33.29	34.38	34.78	34.44	33.78
Operative Temperature (°C)	33.12	32.55	31.99	31.50	31.73	32.47	33.55	34.51	34.94	34.88	34.49
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.58	19.00	19.50	20.14	20.14	19.69	18.76	17.95	17.55	17.43	17.57
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.68	0.68	0.69	0.69	4.04

Figure 17. BS17 simulation charts

<u>BS18/ DW (2.2) H (10) OD(S) NV (1) P (A) RD (4*6)</u>

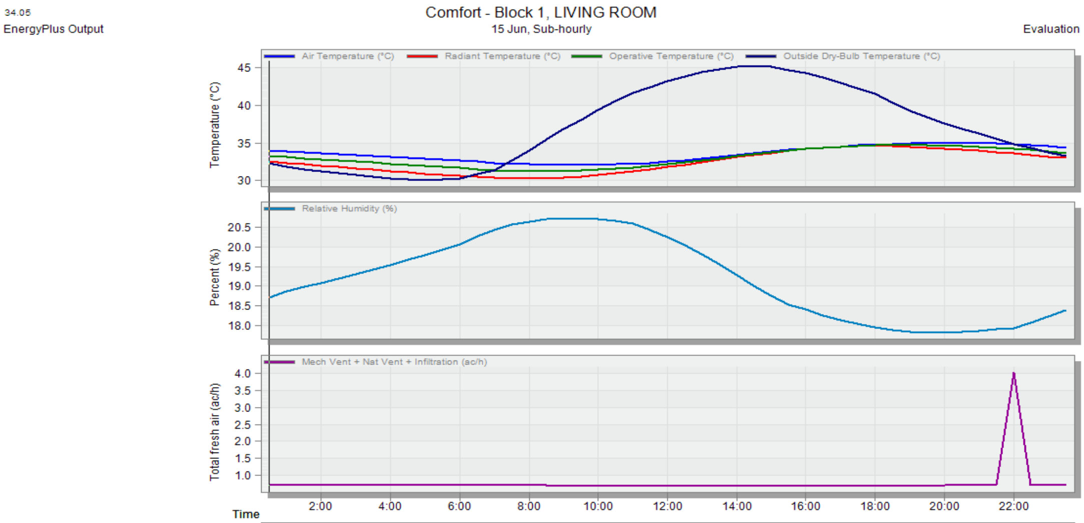


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.43	34.02	33.53	32.88	32.92	33.33	34.17	34.95	35.41	35.61	35.47
Radiant Temperature (°C)	32.32	31.61	30.99	30.64	31.08	32.16	33.46	34.54	34.92	34.59	33.93
Operative Temperature (°C)	33.37	32.82	32.26	31.76	32.00	32.75	33.81	34.75	35.17	35.10	34.70
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.14	18.54	19.02	19.65	19.63	19.18	18.31	17.56	17.19	17.09	17.22
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.69	0.68	0.68	0.68	0.69	0.70	4.04

Figure 18. BS18 simulation charts

APPENDIX-1. (continue) Simulation results charts

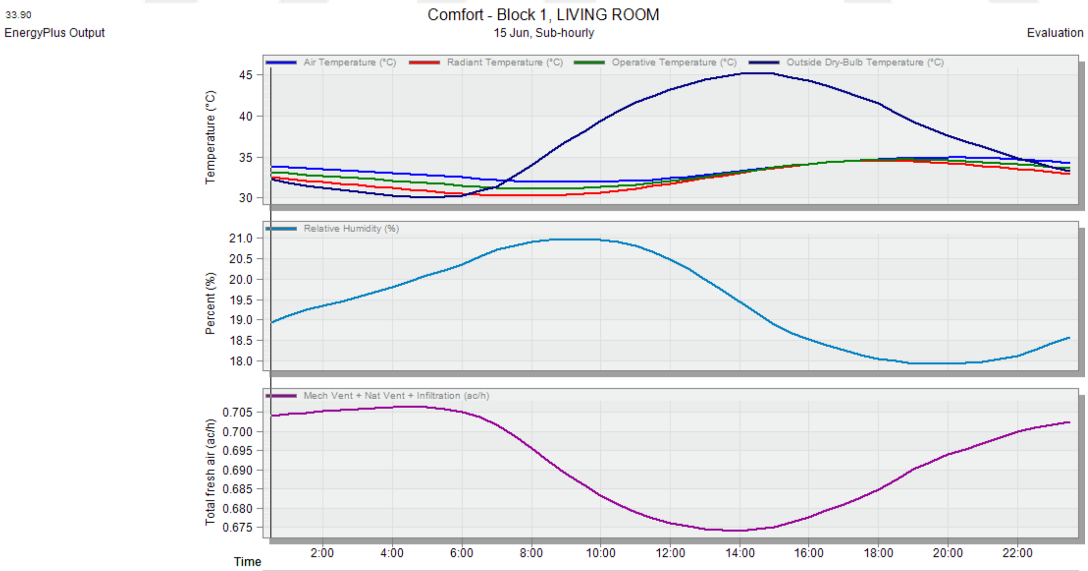
<u>BS19/ DW (2.2) H (6) OD(S-N) NV (1) P (A) RD (4*6)</u>



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.65	33.20	32.70	32.14	32.10	32.50	33.38	34.24	34.76	34.99	34.87
Radiant Temperature (°C)	31.97	31.25	30.61	30.27	30.72	31.80	33.10	34.19	34.60	34.27	33.61
Operative Temperature (°C)	32.81	32.22	31.65	31.21	31.41	32.15	33.24	34.22	34.68	34.63	34.24
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.08	19.54	20.07	20.65	20.71	20.26	19.28	18.40	17.94	17.80	17.93
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	4.03

Figure 19. BS19 simulation charts

<u>BS20/ DW (2.2) H (6) OD (S-N-E-W) NV (1) P (A) RD (4*6)</u>

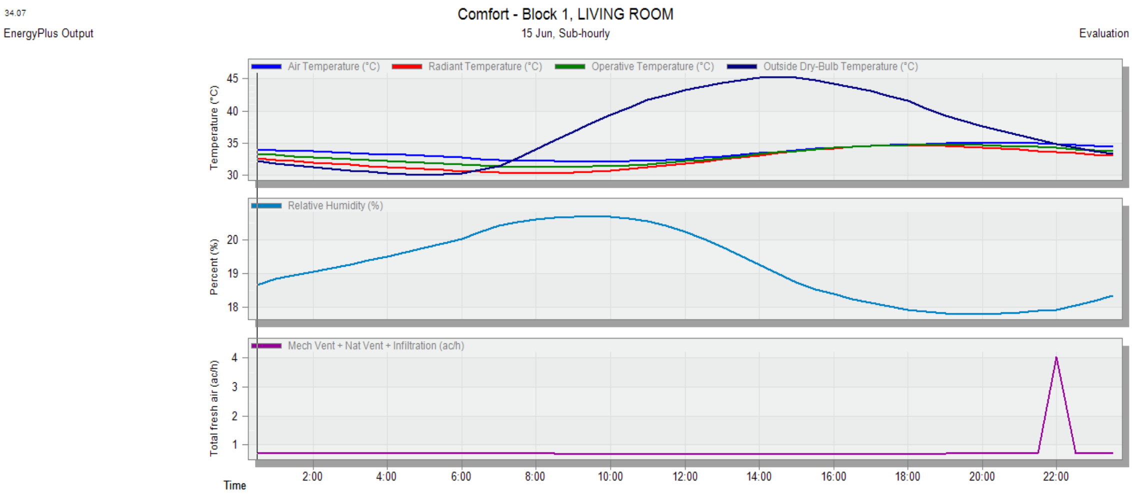


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.48	33.02	32.51	31.98	31.96	32.37	33.27	34.16	34.69	34.91	34.77
Radiant Temperature (°C)	31.91	31.18	30.54	30.20	30.65	31.74	33.04	34.15	34.55	34.23	33.56
Operative Temperature (°C)	32.70	32.10	31.52	31.09	31.31	32.05	33.16	34.15	34.62	34.57	34.17
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.34	19.81	20.36	20.91	20.95	20.47	19.45	18.53	18.05	17.92	18.12
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 20. BS20 simulation charts

APPENDIX-1. (continue) Simulation results charts

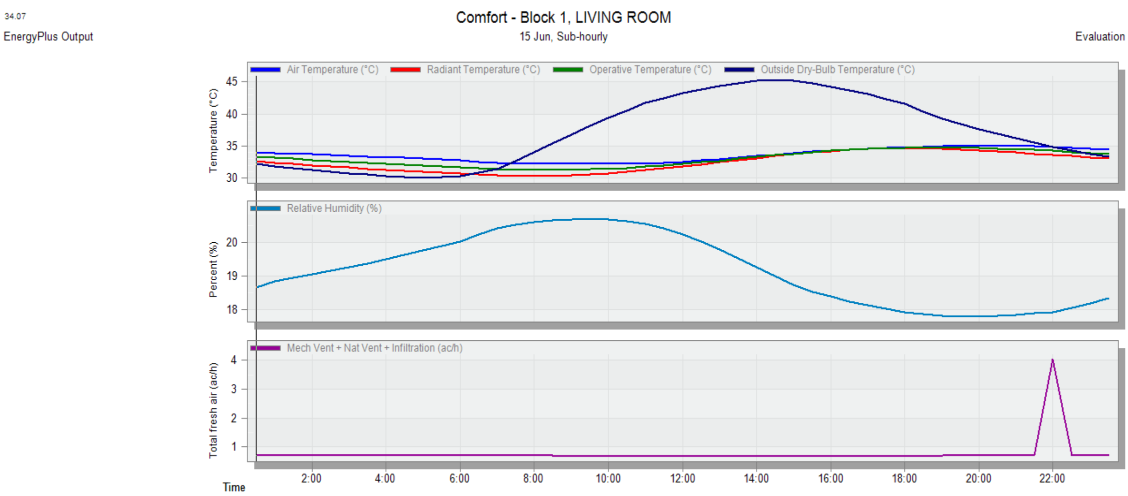
<u>BS21/ DW (2.2) H (6) OD(S) NV (1) P (A) RD (4*6)</u>



