Sudan University of Science and technology
College of Graduate Studies

Integration of intelligent building envelope techniques as a system to Improve Thermal Performance of Multi-story Buildings in the Hot Dry Climate of Khartoum (By Using Simulation Software)

تكامل تقنيات غلاف المبني الذكي كمنظومة لتحسين الأداء الحراري للمباني متعددة الطوابق في مناخ الخرطوم الحار الجاف (دراسة تطبيقية بالإستعانة ببرامج محاكاة الطاقة الحاسوبية)

A thesis Submitted in fulfillment of the requirements for the degree of doctor of philosophy in Architecture.

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Abstract

The recent concept of thermal performance improvement attracted all the researchers and building architects to switch over from the present practice of mechanical systems to environmental methods of performance improvement methods in an efficient modern way. This study has employed performance analysis tools, namely Energy Plus, CFD, and Grasshopper with DIVA plug-in. The research was carried out on a theoretical office building is a rectangular-shaped ten-story building designed as an open plan office with a surface of 552m^2 and height of 4m. This research focused on improving the performance of the building façade, double-skin facade technique was used as a tool to improve the thermal performance, where a detailed analysis of its thermal behavior and performance in hot-dry climate for the best and most effective DSF alternatives was carried out. Thermal modeling was carried out on three DSFs alternatives (shaft type, corridor type, and combined shaft-corridor DSF type) in comparison with the base case single-skin facade, and well-designed single-skin facade (WSS). The simulation results showed, the total cooling load has been reduced by 5% in the well-design single-skin facade, 15% in the combined shaft-corridor DSF, and by almost 4.4% and 7% in the shaft and corridor types, respectively.

And then further investigation possibilities to improve the thermal performance level by applying the two techniques have been conducted (airflow promotion and convective heat transfer reduction). Firstly, investigation possibilities to improve the office airflow by modifying the combined DSF configuration system have been conducted. The strategies include; modifying openings size, shaft height, and cavity depth, where the following findings are tabulated (A DSF system with openings vs. cavity depth. As the opening size increased, the performance improved with the same cavity depth, A DSF system with the opening size vs. shaft height. Increasing the shaft height improved the thermal performance and as the shaft height increases, and DSF system cavity depth vs. shaft height. As the shaft height increases, the cavity depth should be decreased with a constant opening size). Secondly, the effect of convective heat transfer reduction techniques like orientation, shading devices, and glazing properties are studied. For a PMC blind angle of 80 degrees with high slops comparatively and close to external glass skin, the convective heat transfer for the inner environment due to solar radiation is only 28% of the heat transfers for the case without blinds. According to simulation results, an orientation slightly east of south (typically 15° east of south) is expected more effective in Al-Khartoum city. Also the total cooling load has been reduced by 12% in the Body tinted green glazing and by almost 26% in the Reflective glazing active blue.

Finally, the simulation results showed the thermal performance improved by 24.12% when implementing the modified double-skin facade system.

الملخص

جذب المفهوم الحديث لتحسين الأداء الحراري جميع الباحثين والمهندسين للانتقال من الممارسة الحالية للأنظمة الميكانيكية إلى الأساليب البيئية لتحسين الأداء بطريقة حديثة وفعالة. في الوقت الحاضر ، أصبحت العديد من المباني في جميع أنحاء العالم تحتوي علي العديد من الممارسات الخاطئة مثل إدخال مساحات كبيرة من الزجاج والكسوة المعدنية وغيرها من المواد عالية النفاذية الحرارية. وهذا يضعف بشكل كبير الأداء الحراري لأغلفة المباني بسبب إهمال الجوانب البيئية.

إستخدمت هذه الدراسة أدوات تحليل الأداء التالية (CFD - Energy Plus - Grasshopper). تم إجراء البحث على مبنى إداري إفتراضي عبارة عن مبنى مستطيل الشكل مكون من عشرة طوابق مصمم بالنظام المفتوح بمساحة 552 م^2 وارتفاعه 4 أمتار. ركز هذا البحث على تحسين أداء واجهة المبنى. تم استخدام تقنية الواجهة المزدوجة كأداة لتحسين الأداء الحراري، حيث تم إجراء تحليل مفصل لسلوكها الحراري وأدائها في المناخ الحار والجاف للحصول على أفضل البدائل وأكثرها فعالية. تم إجراء النمذجة الحرارية بإستخدام برنامج (CFD) على ثلاثة بدائل من الواجهات المزدوجة (نوع العمود ، ونوع الممر ، والنوع المشترك بين ممر والعمود) مقارنةً بواجهة مبني الحالة الأساسية ذات الجلد المفرد ، والواجهة أحادية الجلد المصممة جيدًا (WSS). أظهرت نتائج المحاكاة أن أحمال التبريد زادت بنسبة 0.09٪ في نوع العمود وانخفضت بنسبة 1.9٪ في نوع الممر مقارنة بالواجهة جيدة التصميم (WSS). تم أيضًا حساب متطلبات التبريد لكل شهر، حيث تم تقليل حمل التبريد الإجمالي بنسبة 5٪ في الواجهة المحسنة (أحادية الجلد)، و 15٪ في الواجهة المزدوجة المدمجة، وبنسبة 4.4٪ و 7٪ تقريبًا في الواجهة المزدوجة من نوع الممر والعمود على التوالي.

ثم تم إجراء مزيد من التحقيق في إمكانيات تحسين مستوى الأداء الحراري من خلال تطبيق تقنيتين (تعزيز تدفق الهواء وتقليل انتقال الحرارة بالحمل الحراري). أولاً ، تم إجراء بحث في إمكانيات تحسين تدفق الهواء في المكتب من خلال تعديل نظام تكوين DSF المدمج. تشمل الاستراتيجيات ؛ تعديل حجم الفتحات وتغيير ارتفاع العمود وعمق التجويف. حيث تم جدولة النتائج التالية (كلما زاد حجم الفتحات ، تحسن الأداء بنفس عمق التجويف مع ثابت ارتفاع العمود، أدت زيادة ارتفاع العمود إلى تحسين الأداء الحراري، بحيث يجب زيادة حجم الفتح لتوفير نفس النتائج، مع زيادة ارتفاع العمود ، يجب تقليل عمق التجويف مع حجم فتحات ثابت).

ثانيًا ، تمت دراسة تأثير تقنيات تقليل انتقال الحرارة بالحمل الحراري مثل التوجيه وأجهزة التظليل وخصائص التزجيج. بالنسبة لزاوية عمياء PMC تبلغ 80 درجة مع انحدارات عالية نسبيًا وقريبة من الجلد الزجاجي الخارجي ، فإن نقل الحرارة بالحمل الحراري للبيئة الداخلية بسبب الإشعاع الشمسي هو 28٪ فقط من عمليات نقل الحرارة للحالة بدون ستائر. وفقًا لنتائج المحاكاة ، من المتوقع أن يكون الاتجاه إلى الشرق قليلاً من الجنوب (عادةً 15 درجة شرقًا جنوبًا) أكثر فاعلية في مدينة الخرطوم ، لأن الواجهة الغربية بهذه الطريقة تمتص درجات حرارة أقل للشمس في الصيف. كما تم تقليل حمل التبريد الكلي بنسبة 12٪ في الزجاج المصبوغ باللون الأخضر وبنسبة 26٪ في الزجاج العاكس باللون الأزرق النشط.

وأخيرًا ، أظهرت نتائج المحاكاة تحسن الأداء الحراري بنسبة 24.12٪ عند تنفيذ نظام الواجهة المزدوجة المعدل.

Dedication

I am dedicating this thesis to the beloved person who has meant and continues to mean so much to me. Although he is no longer of this world, his memories continue to regulate my life. First and foremost, to my late father Dafalla Ahmed whose love for me knew no bounds and, who taught me the value of hard work. Thank you so much, I will never forget you.

I would also dedicate it to my mother due to her greatest encouragement and prayers, with my full respect. And also dedicate it to my family and my friends.

I also dedicate this dissertation to my teachers in the College of Architecture and Planning SUST.

I give special thanks to that continuing prayer which being with me throughout the entire doctorate program, she has been my best cheerleader.

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In the beginning, I thank the Almighty God for helping me to finish this research. Here I intend to express my gratitude to all those who helped and supported me in accomplishing this thesis, my great appreciation to all those who helped in this thesis:

Firstly I want to thank Professor **Saud Sadig Hassan**, my supervisor, for his guidance, assistance, encouragement, and patience.

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Special appreciation has to be given to Eng. Omer Salim, Autodesk Certified Instructor at Autodesk, Writer at BIMArabia, and Research assistant at Qatar University. I would like to thank the BIMArabia family for the online courses about environmental design.

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Chapter One
General Introduction

1.1 Background

With modern movement in architecture, several architectural malpractices were introduced in buildings especially multi-story buildings to improve the aesthetic aspects of architecture. Nowadays many buildings have become all over the world have large areas of glazing, cladding, and other high U-value materials. This substantially weakens the thermal performance of buildings envelopes because of neglecting the environmental aspects. Where, the facade configuration in hot-dry regions is a major contributor towards increasing the thermal loads of buildings.

According to Gasmalla (Gasmalla, 2016) the weakness of the building envelope design leads to an increase the heat gain rate in addition to energy consumption that is necessary to create the building environmentally for the occupant's comfort. To achieve his basic function with expected efficiency and provide the thermal comfort of building occupants to achieving his functions which they are designed for it. The Sudan climate features by a hot-dry climate and a longevity hot summer seasons, made almost the buildings depend on mechanical and electrical services to provide the thermal comfort and ensure suitable conditions of human activity within it, especially in the hot summer period. Where, the last two decade has witnessed a severe energy crisis in developing countries, especially in Sudan during summer season primarily due to the building fabric's inability to respond and control the interchanges occurring between the external and internal environment. The energy consumption in buildings is quite high and is expected to further increase because of improving standards of life and increasing world population. Air conditioning use has increasingly penetrated the market during the last few years and greatly contributes in the upsurge of absolute energy consumption. As a result, buildings are involved in producing about 40% of the sulfur dioxide and nitrogen oxides that cause acid rain and contribute to smog formation. Building energy use also produces 33% of all annual carbon dioxide emissions, significantly contributing to the climate changes brought about by the accumulation of this heat-trapping gas in Sudan, the building sector represents about 47% of total electricity consumption.

Before the advent of mechanical refrigeration, ingenious use was made of the many means of cooling (e.g. damp cloths hung in draughts created by the connective stack effect in buildings). So dwellings and life styles were developed to make best possible use of these sources of cooling. The introduction of mechanical refrigeration permitted not only the ability to increase the likelihood of achieving complete thermal comfort for more extended periods, but also a great deal of flexibility in building design, and simultaneously led to changes in life style and work habits. However, increasingly, the use of a 'higher technology' resulted in natural-cooling techniques being ignored. Now with the growing realization of the rapid depletion of non-renewable energy sources and of the adverse environmental impacts of fossil-fuel dissipating processes, it is accepted that it is foolish to continue consuming vast amounts of non-renewable fuels for the air-conditioning of buildings, when our ancestors achieved thermal comfort by natural means. Hence to reduce the emission of greenhouse gases, caused by fossil fuels to power the cooling requirement of the buildings has stimulated the interest towards adoption of techniques to improve the thermal performance for buildings.

With the emergence of energy-consumption reduction as a major national concern in Sudan, the search for better approaches in improving the thermal performance of buildings is intensifying. Currently, high-performance building design features include lighting and controls, ventilation systems, and an improved building envelope. Lighting quality can be improved through the use of natural daylighting, high efficiency fixtures and controls, such as occupancy sensors that turn lights off when there is no movement, and photosensors that reduce light output as needed to maintain a minimum level. These technologies, combined with architectural details like light shelves, high windows, external shading, and double-skin facades, increase natural daylight while reducing reliance on artificial light. Mechanical systems required for providing fresh air to meet indoor air quality requirements can be reduced or eliminated with the use of passive or hybrid technologies. Hybrid ventilation, or the use of natural and mechanical systems to cool and ventilate buildings, offers opportunities to take advantage of external conditions, but require a backup system to maintain the indoor environment when these conditions are not adequate. Additionally, the building envelope plays an important role in improving the thermal performance.

New concepts were tested that used outdoor conditions in creating climatic-responsive buildings (Givoni, 1998; Szokolay, 1980; Wigginton, 1996). Where, the advanced envelope technologies were developed for the building sector, in particular (Wigginton, 2002), and designers tried to integrate more building services into the building envelope system. By integrating the use of many techniques as a system that can help the building envelope to improve the thermal performance, and reduce the amount of supplementary heating or cooling needed to maintain occupant comfort. The integration of building-envelope techniques in the architectural design process requires many considerations at all levels of design stages. The aim of this integration is to achieve and provide maximum thermal performance. Building-envelope system performances depend mostly on natural and environmental elements like the sun, wind, earth, and water. It is, therefore, significant to study and analyze how envelope system interacts with natural elements and their relationship to a building site.

1.2 Research Problem

With the emergence of energy-consumption reduction as a major national concern in Sudan, the search for better approaches in improving the thermal performance of buildings is intensifying. Several factors have contributed to the existence of thermally inefficient buildings in the country because of a lack of stringent sustainable building practices and codes and limited awareness with performance improvement practices when compared with most of the other countries (Gasmalla et al., 2016). Especially with increasingly of use a 'higher technology' resulted in natural strategies of thermal-performance improvement being ignored, especially with the growing realization of the frequent trouble securing a stable supply of petrol, diesel, and fuel oil, which have resulted in frequent lines at power cuts in Sudan. Where the electricity percentage consumed in summer for providing thermal comfort conditions is about 47% from the total electricity consumption.

Developing a new intelligent and integrated envelope concept is necessary for high-performance building design. While a great deal of interest exists in learning how to integrate the envelope techniques into our current architecture, there is little knowledge or demonstration of how an integrated building envelope system work in a hot-dry climate of Al-Khartoum. In addition, numerous papers describe how improve the thermal performance of a building envelope just through principles and ideas yet provide no calculated or experimental results (Lieb, 2001; Arons and Glicksman, 2001).

1.3 Research Aims and Objectives

The main aim of the research is (creation an intelligent envelope system, that activates the building envelope response to meet external environment variables and improve the thermal performance for buildings in a hot-dry climate of Al-Khartoum, this system includes a set of techniques that work together as an integrated system to improve the thermal performance of the building by following intelligence as a means which to give the integration property of those techniques the ability to achieve optimal performance). In the rood to main objective achievement, other sub-objectives emerge are:

1) **Objective 1- Literature Review**

The literature review was used to narrow the scope of the research field, and further, to come up with the right questions in identifying the knowledge gap on the techniques used in hot climates. This objective is to determine how these are currently implemented, developed, and how these affect thermal performance.

2) **Objective 2- The Thermal performance evaluation tools**

The Strategic aim is how to select and use suitable simulation software in the early design stages to improve the thermal performance of buildings in Sudan.

3) **Objective 3- Effectiveness of intelligent envelope system**

Each technique is developed and assessed in terms of effectively improving thermal performance using a theoretical base case office building located in Al-Khartoum. Key performance parameters are identified to highlight how optimum operation can be achieved when combined building envelope techniques in the hot-dry climate.

1.4 Research Importance

There are many opportunities to improve the thermal performance through combining the envelope techniques to activate the intelligence property as a practical application of the integration concept as a part of buildings design to achieve Intelligent Building Envelope concept. In terms of improving thermal performance, that makes the building envelope effective for responding and adapting to external climate conditions and contributes to environmental control of the building which leads to improved thermal performance.

1.5 Research Hypothesis

The hypotheses to be tested in this research are stated below:

- ***Hypothesis 1**:* In the first hypothesis, the thermal modeling is performed to disprove the hypothesis that double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades.
- ***Hypothesis 2***: The proposed double-skin facade configuration, which combines both shaft box and corridor types, is viable in terms of improving

acceptable internal thermal comfort through natural ventilation while also improving thermal performance.

- ***Hypothesis 3***: the thermal performance can be improved by applying the airflow promotion techniques and convective heat transfer reduction techniques by understanding the conditions are the incorporation of natural ventilation possible with this combined shaft-corridor in a hot-dry summer climate, How are offices next to a DSF ventilated? And study the solutions and techniques that can reduce the convective heat transfer.

1.6 Research Methodology

It has been identified from existing research detailed in the theoretical framework that there is a limited amount of knowledge for generic performance of building envelope when integrating the intelligent envelope techniques for office buildings located in hot climates. Figure 1.1 flow diagram below describes an overview of the approach followed in conducting this research.

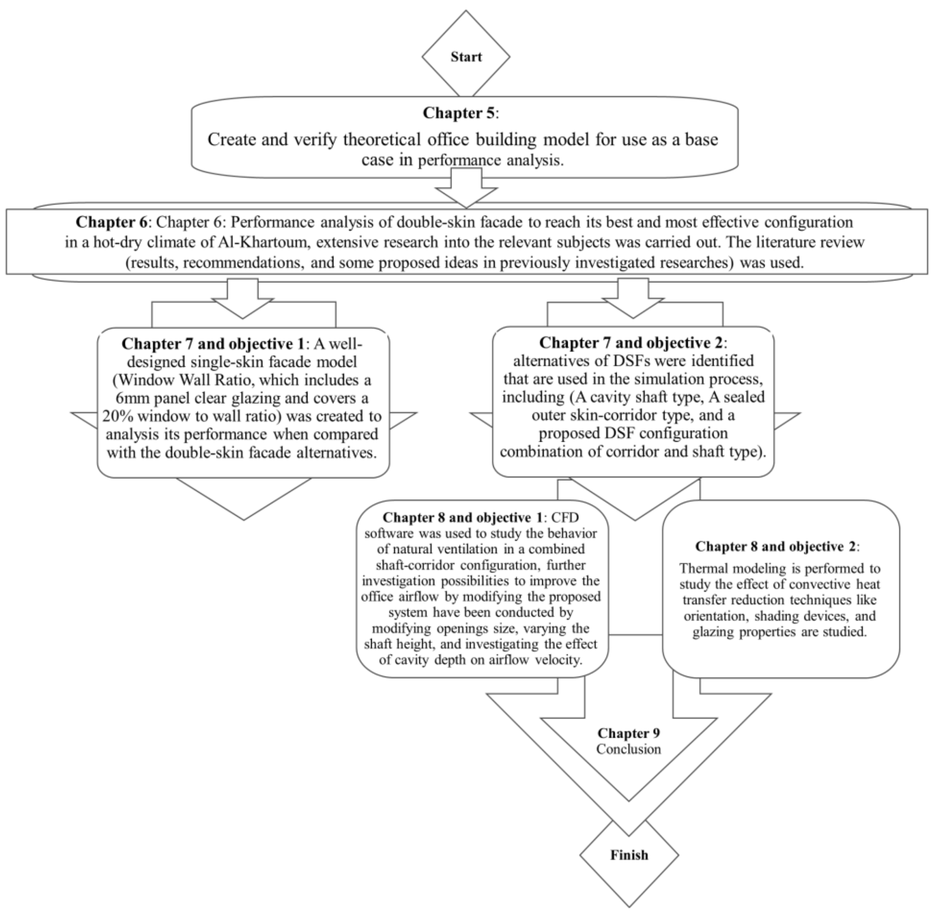


Figure 1.1 an overview of the research road map (Author).

In attempting to test the four hypotheses, it was imperative to design a methodology that shows an overview of the research agendas and approach. Several tests and comparisons of the different variables had been made to achieve the optimized and most effectiveness alternatives that maximum thermal performance when integrated the building envelope techniques, and then will be detailed it's to form a platform for new design guidelines.

Different methods are used in this research depending on the nature of each stage of analysis. That includes a theoretical analytical method and analytical-practical method of the building envelope techniques and the thermal simulation processes, respectively.

1.6.1The analytical theoretical method (Façade performance analysis)

This method is based on a literature analysis to investigate and develop the best possible solutions for building facades. This research focused on improving the performance of building facades as the most exposed envelope element to the external environment conditions in terms of area. The techniques selected for this analysis are as follows:

- Well-design single-skin façade.

This technique is selected to disprove the hypothesis that double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades.

- Double-skin facade technique.

Double-skin facades are mainly designed in the buildings to obtain wholly glazed facades and at the same time improve thermal performance.

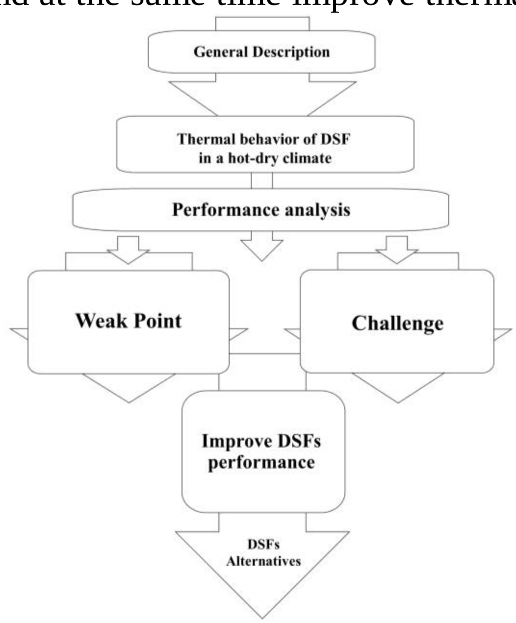


Figure 1.2 The steps of the analytical theoretical method (Author).

1.6.2 The analytical-practical method

This method is based on carrying out the simulation process to test the different envelope alternatives for optimal configuration. This method uses several types of software.

1) Visualization software:

- (Autodesk Revit Architecture - Design Builder – Rhino).

2) Simulation software:

- Energyplus (version 2.1).
  Energyplus has been selected to calculate the thermal loads and thermal properties of materials.
- Computational fluid dynamics (CFD)
  CFD has been selected to simulate the airflow and convective heat transfer.
- Grasshopper software and DIVA plug-in
  Grasshopper and DIVA has been selected the buildings orientation and shading devices.

The purpose and tasks of each simulation software can be summarized in the following table.

Table 1.1 The purpose and tasks of each simulation software (Author).

Simulation Software	**Tasks**	**Chapter**
Energyplue	To calculate the thermal loads and thermal properties of materials	Chapter 7
Computational fluid dynamics (CFD)	To simulate the airflow and convective heat transfer	Chapter 8
Rhino, Grasshopper software, and DIVA plug-in	To simulate the buildings orientation and shading device	Chapter 8

For the research objective, several simulation tests and comparisons of the different variables had been made to achieve the optimized and most effectiveness alternatives that maximum thermal performance when integrated the building envelope techniques, flow diagram below describes the steps of a practical method.

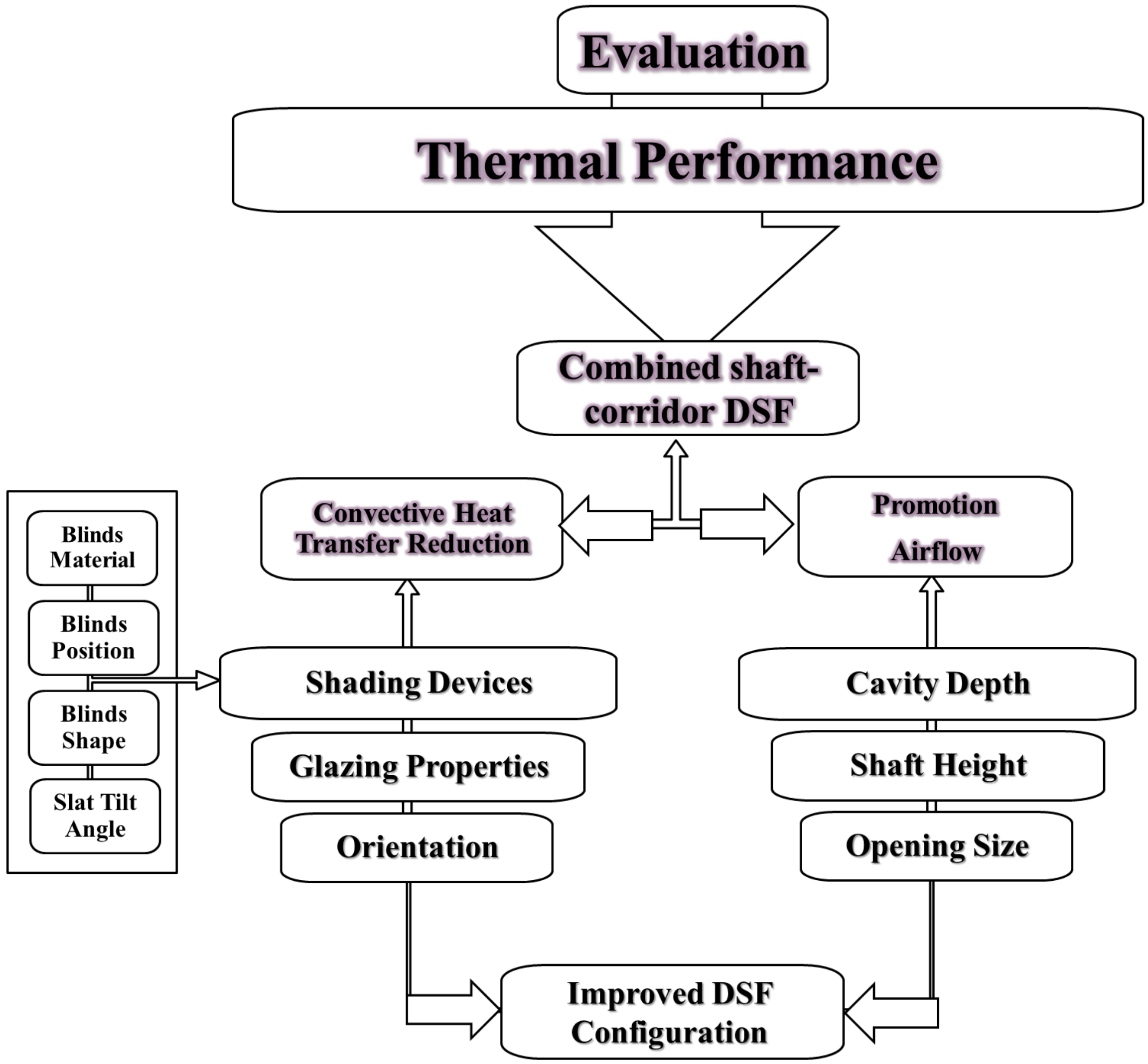


Figure 1.3 flow diagram illustrates describes the practical method steps (Author).

1.7 Source of information

The research depends on several sources of information varied between the theatrical sources for the scientific information, the field study and computer simulation, these sources can be listed as follows:

1) Journal papers.
2) Books and references dealing with some or all parts of the subject.
3) Internet sites accredited to institutions, universities and scientific research centers.
4) Magazines, newspapers, researches and studies published.
5) Computer Simulation of the selected models using the analysis Programs.

1.8 Research Structure

The structure of the thesis chapters is as follows:

- ***Chapter 2***: Buildings Thermal Performance and Intelligent Envelopes.

This chapter discusses the concepts of thermal performance and intelligent building envelopes respectively. For each of the concepts, literature sources are used to identify a definition that fits the scope of this study, and to abstract characteristics that are expected to be fruitful for the system analysis performed in the subsequent chapters.

- ***Chapter 3***: The Building Envelope Techniques.

This chapter reviews the various possible methods to improve thermal performance for buildings envelopes and discusses the representative applications of each method. The building envelope techniques are closely linked to the thermal performance of the buildings, and it is possible to achieve this performance by reducing the heat gains, thermal moderation, and removing the internal heat.

- ***Chapter 4***: Simulation Software.

This chapter describes the application of simulation software in architecture, and the selection methods of suitable simulation software to evaluate the thermal performance of buildings.

- ***Chapter 5***: Research Methodology.

This chapter sets out the research methodology to evaluate the thermal performance of building envelope when integrating the intelligent envelope techniques as required by aims and hypotheses set out in Chapter 1. Also, its presents the knowledge gap and research goals for the study, this will then lead to a discussion of the findings.

- ***Chapter 6***: Thermal behavior analysis to improve the double-skin facade performance

In this chapter, double-skin façades (DSFs) are studied to address the well-known problems of curtain walls. In attempting to improve the thermal performance of the double-skin facade technique, extensive research into the relevant subjects was carried out the literature review was used to narrow the scope of the research field, and further, to come up with the most effective alternatives in DSF configuration.

- ***<u>Chapter 7</u>***: Thermal Performance Assessment of DSF Configurations.

This chapter presents the evaluation of the thermal performance of a reference building model as it was designed and used as a base for performance analysis of several alternatives by verifying the first and second hypotheses of this research. In the first hypothesis, the building is designed to evaluate the thermal performance of different types of DSFs compared to the reference building and the well-designed single skin facade (optimized single skin facade), and thermal modeling is performed to disprove the hypothesis that double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades. In regards to the second hypothesis, the simulation results are used to verify the efficiency of the proposed configuration, which combines both shaft box and corridor types in respect to thermal performance against the other configurations.

- ***<u>Chapter 8</u>***: Performance Optimization Studies of the combined shaft-corridor DSF.

This chapter opens an investigation about the third hypothesis, which is interested in how to improve the thermal performance level by applying the two techniques that arrived at in chapter 6 (airflow promotion and convective heat transfer reduction).

- ***<u>Chapter 9</u>***: Conclusions, Recommendations, and Future Works.

Conclusion of this work highlighting main contributions and findings are presented. In this chapter, the contribution and limitations of the research are discussed and the future work areas are also presented.

A thesis navigation flow diagram is detailed below in Figure 1.4 (below) providing a high level overview of this thesis structure.

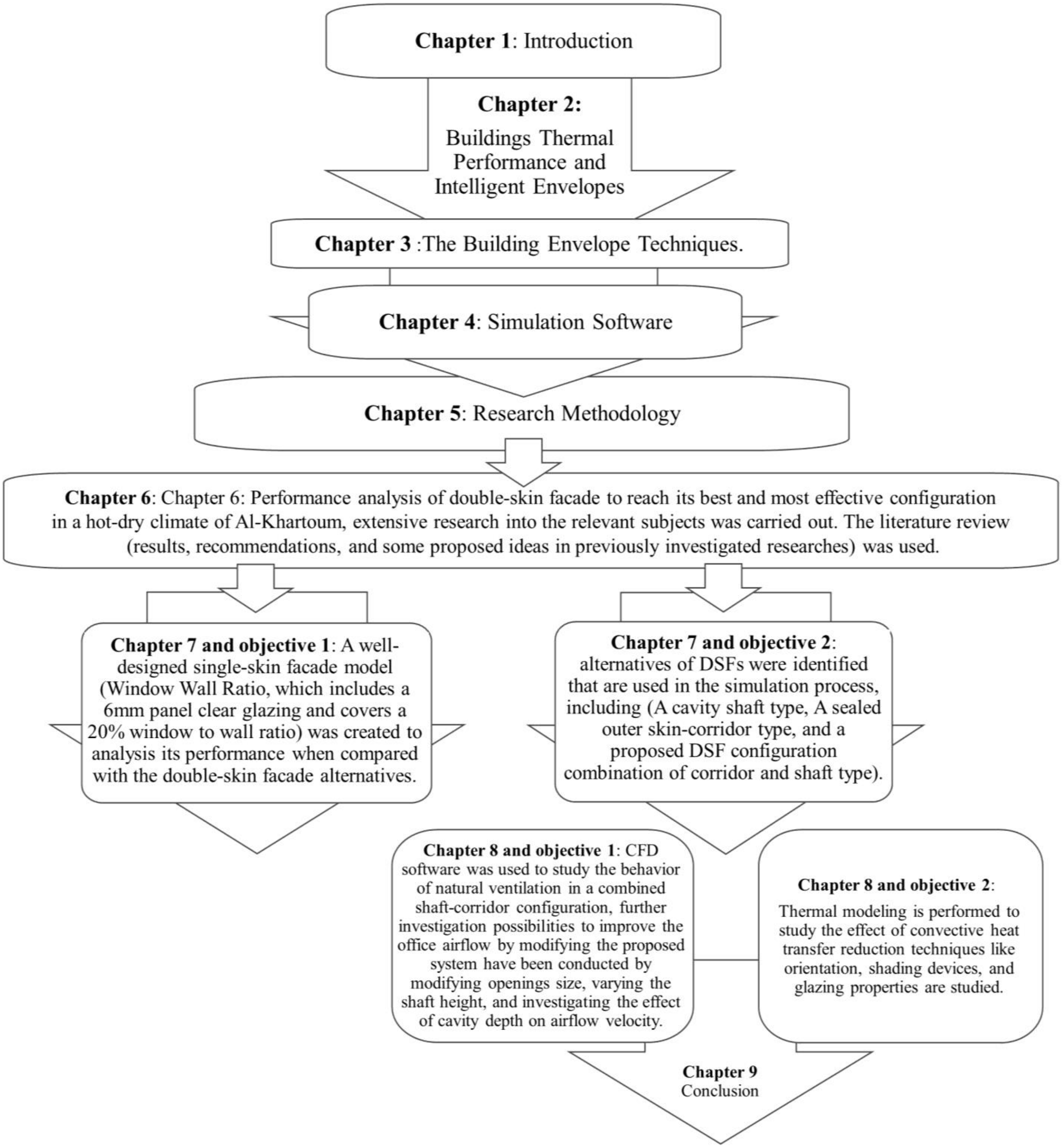


Figure 1.4 The Structure of the thesis (Author).

1.9 Conclusion

The current situation resulting from introducing several architectural malpractices in buildings, especially in the hot-dry regions, has motivated the researcher to conduct this study. The aim of this research is to create an intelligent envelope system, that activates the building envelope response to meet external environment variables and improve the thermal performance for buildings in a hot-dry climate of Al-Khartoum, this system includes a set of techniques that work together as an integrated system to improve the thermal performance of the building by following intelligence as a means which to give the integration property of those techniques the ability to achieve optimal performance.

Also, it aims to describe the application of simulation software in architecture, and the selection methods of suitable simulation software to evaluate the thermal performance of buildings. There is a short description of using the software to model buildings airflow and how to simulate the buoyancy, wind effects, heat transfer, and shading.

There are many techniques used to improve the thermal performance of buildings. These methods aim at achieving different requirements including providing natural ventilation and heat transfer reduction. A theoretical base case ten-story office building is studied to determine the thermal behavior of combined envelope techniques.

Conclusion of this work highlighting main contributions and findings are presented. In this chapter, the contribution and limitations of the research are discussed and the future work areas are also presented.

CHAPTER II

Buildings Thermal Performance and Intelligent Envelopes

2.1 Introduction

This chapter discusses the concepts of thermal performance and intelligent building envelopes respectively. For each of the concepts, literature sources are used to identify a definition that fits the scope of this study, and to abstract characteristics that are expected to be fruitful for the system analysis performed in the subsequent chapters.

This chapter will display an overview of thermal performance. Also, it will explain the mechanism of heat transfer between the building and the environment, which includes conduction, convection, and radiation. It wills overview the factors that affect thermal performance which are design variables, material properties, weather data, and a building's usage data. In addition, it will discuss thermal comfort as a measure of thermal performance. Also, it presents a historical background of intelligent envelopes emergence, and it will define the intelligent building envelopes and intelligent behavior for building envelopes. Finally, it will discuss the architectural concept of intelligent building envelopes and their effect on providing thermal comfort to the occupants.

2.2 Overview of Thermal Performance

Thermal performance is considered one of the most important aspects of energy utilization in buildings. The prediction of the building thermal performance through heat transfer mechanisms is essential for enhancing the indoor conditions using HVAC and estimation of heating and cooling loads (Zain et al. 2007). This section will display a general review of thermal performance and its impact on energy consumption and the mechanisms of thermal transfer.

2.2.1 Definition of Thermal Performance

Nayak and Prajapati (Nayak, 2006) defined the thermal performance of a building as "the process of modeling the energy transfer between a building and its surroundings". The difference of temperature between the building and the outdoor environment is the main engine for energy flow throughout a building. It is also proportional to the thermal quality of the building enclosure (Utzinger and Wasley, 1997).

2.2.2 Impact of Thermal Performance on Energy Consumption

Ghisi and Massignani (2007) stated that the energy consumption of buildings is associated with their thermal performance. The heat transfer through the building components, such as walls, windows and floors, in a mean of heat gains or losses adding to the internal heat gains and ventilation gains are considered the most important factors affecting the thermal performance. In turn, this thermal response determines the required heating and cooling energy in order to maintain acceptable thermal conditions for occupants (Ye et al. 2011). Yu et al. (2011) concluded that the most influential factor on both cooling and heating energy consumption is the heat transfer coefficient of wall, followed by the building shape coefficient.

2.2.3 Thermal Transfer Mechanism

Heat is considered one of the forms of energy which transferred between objects due to the difference in temperature. It always moves from the hotter object to the cooler one (Roos, 2008). Three heat mechanisms which are conduction, convection, and radiation are utilized in the passive solar buildings in such away to control the process of distributing heat throughout the living space (NREL, 2001).

A. Conduction:

Conduction is the way heat moves between molecules through materials. Heat causes vibrations to the molecules close to the heat source and these vibrations spread to neighboring molecules, thus transferring heat energy (NREL, 2001). Conduction requires the physical contact of two objects. It occurs through the different component of building envelop where heat is conducted from the warmer side to the cooler one (Roos, 2008). The quantity of heat transferred through a material is proportions with its thermal conductivity. The basic equation of heat conduction is shown in appendix (1) (Nayak and Prajapati, 2006).

B. Convection:

Roos (2008) defined convection as "heat transfer due to fluid (gas or liquid) or airflow". That explains why warm air rises or cool air falls on a wall’s inside surface. Air convection can be used in the passive solar homes to carry solar heat from a south wall into the building’s interior (NREL, 2001). Convective thermal transmission occurs from air outside of the building to the outer surface of the wall and the inner surface of the wall to the air inside of the building (Mahlia et al. 2007). It can be divided into natural convection which occur due to a temperature difference between zones, and forced convection which occur due to the movement of air by mechanical means. In these two cases convection is responsible for the distribution of heat within the occupied space and between zones (Barakat, 1985). Building's materials have an important role in convective. A modern lightweight material with permeable thermal insulation is sensitive to the convective heat transfer (Svoboda, 2000).

C. Radiation:

Radiation is heat transfer between two surfaces as a mean of electromagnetic waves, such as light, infrared radiation, UV radiation or microwaves with nothing between them. Radiation takes place in the sun-exposed surfaces of buildings and its value increases where there are large temperature differences (Roos, 2008). Materials properties such as transparency and colors play a significant role in determining the percentage of solar radiation absorbed, reflected, or transmitted, depending on certain properties of that object. The solar radiation which transmitted through the glass and absorbed by the home is radiated again from the interior surfaces as infrared radiation (NREL, 2001).

2.3 Factors Affecting Thermal Performance of Buildings

The thermal performance of a building depends on a large number of factors. Nayak and Prajapati (2006) summarized these factors as design variables, material properties, weather data and a building’s usage data.

2.3.1 Design Variables:

Buildings are considered the main responsible for indoor thermal conditions because they form the main contact between indoor and outdoor environment. Many variables must be considered through the building's design will be displayed.

I. The Form of Buildings

The building’s form, spacing and configuration in its neighborhood affect both the solar and wind factors. They play a large role in determining the amount of solar radiation received by the building’s surface and the airflow around it

(Nayak and Prajapati, 2006). As the building surface is the exposed component to the outdoor environment, a small ratio of building surface to the volume which is the main characteristic of compact forms is helpful to maintain thermal balance (LEARN ,2004), see figure (2.1).

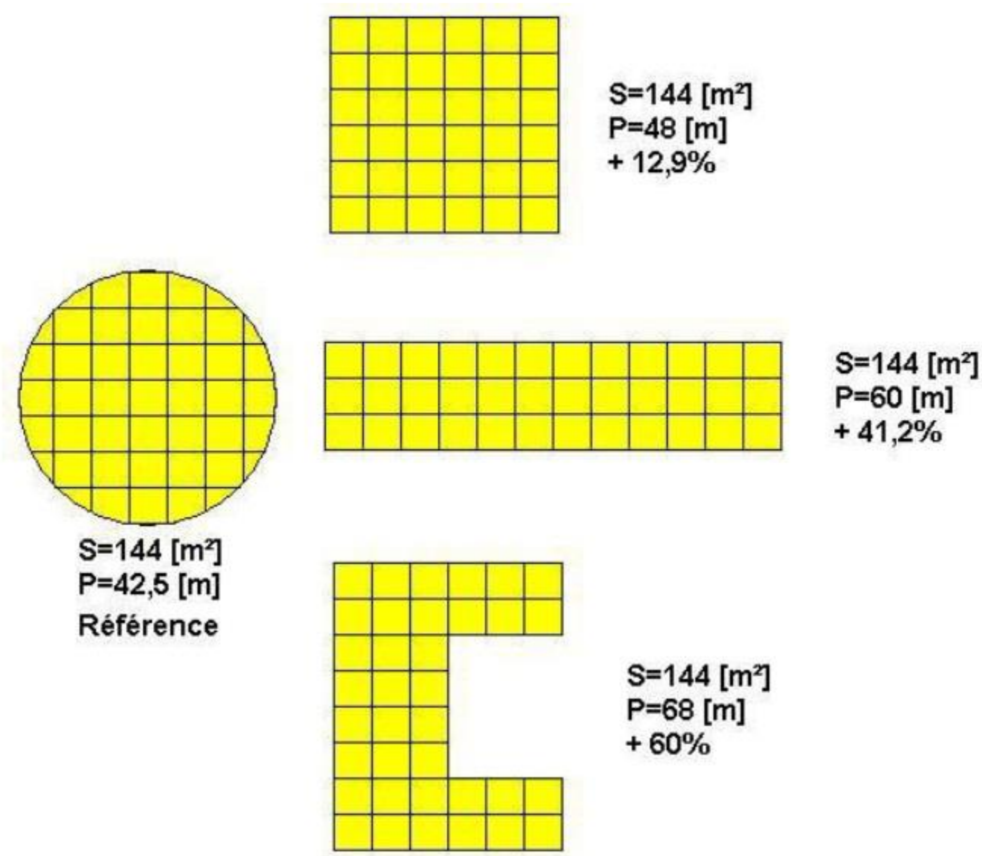


Figure (2.1): Plan to surface area ratios for different shapes of building (LEARN, 2004)

II. Building Orientation

The building orientation can affect the building thermal performances by minimizing the direct solar radiation into the buildings envelop either building openings or opaque walls (Al-Tamimi et al. 2010). Many factors must be taken into consideration during the selecting of building orientation. They include the expected shading impact and the sun movements according to latitude, time of day and time of year (Goulding et al. 1992).

III. The Envelope of the Building

Building envelope has a great influence on both indoor and outdoor space condition (Goulding et al. 1992). It is one of the main components affects the total heat gain andoverall heat transfer coefficient. It’s found that the building envelope accounts for 36%, 25% and 43% of the peak cooling load in Hong Kong, Singapore and Saudi Arabia respectively (Al-Tamimi et al. 2010). So it is important for the building envelopes to have a level of thermal resistance and a minimum of thermal bridges in order to avoid the penetration of water vapor inside the buildings (Matrosov et al. 2007).

IV. Shading Devices

Shading devices have a useful impact especially in Mediterranean and semi-desert climates. The period of the year, the time of the relative transparency of the materials can affect the shading (Goulding et al. 1992). In a study of Abd El-Monteleb and Ahmed (2012), it is showed that the vertical louvers with a protrusion of 38 cm or more result in a decrease of 2^{o} C in indoor temperature in the hot arid climate of Egypt.

2.3.2 Material Properties:

Material properties of buildings components play a fundamental role in controlling the process of heat transfer. The most important thermal properties which are thermal conductivity, thermal resistance, thermal transmittance and density will be outlined.

A. Thermal Conductivity λ

The thermal conductivity is a property of the material, which represents "the quantity of heat per unit time in watts, that flows through a 1m thick even layer of material with an area of 1m2, across a temperature gradient of 1 K (Kelvin) in the direction of the heat flow" (CSR Hebel Technical Manual, 2006). The lower value thermal conductivity is the less thermal transmission will be (Mahlia et al. 2007).The basic equation of thermal conductivity is shown in appendix (1).

B. Thermal Resistance of a Material, R

The thermal resistance of a material is the resistance to heat flow between two surfaces at different temperatures. It can be expressed as the R-value which is a function of the material thickness and the reciprocal of its thermal conductivity (CSR Hebel Technical Manual, 2006).

C. Thermal Transmittance, U

The thermal transmittance, U is a direct measure of the thermal insulating ability of a given building component air to air. It is obtained by reciprocating the total thermal resistance of the building component, R (i.e., U = 1/ R) (CSR Hebel Technical Manual, 2006). It can be defined as “the quantity of heat that flows through a unit area of a building section under steady-state conditions in unit time per unit temperature difference of the air on either side of the section” (Code on Envelope Thermal Performance for Buildings).

D. Density, Porosity

The density, p (kg/m3), is “the mass of a unit volume of the material, comprising the solid itself and the gas- filled pores” (Harmathy, 1988). The density plays a great role for the thermal properties: the lighter the material the more insulating and the heavier the more heat storing (Rosenlund, 2000).

2.3.3. Climatic Factors

The climatic factors can affect the design operation of buildings envelop in order to achieve comfort and save energy. It’s important to understand the general climate of the region and the microclimate (Ridley, 1990).

a. Solar Radiation

Nayak and Prajapati (2006) defined the solar radiation as "the intensity of sunrays falling per unit time per unit area and is usually expressed in Watts per square meter (W/m2)". They determined some factors affect the radiation incident on a surface which are geographic location (latitude and longitude of the place), orientation, season, time of day and atmospheric conditions. Solar radiation is the most weather variable influences the air temperatures. It consists of direct radiation (ID) and diffuse radiation (Id which are varying with the sky conditions.

Another variables affect the total solar radiation are reflections from the ground and adjacent buildings, shading from adjacent buildings and vegetation (Rosenlund, 2000).

b. Humidity

Air contains a certain amount of vapor, which is called air humidity (Rosenlund, 2000). ASHRAE Standard 55P (2003) defined the relative humidity

RH as "the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure". The acceptable rate of humidity differ according to the climate. While a low rate of humidity is preferable in dry climates, it causes discomfort in tropical climate regions (Biket, 2006), See figure (2.2).

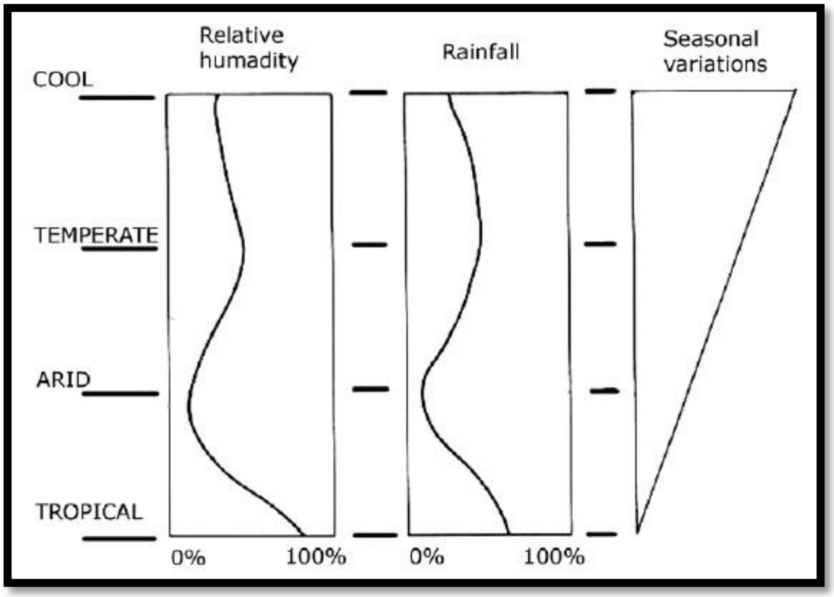


Figure (2.2): Relative Humidity and Rainfall in various climate regions.
Source: Biket (2006).

c. Pressure and Winds

Wind has a great influence on buildings design and their thermal performance. It affects the convective heat exchanges of a building envelope and the air infiltration (Nayak and Prajapati, 2006). It's necessary to avoid the effect of winter wind which increase the infiltration heat loss and utilizing the summer wind in encouraging ventilation (Ridley, 1990). Various climate regions require different wind requirement (Biket, 2006). Show figure (2.3) which clarifies the desirable wind direction in various climate regions.

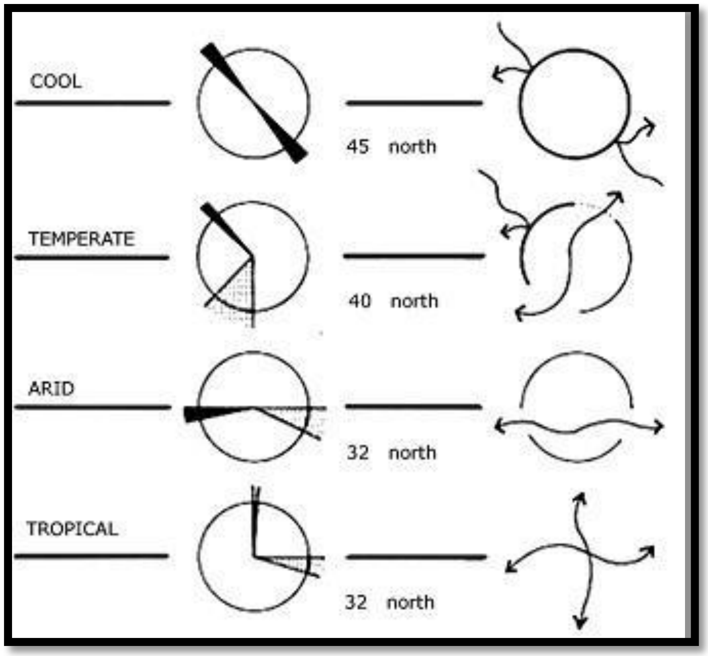


Figure (2.3): Desirable wind direction in various climate regions.
Source: Biket, (2006).

2.3.4 Building Occupancy and Operations

Buildings usage produce heat from their occupancy, lights and equipments. Occupation densities and types of activities affect the total heat gain. It can be significant in crowded spaces (Goulding et al. 1992). People give off the heat of metabolism to maintain a constant body temperature. Electric lights and equipment give off heat to the building equal to the electrical energy they consume (Utzinger and Wasley, 1997).

2.4 The emergence of intelligent building envelopes

During the past few decades, buildings have been imposed to steadily increase their functionality at diminishing cost. In this context, the deployment of new and emerging technologies has led to the use of the terms intelligent building and intelligent building envelope to describe a built form that can meet these demands, be it to a varying degree of success .

Frequently used in architecture, there exists a wide variety of definitions on the concept of intelligent building envelopes, for example, list over thirty definitions of intelligence related to buildings and building envelopes. Simultaneously, this type of built form is denoted by terms like adaptive, advanced, innovative, and interactive [Wigginton & Harris, 2002].

Within the scope of this research, the intelligence of a building envelope is defined by its ability to adapt to a variable environment by means of perception, reasoning and action. This definition, to be elaborated in the course of this chapter, is based on the psychological development of intelligent behavior in human beings. It is chosen because it relates the term intelligence to concrete psychical processes rather than to the more subjective and diffuse concepts of rationality, sensibility and good judgment often associated with human intelligence.

2.5 Defining intelligent building envelopes

Various definitions of intelligence in building envelopes have been identified in literature, and classified into three groups:

- Intelligent design, use and maintenance
- Intelligent technology
- Responsiveness to the environment

As the three groups show considerable overlap, however, this should not be considered a strict taxonomy, but rather an indication of the variety that exists in this field.

2.5.1 Intelligent design, use and maintenance

A first group of definitions relates the intelligence of a building envelope, and architecture in general, to the skillfulness and rationality of the people who design, use and maintain it. the intelligence of a building envelope is often linked to sensible goals such as energy efficiency, compliance with human needs, and the use of renewable energy sources: "A glass facade can only then be properly described as "intelligent" when it makes use of natural, renewable energy sources, such as solar energy, air flows or the ground heat source, to secure a building's requirements in terms of heating, cooling and lighting [Compagno, 1999].

2.5.2 Intelligent technologies

An intelligent building envelope is often related to the use of artificial intelligence and building management systems, where Kroner identified the appropriate use of intelligent technology as one of the three main concerns for intelligent architecture. Willey [Willey, 2006] defines artificial intelligence as:

- The capability of a machine to imitate intelligent behavior.

- A branch of computer science dealing with the simulation of intelligent behavior in computers.

2.5.3 Responsiveness to the environment

The manner in which the envelope is able to adapt to changes in its environment, is the third dimension of intelligence in building envelopes. Intelligence may be related to the responsive performance of the building envelope, "the design and construction of which forms the single greatest potential controller of its interior environment, in terms of light, heat, sound, ventilation and air quality" [Wigginton & Harris, 2002].

In this context, an intelligent building envelope may be defined as "a responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum comfort, by adjusting itself autonomically, with self-regulated amendments to its own building fabric. A flexible, adaptive and dynamic membrane, rather than a statically inert envelope" [Wigginton & Harris, 2002].

The ability of the building envelope to interact with its environment is even more important than the complexity of its control mechanisms; according to Compagno, "an "intelligent" facade is not characterised primarily by how much it is driven by technology, but instead by the interaction between the facade, the building's services and the environment" (Zarzalejo, 2006).

Of particular importance is the manner in which intelligent technology is able to adapt to the needs and preferences of the building users. Croome reports a frequent mismatch between the everyday performance of intelligent building envelopes and the expectations of the user, and argues that "the intelligent building has generally been defined in terms of its technologies, rather than in terms of the goals of the organizations which occupy it. If the user is subservient to the technologies, this usually leads to situations where the technology is inappropriate for the user's needs [Croome, 2000].

Therefore, an intelligent building envelope will be understood as the outer layer of a building, designed through a specific process for adaptability to the challenges posed by interior and exterior conditions using minimum energy. This process has also provided the elements and mechanisms that follow the stages of intelligence, carrying out the adaptation strategies for which it has been planned.

In order to provide this response, an intelligent building envelope needs to be designed with a flexibility that allows it to implement various strategies and to adjust its physical layout accordingly. In designing the envelope, however, it is not possible to anticipate every situation that may arise, create an exhaustive list of requirements, and determine the morphology of the building envelope accordingly. In order to be able to respond to a wide range of real-time situations, therefore, an intelligent building envelope ideally is able to manage its own strategies and layout as the need for adaptation arises.

2.6 Defining intelligent behavior for building envelopes

2.6.1 An operational definition:

An intelligent building envelope adapts itself to its environment by means of perception, reasoning and action. This innate adaptiveness enables the envelope to cope with new situations and solve problems that may arise in its interaction with the environment. This definition does not automatically link an intelligent building envelope to the achievement of specific goals, but rather depicts the skills and behaviour to be expected from an intelligent building envelope in order to attain those goals.

2.6.2 Objectives for an intelligent building envelope:

Given its characteristic processes of perception, reasoning and action, three main objectives are considered to be particularly relevant for an intelligent building envelope to fulfil in its interaction with the environment:

- The ability to construct patterns
- The ability to solve problems
- The ability to adapt to the environment
- The ability to perceive reason and act

2.7 The Architectural concept of intelligent building envelopes

The manner in which the envelope is able to adapt to changes in its environment, is a third dimension of intelligence in building envelopes. Intelligence may be related to the responsive performance of the building envelope, the design and construction of which forms the single greatest potential controller of its interior environment, in terms of light, heat, sound, ventilation and air quality [Choi, 2001].

2.8 Conclusion

It can be concluded that the concept of high-performance buildings in Sudan is absolutely a good solution, which can reduce of energy consumption and environmental pollution. This chapter addressed the issue of thermal performance in buildings to achieve thermal comfort to its occupants, and the improvement potential of building's thermal performance in the hot-dry climate of Al-Khartoum was also discussed. The chapter outlined the factors affecting thermal performance and ways to achieve building thermal balance between heat gain and heat loss. Hence, this chapter highlighted the impact of building thermal performance on energy consumption and environmental pollution.

An intelligent building envelope may be defined as a responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum comfort, by adjusting itself autonomic ally, with self-regulated amendments to its own building fabric a flexible, adaptive, and dynamic membrane, rather than a statically inert envelope.

Adapting the building and improving thermal performance makes the building envelope effective for responding and adapting to changes in the external climate by applying an integration principle of envelope techniques that contribute to environmental control, as illustrative in figure below.

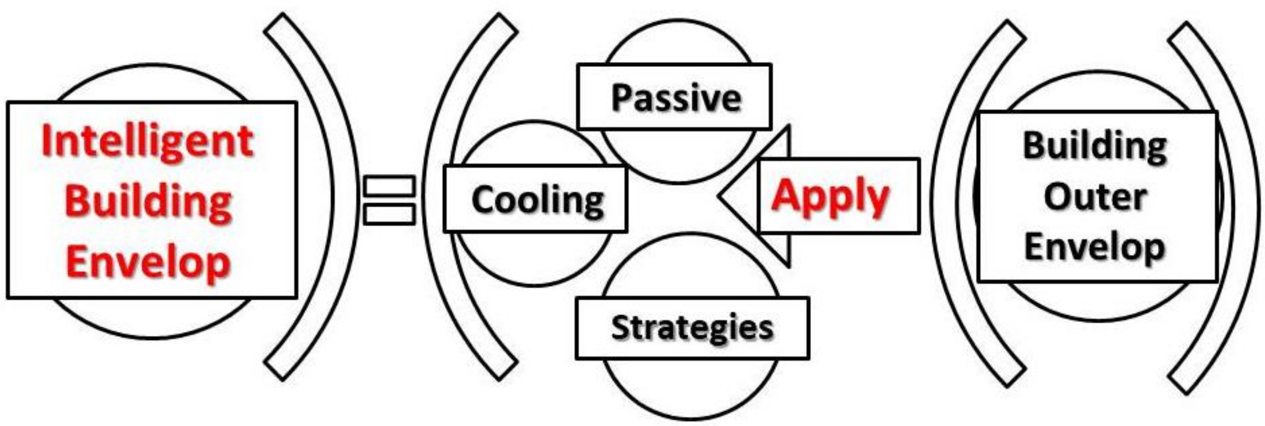


Figure (2.3) The Architectural concept of intelligent building envelopes (Author).

CHAPTER III

Building Envelope Techniques

3.1 Introduction

This chapter reviews the various possible methods to improve thermal performance for buildings envelopes and discusses the representative applications of each method. The passive envelope techniques are closely linked to the thermal performance of the buildings, and it is possible to achieve this performance by reducing the heat gains, thermal moderation, and removing the internal heat. In the present review the various methods adopted under these techniques and the relevant information about the performance of each method reported by various researchers, are collected and presented in detail.

Thermal performance is the process of modeling the energy transfer between a building and its surroundings, in order to achieve a lower temperature than that of the natural surroundings. In recent years, air conditioning systems are used to control the temperature in order to achieve the desired effects for the occupants.

3.2 Solar and heat protection techniques (Reduce heat gains)

A building must be adapted to the climate of the region and its microclimate. It is very important to minimize the internal gains of a building in order to improve the effectiveness of passive cooling techniques. The site design is influenced by economic considerations, zoning regulations and adjacent developments, all of which can interfere with the design of a building. The Solar and heat protection techniques are broadly categorized under two sections; Microclimate and Solar control.

3.2.1. Microclimate

Climate is the average of the atmospheric conditions over an extended time over a large region. Small-scale patterns of climate, resulting from the influence of topography, soil structure, ground and urban forms, are known as microclimates. The principal parameters characterizing climate are air temperature, humidity, precipitation and wind.

a) Vegetation

Vegetation modifies the microclimate and improve the thermal performance of buildings by lowering the air and surface temperatures and increasing the relative humidity of the air. Furthermore, plants can control air pollution, filter the dust and reduce the level of nuisance from noise sources. Green surface temperatures can be 30–40 °F lower than those of conventional roofs and can reduce city-wide ambient temperatures by up to 5 °F (Sailor, 2011).

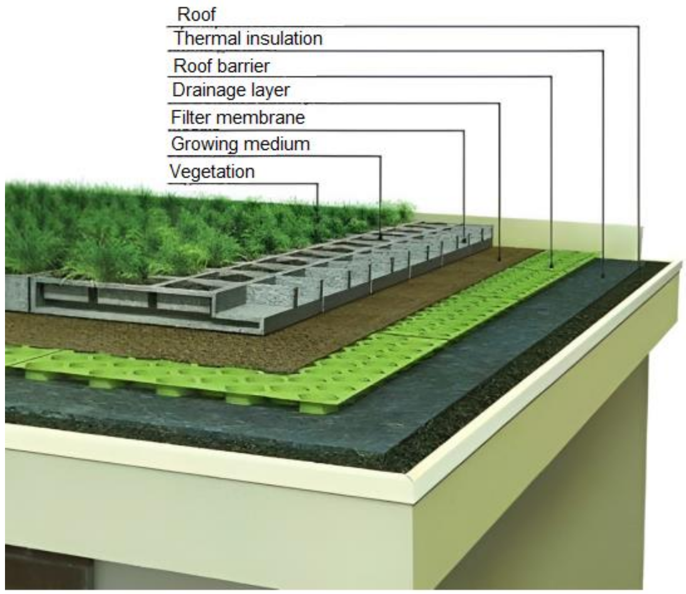


Figure 3.1 Components of green roof.
Source: (Vijayaraghavan, 2016).

b) Water surfaces

Water surfaces modify the microclimate of the surrounding area, reducing the ambient air temperature, either by evaporation, or by the contact of the hot air with the cooler water surface. Fountains, ponds, waterfalls or mist sprays may be used as cooling sources, for lowering the temperature of the outdoor air and of the air entering the building (Goldn , 2009).

3.2.1. Solar control

Solar radiation reaches the external surfaces of a building in direct, diffuse and reflected forms and penetrates to the interior through transparent elements. For a given surface, incident radiation varies with the orientation and the surface's angle to the horizontal plane.

a) Aperture

The appropriate combination of the orientation, size and tilt of the various openings on the building's envelope is of vital importance. Mazria (Mazria, 1979) defines the best orientation for the solar apertures of a building as one which receives the maximum amount of solar radiation in winter and the minimum amount in summer.

b) Glazing

The thermal properties of the glazed surfaces of a building affect the penetration of solar radiation to the interior. The influences of channel width and the dimensions of the inlet and outlet openings affect the convection process, and hence, affect the overall heating performance. Using double glazing could increase the flow rate by 11-17%. On the other hand, insulating the interior surface of the storage wall for summer cooling can avoid excessive overheating due to south facing glazing (Guohui, 1998).

c) Insulation

Belusko et al. (Belusko, 2011) investigated the thermal resistance for the heat flow through a typical timber framed pitched roofing system measured under outdoor conditions for heat flow up. However, with higher thermal resistance systems containing bulk insulation within the timber frame, the measured result for a typical installation was as low as 50% of the thermal resistance determined considering two dimensional thermal bridging using the parallel path method.

d) Shading

Shading denotes the partial or complete obstruction of the sunbeam directed toward a surface by an intervening object or surface. The shadow varies in position and size depending upon the geometric relationship between the sun and the surface concerned.

3.3. Heat modulation or amortization technique (Modify heat gains)

The thermal management of a building could be achieved by two methods. In the first method the thermal mass of a building (typically contained in walls, floors, partitions - constructed of materials with high heat capacity) absorbs heat during the day and regulates the magnitude of indoor temperature swings, reduces peak cooling load and transfers a part of the absorbed heat to the ambient in the night hours. The remaining cooling load can then be covered by passive cooling techniques. In the second method the unoccupied building is pre-cooled during the night by night ventilation, and this stored coolness is transferred into the early morning hours of the following day, thus reducing energy consumption for cooling by close to 20% (Brown, 1990).

3.3.1 Shifting of day heat to night for removal

The thermal mass of a building can be achieved either by the use of bulky construction material or by the use of additional energy intensive phase change material in the building system.

a) Thermal mass in the construction material

The thermal mass within the existing buildings can be effectively used to reduce operating costs through simple adjustments of zone temperature set points within a range that doesn't compromise thermal comfort. The cooled mass and higher on-peak zone set point temperatures lead to reduced on-peak cooling loads for the HVAC equipment, which results in higher thermal performance. The potential for using building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulations, laboratory, and field studies (Braun, 1990). This strategy appears to have a significant potential for improving thermal performance. The following table shows the effectiveness of some common materials.

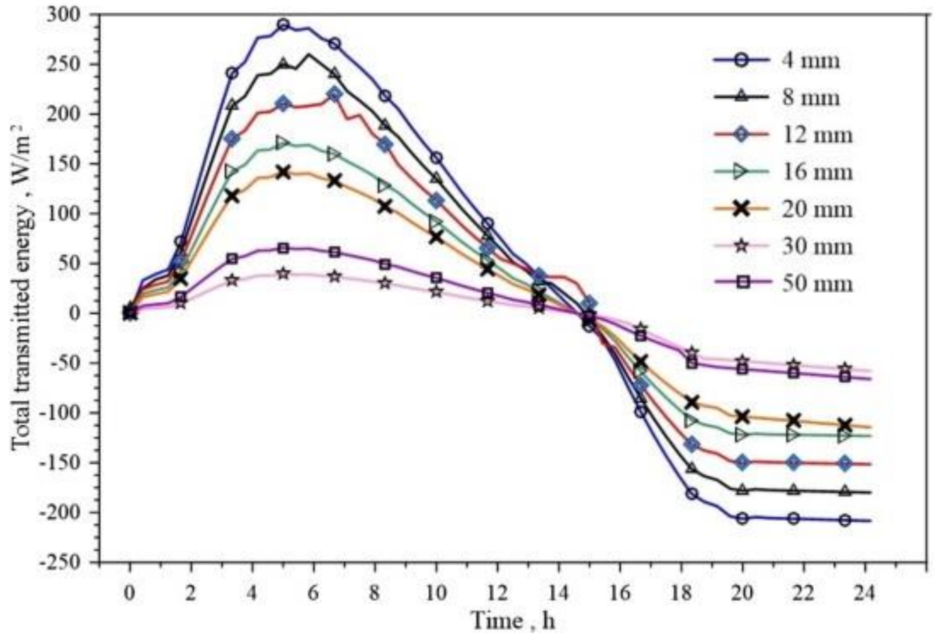
Table 3.1 the effectiveness of some common material.
Source (Tuohy et al, 2004).

Material	Specific heat capacity	Thermal conductivity	Density	Effectiveness
Water	4200	0.60	1000	high
Stone	1000	1.8	2300	high
Brick	800	0.73	1700	high
Concrete	1000	1.13	2000	high
Dense concrete block	1000	1.63	2300	high
Gypsum plaster	1000	0.5	1300	high
Aircrete block	1000	0.15	600	medium
Steel	480	45	7800	low
Timber	1200	0.14	650	low

b) Thermal mass using PCM based systems

In order to enhance the thermal storage effect of the building fabric, thermal mass with high thermal inertia, such as phase change materials (PCMs), is advised to be used. The PCM can be integrated into the building fabric to enhance the thermal storage effect and improve the thermal comfort for the inhabitants.

In a study conducted by Elsayad (Elsayad, 2021), the thermal efficiency of PCM filled DGUs in dry arid region of Cairo, Egypt was investigated experimentally in the temperature field. A CFD study was also carried out using ANSYS FLUENT software to evaluate the impact of different PCM thicknesses on the thermal efficiency of DGUs. The experimental investigations showed that, the temperature of DGU internal surface decreased by 7.6 °C when filled with PCM instead of air, as shown in Graph 3.1.



Graph 3.1 Thermal efficiency of PCM filled double glazing units in Egypt. Sourse: (A.Elsayad, 2021).

3.3.2 Use of night coolness for day cooling

Night ventilation techniques are based on the use of the cool ambient air to decrease the indoor air temperature as well as the temperature of the building's structure.

In a recent study (Santamouris, 2006), night ventilation techniques have been applied successfully too many passively cooled or high-performance buildings, his study concluded night ventilation can be applied to all types of buildings, provided that they are well-insulated and their interior mass enables sufficient cooling potential. Low-mass buildings, however, even when ventilated at night, tend not to retain enough cool reserve to significantly reduce the rate of temperature rise during the daytime, and may actually act as heat traps (Santamouris, 2006).

3.4 Heat dissipation technique (Remove internal heat)

In many cases, the avoidance and modulation of heat gains cannot maintain indoor temperatures at a control level. A more advanced envelop technique includes heat rejection to heat sinks, such as the upper atmosphere and the ambient sky, by the natural processes of heat transfer. The design of a building is a very important factor, which influences the cooling potential of a natural cooling technique. Natural cooling refers to the use of natural heat sinks for excess heat dissipation from interior spaces, including; natural ventilation, double-skin facade, roof pond, ground-air heat exchanger, and radiative cooling system.

3.4.1. Natural ventilation

Natural ventilation is the most important building envelope technique. In general, the ventilation of indoor environments is also necessary to maintain the required levels of oxygen and air quality in a space. Traditionally, ventilation requirements were achieved by natural means. In the majority of older buildings, infiltration levels were such as to provide considerable amounts of outdoor air, while additional requirements were satisfied by simply opening the windows.

a) Wind-driven cross ventilation

Wind-driven cross-ventilation occurs via ventilation openings on opposite sides of an enclosed space. Fig. 3.2 shows a schematic of cross ventilation serving a multi-room building. Sinha et al. (Sinha, 2000) numerically analyzed the room air distribution with or without buoyancy effects for different inlet or outlet configurations for cross-ventilated (Maestre, 2007).

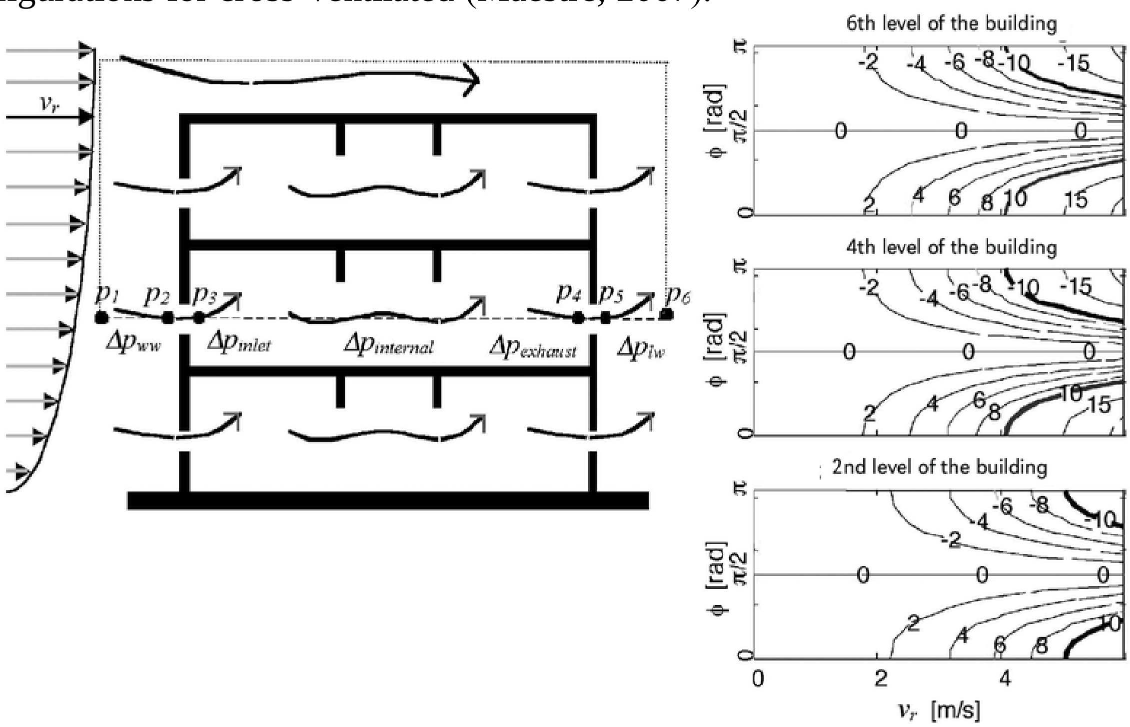


Figure 3.2 Concept of wind driven cross ventilation system.
Source: (Axley, 2001).

b) Buoyancy-driven stack ventilation

Buoyancy-driven stack ventilation or displacement ventilation (DV) relies on density differences to draw cool, outdoor air in at low ventilation openings and exhausts (Bakker, 2005). Fig. 3.3 shows the schematic of stack ventilation for a multi-storied building.

Martí-Herrero and Heras Celemin (Martí-Herrero, 2007) proposed a dynamical model to evaluate the energy performance of a solar chimney with a 24 cm concrete wall as storage surface for solar radiation. The results obtained with the proposed model are coherent with several models' response and experiments reported on solar chimneys.

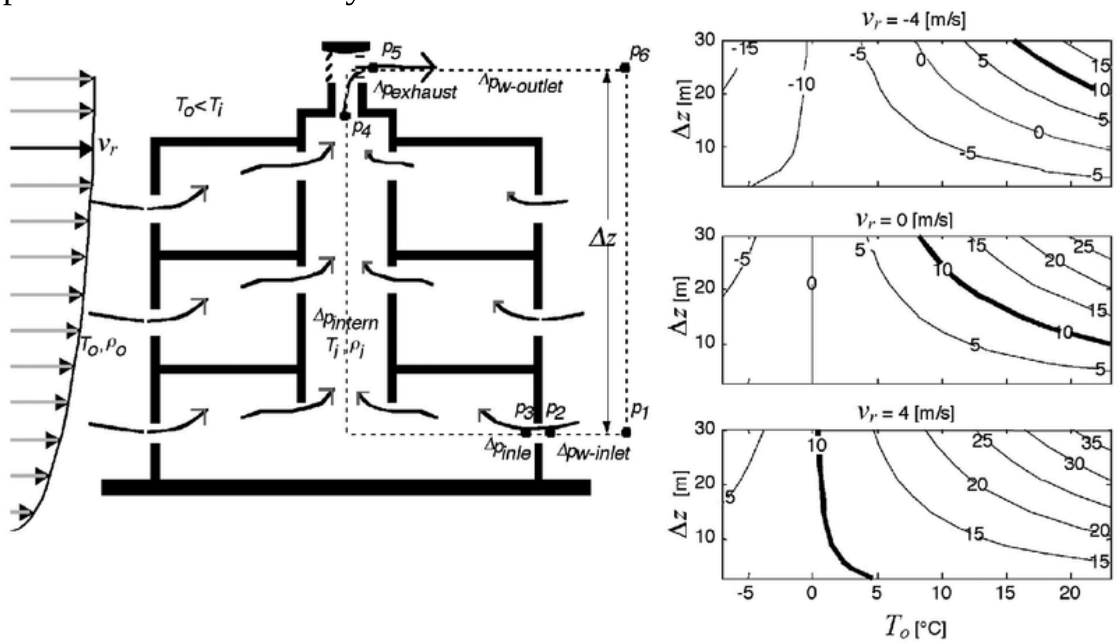


Figure 3.3 Concept of buoyancy driven stack ventilation system.
Source: (Axley, 2001).

c) Single-sided ventilation

Single-sided ventilation typically serves single rooms, and thus, provides a local ventilation solution. Fig. 3.4 shows a schematic of single-sided ventilation in a multi-room building. The ventilation airflow, in this case, is driven by room-scale buoyancy effects, small differences in envelope wind pressures (Goldn, 2007). Consequently, the driving forces for single-sided ventilation tend to be relatively small and highly variable.

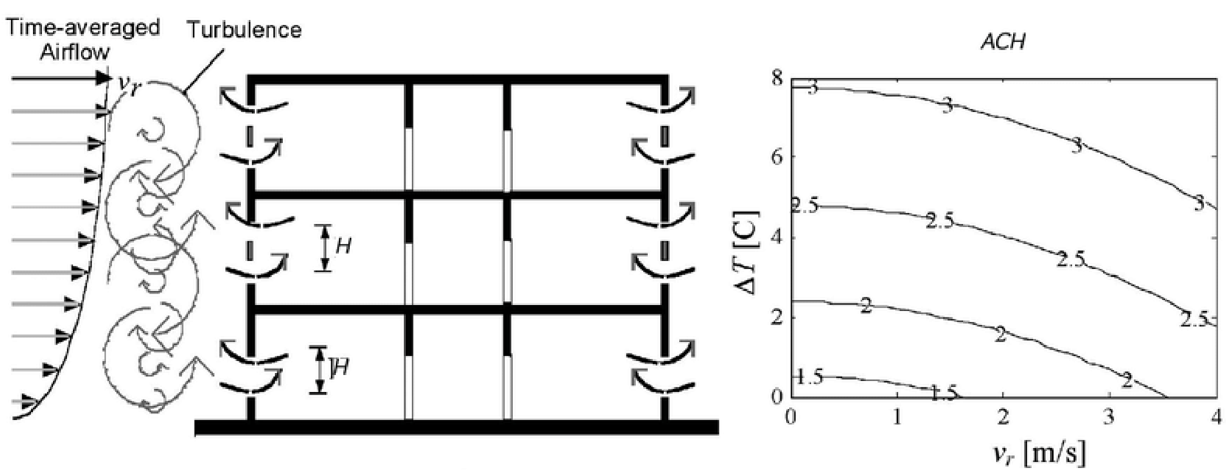


Figure 3.4 Concept of single-sided ventilation system.
Source: (Axley, 2001).

3.4.2. Double-skin façade

a) Definition Single Skin Vs Double

Single skin facade in typical buildings consists of different functional layers including cladding, structure, insulation, etc which separates building interior from exterior. The emergence of curtain walls in the nineteenth century which did not have a load bearing function, made it possible to from an envelope made entirely of glass. Nevertheless, the issues related to thermal comfort condition and low thermal performance of those lightweight single skin envelope supported by the invent of mechanical system.

At the moment the architects tried to incorporate the use of natural ventilation and solar energy which resulted in emergence of new concepts in the facade system such as double skin facade. A double skin facade (DSF) consists of a multilayered facade, which has an external and internal layer that contains a buffer space used for controlled ventilation and solar protection (Arons, 2001). The use of multilayered skins uses building insulation against thermal variation and external noise. As illustrated in Figure 3.5, a DSF could provide outdoor air through operable windows, and preheat or precool the air introduced to the interior space by HVAC system.

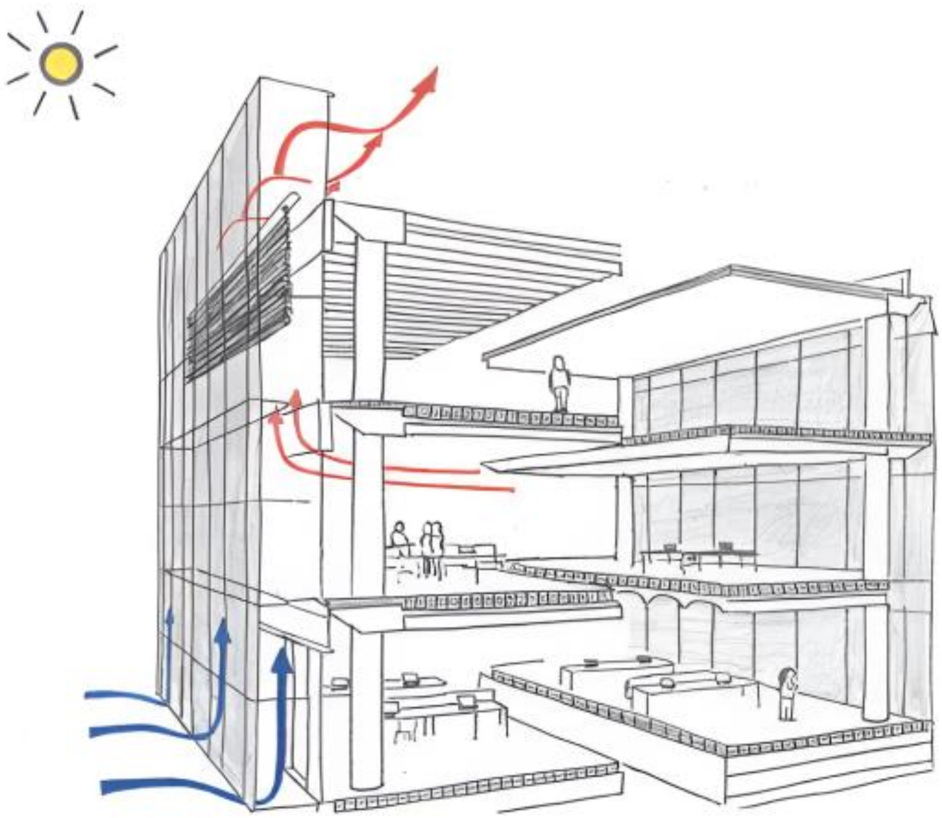


Figure 3.5 Typical DSF (Angus. 2001).

b) History and background

The concept of DSF dates back to when many central European houses utilized box-type windows to increase thermal insulation (Oesterle, 2000). Crespo and Neubert mentioned that a double-skin curtain wall appeared first in 1903, in the Steiff factory in Giengen, Germany, where priorities were to maximize daylight while taking into account the cold weather and strong winds of the region. A DSF was assumed to be energy efficient and environmental friendly, providing a 40-60 percent reduction in energy consumption, external noise reduction, and natural ventilation even in skyscrapers (Oesterle et al., 2001).

Three characteristics identify types of double skin facades. These are based on geometric characteristics and also the ventilation mode and type.

- Type of ventilation.
- Partitioning of the façade.
- The modes of cavity ventilation.

c) Type of cavity ventilation

The two main driving forces of natural ventilation are the differences between the pressure created by the stack effect and wind effects. Natural ventilation drives the air through a space by taking advantage of the pressure differences caused by these two factors due to internal temperature differences or a combination of both. Hybrid ventilation is a controlled compromise between natural and mechanical ventilation.

Note: The stack effect (or chimney effect) is a phenomenon related to the rising of hot air. Applied to a DSF, the concept of stack effect expresses the fact that air is lighter than cold air. As the cavity is generally hotter than the outside, air has a tendency to escape at the top (Loncour, 2002).

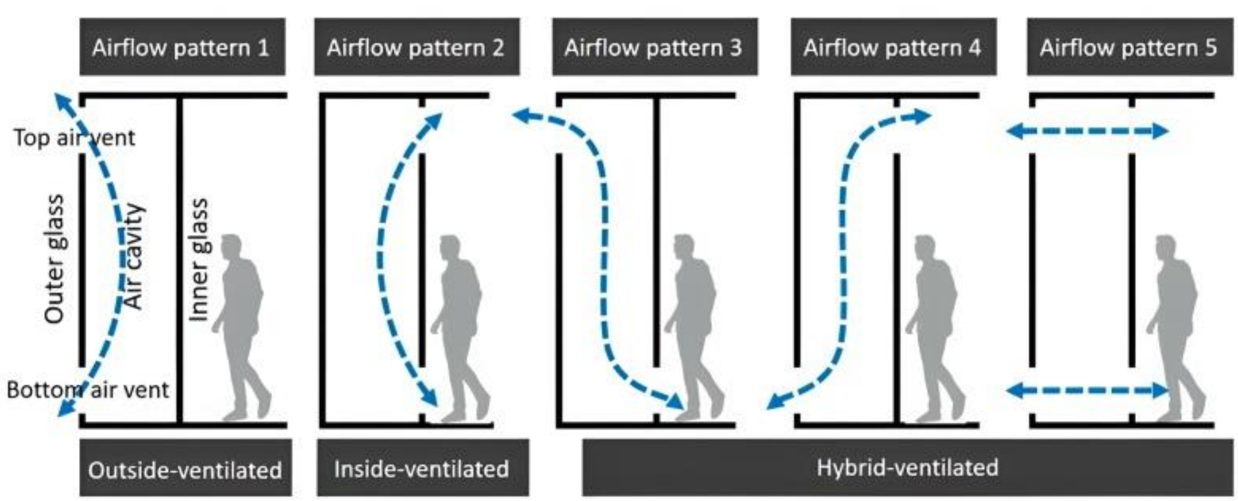


Figure 3.6 the five ventilation modes: outdoor air curtain; indoor air curtain; air supply; air exhaust, and air buffer (Jeehwan, 2019).

d) Airflow concept

Based on the ventilation mode, the DSF was categorized into five groups. The ventilation mode is independent of the type applied (the first classification presented). Not all facades are capable of adopting all the ventilation modes described here; a facade is characterized by a single ventilation mode. However, a facade can adopt several ventilation modes at different moments, depending on whether or not certain components integrated into the facade permit it (i.e. operable openings). One must distinguish between the following five main ventilation modes:

- Outdoor air curtain

  In this ventilation mode, outside air introduced into the cavity is immediately turned back outside. The cavity ventilation thereby forms an air curtain enveloping the outside facade.
- Indoor air curtain

  The air comes from the inside of the room and is returned to the same place or via the ventilation system. The cavity ventilation forms an air curtain enveloping the indoor facade.
- Air supply

  The ventilation of the facade is created with outdoor air. The air then travels to the interior room or into the ventilation system. This makes it possible to supply the building with air.
- Air exhaust

  Air inside the room is evacuated towards the outside. The ventilation of the facade thus makes it possible to evacuate air from the building.
- Buffer zone

  This ventilation mode is distinctive as each of the double facade skins is made airtight. The cavity thus forms a buffer between the inside and the outside, with no possible cavity ventilation.

e) Partitioning of the facade

Based on the geometry of the facade (width openings, cavity height and width, etc.), Oesterle et al. (2001) categorized DSF into the following groups: box window, shaft window, corridor facade and multi-story, as shown in Figure 3.7.

If the DSF extends over the entire height and width of the building, the term, facade, is appropriate. If the facade is divided into smaller units, three main categories can be defined. If the partitioning consists of vertical ducts, the expression shaft facade is adopted. When the facade is horizontally partitioned, the term corridor facade is usually employed. If the facade is both horizontally and vertically subdivided, the DSF is called window or box. The term windows can be used for systems in which the windows act as DSFs.

- Box window

In this type, the facade is horizontally and vertically subdivided, with entirely transparent envelopes. Horizontal and vertical partitioning divides the facade into smaller and independent boxes. This type of window is common in areas with high external sound levels and special requirements relating to sound insulation between adjoining rooms. This form is the only type that provides the function of a DSF with a conventional way of opening (Osterle, 2001).