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.68	33.23	32.73	32.17	32.13	32.52	33.39	34.24	34.76	34.99	34.88
Radiant Temperature (°C)	31.98	31.26	30.62	30.28	30.73	31.81	33.10	34.20	34.60	34.27	33.61
Operative Temperature (°C)	32.83	32.25	31.68	31.23	31.43	32.16	33.25	34.22	34.68	34.63	34.25
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.05	19.50	20.03	20.61	20.67	20.23	19.27	18.40	17.94	17.80	17.92
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	4.03

Figure 21. BS21 simulation charts

<u>BS22/ DW (2.2) H (6) OD(S) NV (3) P (A) RD (4*6)</u>

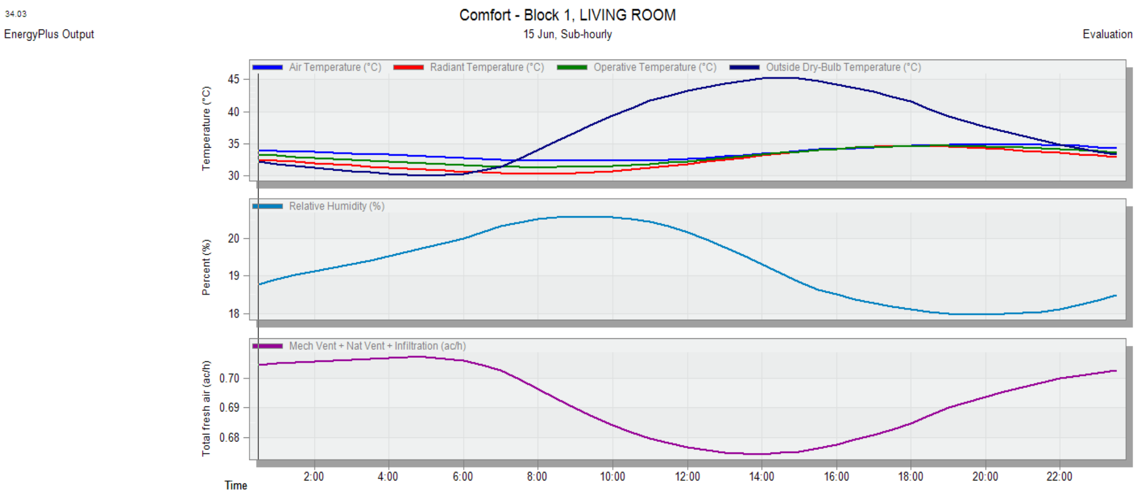


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.68	33.24	32.74	32.18	32.14	32.53	33.40	34.25	34.76	34.99	34.89
Radiant Temperature (°C)	31.98	31.26	30.62	30.29	30.73	31.81	33.11	34.20	34.60	34.28	33.62
Operative Temperature (°C)	32.83	32.25	31.68	31.23	31.44	32.17	33.25	34.23	34.68	34.64	34.25
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.05	19.49	20.02	20.60	20.66	20.23	19.26	18.39	17.94	17.79	17.92
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	4.03

Figure 22. BS22 simulation charts

APPENDIX-1. (continue) Simulation results charts

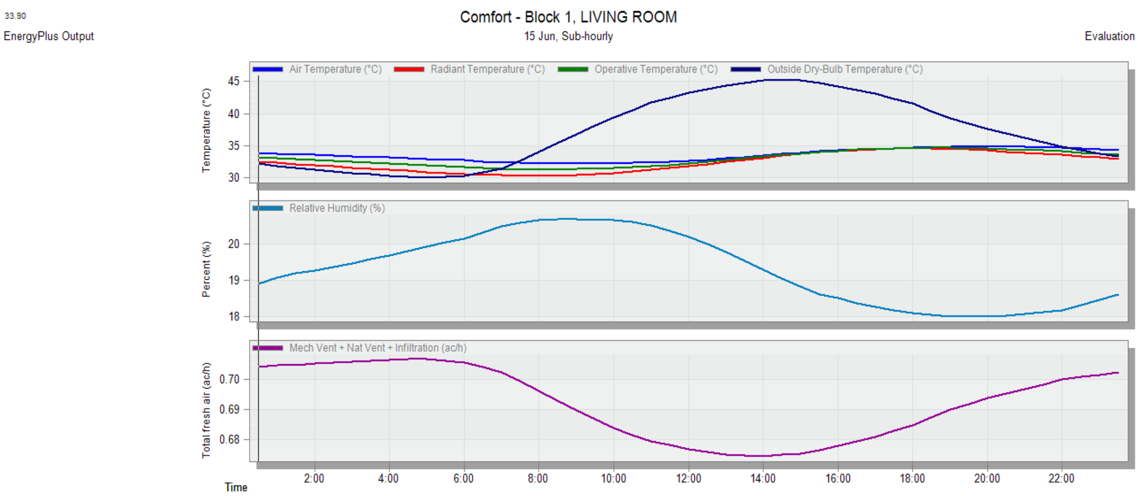
<u>BS23/ DW (2.2) H (6) OD(S) NV (3) P (B) RD (4*6)</u>



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.68	33.28	32.83	32.32	32.30	32.64	33.42	34.19	34.65	34.86	34.76
Radiant Temperature (°C)	31.96	31.24	30.62	30.30	30.75	31.83	33.12	34.20	34.59	34.25	33.58
Operative Temperature (°C)	32.82	32.26	31.73	31.31	31.52	32.23	33.27	34.20	34.62	34.55	34.17
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.12	19.53	20.00	20.53	20.57	20.18	19.31	18.52	18.10	17.96	18.10
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 23. BS23 simulation charts

<u>BS24/ DW (2.2) H (6) OD(S) NV (3) P(C) RD (4*6)</u>

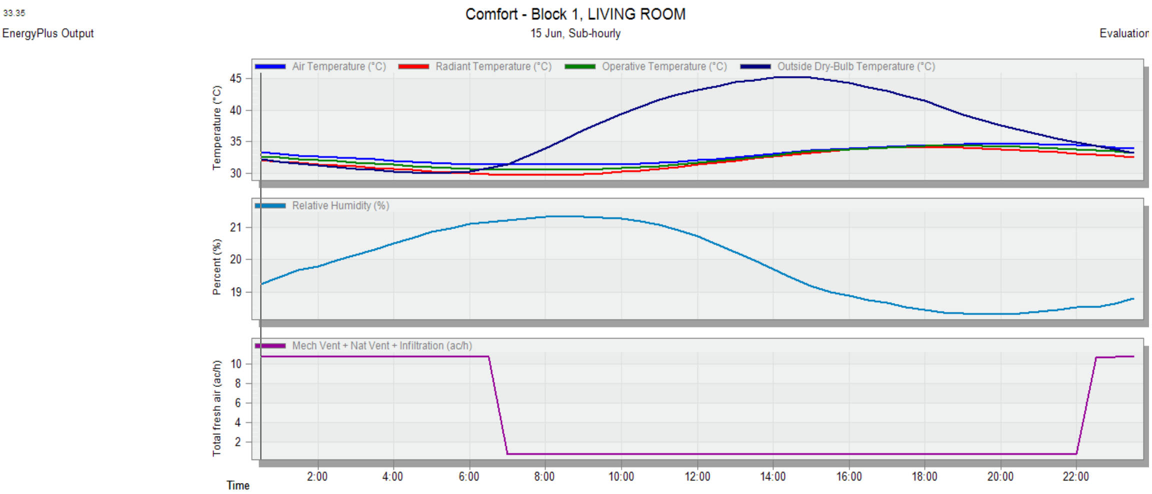


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.54	33.15	32.71	32.24	32.25	32.64	33.44	34.22	34.66	34.83	34.69
Radiant Temperature (°C)	31.92	31.21	30.59	30.27	30.73	31.81	33.10	34.18	34.57	34.23	33.56
Operative Temperature (°C)	32.73	32.18	31.65	31.26	31.49	32.22	33.27	34.20	34.62	34.53	34.12
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.27	19.68	20.14	20.63	20.64	20.19	19.30	18.51	18.11	18.01	18.19
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 24. BS24 simulation charts