- Shaft type

In this case, a set of box-window elements are placed in the facade with continuous vertical shafts that go along a number of stories to create a stack effect. On every story, the vertical shafts are linked with the adjoining box windows by an opening. The stack effect draws the air from the box window into the vertical shafts. The air also can be sucked out mechanically. This type of DSF is suited for low-rise buildings, since the height of stacks is limited (Osterle, 2001). Figure 3.7 shows the plan, elevation, section, and diagram of ventilation in the shaft type. The arrows indicate the route of the airstream through the box windows and the common shaft.

- Corridor type

When necessary, divisions occur horizontally along the corridor for fire protection or ventilation reasons. The intake and extract openings are situated near the floor and the ceiling. They are usually staggered to prevent extracted air on the floor from entering the space on the floor immediately above (Osterle, 2001).

- Multi story

In this DSF case, the cavity is adjoined vertically and horizontally by a number of rooms. Ventilation occurs via large openings near the ground floor and roof. The room behind the DSF should be ventilated mechanically (Osterle, 2001).

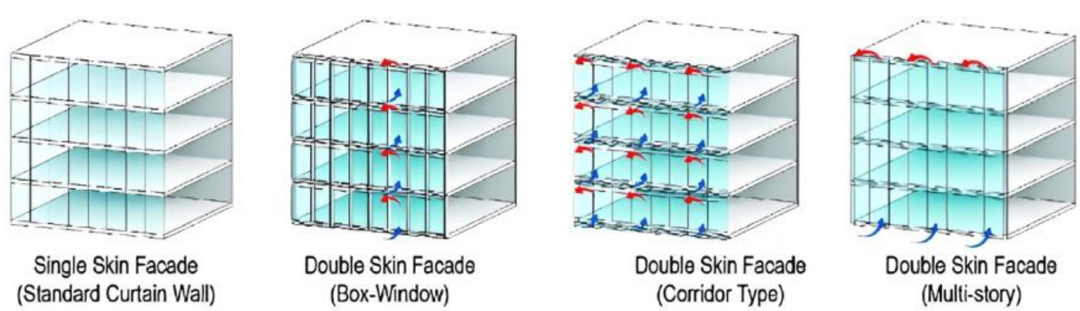


Figure 3.7 The DSFs Classification Based on the partitioning of the façade (Ajla, 2017).

f) Previous work

Double skin facade (DSF) is a concept that is being adopted on many new buildings in the world with the promise of improving thermal performance while maintaining a transparent facade. Research, studies, and several simulation programs have been carried out to explore solar chimneys one way to increment natural ventilation and improve indoor air quality and Trombe walls prior to DSFs. Gan (Gan, 1998) studied Trombe walls for summer cooling of buildings. He used CFD to simulate ventilation rates resulting from natural cooling. He also investigated the effects of the distance between wall and glazing, wall height, and type of glazing. He concluded that, using trombe wall for summer cooling by the buoyancy effect increased with the wall temperature, wall height and thickness. Afonso (Afonso, 2000) compared the behavior and air-exchange rate in a room with both a conventional and solar chimney at different times of the year. He concluded that chimney wall thickness should be chosen according to building utilization. A small thickness is optimal for diurnal operation; for night operation, a larger thickness is advisable. He also mentions that as the nature of wind is variable, the design of the solar chimney can be done without considering the wind effect. Most of the studies using the stack effect idea or the solar chimney concept found that passive summer ventilation is possible even in multi-story buildings. Due to the random nature of the wind, these studies did not consider it in the simulation. In the U.S., people are reluctant to use DSFs due to high first costs and the lack of a precise airflow model that can accurately predict the facade performance. Arons (2000) developed a model of performance and experimentation verification on a small-scale facade for a Japanese climate. An experimental study determining the performance of a single-story, south-facing DSF was done at Virginia Technical Institute by Shang Shiou Li (Shang, 2001).

Saelens (Saelens, 2002) also contributed to the energy performance assessment of single story, multiple-skin facades that are naturally and mechanically ventilated. He undertook a controlled experimental set-up measure and provided data to compare and validate the numerical model. He found that a traditional facade with shading devices were comparable to a naturally ventilated DSF and a mechanically ventilated one. Faggembauu (Faggembauu, 2003) did a numerical study on passive systems in general, and advanced the concept of facades in particular. In the study, a transient code for the simulation of double and single skin facades including advanced technological elements such as phase change materials, transparent insulation, and facade integrated collectors was developed (Manz, 2005).

Nori (Nori, 2004) attempted to look at the impact of DSFs that face south in a temperate climatic condition. Thermal analysis using simulation software for different seasons of a year was performed for a low-rise office building with and without a DSF. The results indicated that significant energy savings are possible if natural ventilation can be exploited by using DSFs. Oesterle et al. (Oesterle, 2001) compiled DSF typologies, advantages, disadvantages, uses and many examples to prove this point. A parametric analysis of overheating in summer conditions in a full-scale DSF laboratory chamber was carried out for this study. CFD was used to compare the results with full-scale experimental models by Hernandez (2006). Numerous papers have described how multiple skin facades should work to improve a building‘s energy efficiency. Manz (2005) mentions that, Gertis correctly points out that only few simulations have been made and that only few measurements are available to support the claimed benefits. Much of the literature deals with specific topics such as the modeling of the convective heat transfer in cavities or the optical properties of glass layers.

3.5 Conclusion

The recent concept of thermal performance improvement attracted all the scientists and building architects to switch over from the present practice of mechanical cooling to ancient methods of performance improvement methods in an efficient modern way. It should be noted that a concept suitable for one place may not be suitable for another, if the climatic conditions are different. Hence, being highly site specific, based on the climatic zones, the selection of suitable techniques, and the associated materials have to be made (Orosa, 2012).

In this chapter several envelope techniques were reviewed and discussed with reference to their design implications and architectural interventions. The continuing increase of energy consumption of air conditioning suggests a more profound examination of the urban environment and the impact on buildings as well as an extended application of these techniques. Appropriate research should aim at better understanding micro-climates around buildings, and to understand and describe performance improvement requirements under transient conditions during the summer period. Also of importance are improving quality aspects, developing advanced envelope systems, and finally, developing advanced solutions for the building envelope (Santamouris, 2005). In today’s architecture, it is now essential for architects and building engineers to incorporate performance improvement techniques in buildings as an inherent part of the design and architectural expression and they should be included conceptually from the outset. Incorporation of these techniques would certainly improve the thermal performance and reduce our dependency on artificial means for thermal comfort and minimize the environmental problems due to excessive consumption of energy and other natural resources and hence will evolve a built form, which will be more climate-responsive, more sustainable, and more environmental friendly of tomorrow.

Chapter Four
Simulation Software: Review and Comparison

4.1 Introduction

The importance of analysing thermal performance in building design has grown, but it is still often done using simple static calculations or estimates. Accurate dynamic thermal simulation software has been available already for decades, but these tools are still not widely used by practitioners in building projects. Currently, there are many software tools available for simulating the performance of buildings, which difference in features and capability from whole-building simulations to model input calibration to building auditing. This software can provide an easy tool used by designers to analyze buildings behavior.

This chapter aims to identify some of the most important software due to their capacity of calculating a significant number of variables and to compare them in order to establish their differences. A comparison between these features was shown as a summary table of the capabilities of each simulation tool. The comparison is conducted in three categories which are: general characteristics of simulation model includes (general modeling features and zone loads), external thermal loads (building envelope, daylighting, and solar infiltration), and ventilation and multi-zone airflow.

4.2 Overview

The climatic conditions inside the building are a result of a complex interaction between human, building, and the environment (Sukjoon, 2013). It is not easy to be comprehensively described or understood through curves, tables, or simple recommendations; Just as facilities in climatic design were provided by old generation. Recent version of these facilities rely on digital representation via computers to assist climatic designer to take careful and climatic designs so that designer can see their results clearly, and computer in its turn play the role to help with that take some loads off the designer (Reddy, 2006). Yearly, tens of programs that take part in building climatic behavior representation or some of its specific parts arrive .

Usually, several of these programs are result of individual university researches and often done by groups while the others are commercial programs that companies provide to professional designers (Hong, 2017). Although there are much software, these tools are still mostly used by researchers, not widely by practitioners in building projects. This issue still at its very early times, because those programs are need much work to become highly efficient. Also, they require much development to become easy and practical for designers and become part of architectural design stages. The energy simulation software allow to determinate with accuracy some variables that can support designers to take decisions about the best measures to apply for any building to built or already existent (Clarke, 2019).

Building performance simulation is a technology of considerable potential that provides the ability to quantify and compare the relative cost and performance attributes of a proposed design in a realistic manner and at relatively low effort and cost. Energy demand, indoor environmental quality (incl. thermal and visual comfort, indoor air quality and moisture phenomena), HVAC and renewable system performance, urban level modeling, building automation, and operational optimization are important aspects of BPS (Pieter, 2018). Simulation software is based on the process of modeling a real phenomenon with a set of mathematical formulas. It is, essentially, a program that allows the user to observe an operation through simulation without actually performing that operation (Dougall, 2007).

Simulation software is used widely to Forecasting design effectiveness so that the final product will be as close to design specs as possible without expensive in process modification. Therefore, studying simulations software is essential to evaluating the climatic state and improves thermal performance of buildings, in addition to focusing on simulation programs that are used and conducting an analytic study for them (Crawley, 2008). There are hundreds of software tools available for simulating the performance of buildings and building subsystems, Where, This chapter aims to identify some of the most important due to their capacity of calculating a significant number of variables and to compare them in order to establish their differences.To compare the thermal performance of these revisions and to visualize this by an easy-understanding way. This chapter shows the recent developments for methods and interoperable software environment to manage spatial thermal performance.

4.3 Important of Simulation Software tools

Nowadays, designers need tools that answer very specific questions even during the initial design phase. Through the use of simulation software, designers can consider specific choices, (e.g., heating and cooling). Designers can also predict the thermal behavior of buildings prior to their construction and simulate the costs of energy in existent buildings in their current conditions, establishing the best thermal retrofitting measures to adopt in the buildings under analysis. Besides that, simulation software tools can also be used calculate to the following variables:

1) Indoor temperatures.
2) Needs for heating and cooling.
3) Consumption needs of HVAC systems.
4) Natural lighting needs of the occupants.
5) Interior comfort of the inhabitants.
6) Levels of ventilation.

The predict the thermal performance of the buildings allows a more accurate determination of design charges and helps to decide with the highest accuracy the possible devices to be used in a room (limited zone) or dwelling. The simulation software tools can also allow considering all the regulations in force and simultaneously provide a sense of comfort to its inhabitants through a correct design of heating and cooling systems. Such software has also available tools to improve constructive solutions through simulating the incorporation of envelope techniques in buildings.

4.4 Barriers to use simulation software

The main barrier of wider usage of dynamic thermal analysis methods has been the required big manual input work. By utilising simulation software as a data source for thermal analysis, the data input will be more efficient and the existing data more reusable. Software facilitates easier verification of the thermal performance in different phases of the building process. While the other barriers for wider utilisation of simulation software in the thermal analysis have been the missing interoperable data interface implementations in thermal simulation tools and the lacking guidelines.

4.5 Presentation of Some Energy Simulation Software tools

Computer simulation has become a good way to create solutions in the environmental studies field of buildings. Before computers arrived, architects used mathematical formulas in any difficulty, if the problem continued they used graphs, there are many problems in the engineering field that can be solved through graphs (Heo, 2012). For the past 50 years, a wide variety of building thermal simulation programs have been developed, enhanced and are in use throughout the building energy community (Mustafaraj, 2014).

In this section, some commonly used building simulation tools and computer application packages are presented for building thermal modeling areas listed in Appendix B (Please refer to table 1 that presents a general review of some common simulation tools for thermal modeling in Appendix B) which are: TRNSYS – TRANCE – TAS – SUNREL - POWERDOMUS - HEED HAP – IES(VE) – IDA(ICE) – ESP-R –QUEST – ENERGYPLUS - ENER(10) – ENERGY EXPRESS - ENER(WIN) – CFD - DOE(2.1E) – DEST - DIVA– BSIM – BLAST .

4.6 Comparison of Energy Simulation Software tools

This section presents the capabilities of simulation software tools. Each software tool has a specific application and certain characteristics. In order to better understand specific features of each tool. A comparison between these features was shown as a summary table of the capabilities of each simulation tool mentioned above. That can support designers to take decisions about the best measures in the early design stages, and encourage users to consider adopting a suite of tools that would support the range of simulation needs they usually see in their practice.

Comparison has been conducted in three categories which are: general characteristics of simulation model includes (general modeling features and zone loads), external thermal loads (building envelope, daylighting, and solar infiltration), and ventilation and multi-zone airflow.

4.6.1 General characteristics level

Comparison between simulation software according to general characteristics of simulation model and internal thermal loads calculation. Tables 2-3 (Appendix A) show how the different software tools are used in buildings simulation according to the climate requirements, models, solutions, and architectural elements that support CAD files.

4.6.2 External thermal loads level

Comparison between simulation tools according to external thermal loads, building envelope design, and daylight. Tables 4-5 (Appendix A) illustrate the role of materials that help to provide thermal comfort whether there is a thermal balance, thermal conductivity, or convection inside zones. And also illustrates the probability to evaluate the thermal performance and the significant difference between tools in using the average of the surroundings radiation temperatures that is used by most tools. Finally, these tables show the simulation software processing of solar radiation outside the building and distributing that radiation in or through the building.

4.6.3 Airflow and ventilation calculation level

Comparison between simulation software in terms of ventilation calculation and Airflow through the zones. Tables 6-7 (Appendix A) show how airflow either outside or through the zones. Some simulation tools provide one airflow model in the zone at least, and very few of these tools can analysis the natural ventilation, and some tools provide an airflow model through Mesh dependency.

4.7 Simulation Software tools available in Sudan

There is a lot of simulation software unavailable in Sudan owing to the American block against Sudan,. In this section, some simulation tools for thermal modeling that are available in Sudan are presented, which are:

- Energy plus.
- Computational fluid dynamics (CFD).
- Grasshopper software and DIVA plug-in.

4.7.1 Energy Plus

Energy Plus is one of the most known energy simulation software tools. Its development began in 1996, (Coakley, 2014). Initially, the company was developing two different software tools, BLAST and DOE-2, which were abandoned after many discussions and represented a first step and the working basis of the Energy Plus. The Energy Plus has the features and capabilities of BLAST and DOE-2, however is an entirely new software tool that combines the heat balance of BLAST with a generic HVAC system. The Energy Plus aims to develop and organize software tools in modules that can easily work together or separately. It is important to outline that in Energy Plus does not exist a visual interface that allow users to see and concept the building. In this case third-party software tools, i.e., Design Builder need to be used. Energy Plus is a thermal simulation software tool that allows the analysis of energy throughout the building and the thermal load and it is used by engineers, architects and researchers to model the energy use and water use in buildings. The software tool simulates models for heating, cooling, lighting, ventilation, other flows of energy and water use. The simulation of a building is divided into two stages (De Wilde, 2018):

- Construction of the building.
- Introduction of data, such as environmental aspects, effects of shading, cooling system, internal gains, etc.

There is an increasing range of energy simulation software tools available, with the ability to calculate increasingly complex energy requirements, with more variables and a more rigorous approach. Generally speaking in energy Plus software there are three steps that have to be performed to a building simulation.

1) First Step - Creation of a Building

The creation of the building is the earlier stage of an energy simulation. This process can be done in Energy Plus simulation software (Figure 4.1) or by uploading files from other software, such as AutoCAD or Google Sketch Up. The introduction of coordinates is performed according to a certain reference (which is located in a pre-determined position).

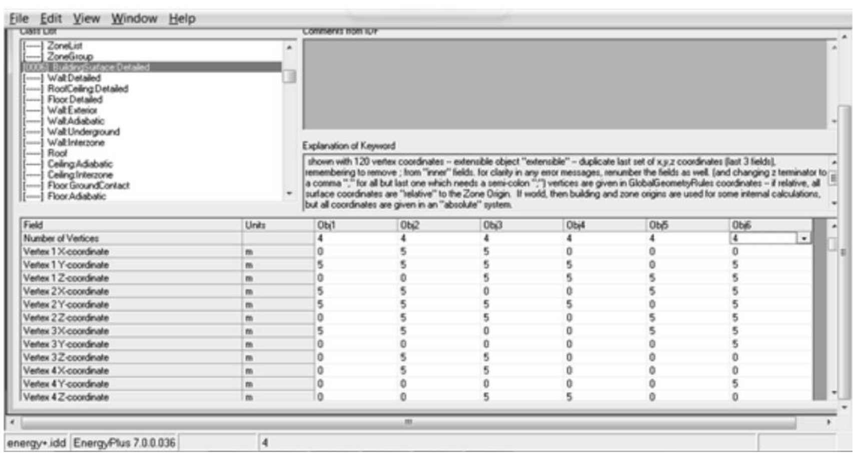


Fig. 4.1. Introduction of coordinates of a cube in the option "Detailed Surface Building" of EnergyPlus (Author).

After this procedure, it is possible to see the figure introduced in the software tool through the DXF button (Figure 4.2) that connects to AutoCad and which allows to view it in this format (Figure 4.3).

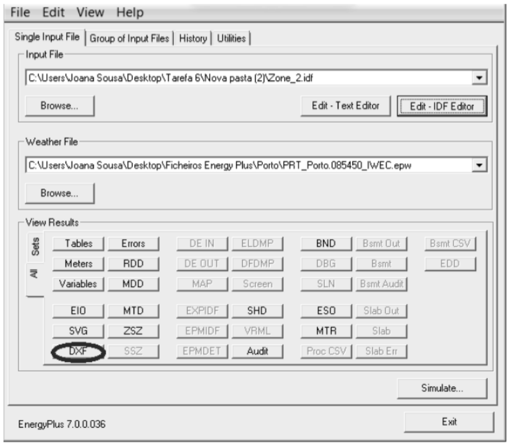


Fig. 4.2. DXF button in the EnergyPlus (Author).

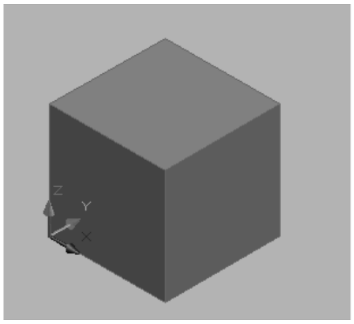


Fig. 4.3. Results of Coordinate Insertion in EnergyPlus (Author).

Concerning the structure of the building and its construction, it is essential to specify the dimensions of the organizational structure, geometry, and materials used in the components of the building architecture (Figure 4.4). The development of the model based on the characteristics mentioned above represents the building itself ready to be computed.

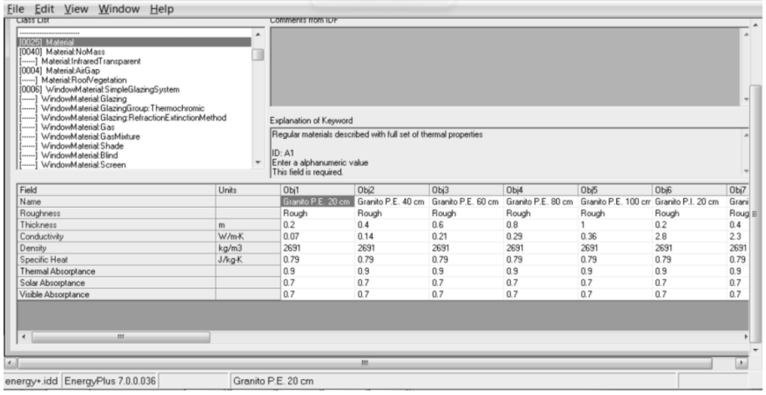


Fig. 4.4. View of the Interface to the Introduction of the Materials in Energy Plus (Author).

2) Second Step - Building Simulation

In this step, it is established which variables are to consider in the simulation of the building and make the software tool run. The thermal performance of the building can vary according to its use. Therefore it is important to specify the type of building (office, housing, etc.), the human activities carried out, the existing equipment (lighting, refrigeration, air conditioning systems, furnaces, etc.), and their daily schedules (Figure 4.5). The description of these parameters allows establishing the internal heat load and ventilation (Figure 4.6).

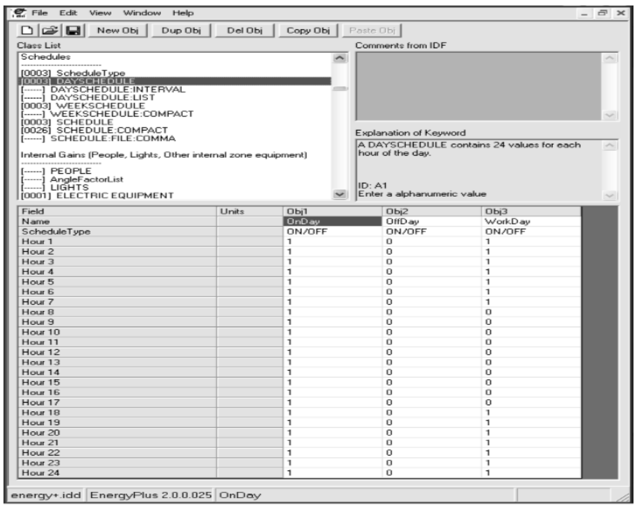


Fig. 4.5. View of the Interface to the Introduction of Schedules in Energy Plus (Author).

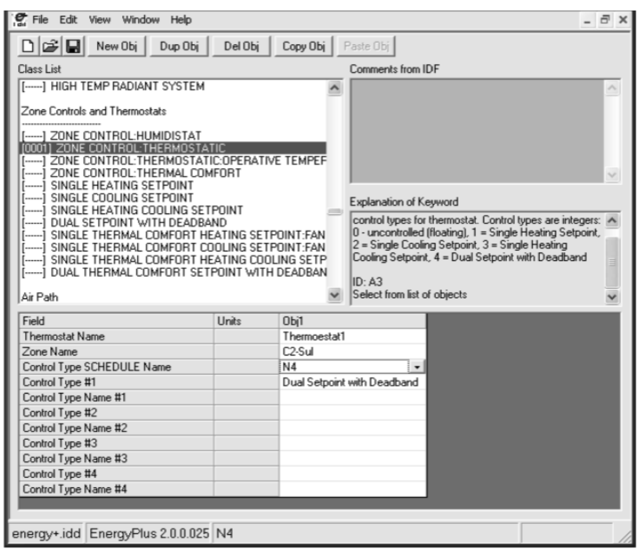


Fig. 4.6. View of the Interface to the Introduction of Thermostat Definitions in EnergyPlus (Author).

3) Third Step - Analysis of Results

After running the software tool, it should be checked if there are any error or severe mismatch introduced in the variables set. In some cases the simulation software tool issues its own warnings in a final report containing the results from which should be retained all the relevant conclusions (Figure 4.7).

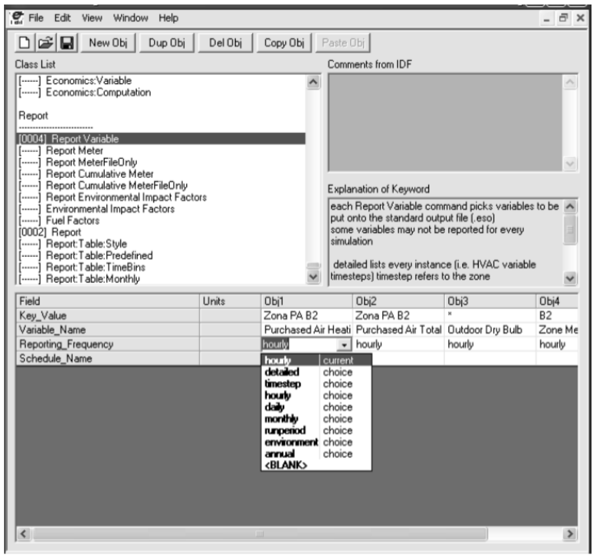


Fig. 4.7. View of the Report Variable Definitions in Energy Plus (Author).

4.7.2 Computational Fluid Dynamics (CFD)

Energy-conscious designers harness the cooling capacity of natural wind to improve the thermal performance and increase indoor thermal comfort for active-space conditioning. Wind can cause air movement and perception of cooling, wind can bring in air of a different temperature and humidity. By numerically solving a series of conservation equations related to mass, momentum, and energy, computational fluid dynamics (CFD) tools help designers predict detailed airflow for special design cases and plan a building with optimal natural ventilation.

1) Application of CFD for building design

Knowledge is often needed about the pattern of airflow and distribution of air temperature within an enclosed space. This may be especially important in checking the performance of a natural ventilation system to predict performance. Different techniques can be used to study the wind effect in building design, such as a model mockup, wind tunnel, nodal/zonal models, and computational fluid dynamics (CFD). It is often inconvenient to evaluate full-scale (model mockup) buildings in the design or occupancy phase of a building, so models are created to simulate the airflow. The goal of modeling is to evaluate systems in feasible, economical way. Modeling techniques have been used to investigate flow around objects and within spaces and buildings in a wide variety of systems.

Three types of models are currently used: mathematical models that provide an analytical solution; computational models that provide a numerical solution; and physical models used for experimental solutions. Analytical solutions are mathematical analyses that describe the phenomena under investigation through a series of equations. An analytical solution is assumed to have a closed-form solution, in that at least one solution can be expressed as a mathematical expression in terms of a finite number of well-known equations. The governing, analytical flow equations for buoyancy. They are applicable to simple configurations and geometries with well-mixed assumptions and a limited number of zones. The numerical solution is a more complex version of the mathematical model described above, in that it is a system of algebraic relationships that are solved simultaneously.

The computational model provides point-like solutions, with unique values for a series of determined points. A common approach to numerical solution in the area of ventilation is the use of CFD software to quantitatively predict fluid flow in or around objects. CFD software programs have the ability to model temperature interactions, heat flow, buoyancy, and air flow in and around buildings. A grid of boundary surfaces and inclosed space is used to solve the mechanical and thermodynamic relationships throughout the environment under analysis, taking into account the layout, ventilation opening(s), geometry, and heat loads (Szucs, 1980).

2) CFD approaches in an indoor environment simulation

CFD programs, in particular, can be used to deal with problems associated with the thermal environment, thermal performance, indoor air quality, and building safety as they estimate important parameters such as temperature, airflow, and relative humidity. CFD applications in indoor environments are very diverse and there are many recent examples of its use for natural ventilation design (Carrilho da Grace et al., 2002), the study of building material emissions for indoor air quality assessment (Murakami et al., 2003), building elements design (Manz, 2003) and for building energy and thermal comfort simulations (Bartak et al., 2002; Beausoleil-Morrison, 2002; Zhai and Chen, 2003).

3) CFD approaches in Thermal performance

By numerically solving the governing equations for fluid flow, CFD provides spatial-and temporal-distributed information of airflow, pressure, temperature, turbulence intensity, and moisture and contaminant concentration. These details can be used to evaluate the thermal performance, indoor air quality, and building system energy efficiency. Air velocity, temperature, and humidity ratio are the most important parameters in determining the predicted percentage dissatisfied (PPD) distribution in a building (Zhai, 2005).

- *Temperature and radiation (dry bulb, mean radiant):* Thermal sensation is dominated by the surrounding temperature. The standard dry bulb temperature, however, is not always a sufficient indicator for establishing a good indoor thermal environment, as it does not take into account the influence of radiant energy. The mean radiant temperature is a more appropriate thermal comfort indicator, as it is a measure of the average radiation exchange between the occupant and the surrounding surfaces.
- *Relative humidity*: Relative humidity is the ratio of moisture content at a certain temperature to the maximum possible moisture content at that temperature (until condensation starts). Generally, humidity affects heat loss by evaporation, which is most important at high temperatures and high metabolic rates (ASHRAE Fundamentals, 2005).
- *Air velocity and turbulence*: The thermal performance is influenced by air velocity and the scale of turbulence. Often the increased velocity can be an advantage in an office space, where the temperatures are higher than the comfort range. A typical way to increase air velocity is to use circulation fans. However, at other times, draughts cause discomfort due to localized cooling.
- *Activity*: activity level results in metabolic rates between 1.0 met and 1.3 met for office building.
- *Operative and resultant temperatures*: The operative and mean resultant temperatures empirically combine the dry bulb and the mean radiant temperatures. The operative temperature is the temperature at which a person emits the same heat output as before, but when air temperature (T_a) = radiant temperature (T_r) = operative temperature (T_{op}) (Peterson, 1991). The Top does not have the same value for all parts of the room.

4) CFD approaches in an outdoor airflow simulation

A CFD program can also calculate the pressure difference around buildings and these data can be used it as boundary conditions for subsequent indoor airflow simulation. Ideally, the calculation should be performed for different wind directions under various wind speeds in a period suitable for natural ventilation. It is also interesting to note that CFD can help develop natural ventilation by modeling and optimizing building site plans and indoor layouts. Jiang and Chen (2002) found that the outdoor environment has a significant impact on the indoor environment, especially in buildings with natural ventilation. They recommended that both the indoor and outdoor environments along with the combined indoor and outdoor airflow need to be studied together.

5) Simulation approach: Model set up

A. Fundamental of airflow modeling

Key parameters calculated as part of a CFD analysis include:

❖ Pressure distribution

Airflow is driven by pressure distribution; therefore the pressure field is fundamental to the whole flow process. Pressure is maintained by a combination of driven air or forced convection and buoyancy forces or natural convection. Free convection is driven by buoyancy forces created by an imbalance in temperature difference.

❖ Velocity field

Air movement is a vector having components in both speed and direction. To determine the air velocity distribution, air flow must usually be represented by three transport equations.

❖ Temperature field

The temperature field is sustained by thermal sources and sinks distributed about the enclosure. Buoyancy forces and free convection currents are generated by the temperature field.

❖ Boundary layer flow

Air flow close to surfaces is subjected to boundary later effects in which the rate of flow is influenced by surface friction.

❖ User input-boundary conditions

Flow, turbulence, temperature, and pollutant fields are unique to the prevailing boundary conditions. Input data must include:

- Location of openings.
- Mass flow into and out of the building.
- Type of flow boundary.
- Velocity (speed and direction of flow through each opening).

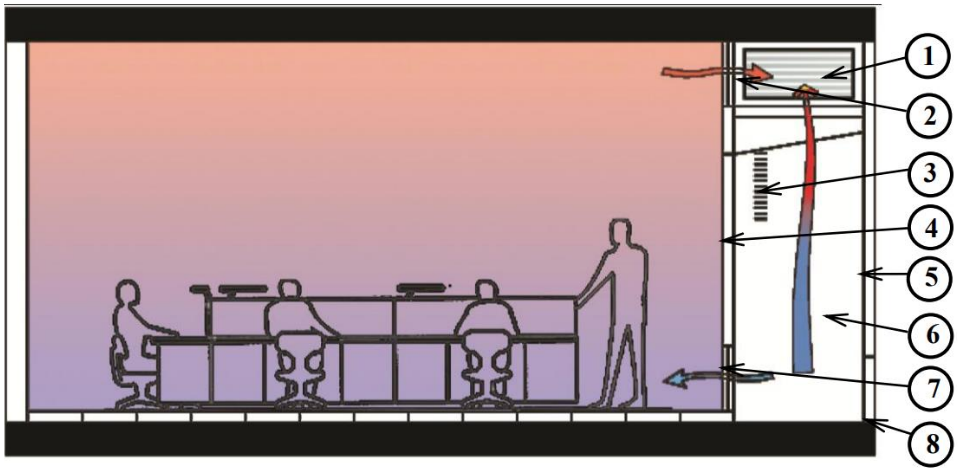


Figure 4.8 The schematic diagram of the module's inputs:
1) upper air outlet to chimney, 2) interior upper operable window, 3) controllable solar control device 4) interior operable or fixed view window, 5) exterior glazing layer
6) air cavity, 7) interior (Mona, 2020).

B. Creating a model geometry for CFD

In order to analyze the CFD model, geometry needs to be created in Gambit (Gambit is a meshing software program), which uses discrete points to describe the space. The Gambit model and the mesh grid are then used to conduct the following CFD analytics.

- Finite volume grid and geometric modeling considerations.
- Modeling and solvers.
- A model grid in Gambit.

C. Boundary conditions of the three-dimensional model

An important initial concept for CFD analyses is that of boundary conditions. Each of the dependent variable equations requires meaningful values at the boundary of the calculation domain in order for the calculations to generate meaningful values throughout the domain. These values are known as boundary conditions, and can be specified in a number of ways. The specification of boundary conditions for two driving forces of wind and buoyancy effect can be defined as a pressure difference on inlet and outlet. By then setting the gravity vector correctly, the Boussinesq approximation calculates the natural convection effect. Regarding the outdoor wind, by specifying pressure inlet and outlet conditions, the dynamic pressure of wind will be taken care of, therefore the following effects can be specified effectively there.

- ➢ Wind speed, wind direction, and mean wind speed profile.
- ➢ Outdoor air temperature, air humidity, and solar radiation.

6) Interpretation of CFD results

The simulation runs for an initial number of 1200 iterations typically. Then residuals will be plotted to check the residuals in the boundary definition would be converged. The simulation needs to be extended with at least all the residuals showing approximation to residuals of $1e^{-8}$. It is also necessary to carefully review the boundary settings and software mesh to solve the problem or trend to diverge of the continuity residual. As a result, the temperature can be plotted

To illustrate the inlet outlet temperature gradient. Also air-velocity magnitude inside the domain shows the influence of the convective forces. The results of the CFD simulation then can be used to evaluate the thermal performance based on the formula described at the beginning of this chapter.

4.7.3 Grasshopper and DIVA is a plug-in

Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application. The program was created by David Rutten at Robert McNeel & Associates.[Tedeschi, 2011] Programs are created by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components.

Grasshopper is primarily used to build generative algorithms, such as for generative art (Loomis, 2010) Many of Grasshopper's components create 3D geometry. Programs may also contain other types of algorithms including numeric, textual, audio-visual, and haptic applications (Payne, 2011). Advanced uses of Grasshopper include parametric modeling for structural engineering, parametric modeling for architecture and fabrication, lighting performance analysis for eco-friendly architecture, and building energy consumption (Tedeschi, 2011).

The first version of Grasshopper, then called Explicit History, was released in September 2007.[Willis, 2016] Grasshopper has become part of the standard Rhino toolset in Rhino 6.0 and later. According to Rutten (Rutten, 2013), Rhino modeling tool is endemic in the architectural design world. The new Grasshopper environment provides an intuitive way to explore designs without having to learn to script. Research supporting this claim has come from product design and architecture.

DIVA for Rhino is Solemma's legacy daylighting and thermal modeling plug-in for Rhinoceros, a NURBS modeling software. DIVA is a plug-in for Grasshopper to run several simulations, such as:

1) Solar radiation analysis
2) Daylight autonomy
3) Glare analysis.

However, it does not produce graphical illustrations for a particular climate (e.g. charts and graphs).

4.8 Simulation tasks and research tools

The required purpose and tasks to achieve its research objectives could include the following:

1) Calculate the thermal loads.
2) Calculate the thermal properties of materials.
3) Airflow analysis.
4) Heat transfer analysis.
5) Solar radiation analysis.
6) Heat dissipation analysis.

The required simulation tasks in this research and the suitable simulation tools for the realization of these tasks are summarized in the following table.

Table 4.1 The purpose and tasks of each simulation software (Author).

Simulation Software	Tasks	Chapter
Energy Plue	To calculate the thermal loads and thermal properties of materials	Chapter 7
Computational fluid dynamics (CFD)	To simulate the airflow and convective heat transfer	Chapter 8
Rhino, Grasshopper software, and DIVA plug-in	To simulate the buildings orientation and shading device	Chapter 8

4.9 Summary

Along with materials and construction techniques also energy simulation software tools of buildings have had developments over the years. Currently, there are several energy simulation software tools with different levels of complexity and response to different variables. Among the most complete simulation software tools are the Energy Plus, the ESP-r (Energy Simulation Software tool), the IDA ICE (Indoor Climate Energy), IES-VE (Integrated Environmental Solutions - Virtual Environment), and TRNSYS. Being the most complete software tools, these are also the most complex and therefore require greater expertise.

From the analyzed energy simulation software tools, TRNSYS is the most complete, but depending on the user perspective and final purpose the other software tools could be more appropriated. The major limitation of TRNSYS is to not being able to connect with AutoCad Software tool for importation and exportation of files. In this aspect, Energy Plus, ESP-r, and IDA ICE are more appropriate.

But a lot of those simulation tools are unavailable in Sudan owing to the American block against Sudan, narrowing the range of tools options used for the simulation processes in this research. In this chapter, some simulation tools for thermal modeling that are available in Sudan are presented such as Energy plus, Design Builder, Computational fluid dynamics (CFD), Grasshopper software, DIVA plug-in, and Autodesk Ecotect. In addition to the steps that have to be performed to a buildings simulation of each software. Finally, The required simulation tasks in this research are identified and the suitable simulation tools selected for the realization of these tasks.

Chapter Five
Methodology and Research Tools

5.1 Introduction

This chapter sets out the research methodology to evaluate the thermal performance of building envelope when integrating the intelligent envelope techniques as required by aims and hypotheses set out in Chapter 1. Also, its presents the knowledge gap and research goals for the study, this will then lead to a discussion of the findings. The goal is to provide a process that can be applied at the different design stages to help a designer make better decisions that will result in more thermally efficient buildings.

This research focused on improving the performance of the building façade as represents the largest element that is exposed to external environment effects than other elements in terms of area, without neglecting the other envelope elements also. And its includes research approach, research goals, methodology design, described the base case theoretical office building, weather data, model verification, the proposed methods that will be tested in chapters (7 and 8), simulation tools selection, implementation software, and results analysis and discussion to archive the proposed methods for each envelope elements and integrated as a system to form a platform for new simplified design guidelines and analytical performance evaluation of the buildings in hot-dry climate.

5.2 Goals of the research

In attempting to answer the research questions raised in the Introduction, extensive research into the relevant subjects was carried out. The literature review was used to narrow the scope of the research field, and further, to come up with the right questions in identifying the knowledge gap. Issues such as natural ventilation strategies, heat transfer reduction strategies, performance improvement requirements, facade technologies, roof techniques, thermal simulation tools, multi-story building designs in the urban context, and other built-environment criteria related to the research topic have been studied and critically reviewed. The research is attempting to incorporate natural ventilation and heat transfer reduction techniques, combined with the developed DSF techniques and other envelope elements techniques, and apply them into multi-story office buildings located in Al-Khartoum city. A series of guidelines for building envelopes designs are proposed to help designers make better decisions. This research will also help designers to make better selections of DSF design features in terms of openings (sizes and locations), cavity depth, shaft height, shading devices, orientation, glazing properties, etc.

5.3 Research Approach

It has been identified from existing research detailed in the theoretical framework that there is a limited amount of knowledge for generic performance of building envelope when integrating the intelligent envelope techniques for office buildings located in hot climates. Figure 5.1 flow diagram below describes an overview of the approach followed in conducting this research.

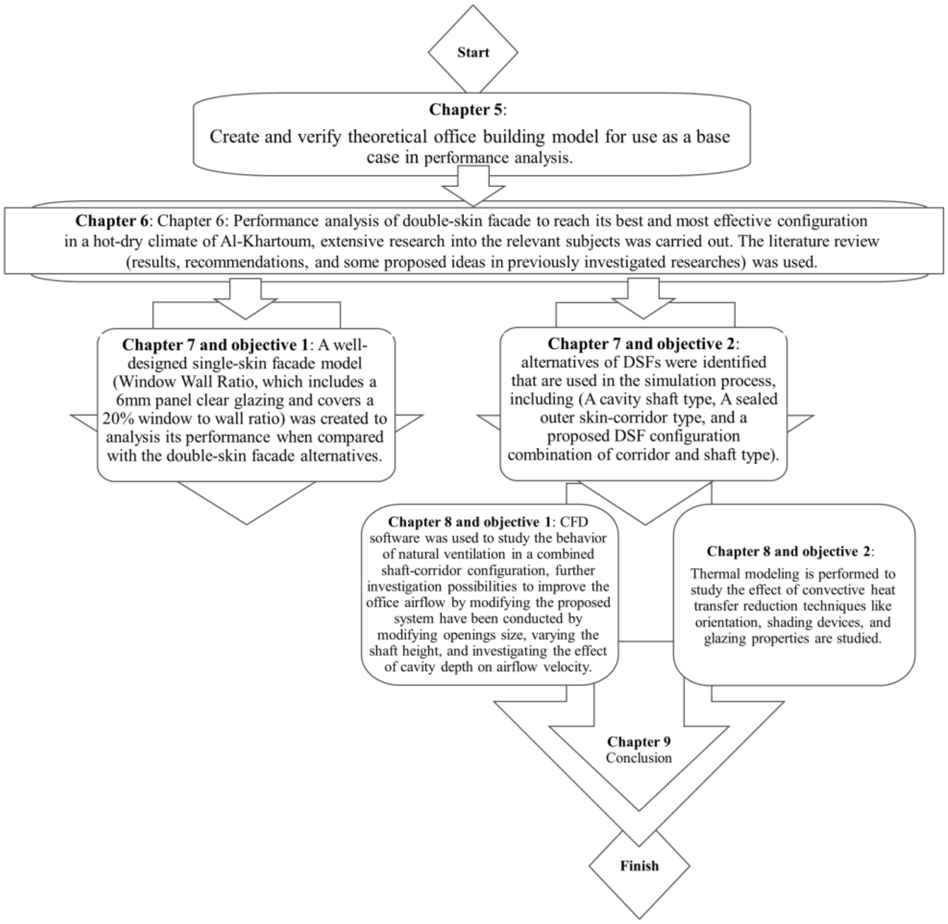


Figure 5.1 an overview of the research road map (Author).

5.4 Methodology Design

In attempting to test the four hypotheses mentioned in Chapter 1, it was imperative to design a methodology that shows an overview of the research agendas and approach. By tracing what it's been summarized from the second, third, and fourth chapters as shown in the flow diagram above. Several tests and comparisons of the different variables had been made to achieve the optimized and most effectiveness alternatives that maximum thermal performance when integrated the building envelope techniques, and then will be detailed it's to form a platform for new design guidelines.

Different methods are used in this research depending on the nature of each stage of analysis. That includes a theoretical analytical method and analytical-practical method of the building envelope techniques and the thermal simulation processes, respectively.

5.4.1The analytical theoretical method

This method is based on a literature analysis to investigate and develop the best possible solutions for building envelopes. This is realized by the following:

1) Façade performance analysis

This research focused on improving the performance of the building façade as represents the largest element that is exposed to external environment effects than other elements in terms of area, without neglecting the other envelope elements also. The techniques selected for this analysis are as follows:

- Well-design single-skin façade (Chapter 7)

This technique is selected to disprove the hypothesis that double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades.

- Double-skin facade technique (Chapter 7,8)

Double-skin facades are mainly designed in the buildings to obtain wholly glazed facades and at the same time improve thermal performance. The DSF provides fully glazed façades that can improve the thermal performance, daylight quality, and acoustic aspects of a building.

The figure below describes the method used for envelope techniques analysis.