APPENDIX-1. (continue) Simulation results charts

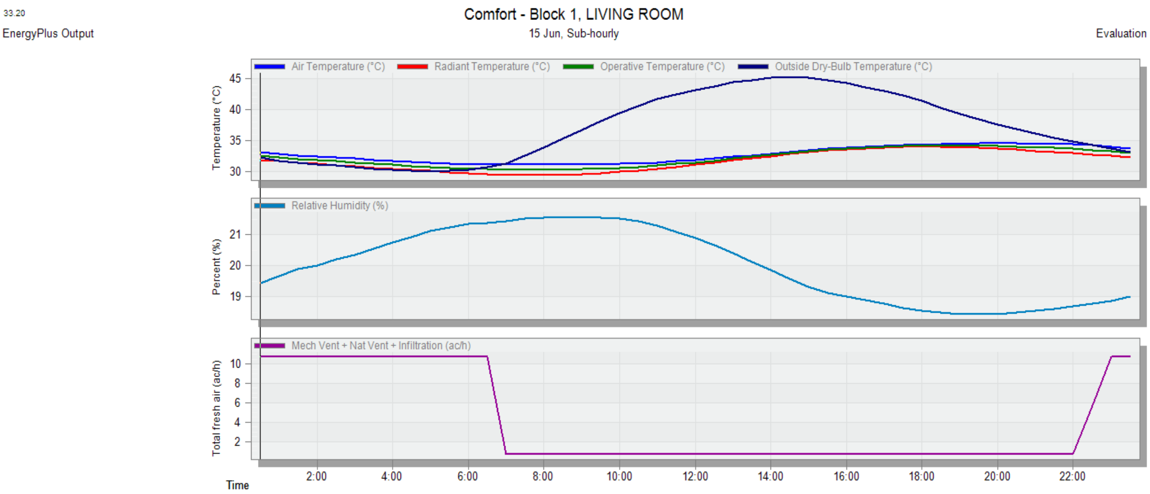
BS25/ DW (2.2) H (6) OD(S) NV (1) P (A) RD (5*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.71	32.02	31.44	31.34	31.47	32.05	33.06	33.93	34.43	34.64	34.52
Radiant Temperature (°C)	31.48	30.71	30.03	29.72	30.22	31.36	32.70	33.77	34.18	33.84	33.16
Operative Temperature (°C)	32.09	31.36	30.74	30.53	30.84	31.70	32.88	33.85	34.30	34.24	33.84
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.80	20.50	21.11	21.32	21.27	20.71	19.70	18.88	18.44	18.31	18.51
Mech Vent + Nat Vent + Infiltration (ac/h)	10.75	10.76	10.74	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 25. BS25 simulation charts

BS26/ DW (2*2) H (6) OD (S) NV (1) P (A) RD (6*6)

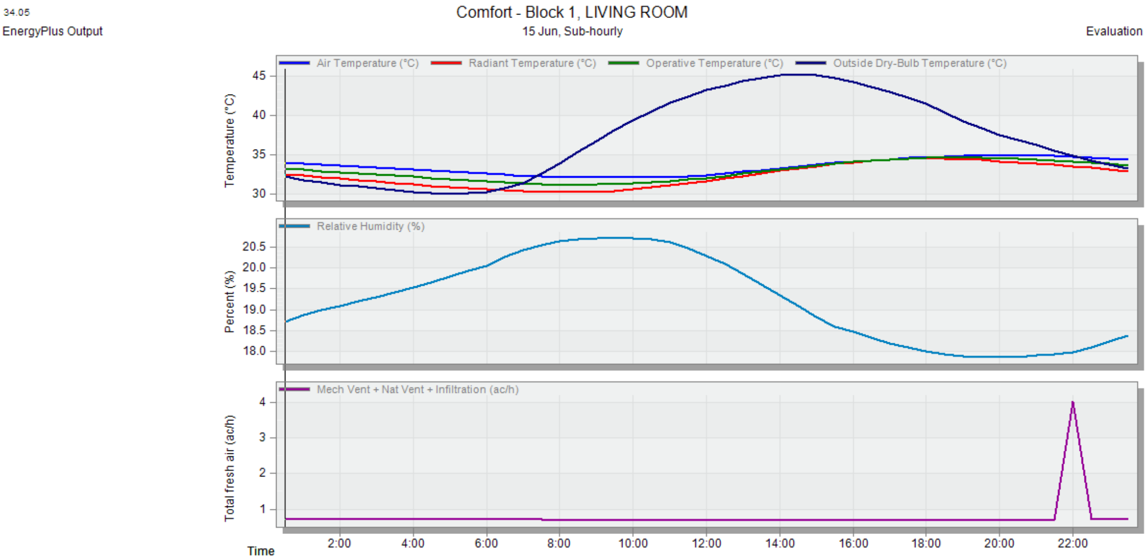


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.52	31.80	31.23	31.14	31.28	31.93	32.98	33.88	34.39	34.58	34.42
Radiant Temperature (°C)	31.29	30.50	29.80	29.48	29.99	31.16	32.54	33.64	34.06	33.72	33.02
Operative Temperature (°C)	31.90	31.15	30.51	30.31	30.64	31.54	32.76	33.76	34.23	34.15	33.72
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	20.02	20.74	21.35	21.56	21.51	20.90	19.86	19.02	18.57	18.46	18.71
Mech Vent + Nat Vent + Infiltration (ac/h)	10.75	10.75	10.73	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 26. BS26 simulation charts

APPENDIX-1. (continue) Simulation results charts

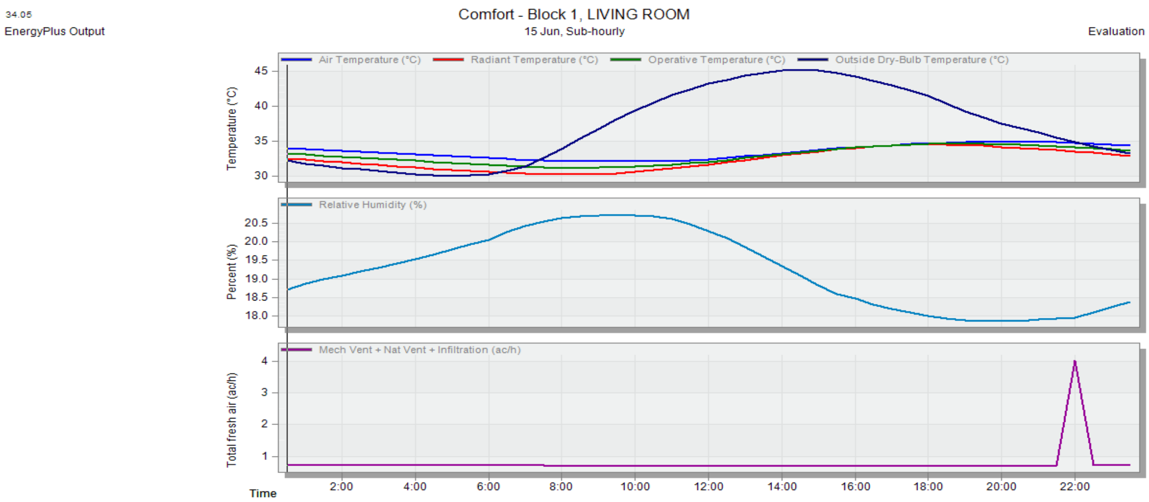
BS27/ DW (2*2) H (6) OD(S) NV (1) P (A) RD (4*6) WL (b) WD (a)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.66	33.23	32.73	32.16	32.11	32.48	33.34	34.19	34.71	34.95	34.85
Radiant Temperature (°C)	31.99	31.28	30.63	30.26	30.66	31.71	32.99	34.09	34.53	34.23	33.59
Operative Temperature (°C)	32.83	32.25	31.68	31.21	31.39	32.10	33.16	34.14	34.62	34.59	34.22
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.09	19.53	20.05	20.64	20.72	20.29	19.34	18.47	18.01	17.85	17.97
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	4.03

Figure 27. BS27 simulation charts

BS28/ DW (2*2) H (6) OD(S) NV (1) P (A) RD (4*6) WL (c) WD (a)

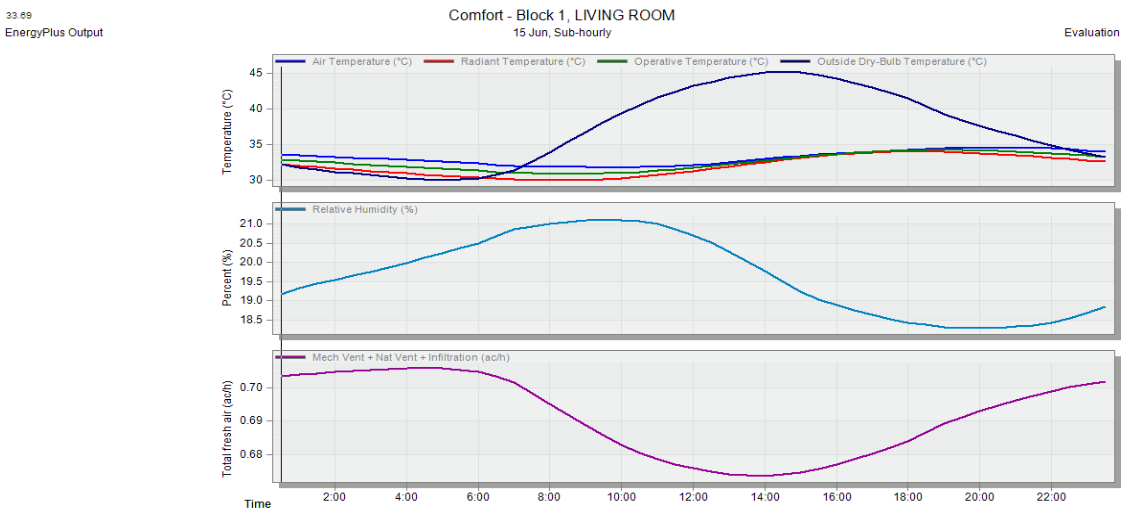


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.66	33.23	32.73	32.16	32.11	32.48	33.34	34.19	34.71	34.95	34.85
Radiant Temperature (°C)	31.99	31.28	30.64	30.26	30.67	31.71	32.99	34.09	34.53	34.23	33.59
Operative Temperature (°C)	32.83	32.25	31.68	31.21	31.39	32.10	33.16	34.14	34.62	34.59	34.22
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.09	19.53	20.05	20.64	20.71	20.29	19.34	18.47	18.00	17.85	17.96
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	4.03

Figure 28. BS28 simulation charts

APPENDIX-1. (continue) Simulation results charts

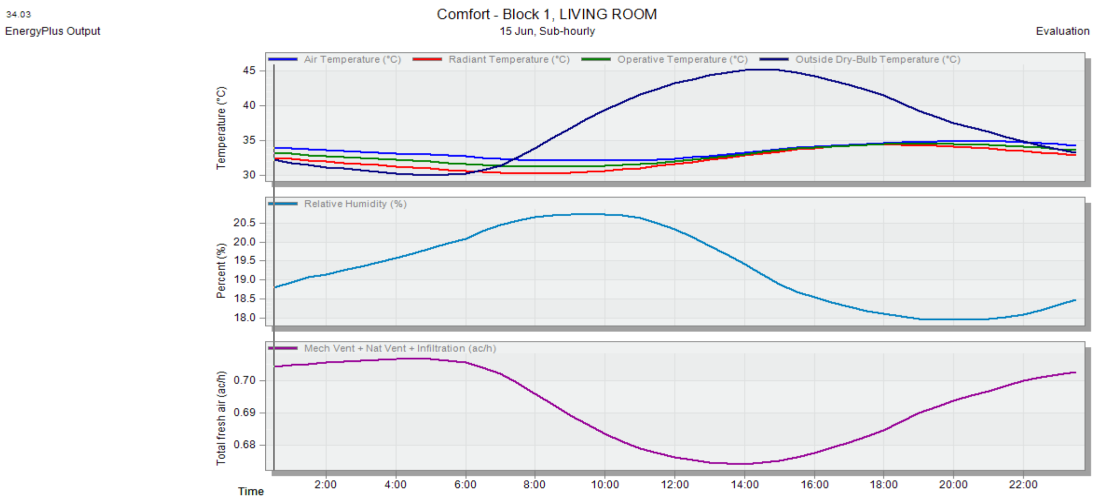
BS29/ DW (2*2) H (6) OD(S) NV (1) P (A) RD (4*6) WL (a) WD (b)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.30	32.87	32.39	31.92	31.84	32.17	32.99	33.81	34.32	34.56	34.48
Radiant Temperature (°C)	31.68	30.99	30.37	30.00	30.36	31.34	32.57	33.64	34.08	33.82	33.22
Operative Temperature (°C)	32.49	31.93	31.38	30.96	31.10	31.76	32.78	33.73	34.20	34.19	33.85
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.54	19.99	20.51	21.02	21.11	20.71	19.77	18.90	18.43	18.27	18.42
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.71	0.70	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 29. BS29 simulation charts

BS30/ DW (2*2) H (6) OD(S) NV (1) P (A) RD (4*6) WL (a) WD (c)

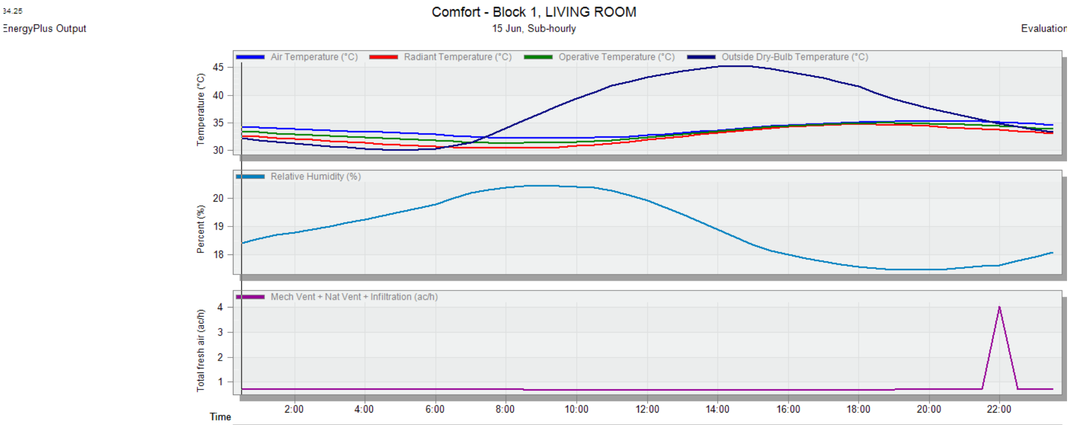


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.65	33.23	32.74	32.18	32.13	32.48	33.31	34.13	34.65	34.89	34.80
Radiant Temperature (°C)	32.02	31.33	30.70	30.32	30.67	31.66	32.89	33.96	34.40	34.15	33.55
Operative Temperature (°C)	32.83	32.28	31.72	31.25	31.40	32.07	33.10	34.05	34.52	34.52	34.18
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.15	19.58	20.09	20.66	20.73	20.33	19.40	18.55	18.09	17.93	18.08
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 30. BS30 simulation charts

APPENDIX-1. (continue) Simulation results charts

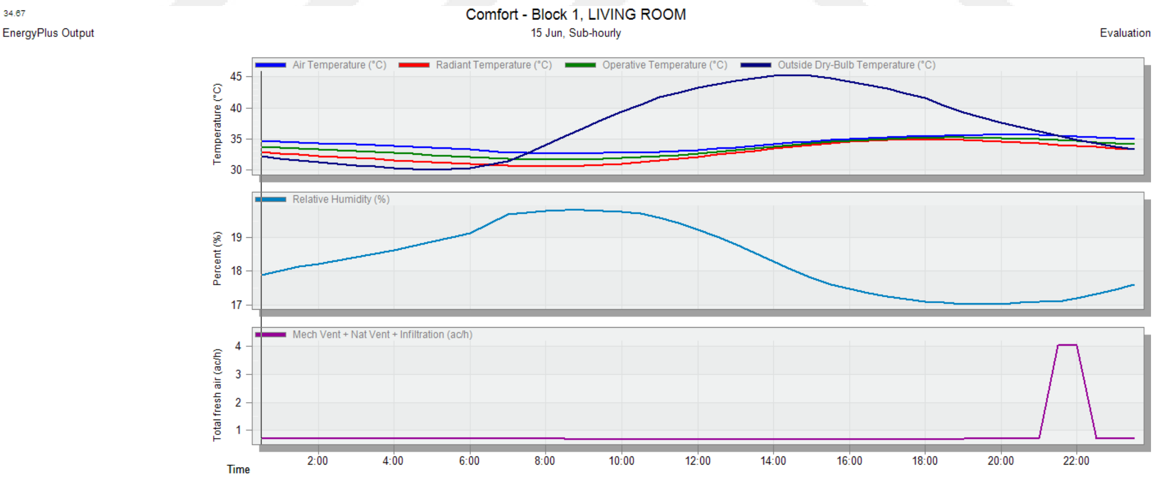
BS31/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (4*6)



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.84	33.38	32.86	32.27	32.27	32.72	33.65	34.54	35.06	35.28	35.12
Radiant Temperature (°C)	32.06	31.33	30.69	30.35	30.79	31.87	33.18	34.29	34.69	34.36	33.70
Operative Temperature (°C)	32.95	32.36	31.78	31.31	31.53	32.30	33.42	34.42	34.88	34.82	34.41
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.79	19.25	19.80	20.40	20.43	19.92	18.90	18.01	17.56	17.46	17.63
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 31. BS32 simulation charts

BS32/DW(3*3)H(8)OD(S)NV(1)P(A)RD(4*6)