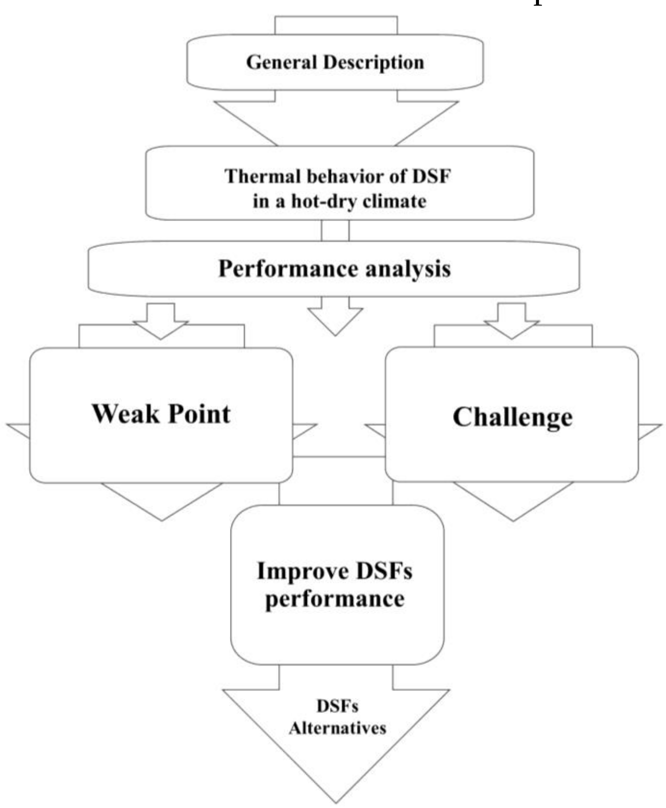


Figure 5.2 The steps of the analytical theoretical method (Author).

5.4.2 The analytical-practical method

This method is based on carrying out the simulation process to test the different envelope alternatives for optimal configuration. There is a lot of advanced simulation software unavailable in Sudan owing to the American block against Sudan. In this section, the selected simulation tools for thermal modeling and that are available in Sudan are presented, which are:

1) Visualization software:

- Autodesk Revit Architecture.
- Design Builder.
- Rhino.

2) Simulation software:

- Energyplus (version 2.1).

  Energyplus has been selected to calculate the thermal loads and thermal properties of materials.
- Computational fluid dynamics (CFD)

  CFD has been selected to simulate the airflow and convective heat transfer.
- Grasshopper software and DIVA plug-in

  Grasshopper and DIVA has been selected the buildings orientation and shading devices.
- Autodesk Ecotect (version 11)

  Autodesk Ecotect has been selected to simulate the heat dissipation techniques.

The purpose and tasks of each simulation software can be summarized in the following table.

Table 5.1 The purpose and tasks of each simulation software (Author).

Simulation Software	**Tasks**	**Chapter**
Energyplue	To calculate the thermal loads and thermal properties of materials	Chapter 7
Computational fluid dynamics (CFD)	To simulate the airflow and convective heat transfer	Chapter 8
Rhino, Grasshopper software, and DIVA plug-in	To simulate the buildings orientation and shading device	Chapter 8

For the research objective, several simulation tests and comparisons of the different variables had been made to achieve the optimized and most effectiveness alternatives that maximum thermal performance when integrated the building envelope techniques, flow diagram below describes the steps of a practical method.

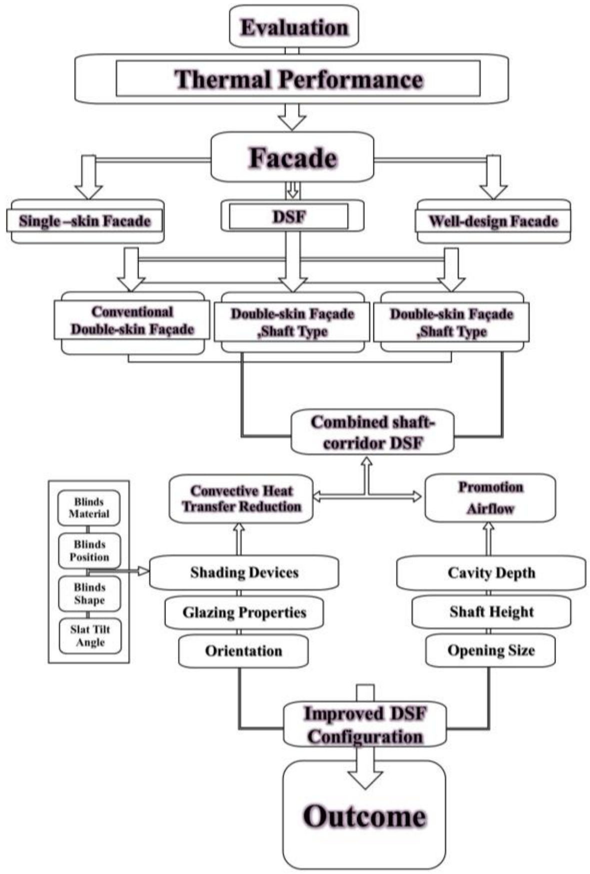


Figure 5.3 flow diagram illustrates describes the steps of a practical method.

5.4 Base Case Theoretical Building (Model)

The research will be carried out on a theoretical building that has been created in compliance with the current demand stipulation of the Sudanese regulation (Appendix C).

5.4.1 Model Discretion

For this model, the Theoretical office building is a rectangular-shaped ten-story building designed as an open plan office with a surface of 552m^2 and height of 4m, as seen in the figure below. This model is located in Al-Khartoum city, at almost the northeast center of Sudan, within a hot-dry region.

According to Grradh (Grradh, 2018), It is preferable to design the buildings in the form of a square or rectangle and avoid the U or Z shapes so as to minimize the generation of vortexes and scattered wind in the small yard. For this model, the Theoretical office building is a rectangular-shaped ten-story building designed as an open plan office with a surface of 552 m2 and height 4m, as seen in the below figure. This model is located in Al-Khartoum city, at almost the northeast center of Sudan, within a hot-dry region.

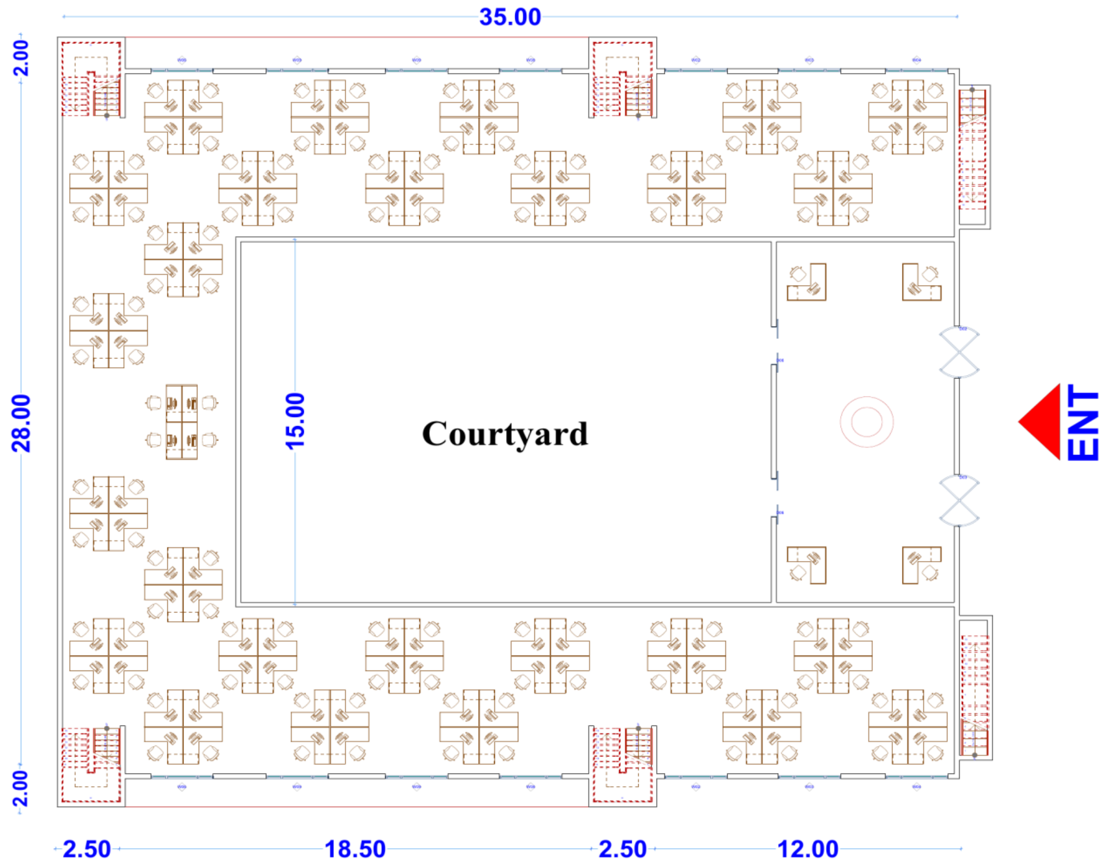


Figure 5.4 The building‘s total floor area for the number of working places (only office rooms) is 15.4 m^2 /occupant (Author).

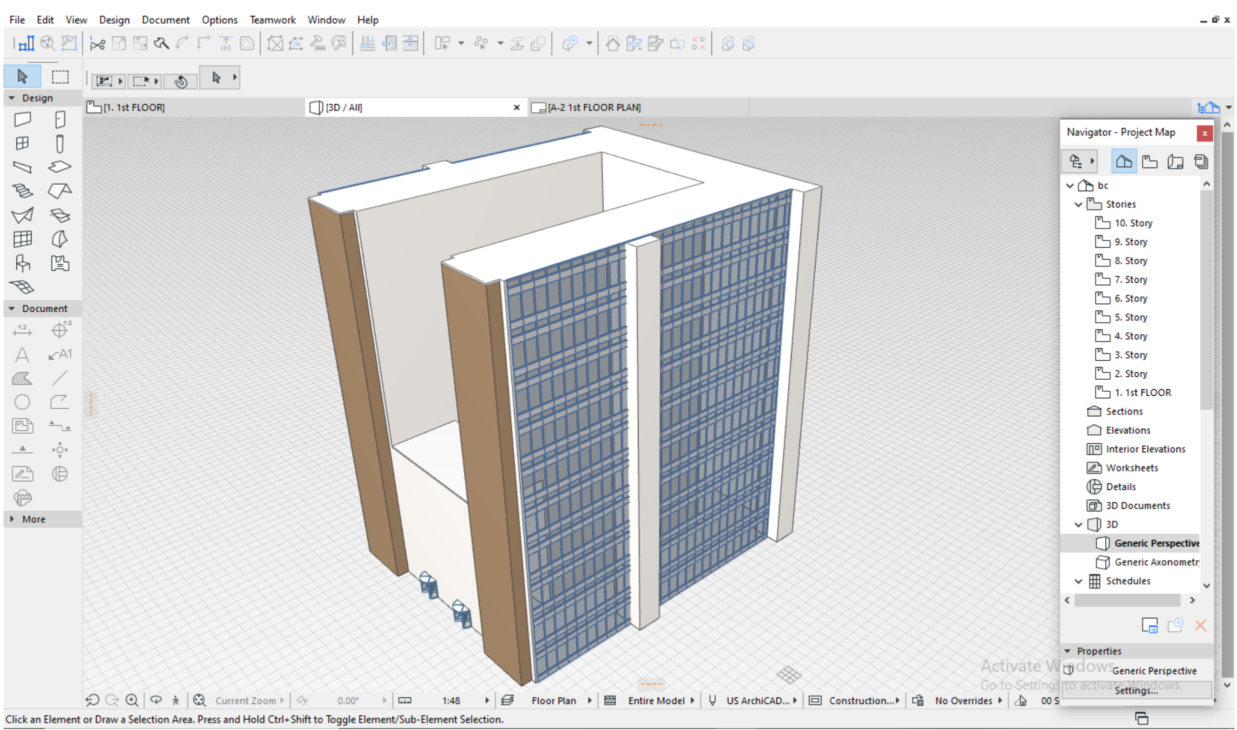


Figure 5.5 View of the modeled proportion of the single skin facade in Revit software (Author).

5.4.2 Why selected office building as Theoretical model?

The office building has been selected causes its need attention due to their large size, occupant numbers, energy consumption, and highly glazed façade.

5.4.3 Why selected Al-khartoum City?

The researcher has chosen Al-khartoum city as study zone for the following reasons:

1. It is located in the center of Sudan, and It is one of the most populated areas in Sudan. The population of Alk-hartoum City is estimated at 2,682,431 people.
2. Under Köppen's climate classification system, Khartoum features a hot arid climate. Based on annual mean temperatures, the city is the hottest major city in the world. Temperatures routinely exceed 40 °C in mid-summer, which increases the cooling load inside the buildings.
3. Al Khartoum City is the most cities consumption electricity for cooling buildings in Sudan. Due to high temperatures most of the year.
4. There are building regulations and architecture design law in Khartoum state, however, this law lacks of Sustainable Architecture Standards, how to take their effects in concern during early architectural design stages.
5. In the past decades, al Khartoum city has seen a huge surge in infrastructure and technology and There is a constant flow of new projects arising, which has led to deterioration of the environment and the increase in pollution levels, It had to been a strong movement towards sustainable architecture across the city, thus leading to a new, transformed, modernised form of architecture.

5.4.4 Material and construction

Specific properties of each building element in terms of the wall properties (type, R-value, exposure, and construction), shading, window properties (type, glazing area, size, and layout) have been set. The description of the building construction is shown in Table 5.2.

The thermal properties of materials were initially calculated by EnergyPlus-DesignBuilder. It should be noted that thermal losses due to thermal bridges were not included in these calculations. In order to be accurate, practical values should be used instead of theoretical values.

Table 5.2 Marital and construction discretion (Author).

Building Elements				
	Material type (from outside to inside)	Thickness (m)	Density (kgm^{-3})	U-value (W$m^{-2}K^{-1}$)
External wall	Window Wall Ratio (WWR) Glazing is clear 6 mm panel and covers a 20% window to wall ratio (WWR). Walls are constructed of a single brick leaf un-insulated wall infill between the structural columns and plaster rendering from both sides.	0.30	-	1.4
Internal wall	Gypsum Plaster	0.025	970	1.92
	Airgap	0.10	1.2	
	Gypsum Plaster	0.025	1090	
Roof	Ceramic tiles	0.25	930	0.25
	Motor 1:8	0.07	530	
	Pre-cast Concrete	0.20	2300	
	Air gap 30 cm	0.30	2.5	
	Gypsum Ceiling	0.20	720	
Ground Floor	UF Foam	0.087	1200	0.35
	Cast concrete	0.10	2300	
	Creed	0.07	900	
	Wooden Flooring	0.03	1000	
Floor	Pre-cast concrete	0.20	2300	4.7
Windows Properties				
Windows	Windows Properties	Description	Aluminum window	
		U value (W/m^2K)	4.719	
	Glazing Properties	Description	Dbl LoE(e3=0.1) Clr 6mm/13Air	
		U value (W/$m2K$)	2.44	
		SHG	0.643	
	Frame Properties	Description	Aluminum Thickness = 0.02	
		Surface resistance (m^2K/W)	0.040	
	Shading Properties	Description	Blinds with high reflectivity slats	
		Control	Scheduled and positioned inside	

The glass area in the base case is 100 percent in all facades, clear glazing type was chosen for the Base case single-skin façade (BC).

Table 5.3 the glazing thermal properties (Author).

	Base case single skin façade (BC)
Description	Clear glazing
U-value (W/m^{2}K)	5.6
SHG	
Solar coefficient (SC)	0.85
g-Value	0.87
Thickness (mm)	10
Transmittance (%)	73
Reflection (%)	7
Absorption (%)	20

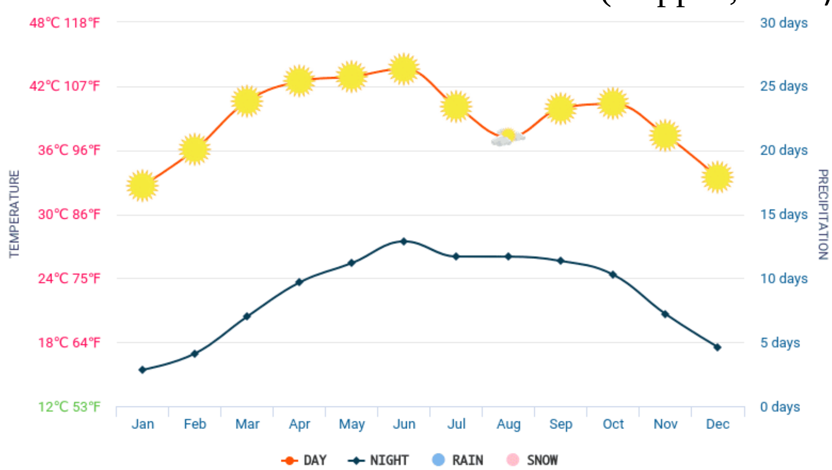
5.4.5 Weather Data

The first step in the research procedure on the thermal performance of the building envelope techniques is to collect climate-condition data and information on the building under study. Al-Khartoum weather data wasn't available through the EnergyPlus website (Energyplus.com) owing to the American block against Sudan.

Simulations were performed with climatic data from Al-Khartoum international airport. Weather data were recorded by the Sudan Meteorological Authority, and then the WeatherShift™ tool was used to upgrade EPW weather files.

Khartoum features a hot desert climate (Köppen climate classification BWh). With an annual average temperature of 30.5 °C (87 °F), in summer, the highest temperatures reach 48 °C (119 °F) in May. Even winter is characterized by high temperatures, with highs around 31 °C (88 °F) in January, but it can sometimes reduce at night, reach record is 13 °C (36.9 °F) in the same month, as shown in the figure below (Please refer to the detailed weather data for Khartoum in Appendix D).

Table 5.4 Climate data for Khartoum (Köppen, 2017).



5.5 Methods Used in Chapter 7

As suggested by Ternoey et al.(1985), the easiest way to evaluate performance improvement in building design is to appraise thermal performance with a base case. In this chapter, a detailed study was carried out focusing on thermal performance levels, where the building is designed to evaluate the thermal performance of different alternatives of DSFs compared to the reference building and the well-designed single skin facade (optimized single skin facade), and thermal modeling is performed to disprove the hypothesis that double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades. This chapter is included three main simulation processes:

- Simulation of the reference single-skin building.
- Simulation of the well-designed single-skin facade.
- Simulation and analysis of the double-skin facade alternatives.

5.5.1 Well-designed single-skin façade (WSS)

Window Wall Ratio (WWR) Glazing is clear 6 mm panel and covers a 20% window to wall ratio (WWR). Walls are constructed of a single brick leaf un-insulated wall infill between the structural columns and plaster rendering from both sides

Table 5.5 Thermal properties of façade materials (Author).

	Well-designed single skin façade (WSS)
Description	double-pane low-E insulation
U-value (W/m^{2}K)	2.44
SHG	0.643
Solar coefficient (SC)	0.27
g-Value	0.42
Thickness (mm)	10
Transmittance (%)	21
Reflection (%)	12
Absorption (%)	67

5.5.2 Double-skin facade alternatives

In this section, alternatives of DSFs were identified that used in the simulation processes. The thermal performances of the following DSFs alternatives were studied:

- A double-skin facade shaft type.
- A double-skin facade corridor type.
- A proposed DSF configuration combination of corridor and shaft type.

Table 5.6 shows a description of these alternatives components.

Table 5.6 Description of the DSF alternatives components (Author).

DSF components	Description
Cavity depth	1.5m
Shaft height	7 stories
Story height	3.5m
Opening size	0.3m
Internal skin	Clear glazing (6mm)
External skin	Single pane window (6mm)
Shadings location	Inside the cavity
Shading devices	White with a slat angle of 45^o

This method of performance assessment is shown below in Figure 3.12 flow diagram below.

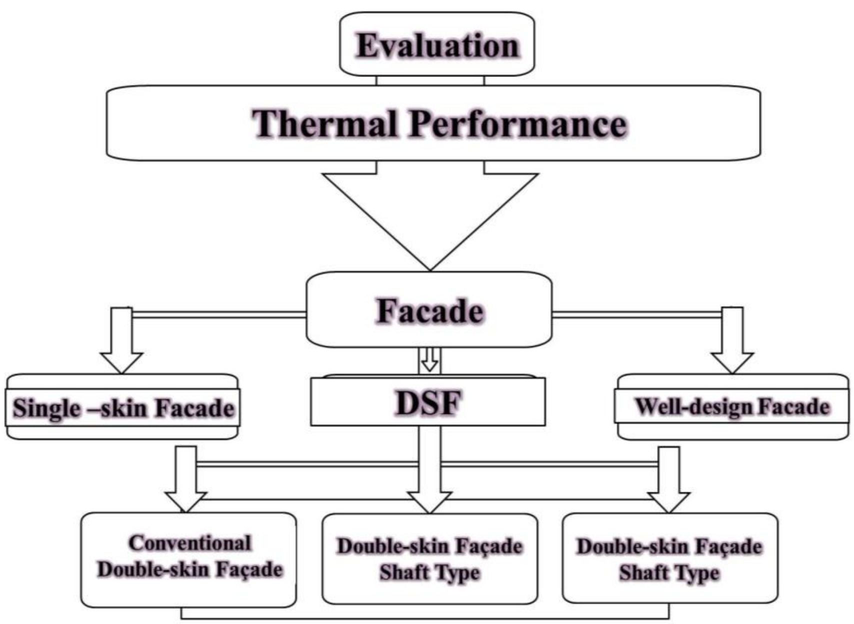


Figure 5.6 Double-skin facades Performance Assessment Methodology (Author).

5.6 Methods Used in Chapter 8

This chapter opens an investigation about the third hypothesis, which is interested in how to improve the thermal performance of the combined shaft-corridor DSF by applying the two techniques that arrived at in chapter 6 (airflow promotion and convective heat transfer reduction). To study the impact of design variables on the thermal performance of the combined DSF configuration in comparison with the base case, different building alternatives were simulated. The optimum alternative should facilitate ventilation and be able to remove hot air continuously from the cavity while optimizing thermal performance.

5.6.1 Air Flow promotion technique

In this analysis, the driving forces for airflow are buoyancy and wind pressure based on the weather data in each of the models, thus allowing for the development of different variants and can be used in the thermal simulation, variables analyzed include:

- Cavity Depth: 0.5 m, 0.9 m, 1.2 m and 1.5 m
- Shaft height: 5 to 9 stories (3.5 m each story)
- Opening Size: 0.3, 0.6 and 0.9m.

5.6.2 Convective heat transfer reduction techniques

1) Shading Devices (Venetian Blinds)

This study looks beyond conventional venetian blinds with a slat angle of 45 of DSF solutions and provides new alternatives for solar protection, reduction temperature, and maximizing the buoyancy effect in the cavities. The possibilities to improve DSF performance have been investigated by modifying the shading devices system. The factors that effect in DSF performance include:

- Varying the blinds material.
- Modifying the blinds position.
- Varying the blinds shape.
- Investigating the effect of slat tilt angle.

2) Facade Orientation

The six proposed orientation angles will be simulated: 0, 15, 30, 45, 60 & 75 degrees, to test their effect on the reduction the direct solar radiation intensities.

3) Glazing properties

This investigation adopts an analytical approach using dynamic simulation software. In this section, a comparative analysis of convective heat transfer on a clear glass base case against three possible changes; clear glazing, tinted glazing, and reflective glazing.

The Performance Optimization method of the combined shaft-corridor DSF configurations is shown below in Figure 5.7 flow diagram.

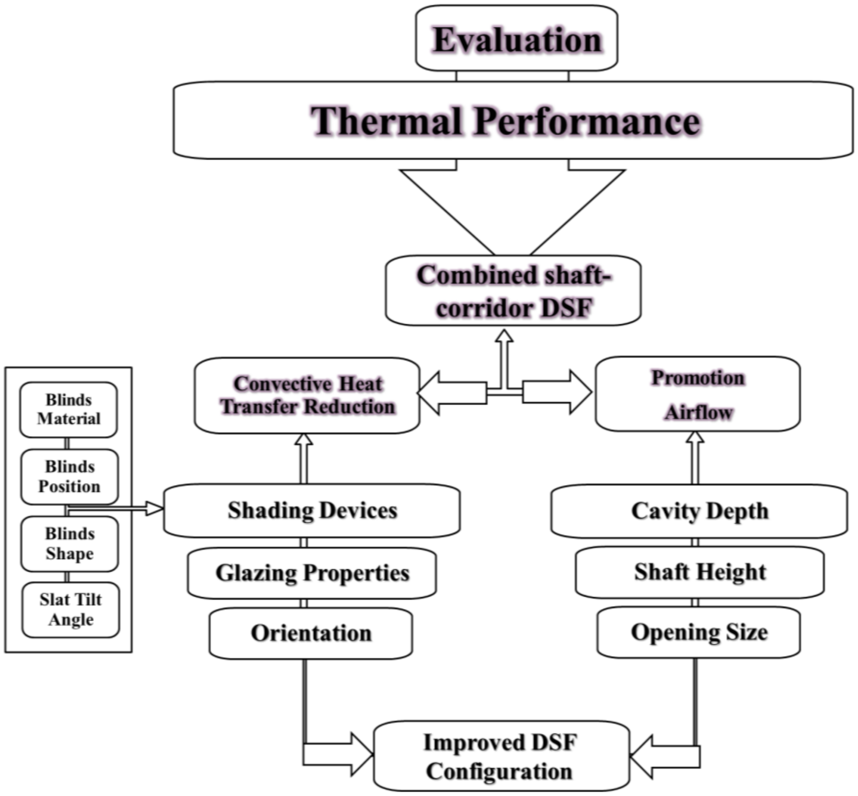


Figure 5.7 The combined shaft-corridor DSF configurations Performance Assessment Methodology (Author).

5.7 Conclusion

The methodology was approached by modeling a theoretical base case office building located in Al-Khartoum, by using thermal simulation software to evaluate thermal performance improvements when integrating the intelligent envelope techniques. For these aims, a new dynamic thermal model was created to evaluate the base case thermal performance. The envelope elements configurations were developed by integrating those techniques as a system, the aim of this integration is to provide maximum thermal performance for the PMC intelligent system by making the envelope as a responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum thermal performance.

Chapter Six
Thermal behavior analysis to improve the double-skin facade performance

6.1. Introduction

This research focused on improving the performance of the building façade as represents the largest element that is exposed to external environment effects than other elements in terms of area, without neglecting the other envelope elements also. Where the building facade plays an important role in improving thermal performance and it's responsible for up to 45% of the thermal loads (Elkadi, 1999).

In this chapter, double-skin façades (DSFs) are studied to address the well-known problems of curtain walls. In attempting to improve the thermal performance of the double-skin facade technique, extensive research into the relevant subjects was carried out the literature review was used to narrow the scope of the research field, and further, to come up with the most effective alternatives in DSF configuration. Issues such as different DSF configurations, Thermal behavior analysis, and performance improvement requirements have been studied and critically reviewed .

6.2 Overview

Recently to improve the thermal performance of glazed facades, the development of Double skin façades (DSFs) grew in as a promising alternative to address the well-known problems of curtain walls, particularly heat gain/loss according to the climate, by combining a sun protection and thermal buffer in a glass zone. As a form of envelope in modern buildings, double-skin façade (DSF) has already become a common architectural design feature around the world with great potential in thermal-performance improvement (Hill, 2017). The use of multilayered skins uses building insulation against thermal variation and external noise. As illustrated in Figure 6.1, a DSF could provide ventilation and solar protection by combining control strategies.

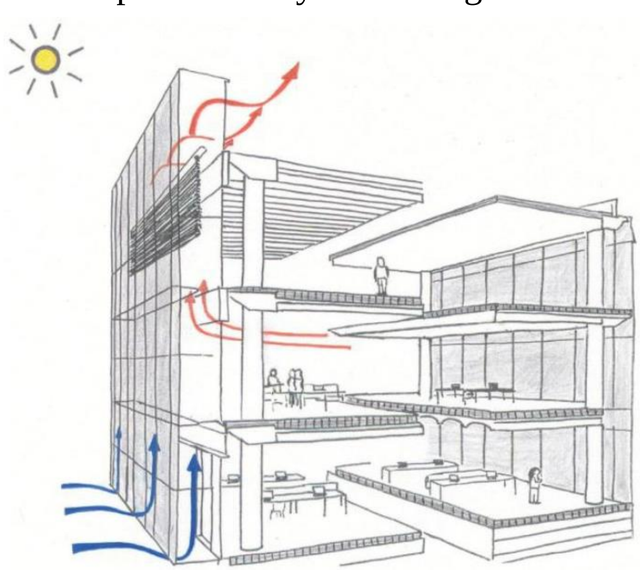


Figure 6.1
Typical DSF (Angus, 2011).

6.3 Aims and objectives

The main aim of this chapter is to present a detailed analysis of the thermal behavior and performance of double-skin facade configuration at different seasons to reach the optimization and most effective DSF alternatives. Later, those alternatives would be tested to evaluate their thermal performance by using simulation software in the next chapters.

The potential benefits of developing the DSF configuration could be summarized as follows:

a) Fully glazed façades that can improve the environmental aspects of a building and offer better use of its perimeter area.

b) By adjusting the cavity airflow and solar shading devices the DSF can improve the thermal performance.

c) A well-performing DSF can improve the indoor environment by maximizing the use of daylight, using natural ventilation, and controlling the solar shading device in order to prevent unwanted thermal gains. These beneficial aspects are the main reasons for the use of DSFs.

6.4 Thermal behavior of DSF in a hot-dry climate: review, challenges, and solutions

In the hot-dry areas in general, and Sudan in particular, people are reluctant to use DSFs due to high first costs and the lack of a precise and developed airflow model that can accurately predict the facade performance (Gasmalla, 2016).

According to the published literature, this technology is so far mostly employed in cold to moderate climates, and in fact, very limited researches have been done on the performance of DSFs in regions with hot climate. Bearing in mind that especially in hot climates huge costs are spent for providing comfortable conditions and maintenance, which are arising when the designs are inappropriate. in this section, the DSF model of performance was developed, as appropriate to the climate conditions. For this purpose, the major available methods of thermal behavior and performance of DSFs models and the possibility of introducing additional techniques mainly in hot climates were studied. Research on the performance of double skin facades mostly considers cold and moderate climates; Very limited research in hot-dry regions has been undertaken. Hashemi et al (Hashemi, 2010) based on simulations, on the case study building with and without double-skin facade, to assess the effectiveness of the facade. The results revealed that the temperature difference between the outer skin, the inner skin, and the cavity can significantly save heating energy in winter. To reduce the cooling loads in summer it is essential to introduce additional techniques.

According to Sarshar (Sarshar, 2015) the countries with high solar incidence, especially in summer, because of the high outside temperature, the cavity becomes hot during the night and increases the cooling load requirements. As a result, additional techniques must be introduced to cool down the inner facade. Nevertheless, both heating and cooling loads are reduced in a building with DSF in comparison to the same building with a normal façade, because the trapped heat in the gap to induce natural buoyancy as a mean to reduce elevated air temperatures away from the inner building skin. This may result in additional reduction of conductive heat gains through the inner facade layers into the occupied space.

Another investigation done about double-skin façade in hot regions declares that the outer layer may decrease the building room's gain of the direct solar heat, however the trapped heat in the intermediate space between layers can help in reducing the hot weather away from the inner layer of the building. In this investigation, to convey the general intuitions about the performances of these buildings specifically in hot areas, in the methodology, an analytical method is adopted, by means of dynamic simulation software (IESVE). The outcomes of this investigation research show the better performance of reflective double skin buildings compared to a reflective single skin one, in terms of performance improvement. As an agreement between the intuitions and the building's performance, is in the angling the buildings, in hot dry weather conditions, due to the direct solar light intensities. In these regions, west and east directions are tried to be avoided, whilst north and south directions reduces the cooling demands. The demand reduces more and in fact gets minimized, when transparent layers, reflective glasses are employed in these building systems (Hashemi, 2010).

Reviews of simulation studies of double skin facades in hot arid areas (Mona, 2019), claim that the exterior leaf would reduce direct solar heat gain in rooms; trapped heat in the gap is expected to induce natural buoyancy as a mean to reduce elevated air temperatures away from the inner building skin. This may result in additional reduction of conductive heat gains through the inner facade layers into the occupied space. To achieve the maximum performance value, the DSF's thermal behavior must be analysed in the hottest and coldest months of the years.

6.5 Performance analysis

It is found that the DSF strategy is suitable in hot climates, where gaining heat is reduced dominantly. This section discusses how DSFs perform in two different climate scenarios (winter and summer):

6.5.1 DSF performance in winter

During the winter, the external additional skin provides improved insulation by increasing external heat-transfer resistance. Although the equivalent thermal transmission coefficient U- Value for a permanently ventilated facade will be poorer in part (than with a single skin facade), the results will improve if the intermediate space (cavity) is closed (partially or completely) during the heating period. The reduced air-flow speed and increased temperature inside the cavity lower the heat transfer rate on the surface of the glass which leads to a reduction of heat loss. This has the effect of maintaining higher temperatures on the inside part of the interior pane. Oesterle et al. (Oesterle et, 2001) describe the proportion of the opening area in order to improve thermal insulation.

During a sunny winter day, the temperatures of the external walls in the DSF are less than that of the normal facade. External walls in the building with DSF lose heat more slowly. This is beneficial to preheating of the inside spaces and heating energy conservation. Surface temperature in the DSF reaches to its maximum a while after the same temperature reaches that point in the normal facade. The transparent double-skin facade was predicted to increase heat loss through the fabric thus increasing heating loads. Based on simulations, it was concluded that the deeper the cavity the more pressure drop leading to slower mass flow rates (Baldinelli, 2009), but lower surface temperatures on the inner double-skin facade were still achieved compared to the external surface temperature of the facade configuration.

6.5.2 DSF performance in summer

During the summer, once radiation passes into the building, it is absorbed by the building fabric and re-radiated as long-wave infrared energy that does not pass back through the glass. As a result, the air in the cavity will be heated via convection. The hot airflow in the cavity can pass through the glazing outside and inside the space via conduction. As the cavity warms up the stack effect is improved respectively. Figure 6.2 shows the effect of various factors on heat transfer through the building‘s envelope and illustrates the impact of solar radiation, conduction, and convection on the airflow through the DSF cavity. A DSF system results in less heat transferred from outside to inside, and less energy required to cool the space. The rate of heat transfer under steady-state conditions is known as the U-value (coefficient of thermal transmission). The U-value expresses the heat flux (in W/2) through a building component (or a combination of components) with a temperature difference of one degree across several components under steady-state conditions. Figure 6.2 shows the heat transfer mechanism through single pane glass; the heat transfer mechanism through DSF is illustrated in Figure 6.3. A low U-value indicates that the building component has a high thermal resistance.

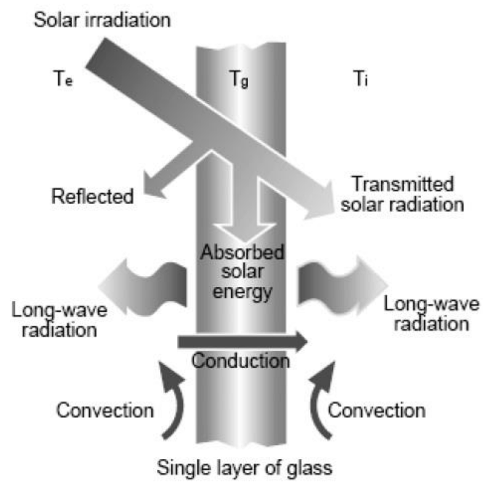


Figure 6.2 Heat transfer through a single pane of glass (Yellamraju, 2004)

The exterior heat source is solar radiation, which is initially reflected on the external glazed skin in this process and, depending on external conditions, determines the external heat transfer coefficient. The remaining radiation passes through the glass. The reflection with the inner glass and inner walls of the cavity creates processes of convection and conduction, which determine the heat transfer coefficient inside the cavity. The accumulated and remaining heat by radiation and conduction received by the room determines the heat transfer coefficient.

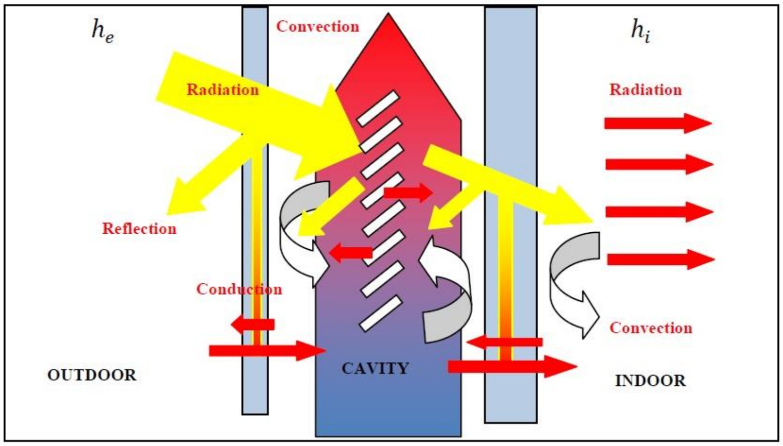


Figure 6.3 Heat transfer through a DSF on a summer day (Haase, 2006).

6.6 Analysis results

Based on the previous analysis, the DSF’s performance in hot-dry climate has been summarized at the following points:

1) In summer, because of the high outside temperature, the cavity becomes hot during the night and increases the cooling load requirements.

2) It is obvious that the walls of the building with DSF lose heat more slowly, this causes the interior spaces to stay warm during the night.

3) The inside temperatures will stay high in the morning and this will increase the cooling load. Lack of natural ventilation is the prime reason for this increase.

4) Due to the cavity’s poor ventilation in the daytime, its temperature becomes higher than the outside.

5) Using clear glass in DSF outer skin doesn't lead to major performance improvements if compared with single skin scenarios, as they increase conduction indoors to the point of offsetting the reduction in direct solar penetration indoors in summer.

6) In winter, the temperatures of the external walls in the DSF are less than that of the normal facade. External walls in the building with DSF lose heat more slowly. This is beneficial to preheating the inside spaces and heating energy conservation.

7) In winter the transparent double-skin facade was predicted to increase heat loss through the fabric thus increasing heating loads. Based on simulations, it was concluded that the deeper the cavity the more pressure drop leading to slower mass flow rates.

8) In a hot climate, DSFs systems are favorable applications in winter and mid-season, but face a major challenge of overheating in summer which tends to result in an uncomfortable indoor environment and increase the cooling loads in buildings.

6.7 Improve DSFs performance

To reach the best-innovative DSF solutions, extensive research into the relevant subjects was carried out. The literature review (results, recommendations, and some proposed ideas in previously investigated researches) was used to narrow the scope of the research field. According to literature analysis, it was found that the best and most effectiveness solution to improve the DSF performance is the successful development of entrapment of solar heat entrapping process by displacing the solar energy by natural means (convective air heat transfer) to the external environment, hence preventing large levels of solar heat gain entering the habitable space.

This study looks beyond typical DSF solutions and provides a developed DSF configuration. The DSF configuration takes advantage of several strategies techniques driven by different variables. This study mainly investigates the DSF applied in a hot-dry climate of Al-Khartoum, where DSFs are favorable applications in winter (Safer, 2015), but face a major challenge of overheating in summer which tends to result in an uncomfortable indoor environment and increase the cooling loads in buildings (Mona, 2019). Previous researchers have raised the overheating problems associated with DSFs and come up with several solutions to dispel the problems.

6.7.1 Natural ventilation in double skin facade

The research is attempting to incorporate natural ventilation techniques, combined with the developed DSF technologies, and apply them into office buildings in Sudan. A series of guidelines for DSF designs for buildings are proposed to help designers make better decisions. The studies have revealed a close link between natural ventilation design and the DSF function. It was found that significant performance improvement is possible if natural ventilation can be exploited through the use of a DSF. Gratia and Herde (Gratia, 2001) found that sufficient day-or night-ventilation rate can be reached by window opening, even if wind characteristics are unfavorable. If natural ventilation strategies are used with double facades, they also provided some general guidelines in improving natural daytime ventilation in office buildings with a DSF, where cavity air ventilation (either natural or mechanical) is used for evacuating the radiative heat absorbed by the façade elements.

Generally, natural ventilation follows three main principles that designers should understand well in order to induce passive ventilation into any building’s design, which includes stack ventilation, Bernoulli’s effect, and the Venturi effect. These three principles use air pressure differences due to height, air temperature, or wind speed, to pull air to or from buildings. To achieved the main concept of air cavity’s ventilation, several considerations must be taken into account to maximizing the use of one or more of the three principles in order to induce cavity ventilation, Where cavity’s poor ventilation is the main reason to increase the cavity’s temperature, and will effectively higher the cooling load during summer (See § 3.4.2 on this subject).

To further reduce solar heat gains into a space, the double facade is ventilated by employed using natural stack/wind effect (individual or combined) mechanisms to reduce the amount contributed into the atrium space. As detailed by Loncour et al. (Loncour, 2004), the main consideration that effecting on DSF ventilated is partitioning of the cavity, the partitioning of the cavity tells us how the cavity situated between the two glazed facades is physically divided. Within the double facades, numerous possibilities of partitioning are imaginable and an additional classification can be created.

In this section, the performance of the following facades was studied:

- A double-skin facade shaft type, as shown in Figure 6.4.
- A double-skin facade corridor type, as shown in Figure 6.5.
- A proposed DSF configuration combination of corridor and shaft type.

Two DSF construction types were assumed: a corridor type and a shaft type. In both cases, the cavity depth was assumed to be 1.5m (maximum depth) and the shaft height and the building height are equal. The main difference of the alternative facades is that a double skin has been added to the building; with the internal skin the same as the reference building and the external skin as a single pane window. The shadings were located inside the cavity. In both DSF types, the cavity was naturally ventilated.

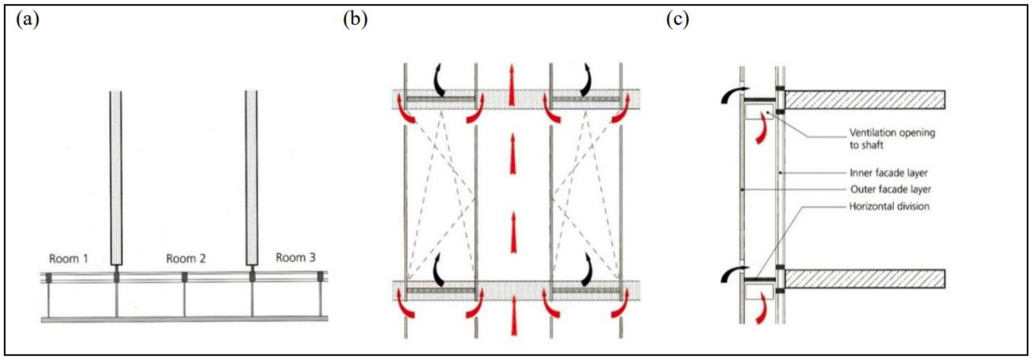


Figure 6.4 Shaft box facade: Plan (a), section (b) and elevation(c) (Osterle, 2001).