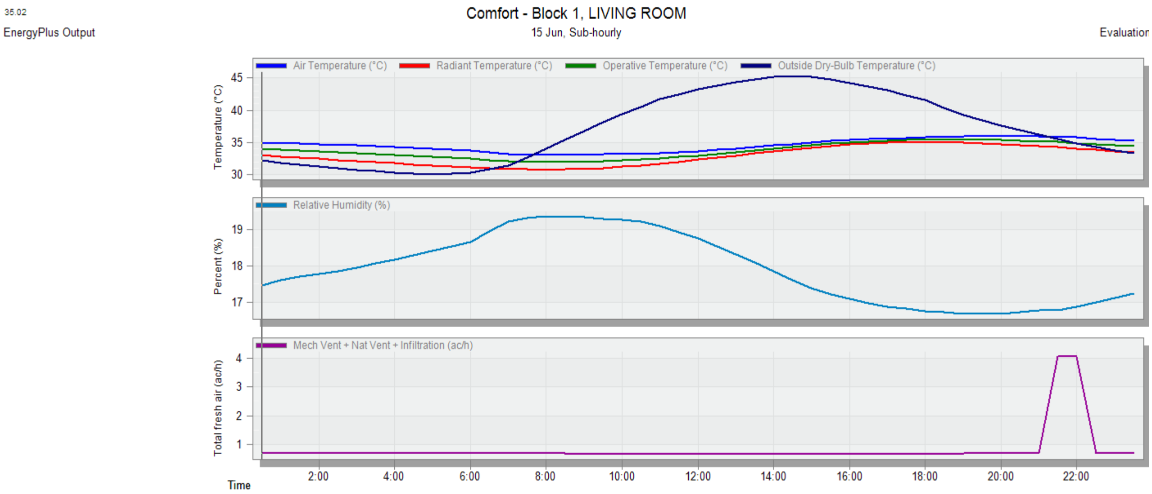


	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.30	33.86	33.35	32.67	32.73	33.21	34.13	34.97	35.45	35.64	35.45
Radiant Temperature (°C)	32.27	31.56	30.93	30.57	31.01	32.10	33.41	34.50	34.89	34.56	33.90
Operative Temperature (°C)	33.28	32.71	32.14	31.62	31.87	32.66	33.77	34.74	35.17	35.10	34.68
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.21	18.63	19.15	19.80	19.76	19.25	18.29	17.49	17.10	17.02	17.19
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.68	0.68	0.69	0.70	4.04

Figure 32. BS32 simulation charts

APPENDIX-1. (continue) Simulation results charts

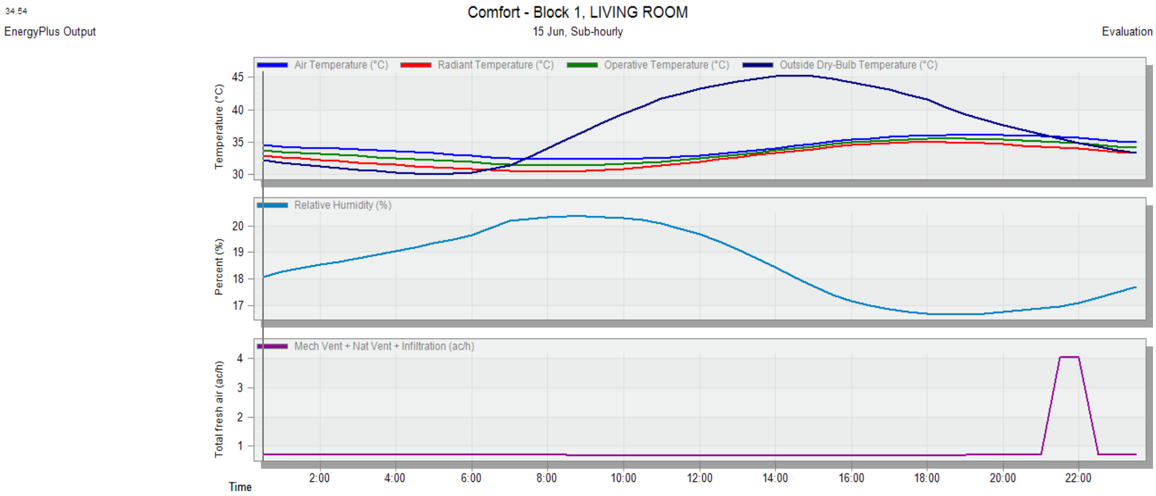
BS33/ DW (3*3) H (10) OD(S) NV (1) P (A) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.69	34.27	33.76	33.03	33.14	33.63	34.52	35.32	35.78	35.95	35.74
Radiant Temperature (°C)	32.44	31.74	31.12	30.75	31.19	32.28	33.59	34.68	35.06	34.72	34.06
Operative Temperature (°C)	33.57	33.00	32.44	31.89	32.16	32.96	34.06	35.00	35.42	35.34	34.90
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	17.77	18.17	18.66	19.36	19.26	18.75	17.84	17.10	16.75	16.69	16.88
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.69	0.68	0.68	0.68	0.69	0.70	4.05

Figure 33. BS233 simulation charts

BS34/ DW (3*3) H (6) OD(S-N) NV (1) P (A) RD (4*6)

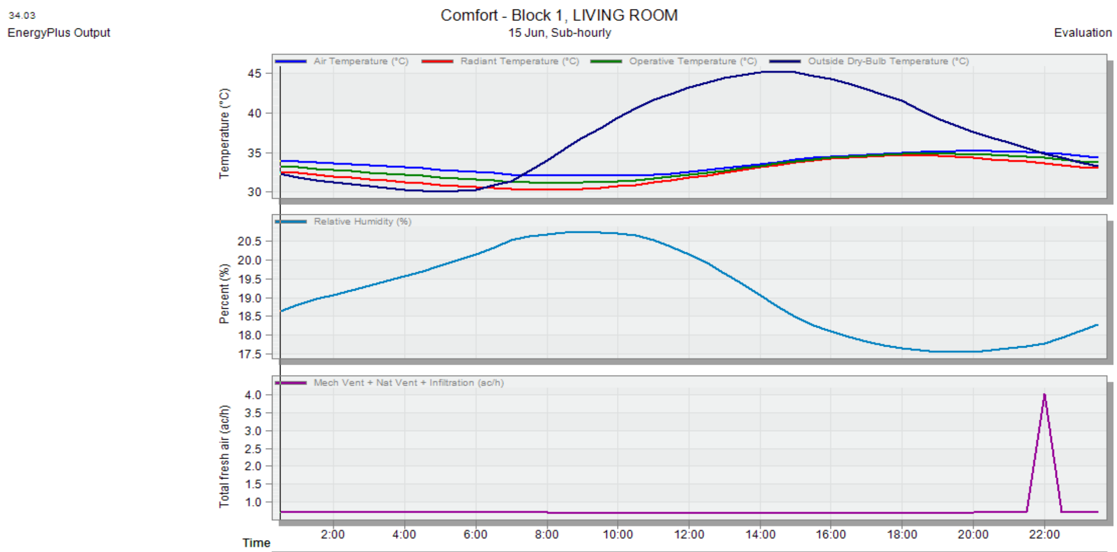


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.06	33.54	32.96	32.30	32.36	32.91	34.07	35.40	35.99	36.01	35.62
Radiant Temperature (°C)	32.24	31.49	30.82	30.45	30.89	31.98	33.31	34.50	34.96	34.64	33.96
Operative Temperature (°C)	33.15	32.51	31.89	31.38	31.62	32.44	33.69	34.95	35.48	35.33	34.79
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.53	19.05	19.65	20.32	20.29	19.67	18.43	17.16	16.68	16.76	17.11
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.68	0.68	0.69	0.70	4.04

Figure 34. BS34 simulation charts

APPENDIX-1. (continue) Simulation results charts

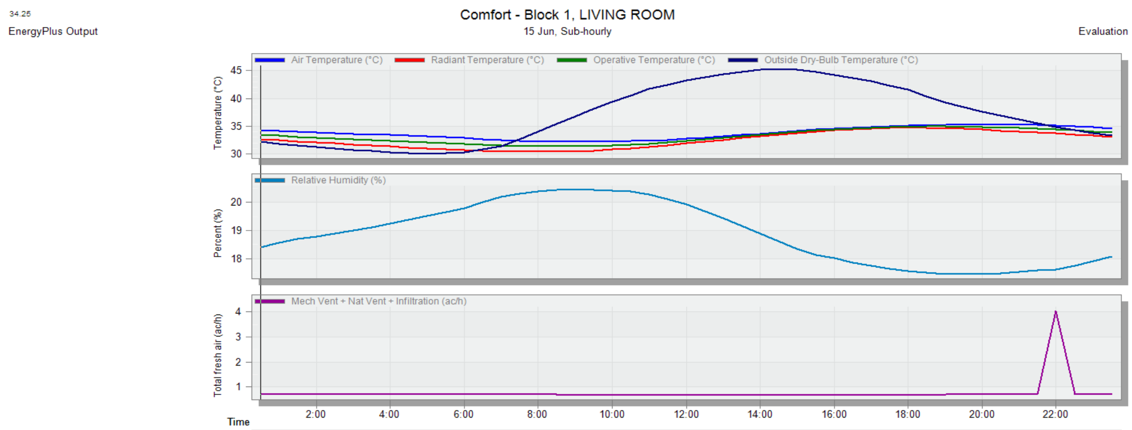
BS35/ DW (3*3) H (6) OD(S-N-E-W) NV (1) P (A) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.59	33.10	32.57	32.04	32.04	32.52	33.51	34.44	34.98	35.17	34.98
Radiant Temperature (°C)	31.97	31.24	30.59	30.24	30.70	31.78	33.10	34.22	34.63	34.30	33.64
Operative Temperature (°C)	32.78	32.17	31.58	31.14	31.37	32.15	33.30	34.33	34.81	34.74	34.31
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.07	19.56	20.13	20.68	20.69	20.14	19.06	18.12	17.65	17.56	17.78
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 35. BS35 simulation charts

BS36/ DW (3*3) H (6) OD(S) NV (3) P (A) RD (4*6)