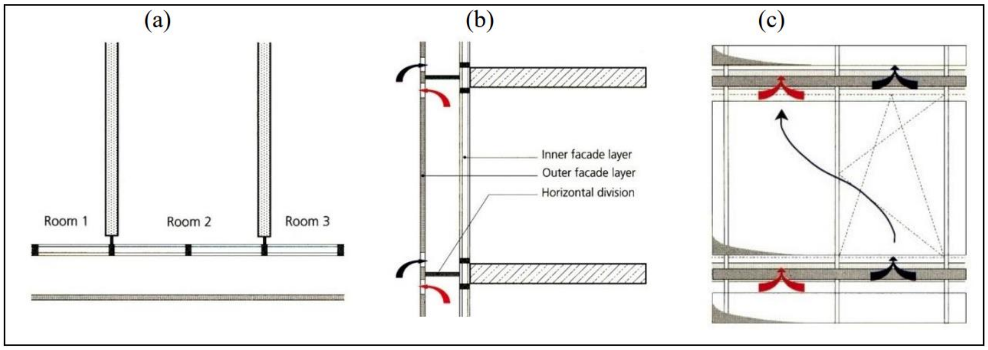


Figure 6.5 Corridor facade: plan (a); section (b) and elevation (c) (Osterle, 2001).

Combined shaft-corridor DSF

This study looks beyond typical shaft and corridor DSF solutions and provide a new type shaft-corridor configuration. The combined shaft-corridor DSF configuration takes advantage of strategies such as ventilation driven by different combinations of wind and external stack. The most distinguishing visual feature of this configuration is it can pronounce a module by projecting or taking back the tower on the facade as presented in Figure 6.7. This configuration combined both shaft box and corridor types on the building's facade while trying to avoid their disadvantages. The cooling stacks allow for further ventilation on hot, stagnant, summer days so the building always remains within reasonable temperature levels, like that of an air-conditioned building.

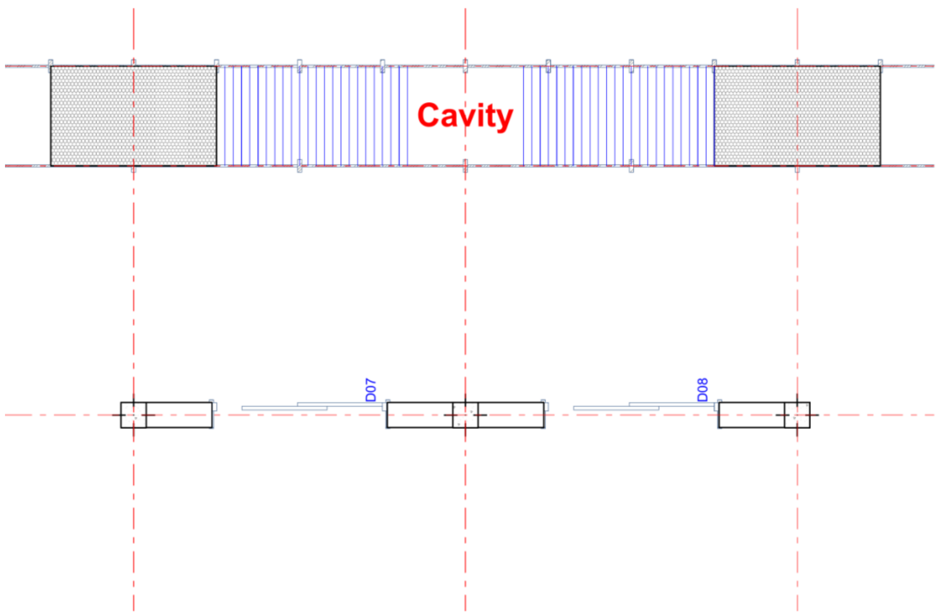


Figure 6.7 Sketch plan of the proposed configuration (Author).

One of the disadvantages of a shaft-type window is that the narrow width makes it difficult to clean and maintain. A corridor type can simply act as an internal or external air curtain. As a result, natural wind cannot be introduced to the interior space; if we open the internal screen the air inlet and exhaust air will mix. With the combined shaft-corridor DSF we tried to avoid the disadvantages mentioned above. To avoid air mixing, the inlet and exhausted air are separated through a channel. Exhausted space air will go directly into the transparent channel, which is connected to the shaft. In addition, the shaft width is increased up to 1.5m, the same as the corridor depth. Ventilation effectiveness is driven by thermal buoyancy, or stack effect, which is determined by the inlet air temperature, the height between inlet and outlet openings, and size of these openings. Figure 6.9 shows how air flows through the chimney and provides ventilation inside each space module. The air gap inlet draws in fresh air at a low level and directs it into the room. The air is exhausted through the outlet at the high-level gap of the inner pane. The chimney sucks the exhausted air through a bypass opening at the top of the corridor facade.

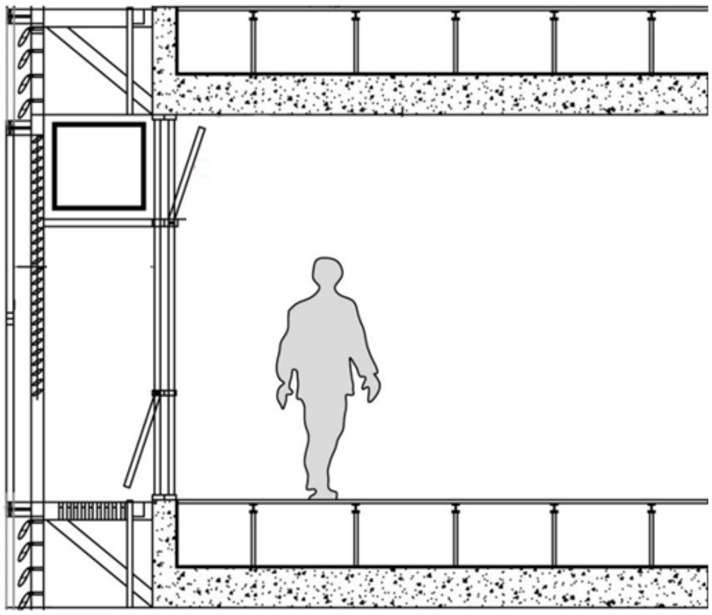


Figure 6.8 The combined shaft-corridor DSF configuration (Author).

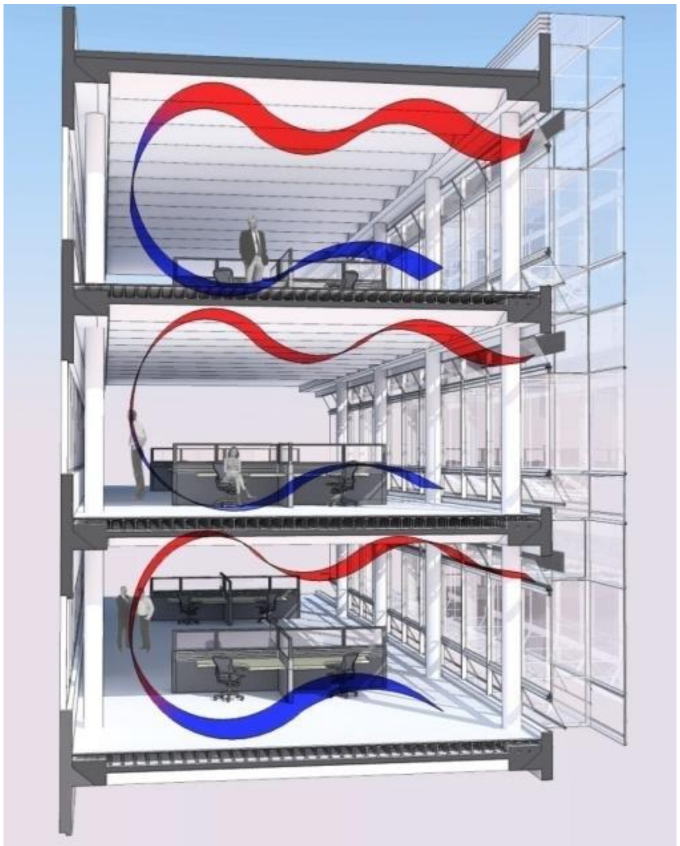


Figure 6.9 The combined shaft-corridor DSF configuration and show air flows within the building (Author).

6.8 Performance improvement techniques of the combined shaft-corridor DSF

According to the previous analysis, it was found that the best and most effective solution to improve the DSF performance is the successful development of entrapment of solar heat entrapping process by displacing the solar energy by natural means (convective air heat transfer) to the external environment, hence preventing large levels of solar heat gain entering the habitable space. in addition, the problem of cavity overheating can be avoided by ensuring a minimum distance between the internal and external panes of a DSF due to greater stack effect and promoting airflow in wider cavities, as shown in Figure 6.10.

Thus, this section aims to carry out a survey of the variables affecting the techniques of airflow promotion and heat transfer reduction.

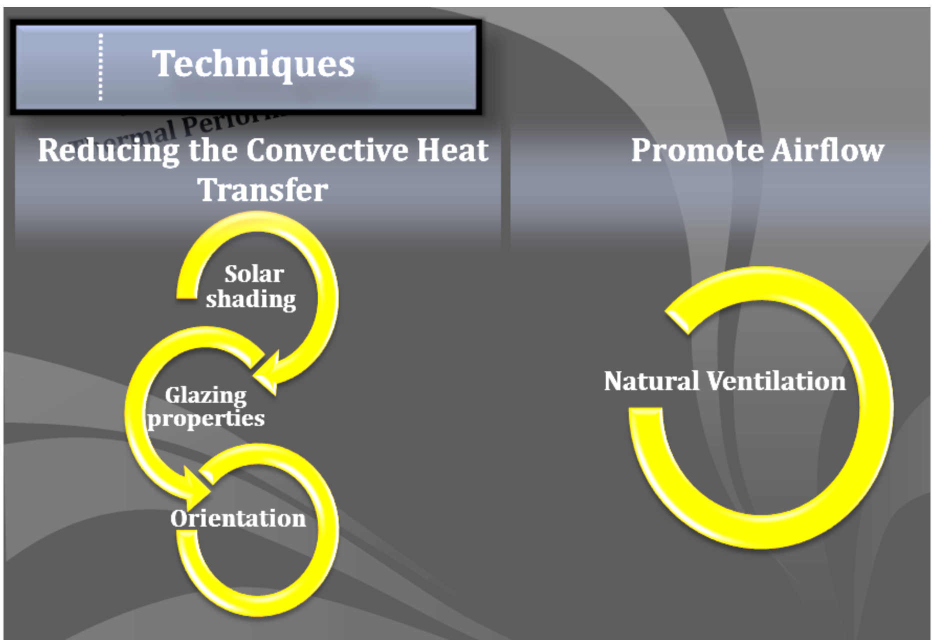


Figure 6.10 The method to improve DSFs performance (Author).

6.8.1 Airflow promotion techniques of the Combined Shaft-corridor DSF

Among the studies performed in this regard, a few have surveyed optimized DSFs aiming to improve thermal performance in climates similar to the hot-dry climate of Sudan. But lack of sufficient knowledge about the optimum configurations of the DSF leads architects to design deficient courtyards especially in terms of thermal performance and outdoor thermal comfort. Thus, the present study aims to carry out a survey of the variables affecting the DSFs' design to promote natural ventilation. Jager et al. (Jager, 2017) indicated that the overheating problem can be avoided by ensuring a minimum distance between the internal and external panes of a

DSF due to greater stack effect and adequate air flow in wider cavities. Wiggin ton et al. (Wiggin, 2015) stated the sizes of ventilation openings are crucial variables influencing the cavity temperature since they determine the efficiency of air exchange between DSF and external environment.

Different researches resulted, the thermal performance of the buildings can be meaningfully improved by controlling the factors of airflow rate and air returning, from multiple skin façades (Hamza, 2008). One of the main arguments for using increased opening areas in buildings is the provision of better natural ventilation. However, the increased opening area leads to a reduction in cooling requirements but not for heating in the building (the larger the opening sizes, the colder during the winter month). To make use of airflow more efficiently, attention has to be paid to how the opening works with the chimney, which will be tested in chapter 8.

As previously stated, the perception of thermal performance depends not only on the mean-air temperatures but also on the surface temperatures that surround the occupant. Thus, the opening size is crucial for improve the thermal comfort as it influences the airflow and radiant temperature as seen in Figure 6.3. The main causes of overheating in DSF which included ineffective removal of heat stored within the DSF system, and inadequate operations of the DSF for specific thermal environmental conditions. Jager et al. (Jager, 2017) and Wigginton et al. (Wiggin, 2015) reported physical consideration sat design stage of DSFs such as adjusting openings sizes for better ventilation in the cavity and ensuring a minimum distance between the outer and inner skins.

After establishing the opening size for the DSF, the second variable to investigate is the effect of different cavity depths on thermal performance. In the context of a hot arid climate, it is argued that the cavity depth needs to be between (600 and 1000 mm) to allow efficient cleaning as dust levels and pollution levels are high.

Ventilation of the cavity is effectively lower the cooling requirements during summer because of cavity's poor ventilation. This is clearly seen in the lower floors. Mona (Mona, 2020) mentioned, after analyzing all simulation results and taking thermal comfort parameters into consideration, a 9-story shaft high provides in average better comfort during naturally ventilated month but in terms of performance, the 5-story shaft high performs better.

According to the literature review, most of the studies have been carried out in a static manner and variation of the variable cannot be predicted in these studies; thus, in order to examine the variables and the schemes, several alternatives and scenarios are introduced. Airflow analysis Studies concluded that are three variables are affecting the DSF performance. For the purposes of this study, three effective configurations of the DSF were modified, to further investigate possibilities to improve the office airflow by modifying the DSF configuration system (as listed below). This includes:

a) Modifying the ventilated stack by varying openings of the DSF system, investigating different sizes for openings and their effects on thermal performance. It should be noted that opening sizes are the same for the inlet, exhaust, and chimney openings.
b) Varying the shaft height by extending the stack through a different number of stories to see the effect on ventilation rates within internal spaces.
c) Investigating the effect of cavity depth on airflow velocity.

The main goal of this analysis is to determine general airflow and temperature profiles by varying the cavity geometry. The driving forces for airflow are buoyancy and wind pressure based on the weather data in each of the models. This allows for correlations to be developed for different parameters and can be used in the simulation. Variables analyzed include:

- Cavity Depth: 0.5 m, 0.9 m, 1.2 m, and 1.5 m
- Shaft height: 4 to 10 stories (3.5 m each story)
- Opening Size: 0.3, 0.6 and 0.9m.

All the measured variables will be simulated in chapter 8, and compare the best performing alternatives in terms of thermal performance.

6.8.2 Convective heat transfer reduction techniques

Convective heat transfer reduction is the process of reducing the effectiveness of heat exchange. This can be achieved when reducing the heat gain through the DSF layers. A variety of techniques can be applied to this effect, including shading devices, orientation, and glazing properties.

1) Shading devices (Venetian Blinds)

The DSF structure can be accompanied by shading devices, like blinds, to decrease the solar energy gain, resulting in improvement of the building's thermal performance. In DSF buildings, Measurements show that in summer almost all day, the cavity temperature is less than the outside temperature during the warmest period of the day. This is because of the shadow that the dividing plates in cavity cast on the facade. Studies show that installing shading devices in the cavity will noticeably decrease its temperature and also the thermal load. Although the building does not have any shading devices, the shadow of the dividing plates in cavity causes the temperature to drop down (Valentín, 2013).

Previous studies proved, the utilization of shading devices (Venetian blind) as the commonest one (Manz, 2004). Even though it may be adopted in DSF systems as a solution to overheating effect, there are some barriers to be overcome and improvements to be made. where, Studies show that the Venetian blinds are being used in providing solar shading but they are believed to contribute to additional heat source linked with complex long wave radiation exchange, increased surface temperature caused by solar absorption on the blinds (Safer, 2005), and buoyancy effect in the cavities (Manz, 2004). The consequences are that the blinds may act as solar heaters which radiate heat and contribute to overheating in adjacent space. Extensive research has been conducted on Venetian blinds and proves that factors such as blind position (Valentín, 2013), slat tilt angle, and material and shape of the blind can influence the DSF performance (Valentín, 2013).

This study looks beyond typical Venetian blinds with a slat angle of 45 of DSF solutions and provides new alternatives for solar protection, reduction temperature, and maximizing the buoyancy effect in the cavities. The possibilities to improve DSF performance have been investigated by modifying the shading devices system. The factors that affect in DSF performance include:

- Varying the blinds material.
- Investigating the effect of slat tilt angle.
- Varying the blind shape.
- Modifying the blinds position.

a) <u>Blinds Materials</u>

The main problem of the existing venetian blind systems for DSFs is the high surface temperature caused by solar absorption on the blinds (Safer, 2005), the consequences are that the blinds may act as solar heaters which radiate heat in the cavity and contribute to overheating in adjacent space. This section is focusing on the development of a physical model of the blinds by the following system.

- ***Phase change material (PCM)***

Recent studies have further reported that the effectiveness of concrete can be enhanced by incorporating phase change materials PCMs (Bentz, 2007). De Gracia et al. (De Gracia, 2013) integrated a PCM system into the air channel of a ventilated facade and observed reduction of overheating effect during the PCM solidification and melting periods. Even though the above highlighted studies have provided possible solutions to the overheating effect in DSFs, it is clear that there are still some technical and scientific barriers that need to be overcome.

Since PCMs have high energy storage capacity over a narrow temperature, large amount of heat can be stored during the melting processes. De Gracia et al. (De Gracia, 2010) adopted PCM in DSF system and found it can prevent the overheating effect between the PCM solidification and melting periods, where the limitations of conventional venetian blind can be eliminated. However, it is necessary to optimize the PCM-DSF system for achieving maximum performance value. Weinlaeder et al. (Weinlaeder, 2007) monitored an integrated PCM solar blind system in a building and achieved some level of temperature reduction in comparison with a conventional blind. However, the systems which consisted of macro-encapsulated salt hydrate panels suffered from low energy storage efficiency and solidification issues. To the author's knowledge, there is still lack of numerical and experimental information on the effectiveness and performance of PCM blind systems in DSFs.

This section is focusing on the development of a physical model of an integrated DSF and PCM blind. By integrating PCM blind in the DSF system, that is intended to absorb any excess solar heat through the external glass skin which may be trapped in the DSF cavity, thus in this way prevents additional heat gain into the adjacent indoor area in hot seasons. Previous investigations carried out by Darkwa et al. (Darkwa, 2015) have shown that laminated composite PCM with narrow phase-change zone was much more thermally effective than randomly mixed PCMs. For this reason a multilayer blind structure consisting of laminated composite PCM blades is proposed as presented in Fig. 6.11. Each blade has a multilayer structure consisting of a laminated PCM layer and a substrate. When the temperature in the cavity increases above the melting temperature of the PCM, the PCM layer can absorb the solar heat trapped in the DSF cavity. The stored heat is then expected to be discharged and removed by means of natural ventilation when the temperature in the cavity drops below the solidification temperature of the PCM.

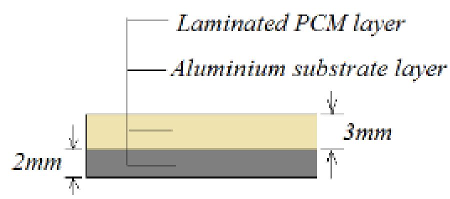


Figure 6.11 Details of the PCM blade (Author).

The physical properties of the integrated systems with PCM and aluminium blinds are presented in Tab. 6.1. Where data for commercially available PCM product RT25HC of Rubitherm Company were adopted (Data Sheet RT25HC, 2020).

➢ *Pastel paints on Aluminum*

Reducing the double reflection can be achieved by modifying the venetian blinds (VB) inner surfaces absorptivity. Gray or pastel paints on aluminum surfaces are a low cost solution that offers an interesting range of absorptivities, as shown in Fig. 6.12. The physical properties of the pastel paints on aluminium blinds are presented in Table 6.1.

➢ *Developed thin-density blackout roller blind T-PVC*

The thin-density blackout roller blind T-PVC is made of 25% fiberglass 75% PVC laminated (1 ply fiberglass, 3 ply PVC), as shown in Fig. 6.12. The thin-density blackout roller blind T-PVC is a roller blind is absorbs heat, isolates noise, fireproof, waterproof, and antibacterial. The physical properties of the T-PVC blind are presented in Table 6.1.

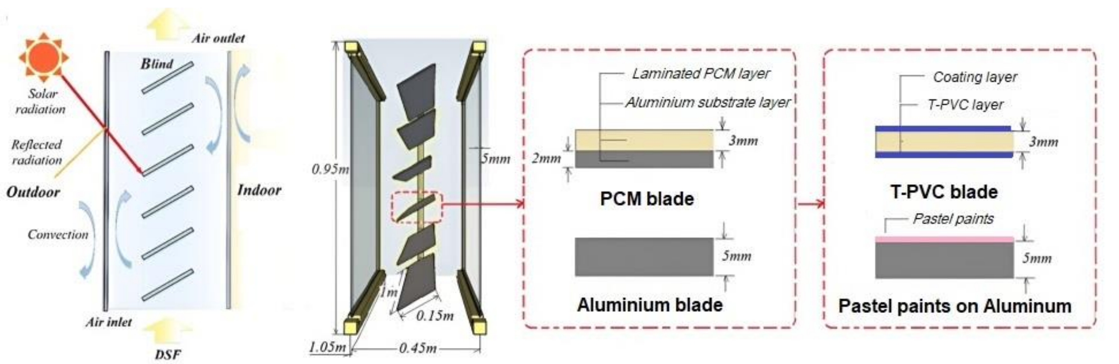


Figure 6.12: Integrated DSF and blind system (Author).
Schematic diagram, dimensions of the modeled system, and details of the PCM/Aluminium/Pastel paints on Aluminum blade/T-PVC.

Table 6.1 is present the physical properties of the different proposed materials of blinds systems.

Table 6.1 thermal properties of the different blind systems.

Material	**Density (kg/m3)**	**Heat storage capacity (kJ/kg)**	**Melting Temperature (°C)**	**Thermal conductivity (W/m K)**	**Reflectivity**	**Emissivity**		**Refractive index**	**Absorptivity**
						Ext	Int		
Aluminum	2719	-	-	202.4	0.67	0.7	0.7	1.44	0.18
Pastel paints On Alum	1707	-	-	100	0.6	0.75	0.75	0.9	0.3
T-PVC	950	90	30-38	0.9	0.56	0.8	0.8	0.75	0.6
PCM (RT25HC)	825	230	22-26	0.2	0.52	0.9	0.9	0.85	0.8

b) The effect of slat tilt angle

In the DSF system, the angles of the venetian blind can be adjusted and a series of angles (0, 30, 45, 60 and 80 degrees) has been modeled, where the little changes of the convective heat transfer coefficients on the glazing surfaces can be caused by the blinds with different angles (Kong, 2016).

The figure below illustrates slat tilt angle Ø of the blinds. A proposed series of angles above-mentioned will be simulated (in chapter 8), to test their effect on the convective heat transfer coefficients on the glazing surfaces.

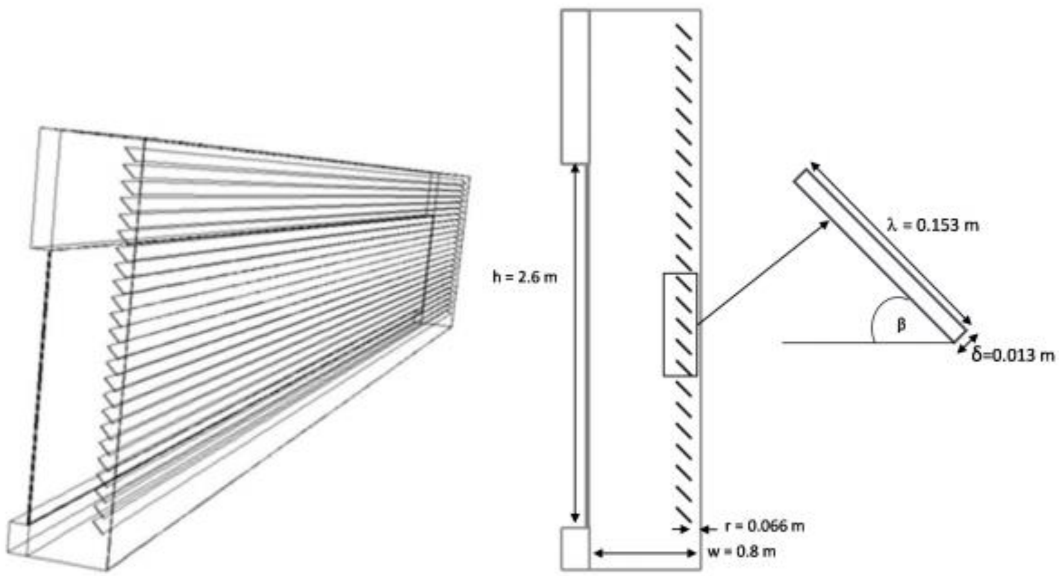


Figure 6.13 illustrates the slat tilt angle Ø of the blinds.

c) Blinds position

Results obtained show that parameters such as the proximity of the Venetian blind to the exterior skin of the façade or a differentiated surface treatment for the exterior and interior faces of the Venetian blinds louvers can notably affect the thermal performance of the DSF and hence the heat gains experienced by the building (Brandl, 2014).

Previous studies suggest that the most efficient positions of shading devices in a DSF is in the middle of the cavity (Código, 2010), but that would be considered a fire hazard according to the local regulations as it blocks accessibility to the cavity in case of emergencies. In this study, two positions (Close to external glass and Close to internal glass) will be tested to determine the best location in comparison with the middle position, in terms of the thermal performance of the DSF.

d) Blinds shape

One of the common issue in typical DSFs, associated with flexible shading devices, in hot climates. The open external skin provides gap for the air to escape from and consequently provide from excessive hot weather, preventing hotness, causing discomfort (Saber, 2012).

Providing the shading devices with high slops comparatively has been proposed to prevent the penetration of solar radiations, as shown in Figure 6.14. In this design strategy, the high slop of slat offers better insulation system, resulting in improve the thermal performance by reduction of cooling and heating requirements in summer and winter respectively. Where the mobile shading system remains horizontal (open) in winter time, to provide the building with the maximum possible solar radiation, which penetrate through the façade of the building, specifically due to lower height of sun at this time of the year. This system becomes more efficient as it is associated with multiple reflection of opaque surface of shading system.

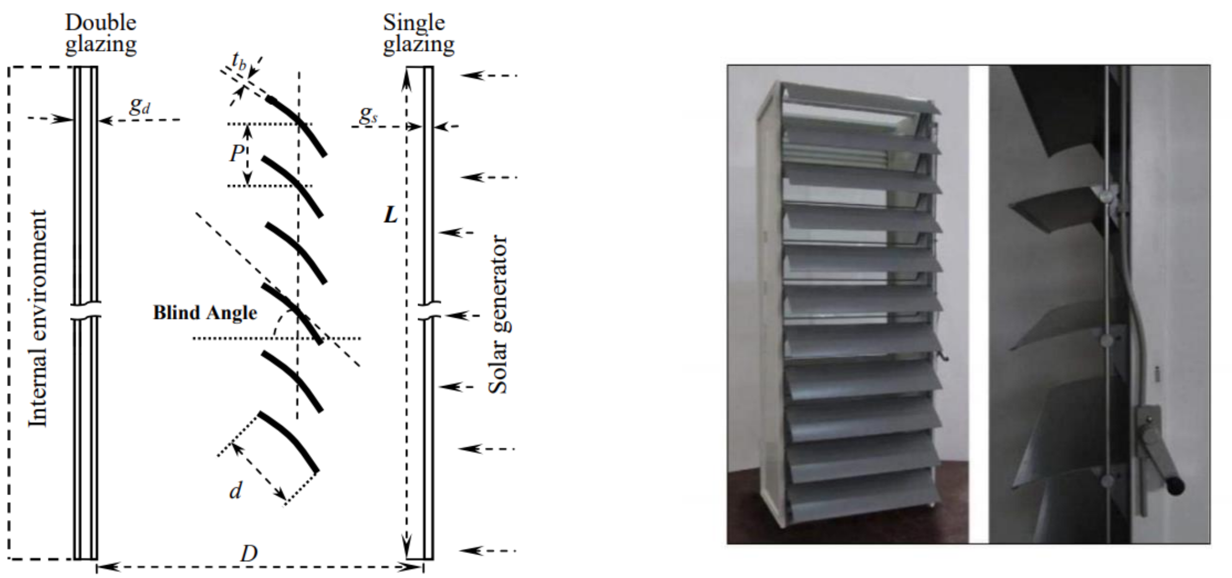


Figure 6.14 Schematic of the proposed blind shape with high slops comparatively.

The proposed alternatives of blinds variables are presented in Table 6.2. Where three different materials of blinds were proposed in comparison with conventional aluminum blinds is (Pastel paints on aluminum, PCM, and T-PVC). And also three different positions in DSF's cavity were suggested (Middle, Close to external glass, and Close to internal glass). In addition to the shading devices were provided with high slops comparatively to prevent the penetration of solar radiation, while a series of angles (0, 30, 45, 60, and 80 degrees) has been selected.

Table 6.2. The proposed blinds alternatives (Author).

<table>
<tr><th>Blinds</th><th>Blinds Material</th><th>Blinds Position</th><th>Blinds Shape</th><th>Slat Tilt Angle</th></tr>
<tr><td>Conventional Blinds (Base case)</td><td>Aluminum Blinds</td><td>Middle</td><td>Straight</td><td>45 degree</td></tr>
<tr><td rowspan="7">Proposed Blinds</td><td>Pastel paints on Aluminum</td><td rowspan="3">Close to external glass</td><td rowspan="7">Provided with High Slops comparatively</td><td rowspan="2">0 degree</td></tr>
<tr><td rowspan="5">T-PVC</td></tr>
<tr><td>30 degree</td></tr>
<tr><td>Middle</td><td>45 degree</td></tr>
<tr><td rowspan="3">Close to Internal glass</td><td>60 degree</td></tr>
<tr><td rowspan="2">80 degree</td></tr>
<tr><td>PCM Product RT25HC</td></tr>
</table>

2) Building Orientation

Common wisdom about orienting buildings in hot-dry climates is that thermal performance is heavily influenced by orientation of the facade where different facade techniques could be used according to orientation. Due to the direct solar radiation intensities in hot arid areas, the East and West orientations are to be avoided as much as possible (Gasmalla, 2016), while the North orientation provides the best thermal performance.

In this section, the facade orientation was tested to reduce the direct solar radiation intensities using Grasshopper and DIVE plug-in. In the hot climate of Al-Khartoum, the sun is the major source of heat. To arrange any site, the position of the sun must be considered for all hours of the day at all seasons as well as the direction of the prevailing winds, especially during the hot season. With good orientation, the heat transfer is reduced. And since the southern wall absorbs most of the solar energy in winter and because the sun is high over the horizon in summer southern wall can be shaded using a relatively small overhang. Furthermore, the eastern and western facades get undesirable heat in summer therefore they should have fewer surfaces exposed to the sun (Kobben, 2020).

Therefore, a series of angles was proposed which form a right angle (a 90-degree angle) confined between east and south directions. For the simulation purpose, a series of angles (10, 20, 30, 40, 50, 60, 70, and 80 degrees) will be tested, to determine the optimum angle and the overhang length, which provide optimum facade shading, as shown in the Figure below.

Table 6.3 The orientation alternatives.

Building Height	Orientation Angles	Overhang Length
10-story	10-80 degree confined between east and south directions	0.5 to 2m

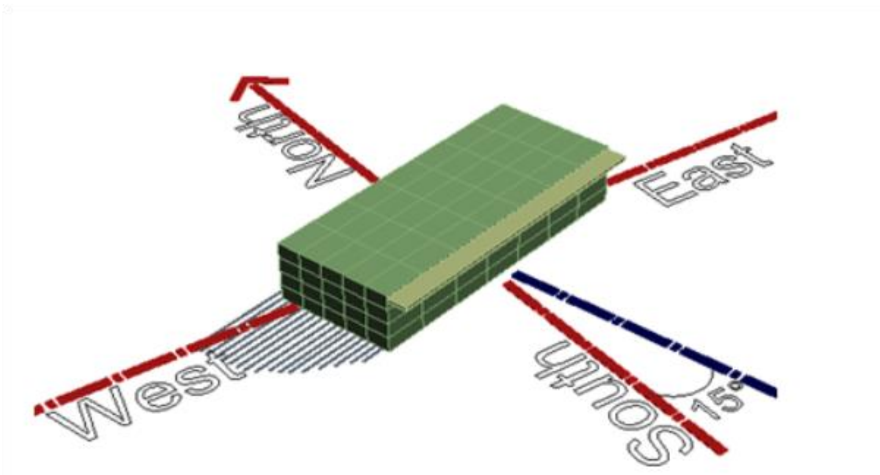


Fig. 6.15: Building orientation relative to South-north axis to reduce conductive heat flow (Author).

3) Glazing properties

In the case of a transparent double-skin facade in comparison with the benchmark single-skin, the previous simulation results predicted an increase in cooling loads in both peak and annual cooling loads (Givoni, 2010). This is due to the low direct solar radiation reflection properties of clear glazing. Therefore, this agrees with the previous hypothesis on the poor thermal performance of transparent double skin facades compared to a well-designed single skin facade (Gratia, 2017), where the glazing properties must be adjusted to improve the DSF system performance.

Changing the glazing properties from clear to reflective coated glass or tinted glass is expected to achieve major improvements in thermal performance on all orientations. The high absorption properties of glazing help in increasing the buoyancy effect of the air in the cavity while reductions of surface temperatures are achieved on the inner facades (Glória, 2014). Therefore, it qualifies to be considered as the benchmark outer skin strategy for improving thermal performance. Table 6.1 shows the thermal properties of each exterior leaf glazing type.

Table 6.4 Glazing properties for the outer leaf of the double-skin façade (Givoni, 2010).

	Exterior leaf glazing type		
	Clear glazing (Base case)	Body tinted green	Reflective glazing active blue
U-value (W/m2K)	5.6	5.6	5.6
Solar coefficient (SC)	0.85	0.59	0.27
g-Value	0.87	0.51	0.42
Thickness (mm)	10	10	10
Transmittance (%)	73	35	21
Reflection (%)	7	5	12
Absorption (%)	20	60	67

6.9 The DSF Alternatives

The proposed alternatives of blinds variables are presented in Table 6.5. Where three different materials of blinds were proposed in comparison with conventional aluminum blinds is (Pastel paints on aluminum, PCM, and T-PVC). And also three different positions in DSF’s cavity were suggested (Middle, Close to external glass, and Close to internal glass). In addition to the shading devices were provided with high slops comparatively to prevent the penetration of solar radiation, while a series of angles (0, 30, 45, 60, and 80 degrees) has been selected.

Table 6.5: The double-skin facade alternatives (Author).

DSF Type	Blinds Material	Blinds Position	Blinds Shape	Slat Angle	Facade Orientation	Glazing properties
Shaft Type	Aluminum	Close to external glass	Straight	0 degree	10-80 degree confined between east and south directions	Clear glazing (Base case)
Corridor Type	Pastel paints on Aluminum			30 degree		
The Proposed DSF (combined shaft-corridor)		Middle	Provided with High Slops comparatively	45 degree		Body tinted green
	T-PVC	Close to Internal glass		60 degree		Reflective glazing
	PCM RT25HC			80 degree		

6.10 Conclusion

This study looks beyond typical shaft and corridor DSF solutions and provides a new type shaft-corridor configuration, this configuration combined both shaft box and corridor types on the building‘s facade while trying to avoid their disadvantages.

According to the literature review, most of the studies have been carried out in a static manner and variation of the variable cannot be predicted in these studies; thus, in order to examine the variables and the schemes, several alternatives and scenarios are introduced. Airflow analysis Studies concluded that are three variables are affecting the DSF performance. For the purposes of this study, three effective configurations of the DSF were modified, to further investigate possibilities to improve the office airflow by modifying the DSF configuration system. This includes: modifying openings size, varying the shaft height, and investigating the effect of cavity depth on airflow velocity. As to the second technique, Convective heat-transfer reduction can be achieved when reducing the heat gain through the DSF layers. A variety of techniques can be applied to this effect, including; shading devices, orientation, and glazing properties.

The proposed alternatives of blinds variables are presented in Table 6.1. Where three different materials of blinds were proposed in comparison with conventional aluminum blinds is (Pastel paints on aluminum, PCM, and T-PVC). And also three different positions in DSF’s cavity were suggested (Middle, Close to external glass, and Close to internal glass). In addition to the shading devices were provided with high slops comparatively to prevent the penetration of solar radiation, while a series of angles (0, 30, 45, 60, and 80 degrees) has been selected.

Chapter Seven
Thermal Performance Assessment of DSF Configurations

7.1 Introduction

This chapter presents the evaluation of the thermal performance of a reference building model as it was designed and used as a base for performance analysis of several alternatives by verifying the first and second hypotheses of this research.

In the first hypothesis, the building is designed to evaluate the thermal performance of different types of DSFs compared to the reference building and the well-designed single skin facade (optimized single skin facade), and thermal modeling is performed to disprove the hypothesis that double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades. In regards to the second hypothesis, the simulation results are used to verify the efficiency of the proposed configuration, which combines both shaft box and corridor types in respect to thermal performance against the other configurations.

7.2 Simulation of facade alternatives

In this Chapter, the thermal performance of three different DSF configurations was evaluated in comparison with the reference building and the well-designed single skin facade.

7.3 Simulation software

For simulation, the Energy plus Version 2.1 software was used. The thermal modeling is performed on the southern facade of the model was simulated (Figure 7.1) as the worst thermally architectural facades) to evaluate the thermal performance of different types of DSFs compared to the reference building and the well-designed single skin facade (optimized single skin facade). To simulate these models, simulation inputs should be defined.

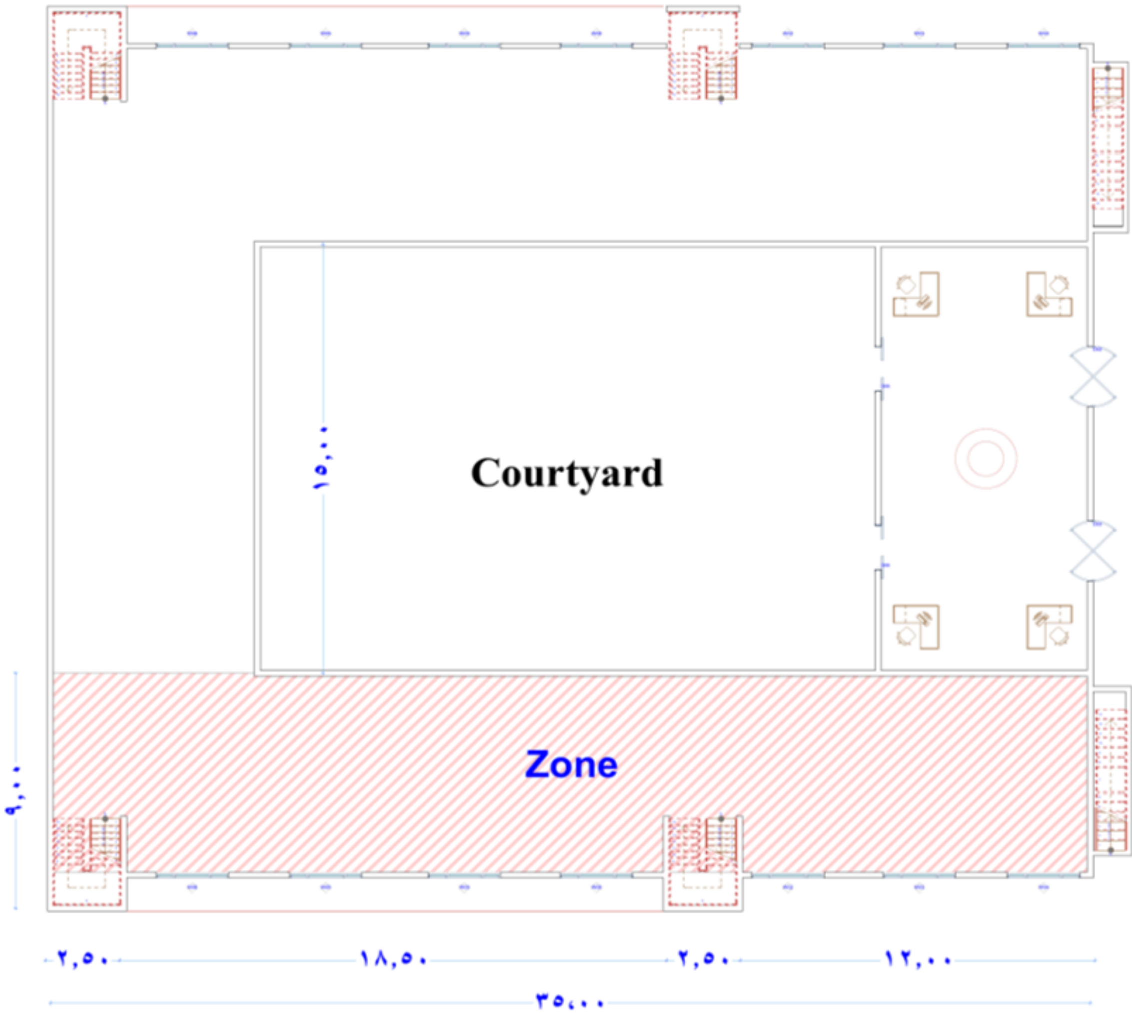


Figure 7.1 The thermal modeling zone (Author).

7.4 Simulation Inputs

Include the building's geographical location, weather data, The operational profile (activity template, occupancy schedules and other data, such as metabolic rates and levels of equipment use, were set based on the office space requirements), and description of the facade alternatives.

7.4.1 Weather data

Khartoum features a hot desert climate (Köppen climate classification BWh). With an annual average temperature of 30.5 °C (87 °F), in summer, the highest temperatures reach 48 °C (119 °F) in May. But it can sometimes reduce at night, reach record is 13 °C (36.9 °F) in the same month, as shown in the figure below (Please refer to the detailed weather data for Khartoum in Appendix B).

Fig. 7.2 Temperature range in Al-Khartoum (Appendix B).

7.4.2 The operational profile

The operational profile is considered as an independent variable in all simulations:

- ❖ Outdoor air supply rates for sedentary occupants is 8 ls/person1.
- ❖ Summer dry resultant temperature (operative temperature) in office buildings general spaces/open plans is maintained between 22 and 24 ^{o}C.
- ❖ Humidity levels are controlled between 30 and 60%.
- ❖ Infiltration is calculated at 0.5 ac/h. Recent air tightness levels were shown to achieve 0.25 ac/h. Due to the age of office stock in Khartoum and from experience with workmanship levels, the higher value was used in simulations.
- ❖ A 16 W/m^2 and lighting maintained luminance levels of 500 lux were assumed for lighting electricity consumption. For office machinery sensible gains of 15 W/m^2 were assumed.
- ❖ Schedule for office (from 7:00 a.m. to 16:00 p.m.).

The occupants' schedules, activity levels, clothing and room use are shown in Table 7.1.

Table 7.1. The occupants schedules (Author).

Winter schedule	5 days in a week, 08:00 - 17:00, otherwise 100% weekends all official holidays closed.
Summer schedule	5 days in a week, 07:00 - 16:00, otherwise 100% weekends all official holidays closed.
Activity level	Office Activity: 1 met = 108 W / occupant (1 met corresponds to 58.2 W / m^2 body surface). Task: sitting and reading.
Clothing	For winter conditions: 1 clo For summer conditions: 0.6 clo

7.4.3 Other settings

Control points for the indoor environment were set at 22 ℃ minimum for winter and 24.5 ℃ for summer. The infiltration rate assumed for the reference building was 0.5 ACH (air changes per hour). There were 300 occupants in the building. The lighting was assumed to be florescent with a power of 10 W/m^2 200lux and the annual equipment energy use for the open plan was 57 kWh/m^2. Another parameter was a control set for artificial lights, assuming that they are switched on according to occupant schedules.

7.4.4 Description of single-skin façade (BC)

After obtaining basic building and weather data, this information was used to simulate the thermal performance of the base case single-skin facade model (BC) and Well-designed single skin façade (WSS).

Specific properties of each building elements in terms of the wall properties (type, R-value, exposure, and construction), shading, window properties (type, glazing area, size and layout) has been set. The description of building‘s construction is shown in Table 7.2. The glass area in the base case is 100 percent in all facades, clear glazing type was chosen for the Base case single-skin façade (BC), and Table 7.3 shows its thermal properties.

The thermal properties of materials were initially calculated by Energy Plus and Design Builder. It should be noted that thermal losses due to thermal bridges were not included in these calculations. In order to be accurate, practical values should be used instead of theoretical values.

7.4.5 Description of well-designed single skin façade

Window Wall Ratio (WWR) Glazing is clear 6 mm panel and covers a 20% window to wall ratio (WWR). Walls are constructed of a single brick leaf un-insulated wall infill between the structural columns and plaster rendering from both sides.

Table 7.2 Description of building construction (Author).

Building Elements				
	Material type (from outside to inside)	Thickness (m)	Density (kgm^{-3})	U-value ($Wm^{-2}K^{-1}$)
External wall	Window Wall Ratio (WWR) Glazing is clear 6 mm panel and covers a 20% window to wall ratio (WWR). Walls are constructed of a single brick leaf un-insulated wall infill between the structural columns and plaster rendering from both sides.	0.30	-	1.4
Internal wall	Gypsum Plaster	0.025	970	1.92
	Airgap	0.10	1.2	
	Gypsum Plaster	0.025	1090	
Roof	Ceramic tiles	0.25	930	0.25
	Motor 1:8	0.07	530	
	Pre-cast Concrete	0.20	2300	
	Air gap 30 cm	0.30	2.5	
	Gypsum Ceiling	0.20	720	
Ground Floor	UF Foam	0.087	1200	0.35
	Cast concrete	0.10	2300	
	Creed	0.07	900	
	Wooden Flooring	0.03	1000	
Floor	Pre-cast concrete	0.20	2300	4.7
Windows Properties				
Windows	Windows Properties	Description	Aluminum window	
		U value (W/m^2K)	4.719	
	Glazing Properties	Description	Dbl LoE(e3=0.1) Clr 6mm/13Air	
		U value ($W/m2K$)	2.44	
		SHG	0.643	
	Frame Properties	Description	Aluminum Thickness = 0.02	
		Surface resistance (m^2K/W)	0.040	
	Shading Properties	Description	Blinds with high reflectivity slats	
		Control	Scheduled and positioned inside	

The glass area in the base case is 100 percent in the south facade, clear glazing and double-pane low-E insulation glazing type was chosen for the Base case single skin façade (BC) and Well-designed single skin façade (WSS) respectively, as shown in Table below.

Table 7.3 Thermal properties of façade's materials (Author).

	Base case single skin façade (BC)	**Well-designed single skin façade (WSS)**
Description	Clear glazing	double-pane low-E insulation
U-value (W/m^2K)	5.6	2.44
SHG		0.643
Solar coefficient (SC)	0.85	0.27
g-Value	0.87	0.42
Thickness (mm)	10	10
Transmittance (%)	73	21
Reflection (%)	7	12
Absorption (%)	20	67

7.4.6 Description of double skin facade alternatives

In this section, alternatives of DSFs were identified that used in simulation process. The thermal performances of the following facades were studied:

- A naturally ventilated cavity shaft type.
- A sealed outer skin-corridor type comprised of a single pane of clear glazing, where in the facade acts as an external air curtain.
- A naturally ventilated proposed DSF configuration combination of corridor and shaft type. Table 7.4 shows a description of these alternatives components.

Table 7.4 Description of the DSF alternatives components (Author).

DSF components	Description
Cavity depth	1.5m
Shaft height	7 stories
Story height	3.5m
Opening size	0.3m
Internal skin	Clear glazing (6mm)
External skin	Single pane window (6mm)
Shadings location	Inside the cavity
Shading devices	White with a slat angle of 45^o

7.5 Simulation results

An annual thermal simulation on an hourly basis under Khartoum climatic conditions was performed for different DSF alternatives. All inputs were the same as the reference building, with the same floor area. When heating and cooling loads were compared, it is apparent that cooling is the largest component of comfort demand; the cooling season period is longer than the heating season in Khartoum. The thermal performances of the different DSFs during the cooling and heating months will be discussed in detail in this section.

7.5.1 Cooling months (summer)

The simulation results are presented for a typical m^2; therefore any reduction may be multiplied by the actual building footprint to give guidance on actual thermal performance.

For the single-skin facade, reducing the solar co-efficient (SC) of glazing from 0.85 to 0.27 equivalent to changing the glazing properties from clear to double low-E insulation glass achieved major reductions in cooling loads in peak and annual cooling loads. Therefore, it qualifies to be considered as the benchmark single skin strategy for improving thermal performance. Thermal modeling is carried out to refute the first hypothesis that double-skin facades do not lead to major thermal performance except when compared to poor construction and poor insulation standards in single-skin facades, Figure 7.3 shows the cooling demands of each month for each alternative.

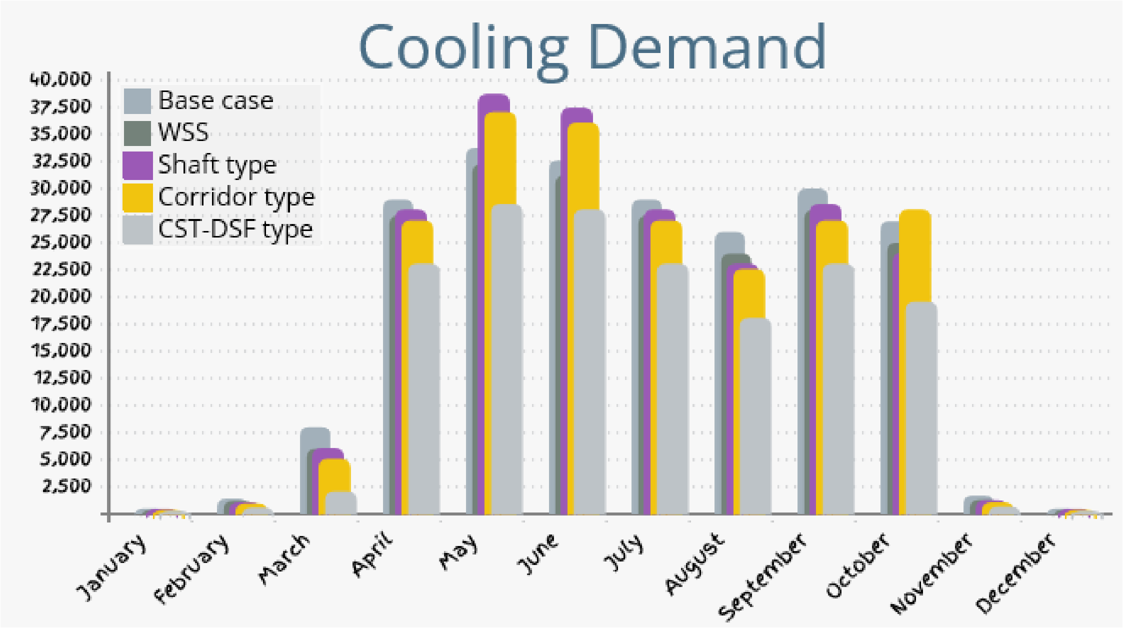


Figure 7.3 shows the cooling demand of each month for each alternative (Author).

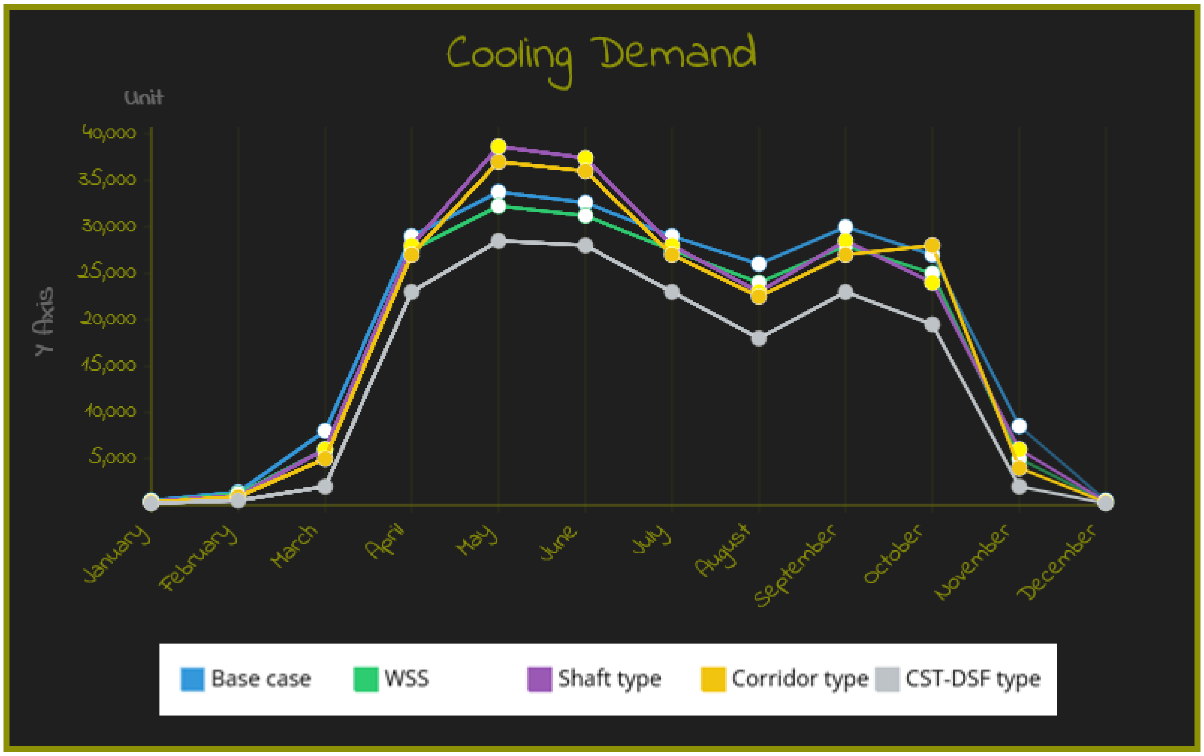
Result (1)

The simulation results showed (Table 7.5), the cooling loads were increased by 0.09% in the shaft type and decreased by 1.9% in the corridor type in comparison with the well-designed single-skin façade (WSS). This is due to the low direct solar radiation reflection properties of clear glazing. Therefore, this agrees with previous hypotheses on the poor thermal performance of transparent double skin facades compared to a well-designed single skin facade.

Table 7.5 Comparison between BC, WSS and three double-skin facades types (Author).

Southern Zone	BC	WSS	Cooling loads (%)	ST DSF	Cooling loads (%)		CT DSF	Cooling loads (%)		CST DSF	Cooling loads (%)	
					BC	**WSS**		**BC**	**WSS**		**BC**	**WSS**
	225	213	-5%	215	-4.4%	+0.09 %	209	-7%	-1.9%	191	-15%	-10%

- (**BC**): Base case single skin façade.
- (**WSS**): Well-designed single skin façade.
- (**ST-DSF**): Shaft type.
- (**CT-DSF**): Corridor type.
- (**CST-DSF**): Combination of corridor and shaft type.



Graph 7.1 Comparison between the performance of BC, WSS and three DSF alternatives in summer.

Figure 7.3 shows the cooling demand of each month for the four different alternatives in comparison with the base case single skin (BC). The total cooling load has been reduced by 5% in the well-design single-skin facade (WSS), 15% in the combined shaft-corridor DSF, and by almost 4.4% and 7% in the shaft and corridor types, respectively.

<u>Result (2)</u>

Therefore, this agrees with the second hypothesis that the proposed configuration, which combines both shaft and corridor types led to improve thermal performance in the hot-dry climate of Khartoum by taking the advantages and avoiding the disadvantages of both types. Where, the cooling stacks allow for further ventilation on hot, stagnant, summer days so the building always remains within reasonable temperature levels.

7.5.2 Heating months (winter)

The combined shaft-corridor design presents a significantly lower heating load than the base case demands, WSS, and other DSF configurations. In general, the results seem to be remarkably different than the cooling results and can be explained by the following reasons: during the heating season, the system would be closed thus no air is moving in the cavity. The cavity then heats up and increases the temperature of the inner pane and thereby reducing conductive, convective, and radiant losses. In addition, the whole system increases the R-value of the enclosure by providing a buffer zone in front of the inner pane. The difference between the maximum and minimum heating load is more pronounced than it was for the cooling demand. It can be concluded that in the Khartoum climate, the extra pane can lower the heating load by 22 percent annually.

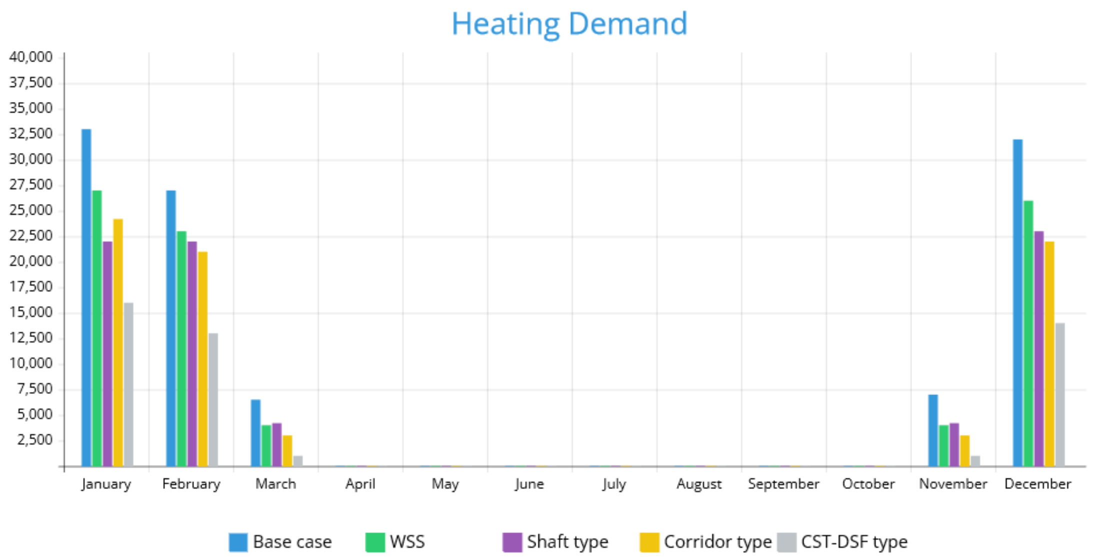
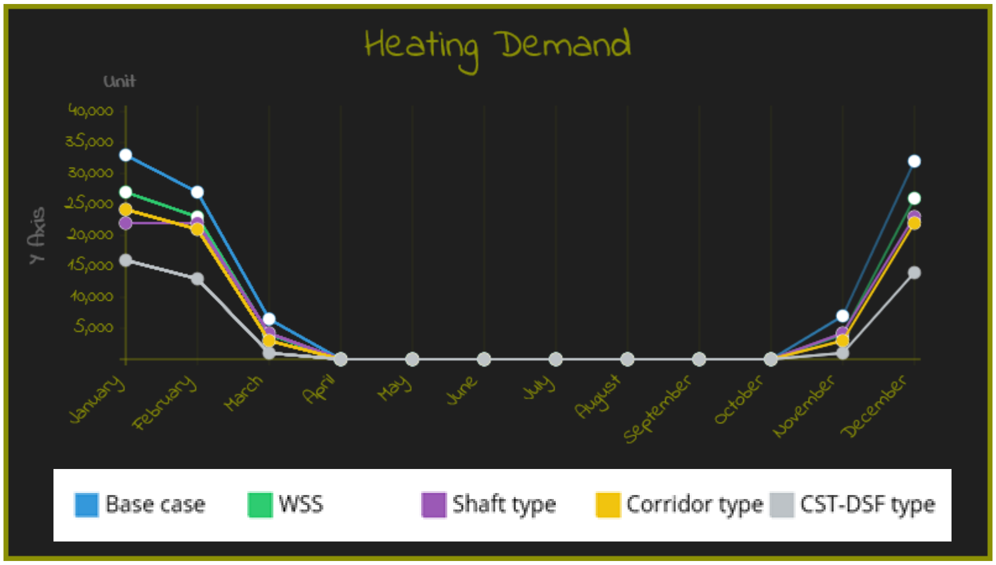


Figure 7.4 shows the heating demand of each month for each alternative (Author).

The difference between the maximum and minimum heating load is more pronounced than it was for the cooling demand. It can be concluded that in the Khartoum climate, the extra pane can lower the heating load by 22 percent annually, Graph 7.1 shown the comparison between the performance of BC, WSS, and the three DSFs alternatives in winter.



Graph 7.2 Comparison between the performance of BC, WSS, and three DSFs alternatives in winter.

7.5.3 Average mean air temperatures

The mean air temperature difference between the proposed DSF type and the base case is very small. As expected, the new configuration and other DSF alternatives provided a lower temperature than the base case during the summer months, although they also reduced the cooling loads.

7.6 Conclusion

This chapter sought investigation validates of two hypotheses by thermal modeling was carried out on three DSFs alternatives in comparison with the base case single-skin facade, and well-designed single-skin facade (WSS). This study adopts a quantitative analytical methodology to test and refute hypothesis on the efficiency of double skin facades as a facade technology suitable for improving thermal performance in the hot-dry climate of Khartoum.

The simulation results showed, the cooling loads increased by 0.09% in the shaft type and decreased by 1.9% in the corridor type in comparison with the well-designed single-skin façade (WSS). This is due to the low direct solar radiation reflection properties of clear glazing. Therefore, this agrees with previous hypotheses on the poor thermal performance of transparent double skin facades compared to a well-designed single skin facade.

The cooling demands of each month have been calculated for the four different alternatives in comparison with the base case single skin (BC). Where, the total cooling load has been reduced by 5% in the well-design single-skin facade (WSS), 15% in the combined shaft-corridor DSF, and by almost 4.4% and 7% in the shaft and corridor types, respectively. Thus, this agrees with the second hypothesis that the proposed configuration, which combines both shaft box and corridor types led to improve thermal performance by taking the advantages and avoiding the disadvantages of both types. Where, the cooling stacks allow for further ventilation on hot, stagnant, summer days so the building always remains within reasonable temperature levels.

Chapter Eight
Performance Optimization Studies of the combined shaft-corridor DSF

8.1 Introduction

This chapter opens an investigation about the third hypothesis, which is interested in how to improve the thermal performance level by applying the two techniques that arrived at in chapter 6 (airflow promotion and convective heat transfer reduction).

The first technique is interested in studying the behavior of natural ventilation in a combined shaft-corridor configuration (CSC-DSF). To that end, computational fluid dynamics software (CFD) was used to study the office airflow path to reveal that the CSC-DSF system is viable in terms of providing an acceptable indoor environment through natural ventilation. And then further investigation possibilities to improve the office airflow by modifying the proposed DSF configuration system have been conducted. The strategies include; modifying openings size, varying the shaft height, and investigating the effect of cavity depth on airflow velocity. As to the second technique, the effect of convective heat transfer reduction techniques like orientation, shading devices, and glazing properties are studied and compared with the best performing alternative that was verified in the first section of this chapter.

8.2 Air Flow promotion technique

To improve thermal performance, natural ventilation strategies can be incorporated into buildings. In this section, the behavior of natural ventilation in a combined DSFs configuration will be studied. And then further investigation possibilities to improve the office airflow by modifying the proposed DSF configuration system have been conducted.

8.2.1 CFD Modeling of the combined shaft-corridor DSF

In general, incorporating natural ventilation into multi-stories buildings is prohibitive due to high outdoor noise levels and/or high-wind speed levels. But under what conditions is the incorporation of natural ventilation possible with this combined shaft-corridor in a hot-summer climate of Khartoum? And how are offices next to a DSF ventilated؟

In this section, the behavior of natural ventilation in a combined DSF configuration will be studied. To that end, computational fluid dynamics software

(CFD) was used to study the office airflow path. First, Energy Plus and Design Builder was used to solve some boundary conditions, such as solar thermal energy. Then a strategy was developed to reduce computation time, in which the southern section of the model was analyzed instead of running the whole model (the building is symmetrical). The temperature profile and air velocity within the DSF‘s cavity and the internal office space were simulated.

1) <u>Computational Fluid Dynamics</u>

The computational fluid dynamics (CFD) software was used to analyze the Thermal performance of the combined shaft-corridor DSF cavity with wind and buoyancy-driven airflow. Developing a CFD model for this case was a lengthy process and typically taking 72 hours for each run. CFD has become a useful tool for designers in investigating the indoor environment conditions in building designs. The parameters such as air velocity and air temperature solved by CFD are critical for designing a comfortable environment. The application of Fluent in built environment has been introduced in Chapter 4. In order to investigate the DSF design three steps were taken:

- ***Step one***: Establishing and assessing of the reference building. Typical single skin facade office building (reference building) compared with two typical double skin facade systems shaft and corridor types. To study the facade design‘s impact on the thermal performance.
- ***Step Two***: Base case with Shaft-corridor DSF type assessment To investigate the thermal performance of the combined shaft-corridor DSF, the boundary conditions and domain needed to be established based on the climatic condition. The initial simulation was concentrated on 7-story shaft height new configuration within a high-rise office building. The office module is constructed using Autodesk Revit software which described in chapter 5 in details. Instead of using the CFD software to model the whole multi-story building in one complete computer model, the office building has been divided‘ into several blocks‘ vertically since the height of the shaft is limited to a number of floors (the upper seven floors). Also, just the southern part of the plan (division occurs horizontally) is modeled.

The reason for the simplification is to reduce the simulation time needed for each simulation run and any problem in the modeling process or domain settings will be identified easier. The high-rise office building can be divided vertically‘ into four office blocks of 7-storey each. One of the office blocks‘ of

7-storey shaft height modeled with the similar boundary conditions and simulations were run to study the thermal performance.

❖ ***Step three***: Variables runs: This level of simulation is to optimizing the Shaft-corridor DSF of double-skin facade (combined shaft-corridor) which is presented in Chapter 6. These variables are found to be most important in affecting the facade system in providing optimum thermal performance.

2) Climate data

Simulations were performed with climatic data of Khartoum (Khartoum international airport). Weather data were recorded by the Sudan Meteorological Authority (Please refer to the detailed weather data for Khartoum in Appendix B). For this study, the annual wind velocity average was regarded. The wind velocity range is presented in the Figure 8.1.

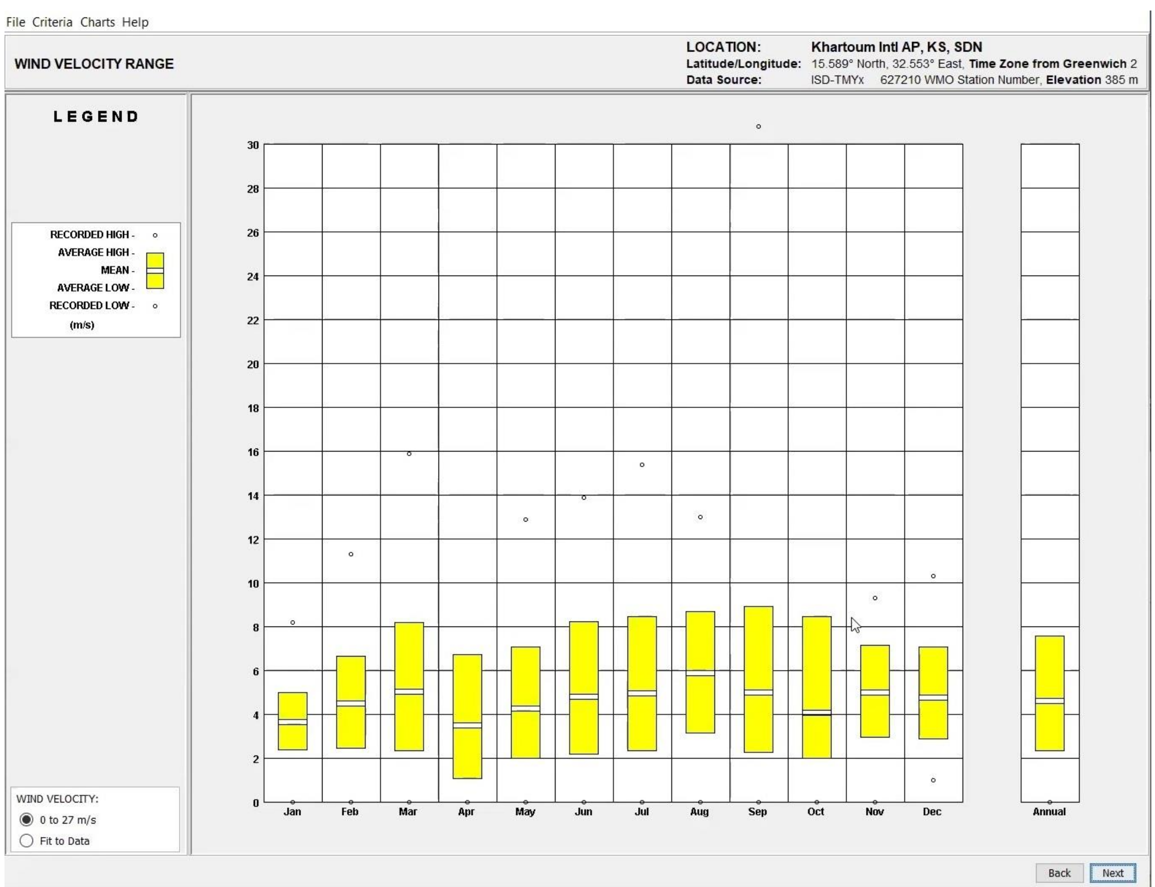


Figure 8.1 The wind velocity range.

3) External airflow modeling

One approach to study the external airflow path is to build the building in its context in the CFD software. In this strategy, the reference office building was modeled to analyze the wind pressure variable. The model was run with a number of reference wind velocities to solve for air velocities near cavity openings. These velocities could then be used as boundary conditions for a cavity model. The modeled wind pressure around the building was used as a boundary condition for internal airflow modeling.

The model is not surrounded by other buildings, but in the models of the existing buildings, it is important to consider the surrounding building's effect, which can either block or enhance wind speed around the site. The domain length is about five times that of site length in four horizontal directions. The wind distributions around the building were calculated for all directions with a typical wind speed for each one. In assessing wind effects on buildings, it is important to consider the characteristic wind nature and the speed with height variability. The second approach to include the urban context effect on airflow path is to solve the equation for specific airflow terrain. Vertical profiles of mean wind speed for boundary layers are approximated by assuming the speed to be proportional to the height raised to some power – a power-law variation (Davenport, 1965). The simple expression used extensively has the following form:

$$V_h = aV_{met}h^b.$$

Wind speed from the meteorological data corresponds to the speed at 10 m height in open country. Since the model is not surrounded by other buildings, the appropriate wind profile was assumed to be (a=0.35 and b=0.25 are the constants that depend on the terrain in the vicinity of the buildings);

$$V_h = 0.35\, V_{met}\, h^{0.25}$$

Where; V_h is the local wind speed at height, h, and V_{met} is the meteorological wind speed. Based on this formula, the wind has been calculated for the specific times that the CFD analysis was performed.

4) <u>Wind pressure assessment</u>

The wind-pressure distribution around a building depends very closely upon the local variation in wind velocity that the building produces. In accordance with the elementary pressure-velocity relationship, the pressure distribution is represented by a dimensionless pressure coefficient C_p :

$$P_w = C_p * \rho U_r^2 / 2 \qquad (8.1)$$

Where:

P_w= wind pressure, Pa.

ρ = air density, kg m^3.

V_r = wind speed at specified height, m/s.

These formulas have been used to calculate the boundary conditions for the inlet pressure in Fluent. This pressure plus static pressure is the total inlet pressure. There are default C_p values provided in the airflow network-model simulation tools. These are based on the Air Infiltration and Ventilation Centre‘s (AIVC) Guide to Energy Efficient Ventilation (Liddament, 1996), which consists of a number of wind tunnel tests for generic, low-rise buildings. Typically, these C_p values only apply as acceptable initial approximations for buildings that are close to rectangular shaped. The other approach to calculate more accurate pressure coefficients is to analyze the external CFD analysis to provide the air velocity distributions and pressure around the building due to wind effect. For simplicity, this investigation used an external CFD to calculate the pressure difference as the boundary conditions for indoor airflow simulation. Wind profiles one cell away from the building was recorded as inputs for the cavity model. These are shown graphically in Figure 8.2, and values for x, y, z, and net velocities one cell away from the building at the chimney entrance. These velocities are used as boundary conditions for a cavity model, allowing for the analysis of cavities at any height. The results shown are for reference velocities of 5 m/s and 8 m/s at 10 m above ground.

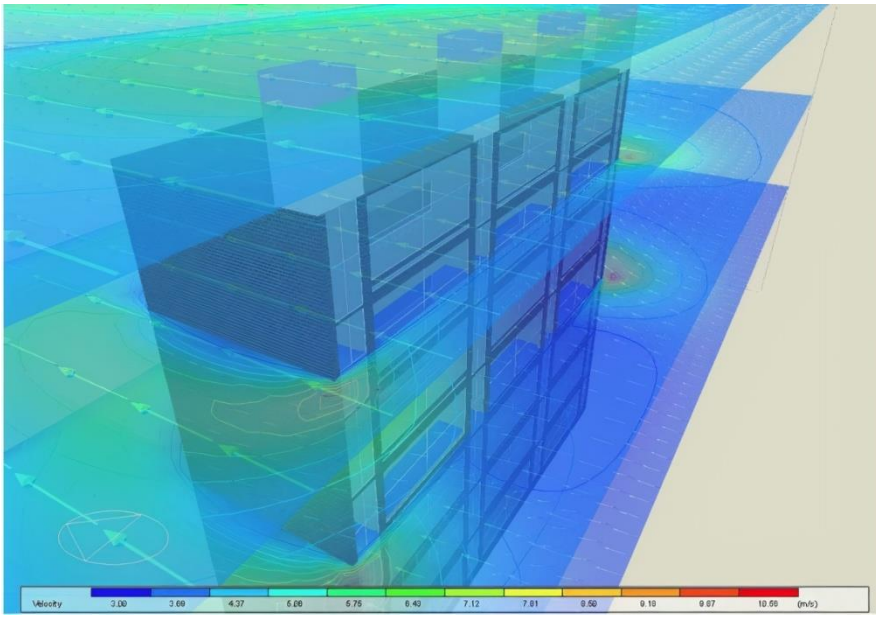
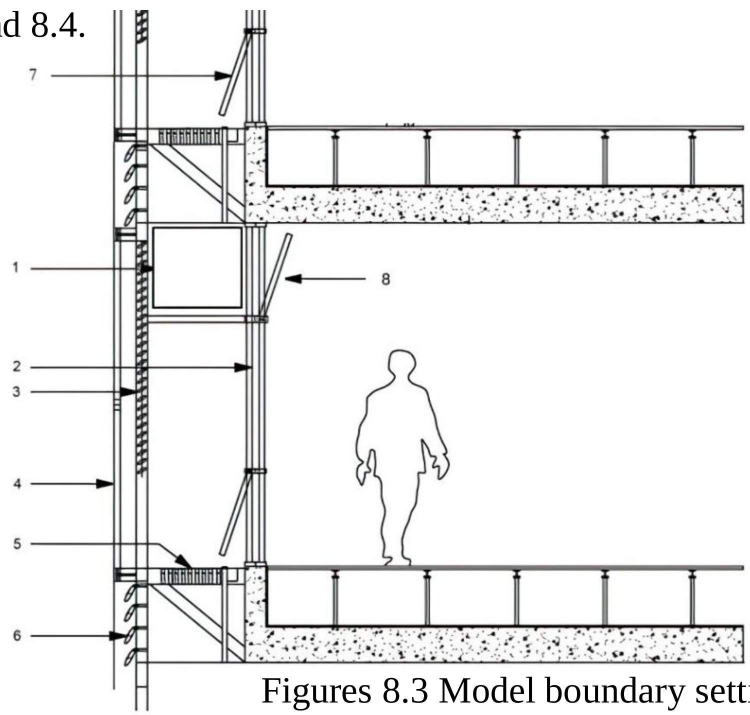


Figure 8.2 Velocity distribution around the building the prevailing wind, south at 5m/s.

5) The geometry of the CFD model

The first stage of the internal CFD modeling is to construct a seven-story office module with geometrical dimensions of 27x7 m, with 3.5 m ceiling height and 1.5 m cavity corridor in front of the offices in the Gambit. The simplified single skin facade of the model has openings on panes with 6mm thick glass. The DSF construction has one opening (inlet) at the outer pane and two openings (air inlet and exhaust) at the inner pane. The model is constructed in 3-D in Gambit as shown in the Figures 8.3, and 8.4.



Figures 8.3 Model boundary settings (Author).

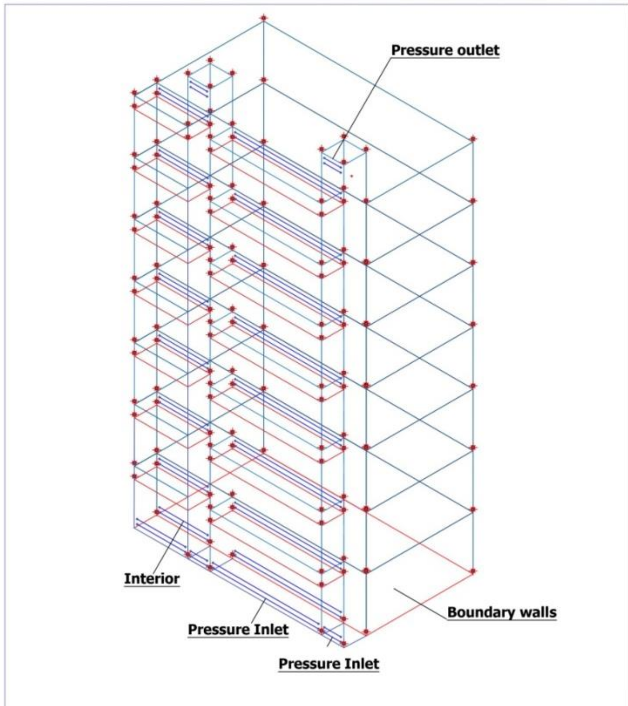


Figure 8.4 3D-Model boundary settings (Author).

a) Model construction materials and components

The outer pane of the DSF consists of a single pane 6 mm clear glass, and the inner pane, as described in the previous chapter, is a double-pane glazing. Simulations are performed under steady-state conditions using the k-epsilon turbulent model. Simulated wind speeds are used to model expected wind velocities at the levels understudy with corresponding ambient and radiant temperatures shown later in this chapter. For this study, only wind direction which is perpendicular to the DSF has been considered.

b) CFD model boundary conditions

This study is going to model levels from the fourth to the tenth story of a multi-story building. In the proposed configuration, the DSF has a ventilated shaft, which is (1.5*1.5) m with two openings on the lower and high chimney levels. This study introduces a shaft to improve the possibility of the natural-ventilation stack effect to extract heat from the offices and improve airflow rates required to reach thermal comfort level within the interior. The results of CFD model of this seven story block looked at the velocity profile, airflow patterns, temperature within the double skin, and the internal office space. To calculate thermal comfort, the boundary conditions for wind velocity, external temperature, and relative humidity were set to the ranges similar to Chicago climatic conditions, and the inputs and assumptions are presented in the Table 8.1.

Table 8.1 Model assumptions and inputs required by CFD (Author).

Domain	Domain material	Air at 30°C, 1 atm
	Reference pressure	100,000 Pa (Atmospheric pressure)
Sources	Buoyancy model difference rather than density difference.	Boussinesq-calculates airflow from temperature
	Buoyancy reference temperature	Outdoor air temperature.
	Gravitational acceleration	-9.81 m/s in the y-direction.
Boundary Conditions	Side, top, bottom, & front domain boundary conditions	Openings with (deduced) air velocities, external temperature = outdoor air temperature at inflow only, external pressure at atmospheric pressure.
	Back boundary conditions	Adiabatic solids (concrete) with depth = cavity Depth, glass: standard 6 mm clear glass.
	Heat source(external glass)	11.43 W/m^2
	Heat source(internal glass)	7.93 W/m^2
	Walls heat	25 W/m^2
	Velocity inlet	5 m/s
Cavity Details	Cavity size	3.5 m high by 7 m wide by 1.5 deep.
	Cavity external facade	Internal plate with surface temperatures on both sides is calculated based on heat source.
	Cavity internal facade	External plate with surface temperature base on heat source.
Shaft and opening details	Shaft size	1.5 m deep,1.5 long, 24.5 m high
	DSF opening size for inner pane, air gap size (inlet and exhaust).	300 mm

6) CFD simulation results

Based on those data, the temperature within the space will be predicted. To evaluate thermal performance, the specific internal space temperature and velocity at a particular height have been derived from the CFD analysis. The chimney opening size and inlets and outlets are 0.3 m; the chimney size is 1.5 m .

1) Cavity and interior spaces air temperature

The location of the chimney openings in this shaft-corridor type in relation to the chimney exhaust will have an effect on the indoor thermal comfort and airflow velocity. It is a fact that the higher the exhaust opening is located from the inlet, the stronger the stack effect will be within the air gap. This effect will then pull more air from office spaces to circulate throughout the building. The other factor that affects on air velocity are inlet and outlet sizes. Due to the venturi effect, the smaller the size the more the velocity. Figure 8.5 illustrates the room's temperature gradient, which is clearly lower than the outside temperature. There is some temperature variation as the cavity is ventilated.

Figure 8.6 clearly illustrates an increase in the gradient temperature from the inlet to the outlet where higher-surface temperatures were reached due to accumulated heat and buoyancy effect.

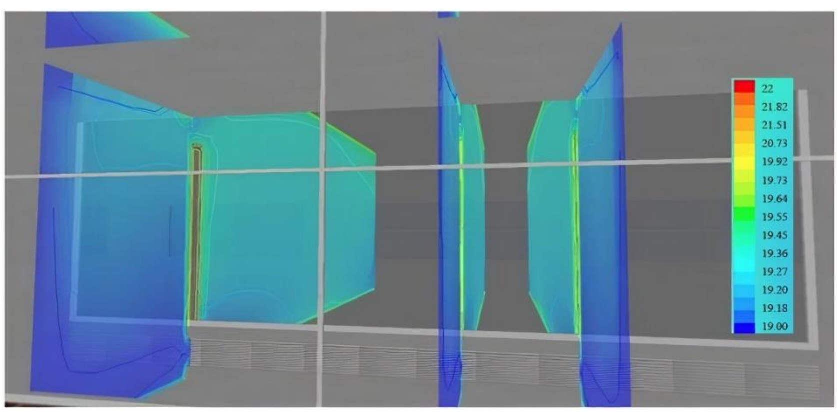


Figure 8.5 As displayed in Fluent analysis of room temperature profile (Author).

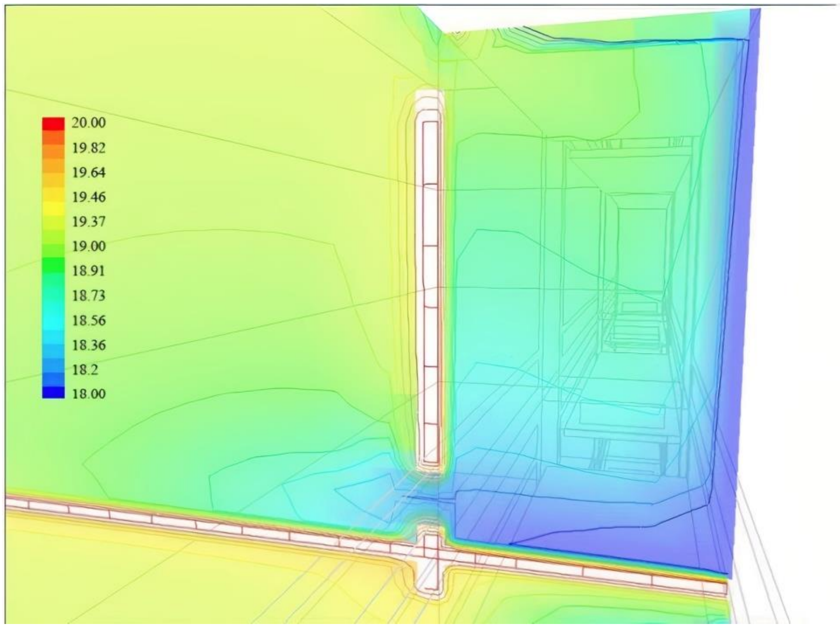


Figure 8.6 Cavity temperature gradient (Author).

As illustrated in Figures 8.5 and 8.6, the interior air temperature is slightly higher than the exterior in the half of the room closer to the cavity and also in the half upper part. The temperature at the bottom opening than the top opening is increased by 1 c. Figure 7.12 illustrates the temperature stratification from lowest on the floor to highest close to the ceiling.

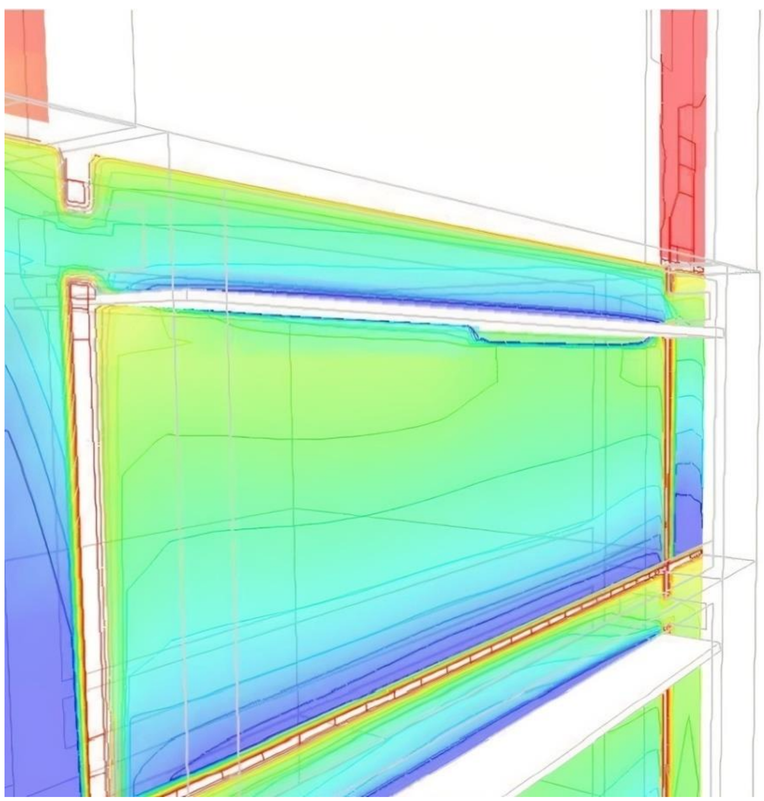


Figure 8.7 Cavity temperature gradient (Author).