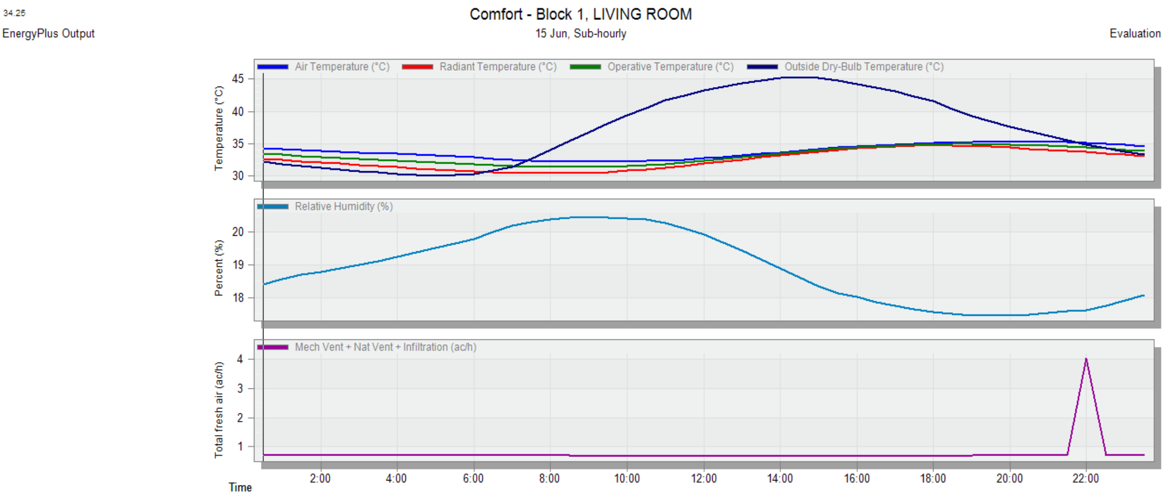


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.85	33.39	32.87	32.28	32.27	32.72	33.66	34.54	35.06	35.28	35.12
Radiant Temperature (°C)	32.06	31.33	30.70	30.35	30.79	31.88	33.19	34.29	34.69	34.36	33.70
Operative Temperature (°C)	32.95	32.36	31.78	31.31	31.53	32.30	33.42	34.42	34.88	34.82	34.41
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.78	19.24	19.79	20.39	20.42	19.91	18.90	18.01	17.57	17.46	17.63
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 36. BS36 simulation charts

APPENDIX-1. (continue) Simulation results charts

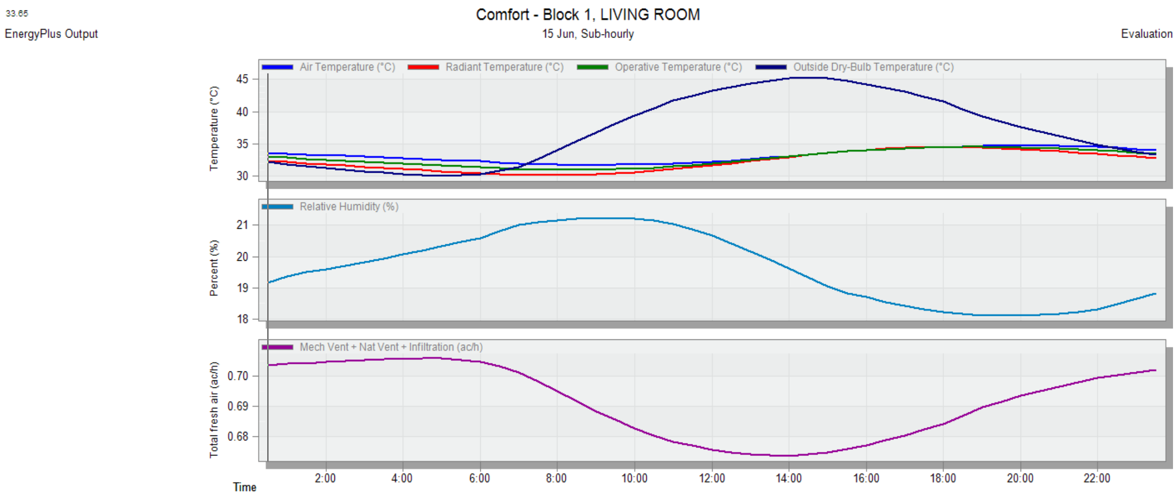
BS37/ DW (3*3) H (6) OD(S) NV (5) P (A) RD (4*6)



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.85	33.39	32.86	32.28	32.27	32.72	33.66	34.54	35.06	35.28	35.12
Radiant Temperature (°C)	32.06	31.33	30.69	30.35	30.79	31.88	33.18	34.29	34.69	34.36	33.70
Operative Temperature (°C)	32.95	32.36	31.78	31.31	31.53	32.30	33.42	34.42	34.88	34.82	34.41
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.79	19.25	19.79	20.39	20.42	19.92	18.90	18.01	17.56	17.46	17.63
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 37. BS37simulation charts

BS38/ DW (3*3) H (6) OD(S) NV (1) P (B) RD (4*6)

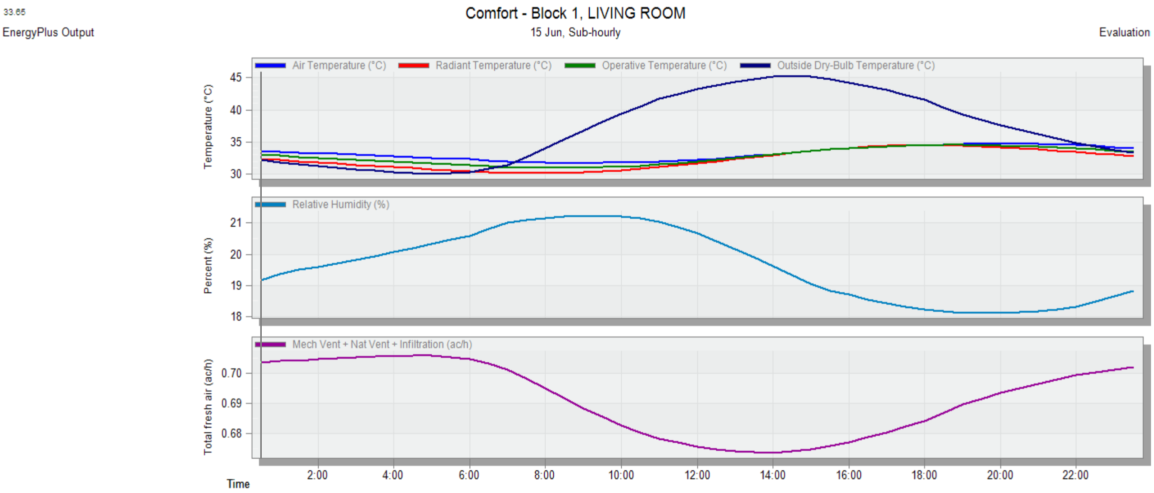


	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.24	32.78	32.30	31.75	31.73	32.18	33.11	33.98	34.49	34.70	34.55
Radiant Temperature (°C)	31.80	31.08	30.43	30.09	30.55	31.64	32.95	34.06	34.45	34.12	33.46
Operative Temperature (°C)	32.52	31.93	31.37	30.92	31.14	31.91	33.03	34.02	34.47	34.41	34.00
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.59	20.07	20.59	21.17	21.21	20.66	19.61	18.70	18.24	18.11	18.32
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.71	0.70	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 38. BS38 simulation charts

APPENDIX-1. (continue) Simulation results charts

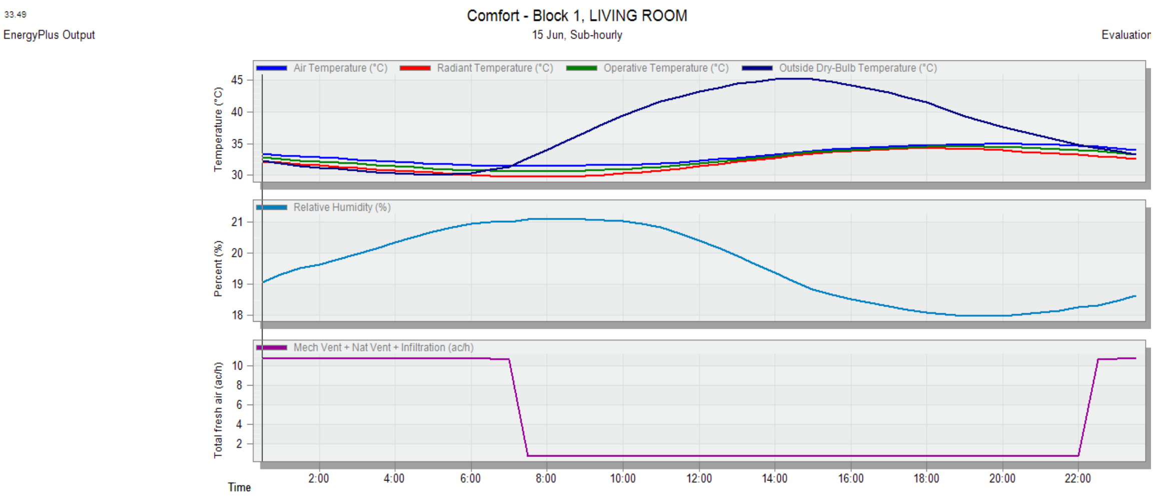
BS39/ DW (3*3) H (6) OD(S) NV (1) P(C) RD (4*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.24	32.78	32.30	31.75	31.73	32.18	33.11	33.98	34.49	34.70	34.55
Radiant Temperature (°C)	31.80	31.08	30.43	30.09	30.55	31.64	32.95	34.06	34.45	34.12	33.46
Operative Temperature (°C)	32.52	31.93	31.37	30.92	31.14	31.91	33.03	34.02	34.47	34.41	34.00
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.59	20.07	20.59	21.17	21.21	20.66	19.61	18.70	18.24	18.11	18.32
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.71	0.70	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 39. BS39 simulation charts