Figure 8.7 also shows the cavity air temperature near the interior glazing. The temperature at the bottom opening is increased by 1.5 c than the top opening. The stack air temperature increases towards the top of the chimney in a fairly linear progression, as shown by gradients in Figure 8.9.

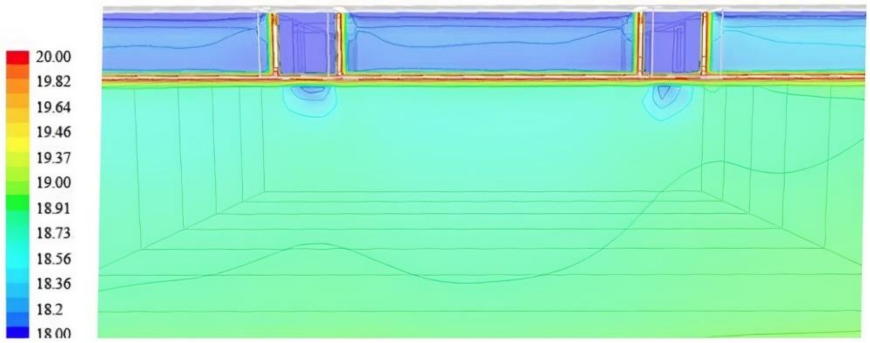


Figure 8.8 The horizontal temperature profile of the room (Author).

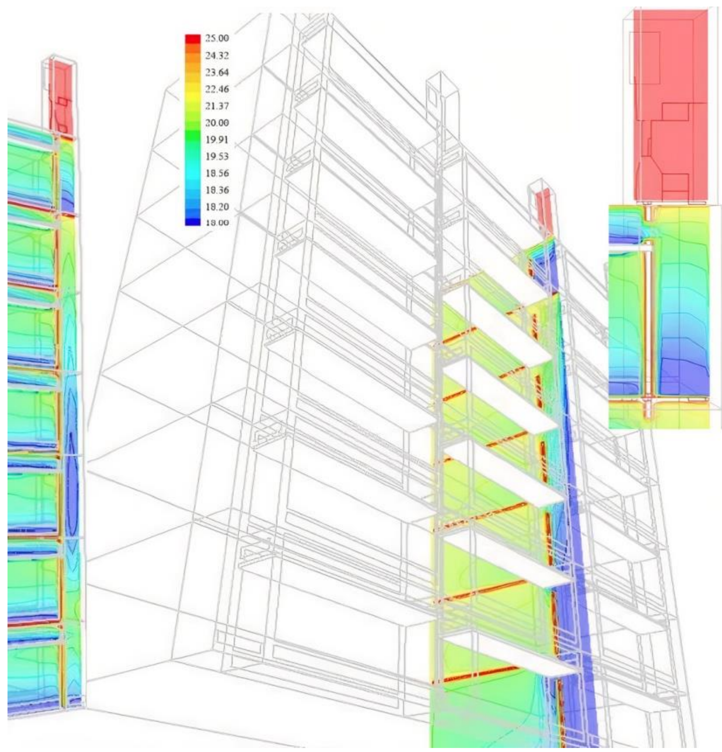


Figure 8.9 Chimney air temperature profile (Author).

Figure 8.9 shows a horizontal temperature profile at the level of 1 m from the floor (this is the height of the body mass of a seated person). The air temperature in this direction from near the glazing is highest than the center and back of the room by 0.7 oC and 2 oC, respectively. The air reaches the higher temperature near the middle of the room, the point at which air velocity is lowest. This Figure also illustrates how the concentration of heat is accumulated mostly towards the center of the space.

A temperature contour study has shown that the office space‘s lower floors have lower internal temperatures compared to the higher floors. As we increase the shaft height, the upper floors would be hottest and probably uncomfortable for occupants during the summer month. It is interesting to discover that the office‘s mid-portion floor areas for all the floors are having higher temperatures when compared to the floor area of the front part. This could be due to the airflow pattern shown in the next section.

2) Airflow

The building‘s air velocity in this model ranges from 8 m/s inlet to 2.7 m/s outlet of the chimney. The inflow from the external screen is 1.2 m/s and the internal screen inflow velocity is 0.55 m/s, while the exhaust airflow is 0.65 m/s on average. The exhaust air velocity to the chimney averages 1.5 m/s. The greatest velocity is near the inlet to the chimney and exhaust from the stack. As shown in the Figure below, the velocities are increased relative to the one-story high cavity.

Figure 8.10 shows the section of airflow at the opening of one story horizontally. Velocities are greatest near the opening, when the air is forced through the smaller area. In the back of the room, air velocities are high as they move toward the exhaust to get out from the stack.

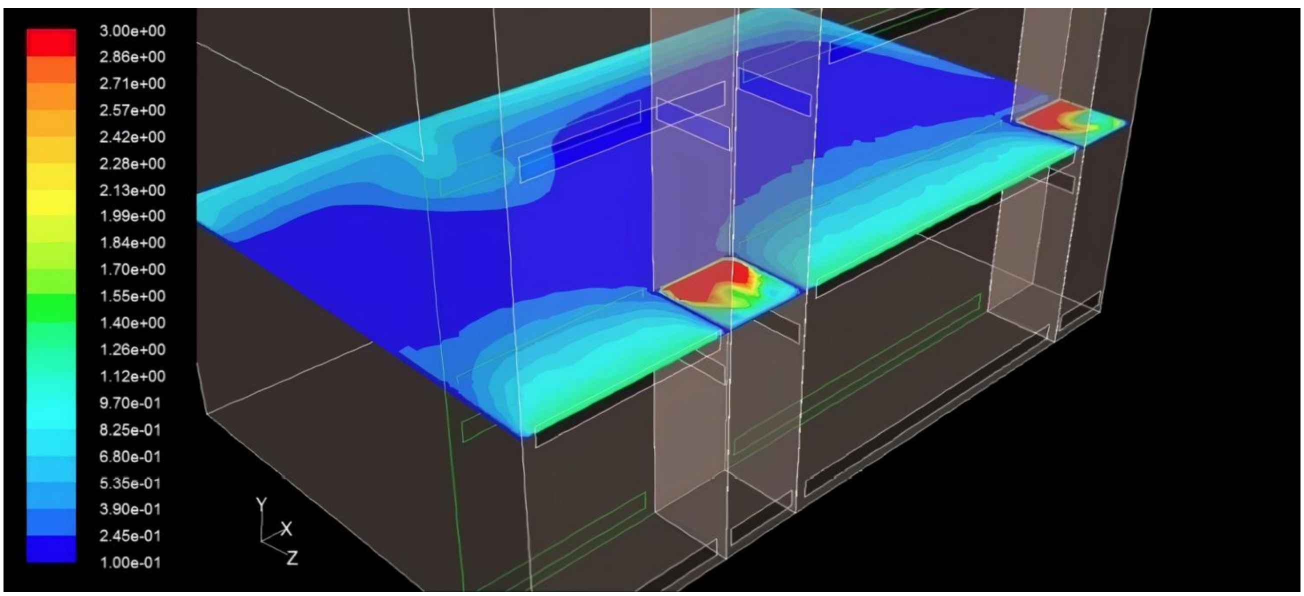


Figure 8.10 Horizontal velocity profiles (Author).

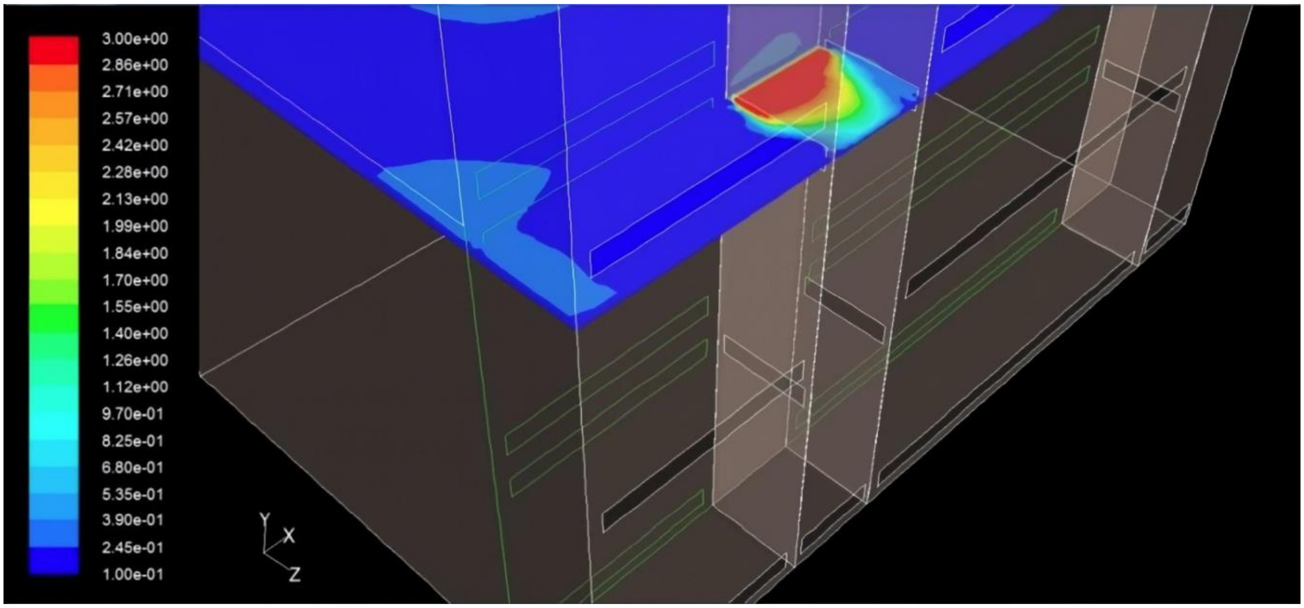


Figure 8.11 Horizontal velocity gradient (Author).

Figure 8.11 illustrates the horizontal velocity profile in the cavity and chimney. Where the velocity ranges away from the surface is less than near the opening. The variation from the greatest to the least velocity magnitude are in the range of perception (0.1-1m/s) based on the ASHRAE standard (2004).

Figure 8.12 shows velocity vectors at the openings of the chimney cavity model. The greatest velocities are near the cavity openings where the wind impacts the airflow rate, when air is forced through the smaller area. In this model, the maximum velocity at the inlet is about 8 m/s. Other than at the openings, airflow through the chimney well is around 5 m/s and is driven by both wind and stack effects.

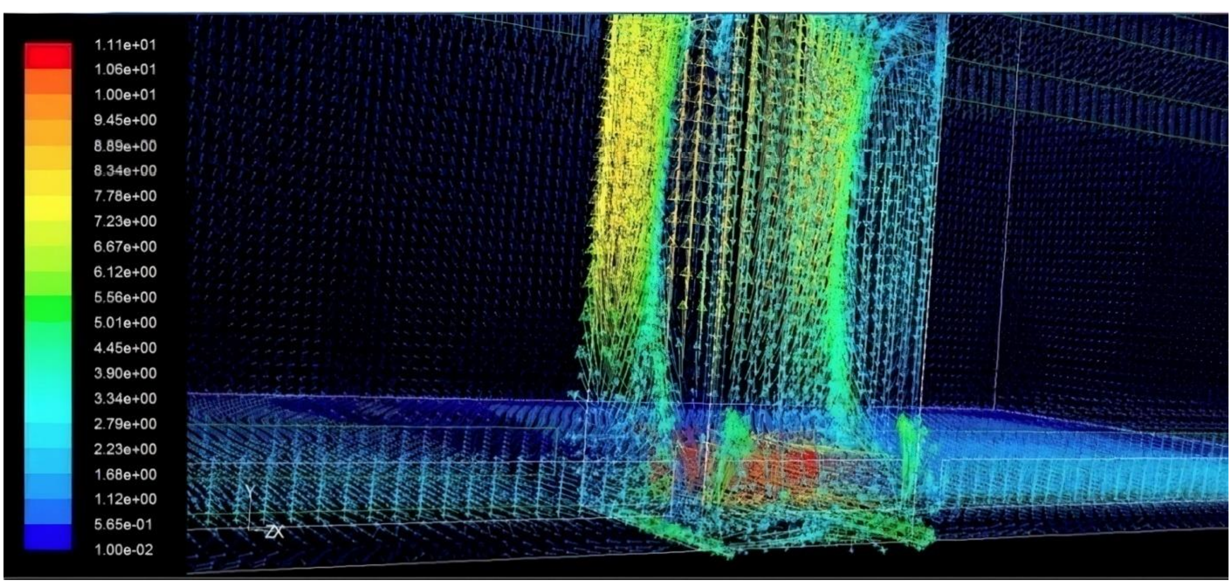


Figure 8.12 Model of air velocity close to the inlet opening (Author).

A small turbulent flow forms at the stack inlet and outlet, and stack airflow is generally laminar when it is only driven by buoyancy. Figure 8.13 shows a vertical profile of air velocity vectors to the stack from the cavity. The velocity is quite high and it extracts hot stuffy air from offices to the stack and outdoors. The airflow is likely to be more effective in extracting heat when the wind velocity is high and the temperature gradient occurs in the shaft increase the buoyancy effect.

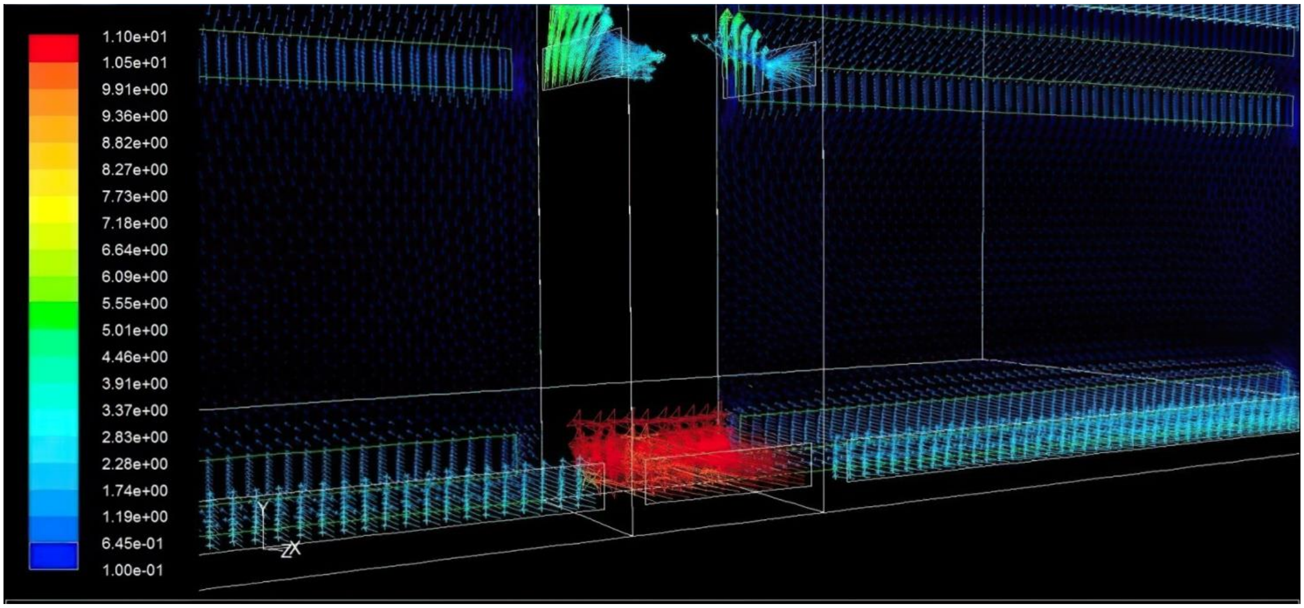


Figure 8.13 Air velocity vectors in the cavity and chimney (Author).

Figure 8.13 shows how air comes inside the chimney, which is then extracted from the offices through the chimney opening.

Figure 8.14 shows the section of airflow path inside the cavity and shafts and how air from the office outlet is directed outside. The air is basically induced to flow upwards by a buoyancy effect created by the accumulated heat. The figure below illustrates how the flow reaches higher velocities within the inlet and outlet where pressures are higher. As depicted, the flow tends to be turbulent near the glazed surfaces and openings where forces are higher. The airflow inside the cavity is much higher than what is measured by typical examples in the literature.

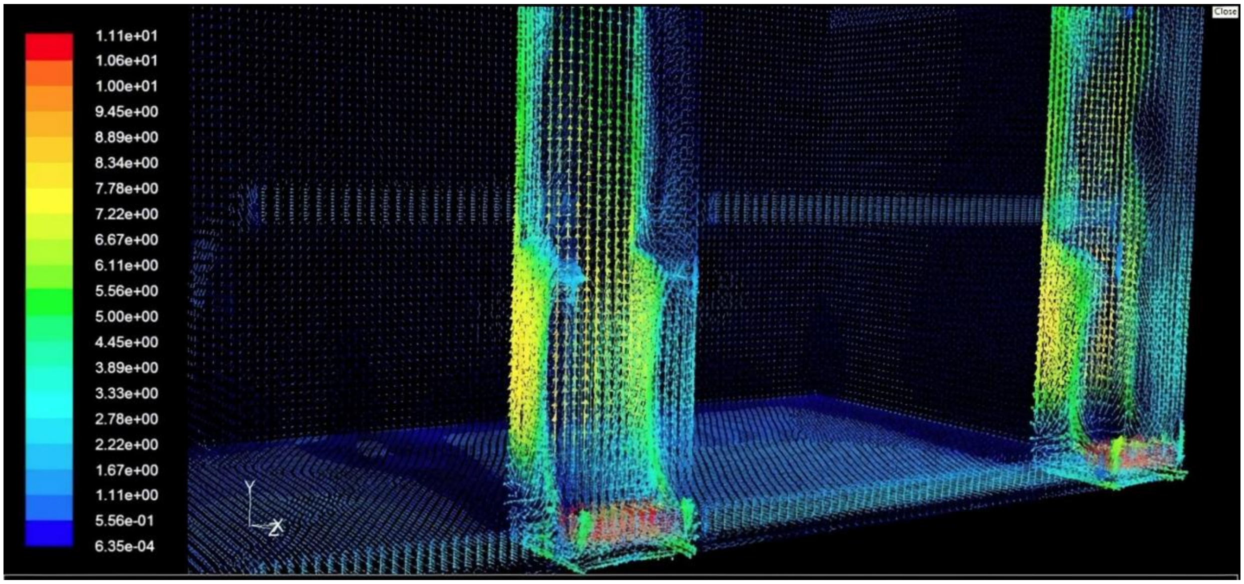


Figure 8.14 Velocity vectors in the chimney and cavity (Author).

The airflow inside the room is illustrated in Figure 7.22. where shows an air-movement trend from laminar close to the wall boundaries to turbulent in the room‘s center. The airflow inside the rooms is less than 1 m/s and more than 0.1 m/s.

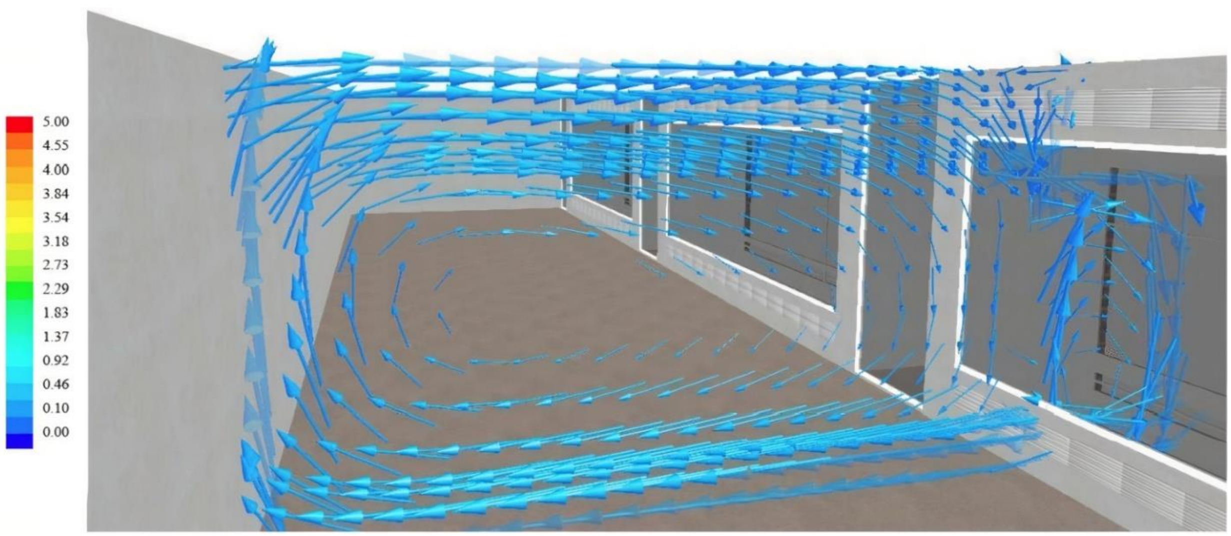


Figure 8.15 Velocity vectors in the room (Author).

3) CFD result findings and analysis of the combined shaft-corridor DSF

Simulation results for the combined shaft-corridor DSF type indicate that the DSF air gap size of 0.3m gives a comfortable result for these particular conditions in a natural ventilated space. The office space‘s lower floors would generate the lowest operative temperature due to the stack effect provided by the DSF configuration. This has enhanced the natural ventilation strategy to improve thermal performance by providing better internal thermal comfort conditions.

There is an internal temperature difference of 1 ˚C for the DSF mid-floor, which could be due to the slower internal air velocity generated. The south-facing DSF configuration produced a 59% acceptability limit for the 0.3 m opening size, according to the Thermal Environmental Conditions for Human Occupancy from ANSI/ASHRAE Standard 55- 2004.

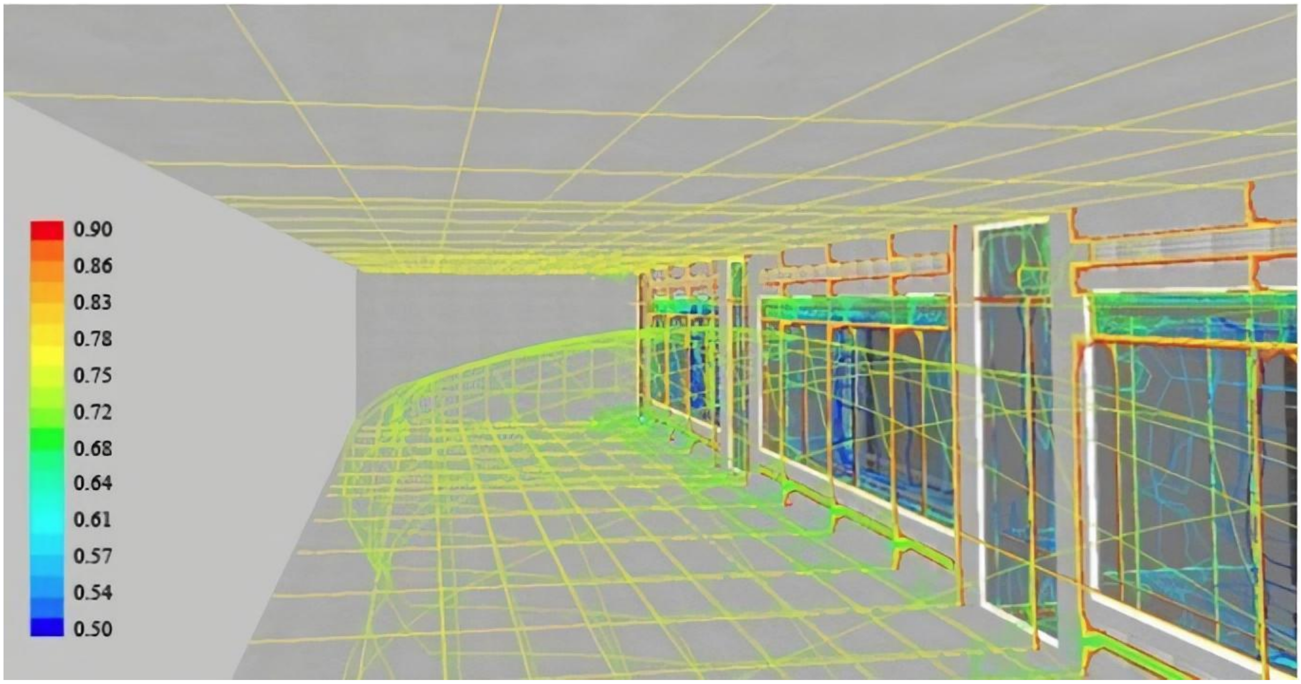


Figure 8.16 Average PMV as calculated in the room (Author).

It was found that the combined shaft-corridor DSF will generate a strong stack effect within the air gap, which, in turn, will pull more air out from the office space through rear-wall vents. The temperature generated within the office space is then desirable and close to the human comfort requirement. The airflow pattern created will have a good ventilation effect with cool air coming from the vents, and across and above the internal space, and discharge through the inner pane high level opening.

Result (1)

This section has shown that the combined shaft-corridor DSF has a possibility of improving thermal performance by providing acceptable internal temperatures through a natural ventilation strategy in the hot-summer climate of Khartoum. These results answered the first question posed in the introduction of this section.

8.2.2 Variables modeling (alternatives tested)

The main goals of the modeling process in the previous section of this chapter were to determine general airflow and temperature profiles by varying the cavity geometry. In this analysis, the driving forces for airflow are buoyancy and wind pressure based on the weather data in each of the models, thus allowing for the development of different variants and can be used in the thermal simulation. Variables analyzed include:

- Cavity Depth: 0.5 m, 0.9 m, 1.2 m and 1.5 m
- Shaft height: 4 to 10 stories (3.5 m each story)
- Opening Size: 0.3, 0.6 and 0.9m.

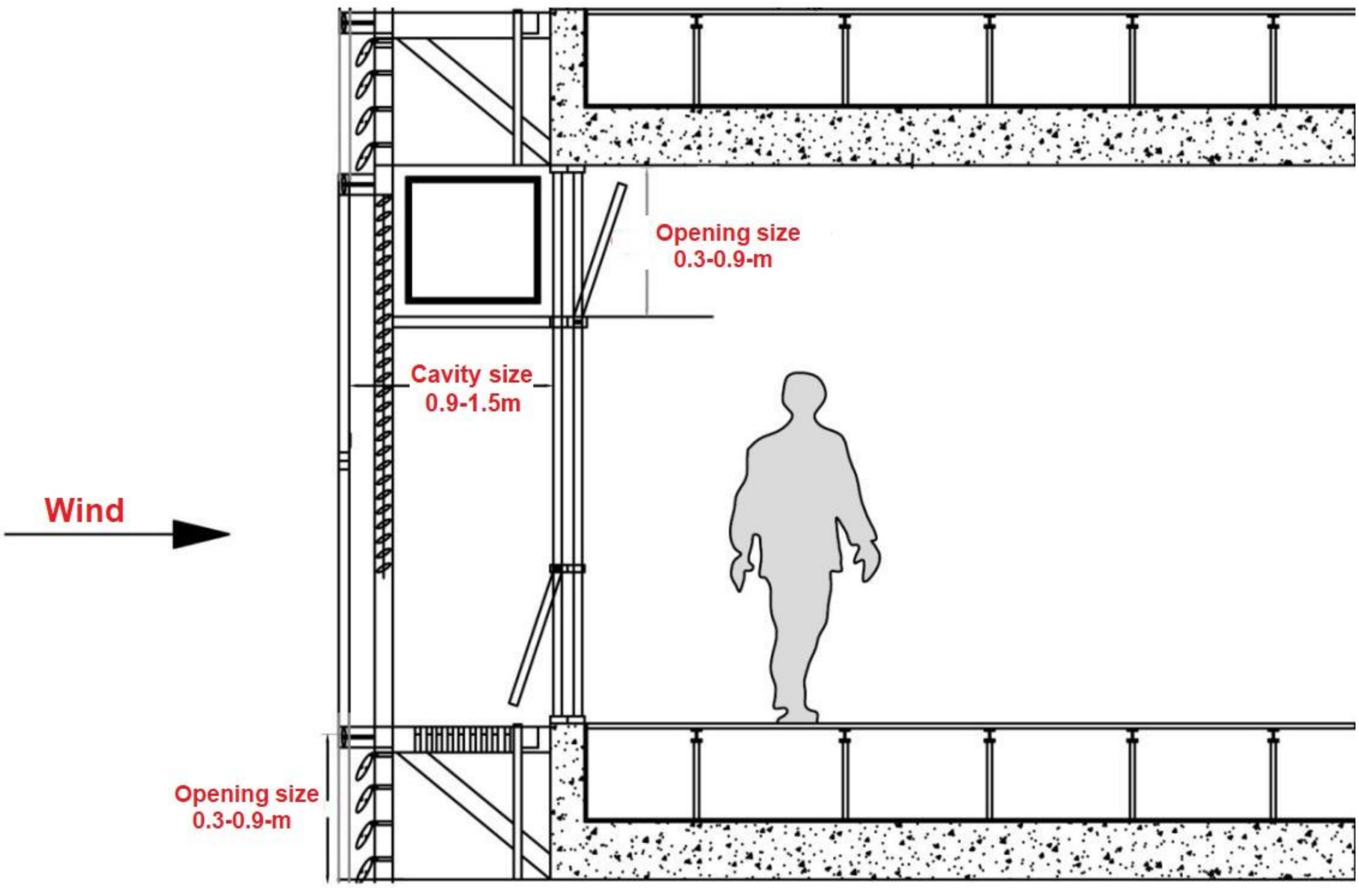


Figure 8.17 Variables used in simulation (Author).

1) <u>Simulation process</u>

Thirty-six different models were developed to analyze the cavity geometry variables. Each of the models was investigated at 1.2 m above floor level and at the office space‘s center. And they were run in CFD under a number of different environmental conditions to determine trends in the cavity‘s airflow and temperature performance. Table 8.2 summarizes all alternatives used in the simulations with constant input conditions included an external temperature of 48 °C, wind velocity of 5 m/s and relative humidity of 19%.

Table 8.2 The different scenarios of the combined DSF (Author).

Variables	Opening Size	Cavity Depth	Shaft Height
Combined shaft-corridor DSF	0.3	0.5	4 - story
	0.6	0.9	7 - story
		1.2	
	0.9	1.5	10 - story

2) <u>Impact of opening size on thermal performance</u>

One of the main arguments for using increased opening areas in buildings is the provision of better natural ventilation. However, the increased opening area leads to better performance in cooling months but not in heating months. To make use of airflow more efficiently, attention has to be paid to how the opening works with the chimney, which will be discussed in the next section. In order to study the impact of the opening area on thermal performance, openings of 0.3, 0.6, and 0.9m (as described in the previous section, results were taken for the highest temperature in May) were generated.

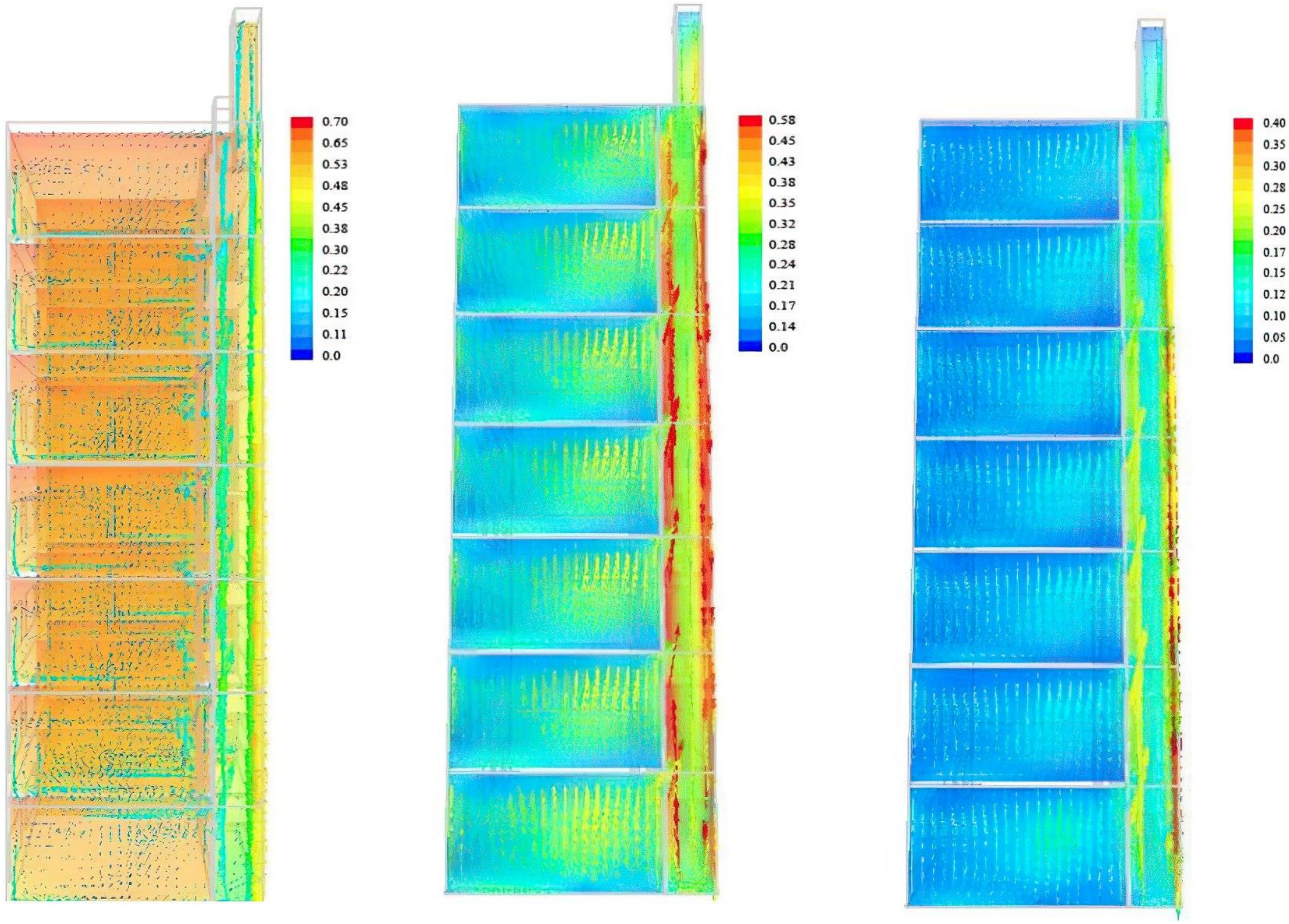


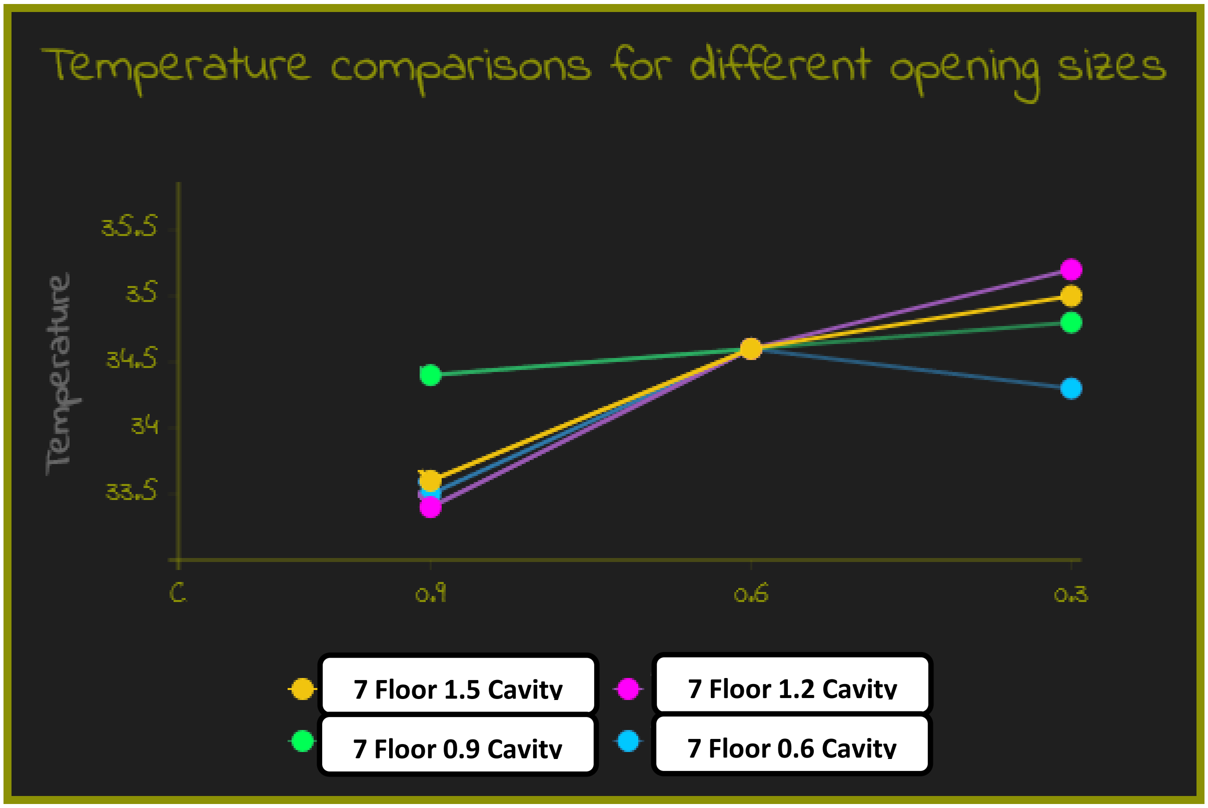
Figure 8.18 shows the configurations of the CFD model for simulations under specific conditions.

Different opening sizes are tested to optimize performance for the combined shaft-corridor DSF. The findings were summarizing in the below table:

Table 8.3 Performance comparisons for different opening sizes (Cavity Depth: 1.5 m)

Shaft Height	**Cavity Depth**	**The Best Scenario for the Opening Size**
4-story	1.5 m	0.6 m to 0.9 m
7-story		0.9 m
10-story		0.6 m

For 7-story shaft height and 1.5 m cavity depth, the best case would be a 0.6 m opening size. And for 10-story shaft height and 1.5 m cavity depth the best scenario for the opening size would be 0.9 m. But for a shorter shaft height (4-story), the variability of opening size from 0.6 m to 0.9m does not impact much on thermal performance. As we reduce the shaft height and keep the cavity depth intact, the best case for an opening size would be 0.6 m. As the shaft height decreased for the same cavity size, the smaller opening size cannot provide acceptable internal temperatures.



Graph 8.1 Temperature comparisons for different opening sizes
(Shaft height: 7-story)

Graph 8.1 shows temperature comparisons for different opening sizes. The 0.9 m opening for the bigger cavity depth shows a lower indoor temperature, but as we reduce the cavity size (to 0.9m), the opening has not impacted the operative temperature. As for a 0.5 m cavity, the temperature of the 0.6 m opening increased in comparison with a 0.3m opening size, while the case 0.9 m cavity depth the temperature has not changed much by increasing the opening size. After taking all thermal comfort parameters into consideration, an opening of 0.3 m would provide optimum results, as shown in table 8.4.

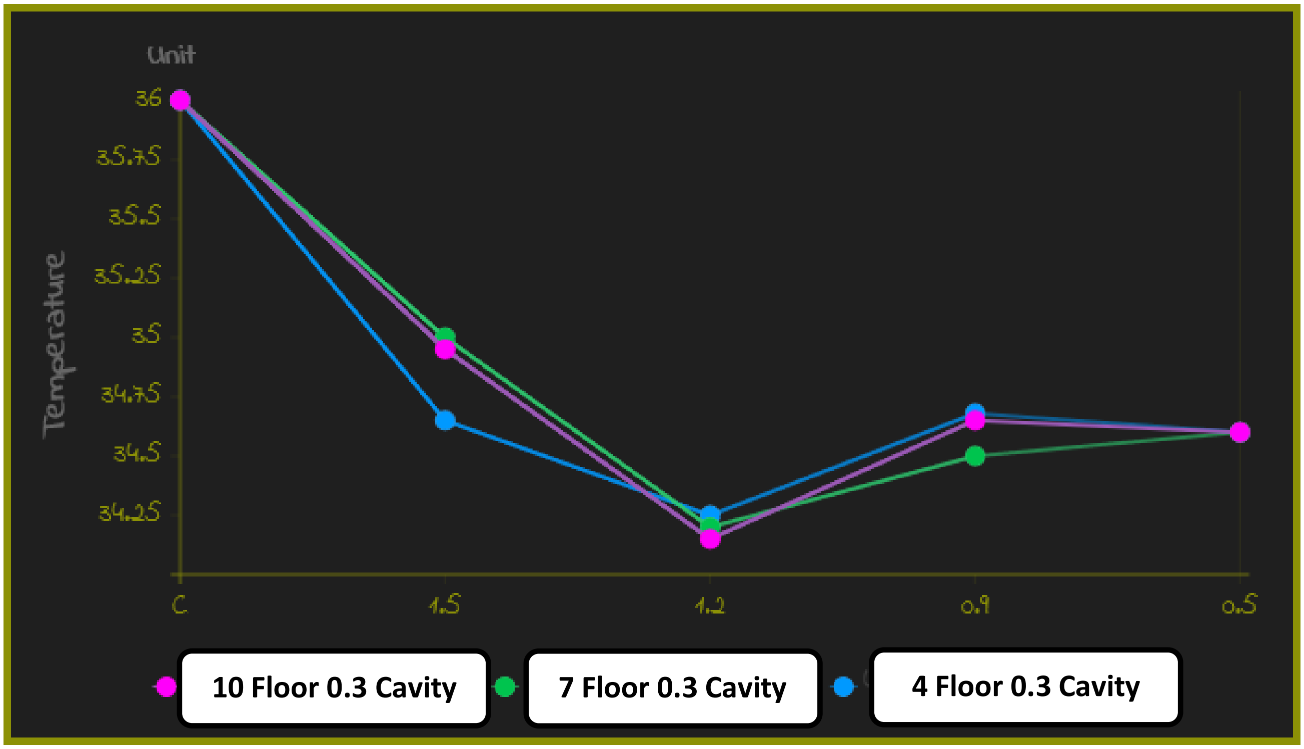
Table 8.4 Performance comparisons for different opening sizes (Shaft height: 7-story).