BS40/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (5*6)

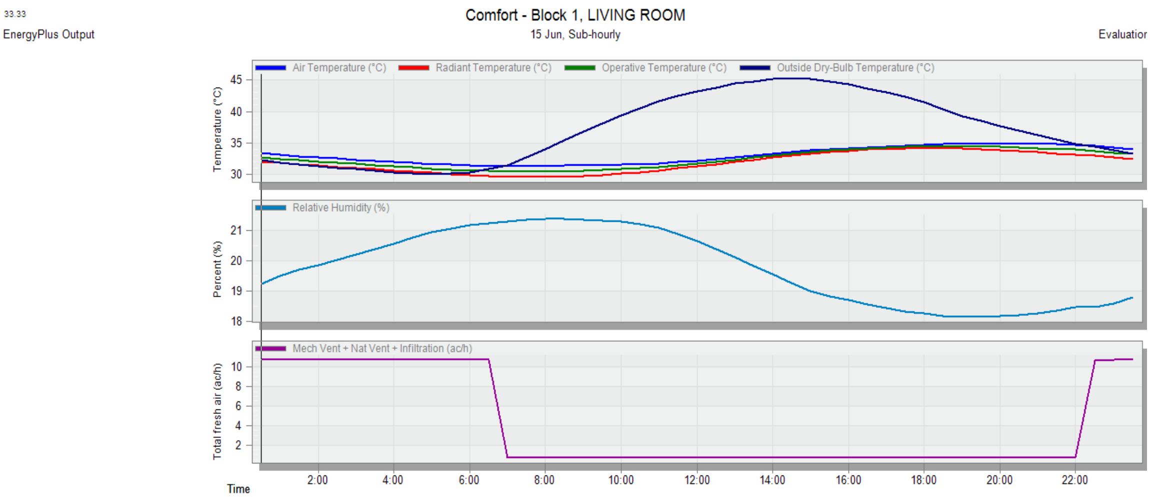


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.84	32.15	31.57	31.49	31.65	32.28	33.34	34.23	34.73	34.93	34.76
Radiant Temperature (°C)	31.55	30.78	30.09	29.78	30.29	31.43	32.79	33.86	34.27	33.93	33.26
Operative Temperature (°C)	32.20	31.46	30.83	30.64	30.97	31.86	33.07	34.05	34.50	34.43	34.01
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.64	20.34	20.94	21.11	21.03	20.41	19.36	18.53	18.10	17.99	18.25
Mech Vent + Nat Vent + Infiltration (ac/h)	10.76	10.76	10.74	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 40. BS340 simulation charts

APPENDIX-1. (continue) Simulation results charts

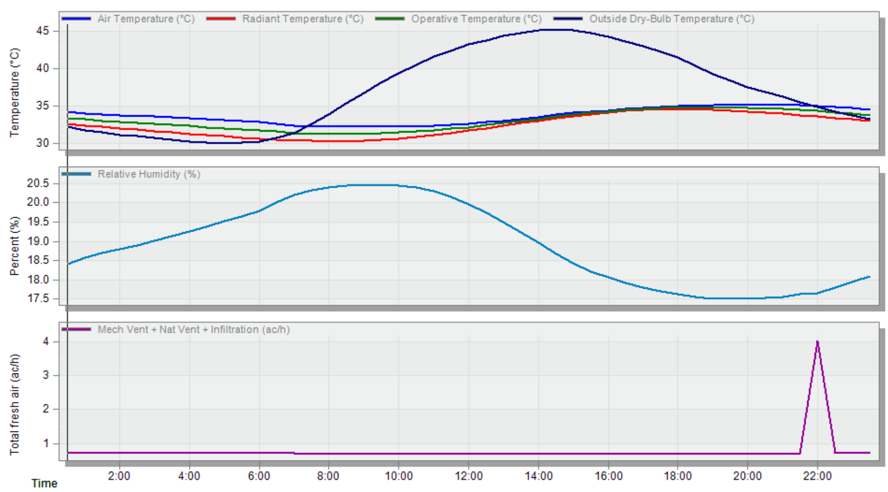
BS41/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (6*6)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.65	31.93	31.35	31.29	31.46	32.13	33.24	34.16	34.67	34.85	34.67
Radiant Temperature (°C)	31.35	30.55	29.85	29.53	30.05	31.22	32.62	33.73	34.15	33.80	33.11
Operative Temperature (°C)	32.00	31.24	30.60	30.41	30.76	31.68	32.93	33.94	34.41	34.33	33.89
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.83	20.57	21.18	21.37	21.28	20.63	19.55	18.69	18.25	18.16	18.45
Mech Vent + Nat Vent + Infiltration (ac/h)	10.75	10.76	10.74	0.69	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 41. BS41 simulation charts

BS42/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (4*6) WL (b) WD (a)

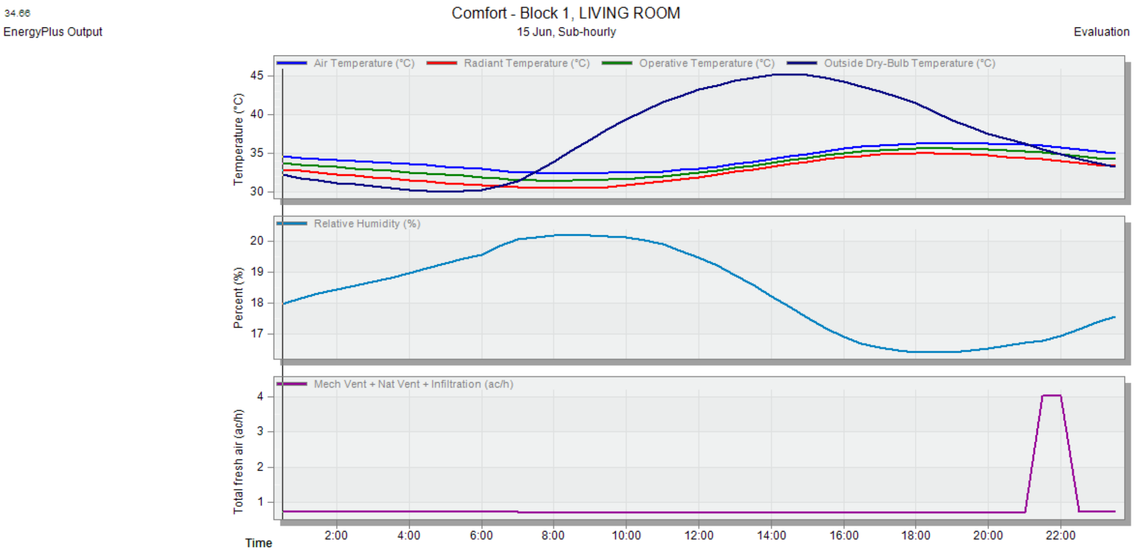


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.84	33.38	32.86	32.27	32.25	32.68	33.60	34.48	35.01	35.23	35.09
Radiant Temperature (°C)	32.07	31.35	30.71	30.33	30.73	31.78	33.07	34.18	34.62	34.32	33.68
Operative Temperature (°C)	32.95	32.37	31.79	31.30	31.49	32.23	33.34	34.33	34.81	34.78	34.39
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.80	19.25	19.79	20.40	20.44	19.96	18.95	18.07	17.62	17.50	17.66
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 42. BS42 simulation charts

APPENDIX-1. (continue) Simulation results charts

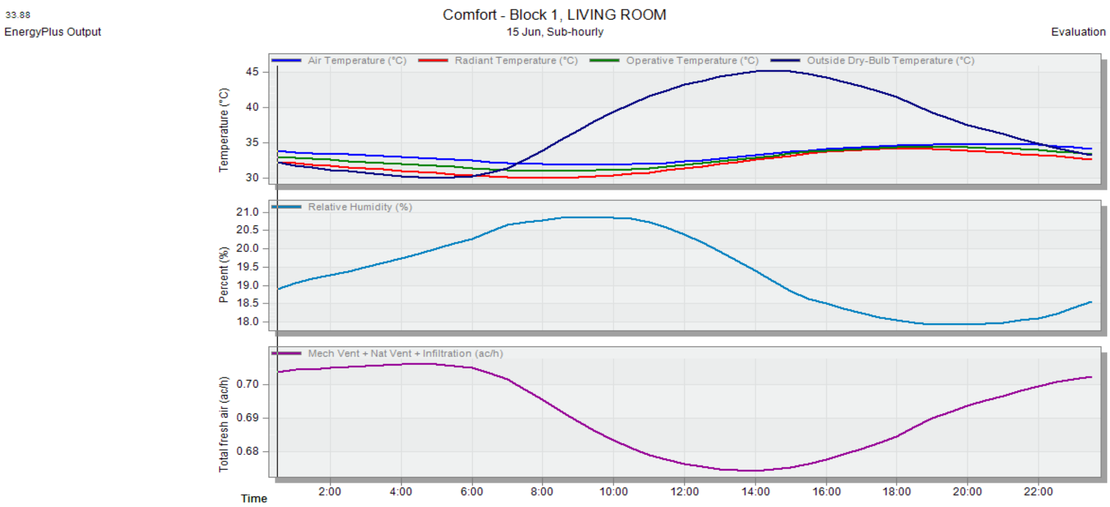
BS43/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (4*6) WL (c) WD (a)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	34.17	33.63	33.05	32.45	32.53	33.10	34.28	35.69	36.31	36.26	35.80
Radiant Temperature (°C)	32.33	31.58	30.91	30.50	30.90	31.97	33.30	34.50	35.02	34.73	34.06
Operative Temperature (°C)	33.25	32.61	31.98	31.47	31.72	32.54	33.79	35.09	35.67	35.50	34.93
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.43	18.96	19.56	20.17	20.10	19.46	18.23	16.90	16.40	16.54	16.96
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.68	0.68	0.69	0.70	4.05

Figure 43. BS43 simulation charts

BS44/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (4*6) WL (a) WD (b)

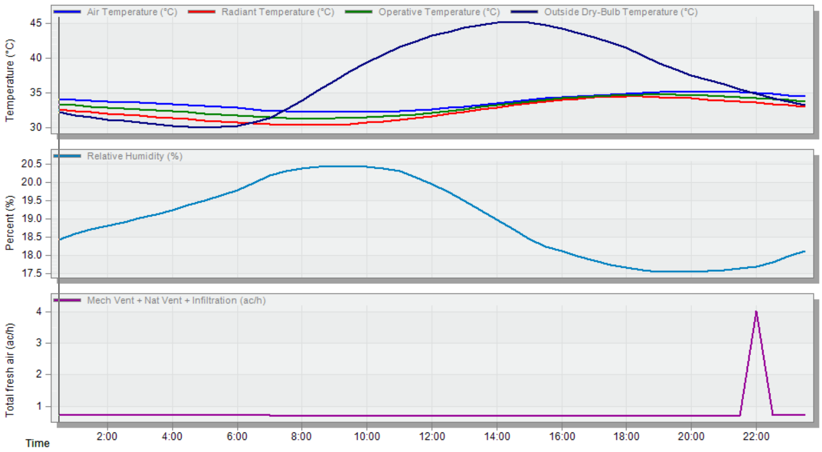


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.48	33.03	32.52	32.03	31.98	32.37	33.25	34.11	34.63	34.85	34.74
Radiant Temperature (°C)	31.77	31.08	30.45	30.07	30.42	31.41	32.65	33.73	34.17	33.91	33.32
Operative Temperature (°C)	32.62	32.05	31.48	31.05	31.20	31.89	32.95	33.92	34.40	34.38	34.03
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	19.28	19.73	20.27	20.78	20.85	20.39	19.39	18.50	18.04	17.92	18.11
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.68	0.69	0.70

Figure 44. BS44 simulation charts

APPENDIX-1. (continue) Simulation results charts

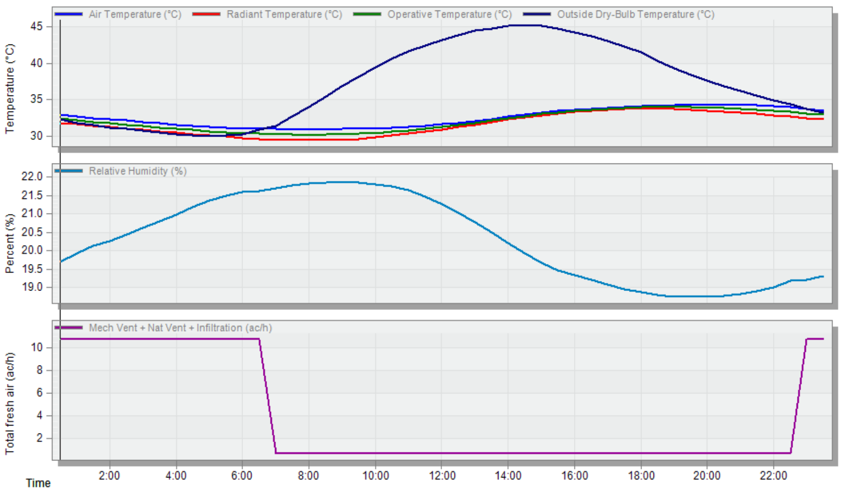
BS45/ DW (3*3) H (6) OD(S) NV (1) P (A) RD (4*6) WL (a) WD (c)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	33.83	33.38	32.87	32.29	32.27	32.68	33.57	34.43	34.95	35.18	35.05
Radiant Temperature (°C)	32.10	31.41	30.78	30.39	30.74	31.73	32.97	34.05	34.49	34.24	33.65
Operative Temperature (°C)	32.97	32.40	31.83	31.34	31.51	32.21	33.27	34.24	34.72	34.71	34.35
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	18.80	19.25	19.78	20.38	20.42	19.96	18.98	18.12	17.67	17.55	17.70
Mech Vent + Nat Vent + Infiltration (ac/h)	0.71	0.71	0.71	0.70	0.68	0.68	0.67	0.68	0.69	0.69	4.04

Figure 45. BS45 simulation charts

SBS1/ DW (1.5*1.5) H (6) OD(S-N-E-W) NV (1) P (A) RD (6*6) WL (B) WD (B)

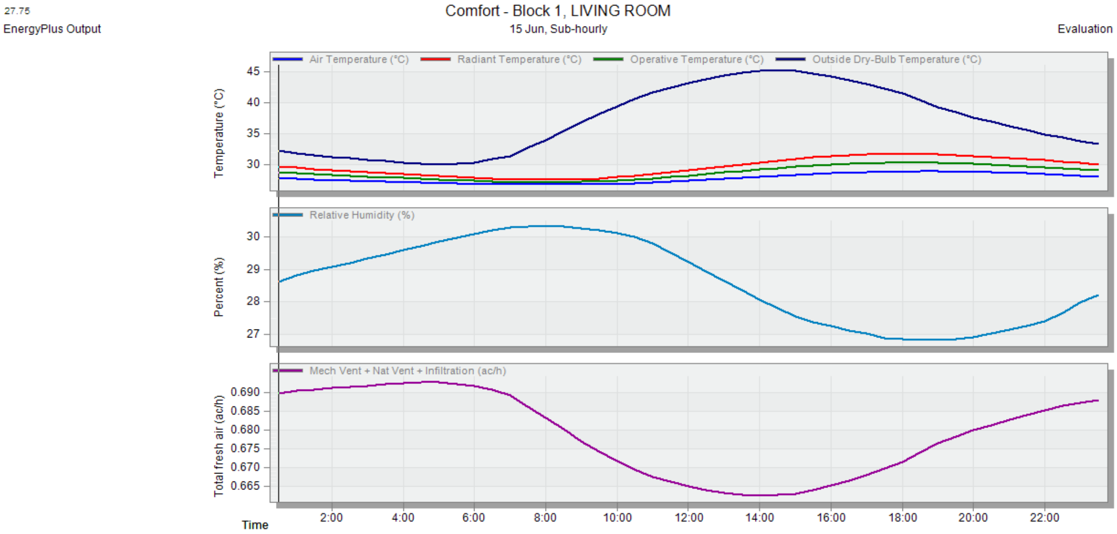


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	32.32	31.60	31.03	30.92	31.04	31.62	32.66	33.57	34.09	34.30	34.14
Radiant Temperature (°C)	31.24	30.48	29.78	29.42	29.85	30.94	32.26	33.34	33.81	33.53	32.89
Operative Temperature (°C)	31.78	31.04	30.41	30.17	30.44	31.28	32.46	33.46	33.95	33.91	33.51
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	20.27	21.00	21.60	21.84	21.82	21.26	20.22	19.35	18.87	18.75	19.01
Mech Vent + Nat Vent + Infiltration (ac/h)	10.74	10.75	10.73	0.69	0.68	0.67	0.67	0.68	0.68	0.69	0.70

Figure 46. SBS1 simulation charts

APPENDIX-1. (continue) Simulation results charts

SBS2/ DW (1.5*1.5) H (6) OD(S-N-E-W) NV (1) P (A) RD (6*6) WL (B) WD (B) + WATER SPRAY



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	27.47	27.16	26.86	26.73	26.86	27.36	28.06	28.57	28.83	28.79	28.50
Radiant Temperature (°C)	29.08	28.40	27.80	27.49	27.96	29.06	30.35	31.35	31.74	31.39	30.68
Operative Temperature (°C)	28.28	27.78	27.33	27.11	27.41	28.21	29.21	29.96	30.29	30.09	29.59
Outside Dry-Bulb Temperature (°C)	31.22	30.30	30.30	33.95	39.42	43.22	45.20	44.29	41.55	37.60	34.86
Relative Humidity (%)	29.06	29.59	30.08	30.32	30.12	29.23	28.07	27.25	26.86	26.93	27.42
Mech Vent + Nat Vent + Infiltration (ac/h)	0.69	0.69	0.69	0.68	0.67	0.67	0.66	0.67	0.67	0.68	0.69

Figure 47. SBS2 simulation charts

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