Cavity Depth	**Shaft Height**	**Opening Size**	**Remark**
1.5 m	7-story	0.9 m	Best performance
1.2 m		0.6 m	Best performance
0.9 m		0.9 - 0.6 - 0.3	The opening size hasn't impacted the operative temperature.
0.5 m		0.3 m	The temperature of the 0.6 m opening increased in comparison with a 0.3m opening size

3) Impact of cavity depth on thermal performance

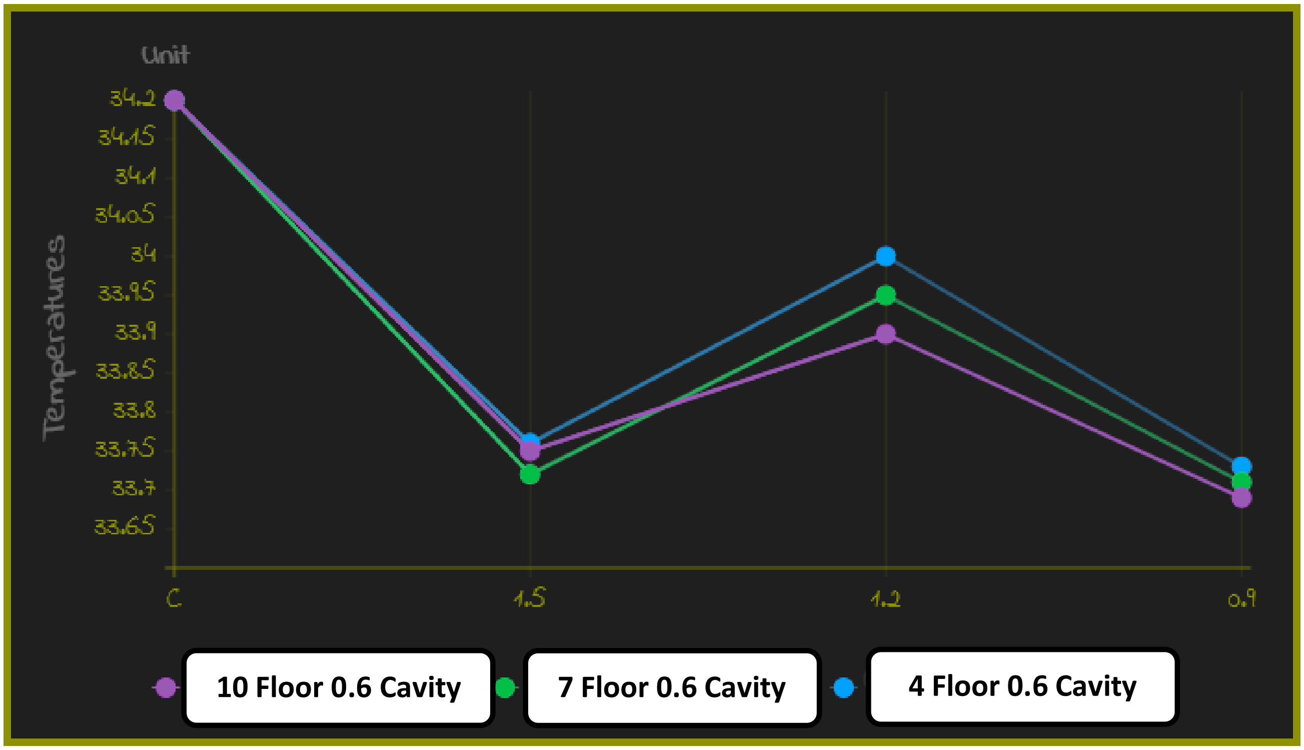
After establishing the optimum opening size for the combined shaft-corridor DSF, the second variable to investigate is the effect of different cavity depths on thermal performance and indoor temperatures. Different cavity depth sizes of 0.5 m, 0.9 m, 1.2 m, and 1.5 m will be introduced to the DSF system, with an optimum outer skin opening size of 0.6 m, and 0.3 m. It should be noted that the inner pane and shaft exhaust openings are also equal to the outer skin opening size.

It was expected that as the shaft height increased, the performance level would be higher. However, the results do not show much difference. This does not mean that air velocity has not increased by adding to the shaft height. Air speed has increased but there are several other issues that impact thermal performance. The results in Graphs 8.2 and 8.3 indicate a slightly better performance level in a 7-story shaft height with cavity depth of 1.2 m.



Graph 8.2 Temperature comparisons for different cavity depth and shaft height (Author).

Comparing the operative temperature of different cavity depths shows that 1.2 m provides a lower temperature and would be the optimum choice for a 0.3 m opening. And due to maintenance issues for a 0.5 m cavity depth, the next optimum sizes would be 0.9 and 1.2 m.



Graph 8.3 Temperature comparisons for different cavity depth and shaft height (Author).

In comparison of air temperature values shown in the graphs above for a 0.6 m opening, the optimum cavity size would be 0.9 m and the results doesn't show much difference as the shaft heights varied .

The results show better thermal performance when opening size increased to 0.6 m -optimum opening size- in comparison with 0.3 m. The cavity depth of 0.9 m shows better performance with 0.6m opening and the second best option would be 1.2 m with 0.3 m opening size. As shown in the table below.

Table 8.5 Performance comparisons for different Cavity Depths (Author).

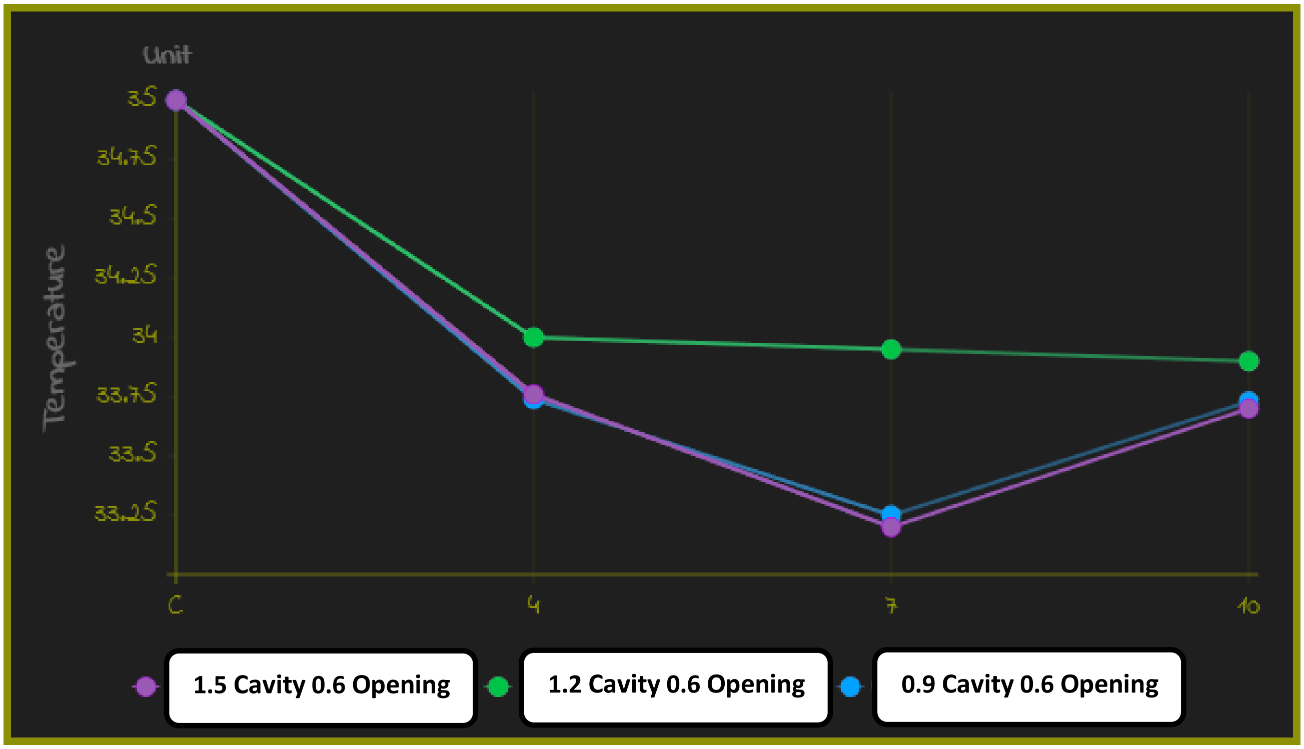
Opening Size	**Shaft Height**	**Cavity Depth**			
		0.5 m	0.9 m	1.2 m	1.5 m
0.3 m	4-story 7-story 10-story	Maintenance issues	The second best option	The optimum option	The lowest option
0.6 m		Maintenance issues	The optimum option	The lowest option	The second best option

Remark, The results doesn't show much difference as the shaft heights varied.

4) Impact of shaft height thermal performance

In order to investigate the shaft height on the combined shaft-corridor DSF, three different shaft heights have been introduced to the system. The shaft height will be tested to provide the better thermal performance. At this stage, the shaft height will also be tested on the optimum openings size and cavity depth obtained for the system in previous sections. The optimum opening size for the outer pane is 0.3 m–0.6 m and the cavity depth size is set to 0.9–1.2 m.

It was found out the 7-story shaft height provides a slightly better performance than the 10-story shaft height. Although the air velocity will be increased in a 10-story shaft, the top floor would be slightly warmer when the shaft height is increased more than 7 stories as illustrated in the graph 8.4.



Graph 8.4 Temperature comparisons for different shaft height and cavity depth (Author).

The temperature graph of different shaft heights shows that the 1.2 m cavity size in the case of an 0.3 opening has a lower operative temperature in comparison with other depths. In the case of a 1.2 m cavity depth, the 10-story shaft high has a lower temperature than the 7-story high. It was found out that a 0.9 m cavity depth performed better when the opening size increased from 0.3 to 0.6 m. In the case of 0.9 m cavity depth and 0.6 opening size, the shaft height has not had much impact on the temperature.

After analyzing all simulation results in respect to thermal performance, a 7-story shaft high is the optimum solution and provides better indoor operative temperatures for offices spaces.

5) Comparison of the optimum performance alternatives

Several attempts and comparisons have been conducted, to optimize DSF configurations to find acceptable indoor conditions for office occupants, a number of positive findings were observed. These results will be of utmost importance as indications of whether this proposed type of facade (Shaft-corridor DSF configuration) can be used as a mean to introduce natural ventilation to multi-storey buildings in the hot climate of Al-Khartoum. Optimization findings are summarized in the table below:

Table 8.6 Optimization findings (Author).

Variables	**The optimum option**	**Remark**
Opening size	0.3 – 0.6 m	The optimized DSF for Al-Khartoum climate is 7-story high shaft, 1.2m cavity depth, and 0.6m opening size.
Cavity size	0.9 – 1.2 m	
Shaft height	7-story	

The studies in optimizing the configurations of the DSF system have led to construct of an improved system for use in a hot-dry climate. Some of the important findings are tabulated below:

- **a)** A DSF system with openings vs. cavity depth (shaft height constant). As the opening size increased, the performance improved with the same cavity depth. In order to get the same results in thermal performance, as the cavity depth is decreased, the opening size should be increased.
- **b)** A DSF system with the opening size vs. shaft height (cavity depth constant). Increasing the shaft height improved the thermal performance and as the shaft height increases the opening size needs to increase to provide the same results.

c) DSF system cavity depth vs. shaft height (opening size constant). As the shaft height increases, the cavity depth should be decreased with a constant opening size to provide the same results.

It was hypothesized that the combined shaft-corridor DSF would show significant improvements in terms of enhancing the airflow. This is promising for the combined shaft-corridor DSF in its ability to improve the thermal performance.

8.3 Convective heat transfer reduction techniques

Convective heat transfer reduction is the process of reducing the effectiveness of heat exchange. This can be achieved when reducing the heat gain through the DSF layers. A variety of techniques can be applied to this effect, including orientation, shading devices, and glazing properties.

8.3.1 Shading Devices (Venetian Blinds)

This study looks beyond conventional venetian blinds with a slat angle of 45 of DSF solutions and provides new alternatives for solar protection, reduction temperature, and maximizing the buoyancy effect in the cavities. The possibilities to improve DSF performance have been investigated by modifying the shading devices system. The factors that effect in DSF performance include:

- Varying the blinds material.
- Modifying the blinds position.
- Varying the blinds shape.
- Investigating the effect of slat tilt angle.

The alternatives simulated are presented in Table 8.7. Where three different materials of blinds were simulated in comparison with conventional aluminum blinds is (Pastel paints on aluminum, PCM, and T-PVC). And also three different positions in DSF's cavity were tested (Middle, Close to external glass, and Close to internal glass). In addition to the shading devices were provided with high slops comparatively to prevent the penetration of solar radiation. While a series of angles (0, 30, 45, 60, and 80 degrees) has been modeled.

Table 8.7. Simulation alternatives (Author).

	Blinds	Blinds Material	Blinds Position	Blinds Shape	Slat Tilt Angle
1	**Conventional Blinds (Base case)**	Aluminum Blinds	Middle	Straight	45 degree
2	**Proposed Blinds**	Pastel paints on Aluminum	Close to external glass	Provided with High Slops comparatively	0 degree
		T-PVC	Middle		30 degree
		PCM Product RT25HC	Close to Internal glass		45 degree
					60 degree
					80 degree

1) Effect of blinds material on thermal performance

In order to test the effect of blinds material to show its ability on heat absorption and heat flux reduction, the blind was regarded to be in the middle of the cavity and tilt angle of 45°. The physical properties of the blind materials are shown in Table 8.8.

Table 8.8 Physical properties of the system.

Material	Density (kg/m3)	Heat storage capacity (kJ/kg)	Melting Temperature (°C)	Thermal conductivity (W/m K)	Refl	Emissivity		Refractive index	Absorptivity
						Exl	Int		
Glass	2500	-	-	1.1	0.16	0.84	0.84	1.5	0.15
Aluminum	2719	-	-	202.4	0.67	0.7	0.7	1.44	0.18
Pastel Paints on Aluminum	1707	-	-	100	0.6	0.75	0.75	0.9	0.3
T-PVC	950	90	30-38	0.9	0.56	0.8	0.8	0.75	0.6
PCM (RT25HC)	825	230	22-26	0.2	0.52	0.9	0.9	0.85	0.8

Heat Transfer Model

As shown in Fig. 8.19, there are multiple heat transfer pathways involving convection, conduction, and radiation which exist in the DSF and the proposed blinds system based on the following assumptions:

- Both convective and radiative heat transfer exist on the blind surface.
- Only one-dimensional conduction is considered within each blade and convective heat transfer is negligible.
- The PCM is homogeneous and isotropic with constant thermo physical properties except its enthalpy.
- The thermo physical properties of the aluminium substrate are constant in cases 1,2.
- There is no transmitted solar radiation on the internal glass skin of the DSF due to the length of the blade and the tilt angle of the blind.
- The airflow is treated as two-dimensional incompressible flow with constant air density.

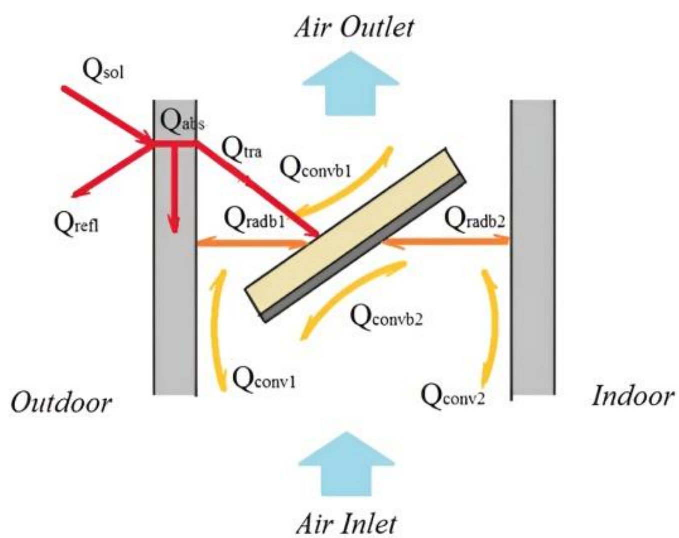


Figure 8.19 Heat transfer paths (Author).

Simulation process

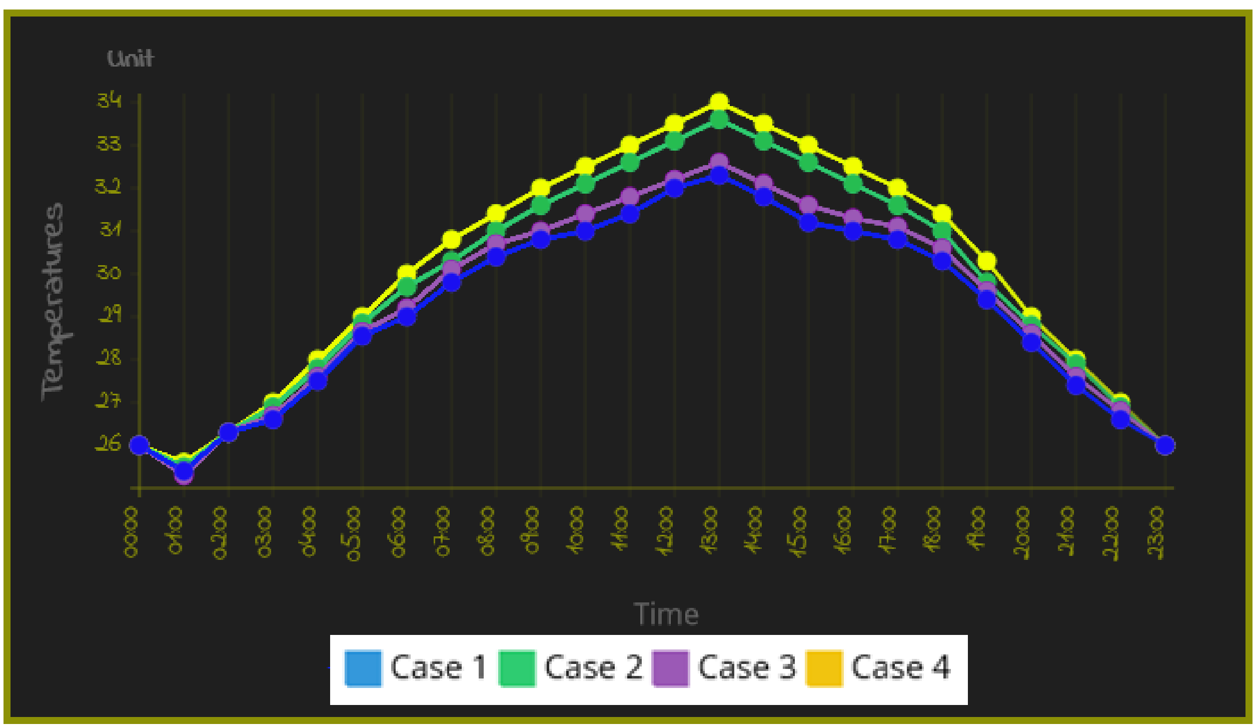
The computational Fluid Dynamics (CFD) method has proved to be the most accurate approach (Zeng, 2012) to investigate more detailed heat transfer and airflow behaviors in DSF systems, and for that reason, it was used for evaluating the heat and airflow distribution profiles in the DSF.

RNG k-ε model was selected as the turbulence model since it is applicable for a wider class of flows than the standard k-ε model (Brandl, 2014). The discrete ordinates (DO) model was applied as the radiation model due to its ability in solving most radiation problems. For the purpose of comparison, four cases of blinds systems were simulated: Case 1 (DSF containing conventional aluminium blind), Case 2 (DSF containing aluminum blind covered with a pastel paint), Case 3 (DSF containing T-PVC blind), and Case 4 (DSF containing PCM blind) at the hottest-temperature day of the year, and the same boundary conditions listed in the last section of this chapter.

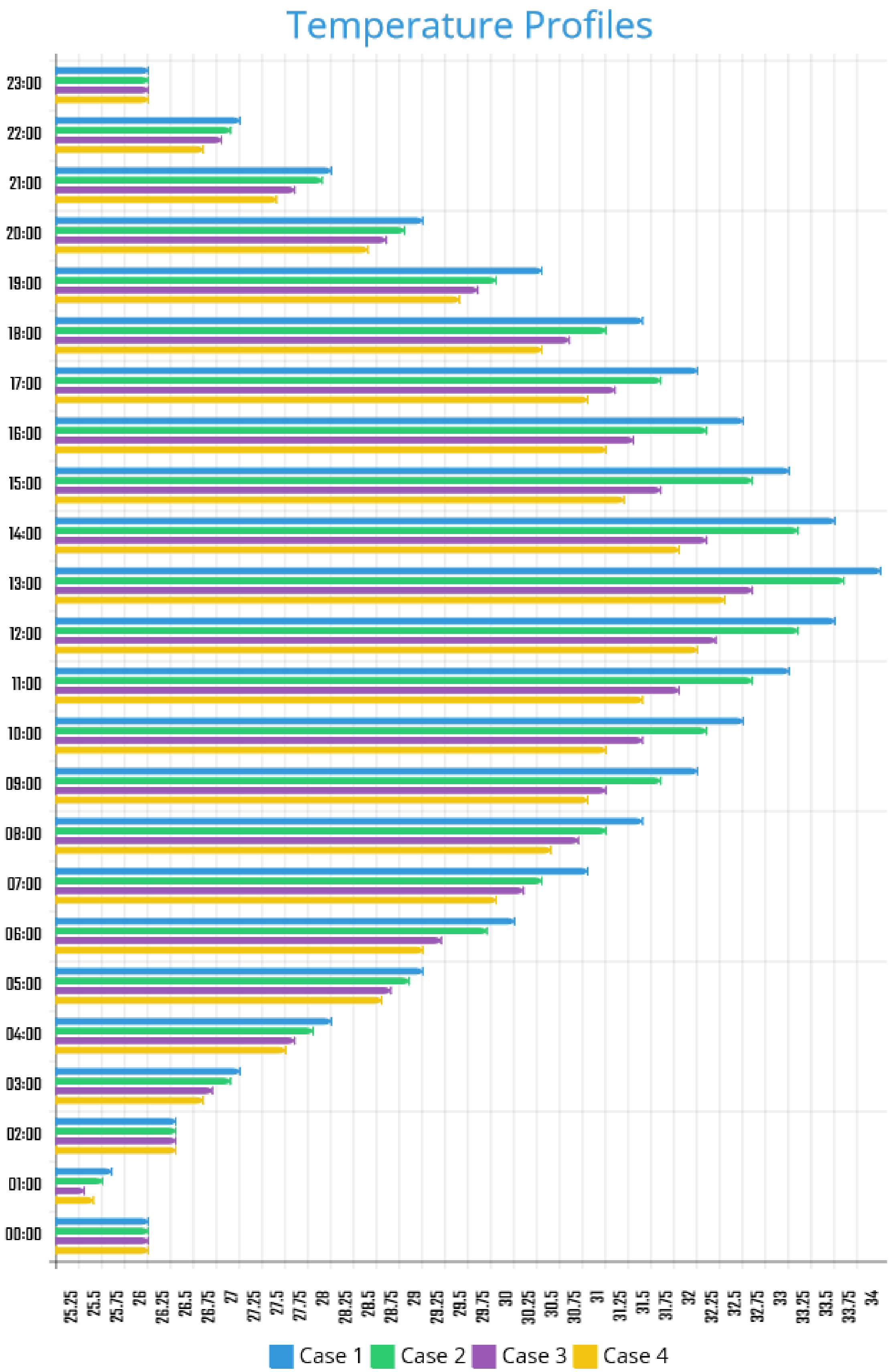
Simulation results

➢ ***Temperature Profiles***

Simulation Cases with the blind in the middle of the cavity and tilt angle of 45° was regarded as a base case. The simulated average cavity air temperature of Cases 2,3, and 4 has been compared against case 1 (Base case) as shown in Graph 8.5. The Graph below shows the surface temperatures on the sunny side of the different blinds systems. Among these cases, the surface temperature of the aluminum blind in Case 1 was obviously higher than those of blinds in other cases. The heat flux profiles indicate that the PCM and T-PVC blinds can absorb heat from the air cavity while the aluminum blind releases heat to DSF cavity during the simulation. The heat flux for the aluminum blind was almost constant due to that there was little change in the temperature difference between the sunny side and the shaded side throughout the day, other than Case 1.



Graph 8.5 Temperature profiles for DSF of different blinds materials (Author).



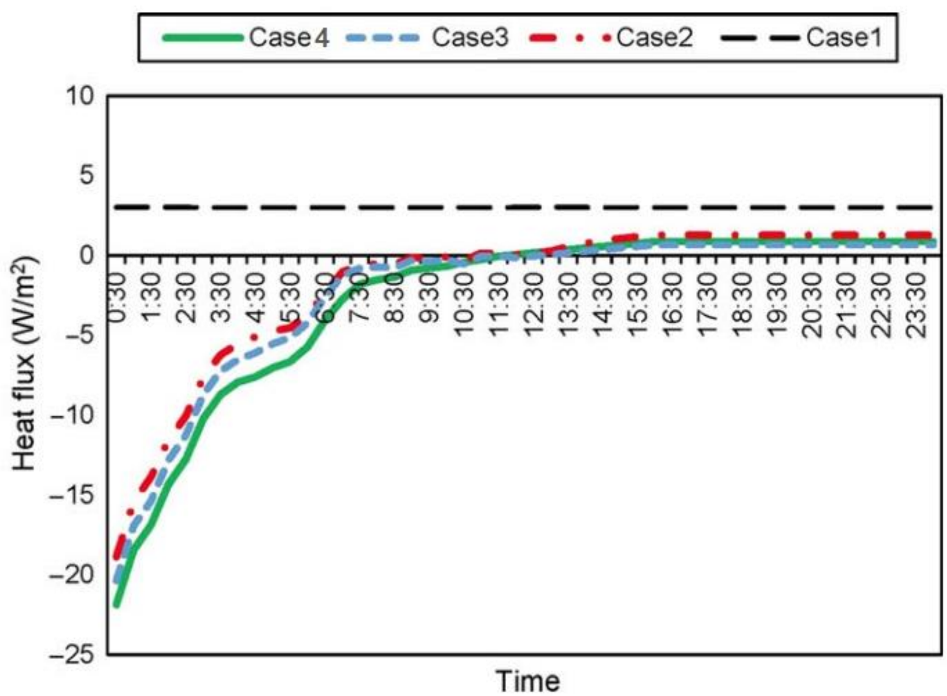
Graph 8.5 Temperature profiles for DSF of different blinds materials (Author).

Among these cases, Case 4 (DSF containing PCM blind) shows the highest heat absorption ability with the lowest negative heat flux, and the aluminum blind also shows the highest temperature and no heat-absorption ability.

The results of Cases show that the largest air temperature in DSF during a day occurred at 13:00 of the daytime when the ambient temperature was the highest. Where the thermal performance of the blinds alternatives in comparison with case 1 (base case) has been improved at 13:00 of the daytime by 1.4% in the aluminum blind covered with pastel paints (case 2), 4.1% in the T-PVC blind (case 3), and by 5% in the PMC blind (case 4).

- ***Heat Transfer Profile***

Graph 8.6 shows the heat flux profiles of the three proposed cases in comparison with aluminum blinds (base case). It can be seen that the PCM blind started to absorb heat from the cavity air from the beginning (t=0s) of the simulation and this process lasted till time step 41400s (11:00 am). In contrast, the aluminum blind re-emitted and released heat from its surface to the surroundings during the whole cycle. Therefore compared with the aluminum blind, the PCM blind was able to absorb the solar heat gain in the DSF cavity with its heat storage capacity during the melting process. However, there is still great potential for the PCM blind in capturing more heat in DSF cavity since the absorbing process ended before night-time.



Graph 8.6 Heat flux profiles of the three proposed cases in comparison with Conventional aluminum blind (Author).

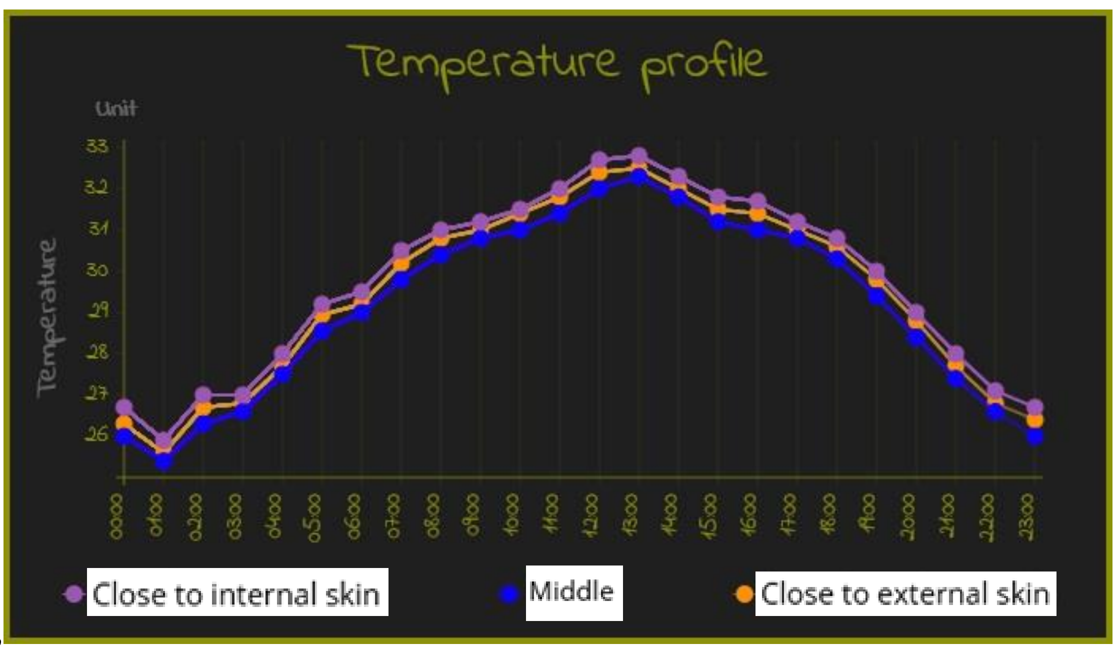
2) Effect of blinds position on thermal performance

The alternatives simulated to test the effect of blinds position are presented in Table 8.9 Where three different positions in DSF cavity were tested (Middle, Close to external glass, and Close to internal glass), and tilt angle of 45°.

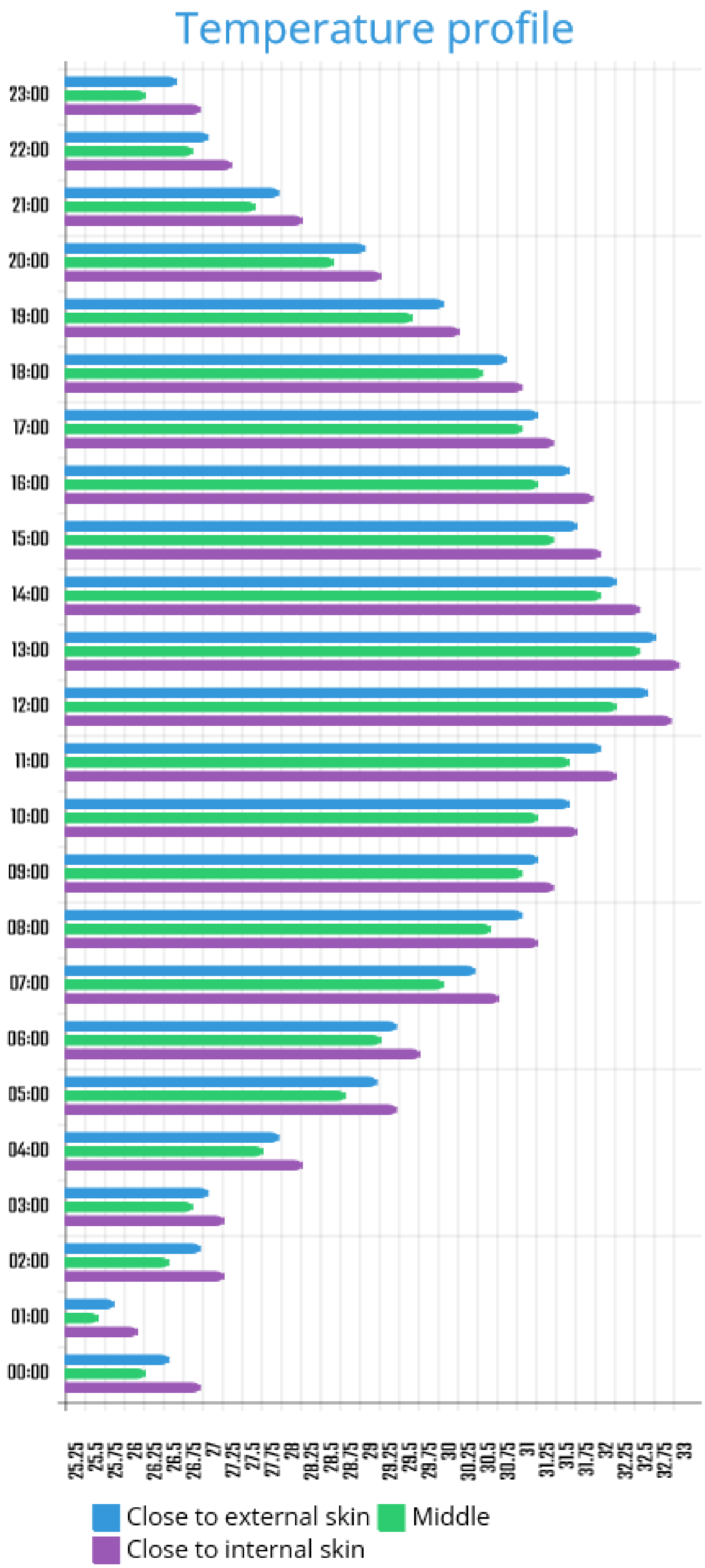
Table 8.9 The different positions in DSFs cavity (Author).

Blinds Material	**Blinds Position**	**Blinds Shape**	**Slat Tilt Angle**
PCM Product RT25HC	Close to external glass	Straight	45 degree
	Middle		
	Close to Internal glass		

The simulation results are shown in Graph 8.7 display that the most efficient position of shading devices in a DSF is in the middle of the cavity but that would be considered a hazard as it blocks access to the cavity in case of emergencies. For this study, the blind was regarded next to the external glazing (blind close to external glass skin), as the second-best location in terms of the thermal efficiency of the DSF.

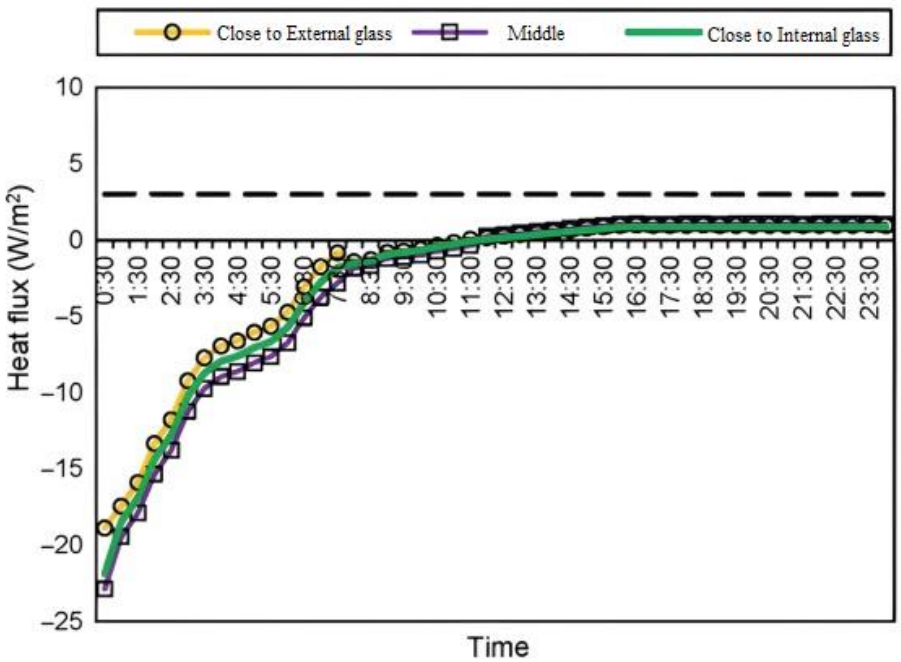


Graph 8.7 Temperature profile of system with different positions in DSF (Author).



Graph 8.7 Temperature profile of system with different positions in DSF (Author).

Graph 8.8 demonstrates the heat flux profiles of systems with different blind positions in the DSF. There was no clear difference between the heat flux profiles of different blind positions.



Graph 8.8 Heat flux profile s of system with different positions in DSF (Author).

3) Effect of blinds shape and angles on thermal performance

Providing the shading devices with high slops comparatively has been proposed, to prevent the penetration of solar radiations. As shown in Figure 8.20, in this design strategy, the high slop of slat offers a better insulation system, and then a comparison with the straight conventional Blinds performance was created. And also, the five proposed angles will be simulated: 0, 30, 45, 60 & 80 degrees, to test their effect on the convective heat transfer coefficients on the glazing surfaces. The alternatives simulated are presented in Table 8.10.

Table 8.10 The different DSFs shapes in cavity (Author).

Blinds Material	**Blinds Position**	**Blinds Shape**	**Slat Tilt Angle**
PCM Product RT25HC	Close to external glass	Straight	0 degree
		Provided with High Slops comparatively	30 degree
			45 degree
			60 degree
			80 degree

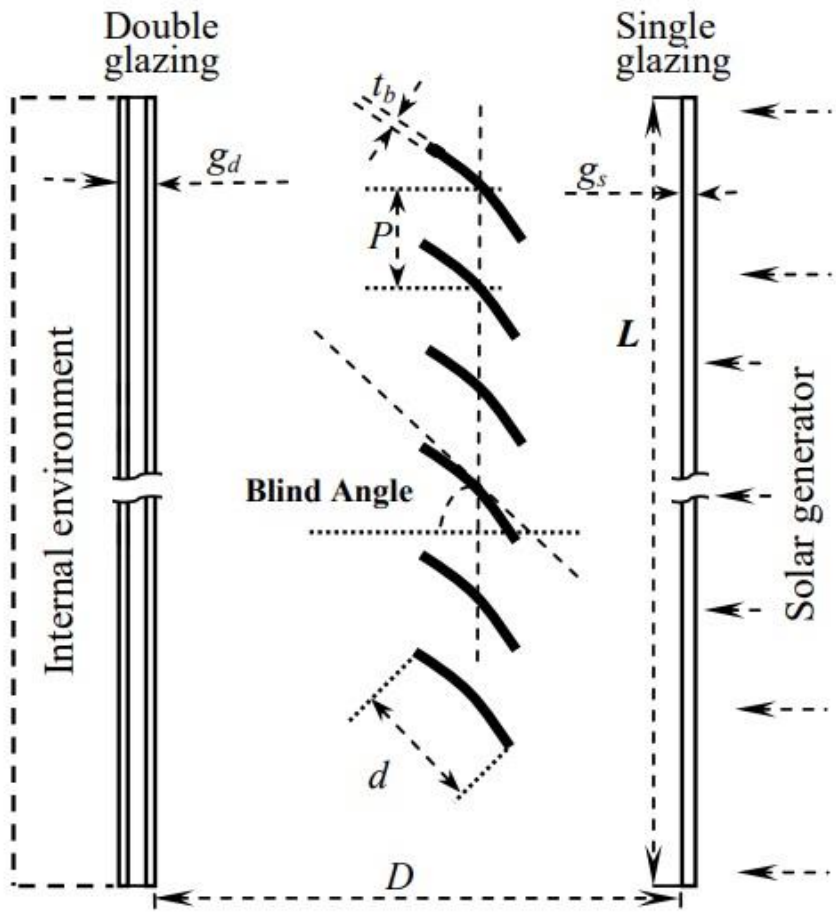
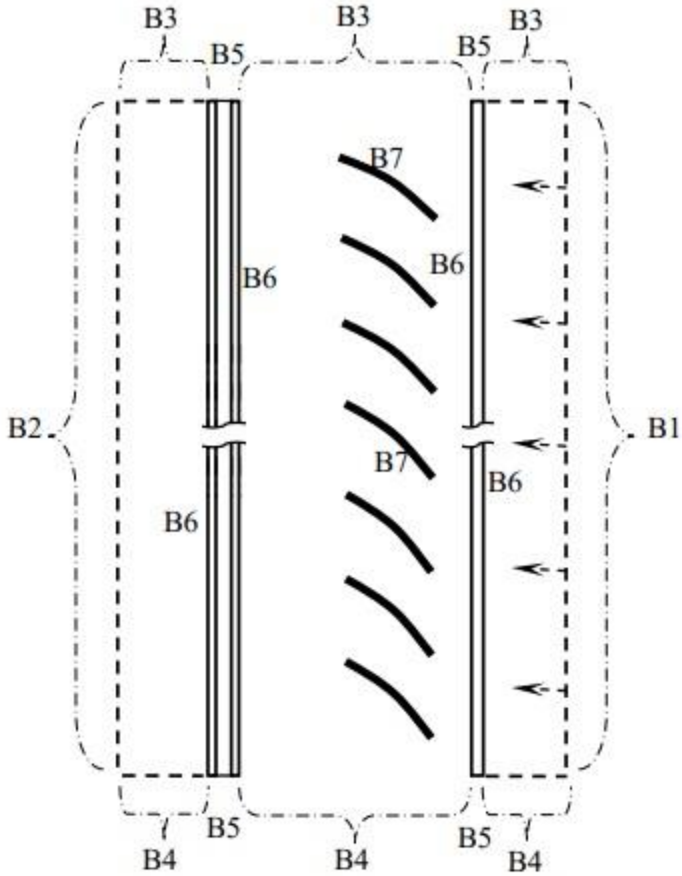


Figure 8.20 Schematic of the blind with high slops comparatively (Author).

Simulation process (CFD Modeling)

The CFD was used to model heat transfer in this work. Primitive variables (velocity, pressure, enthalpy, etc) are defined at nodes at the corners of each element. Conservation equations are obtained by integration over the elements, creating arbitrary polyhedral control volumes about each node. The solver assembles one big matrix for the entire set of hydrodynamic equations (mass and momentum) and solves them simultaneously. In theory, there is no upper limit for the time step due to the fully implicit discretization of the coupled equations and this will potentially speed up the calculation by using large time steps to reach a steady-state calculation.

The CFD geometry is simplified from the testing by ignoring the curvature and swapping the ventilation inlet and outlet from one side to top and bottom (Figure 8.21). This simplification will potentially change the airflow pattern inside the façade cavity but it can keep the thermal performance the same as the rig and substantially reduce the mesh size which may limit the CFD calculation. The imposed boundary conditions were presented in Table 8.8:



B1	Opening pressure for entrainment with a solar heat flux (715w/m2) as the boundary source for radiation modeling. This is to simulate the external environment.
B2	Opening pressure for entrainment and the local temperature (Tin =20°C). This is to simulate the internal environment.
B3	Static pressure and direction using the averaged opening temperature.
B4	Static pressure and direction using the averaged opening temperature.
B5	Opening pressure and direction, and the local temperature (Tin =20°C).
B6	Adiabatic condition.
B7	Conservative interface flux for both heat transfer and thermal radiation.
B8	Conservative interface flux for heat transfer and opaque surface for radiation (i.e. emissivity ε =0.7).

Figure 8.21 Computing domain showing labels for boundary conditions (Author).

Mesh dependency test

A large amount of cells is needed to make a mesh generation, which represents a major challenge for this type of geometry due to the huge differences between the smallest and the largest edge length scales. This is also the reason why three-dimensional modeling is limited by the current software capability, particularly when heat transfer is modeled.

A hybrid mesh was made by different software packages and the computer domain consists (from right to left) the external environment, the single glazing, the PMC blinds inside the façade cavity, the double glazing and the internal environment (Figure 8.22). The total mesh elements used in this 2D modeling is around 110K with slight variations between different blind angles. A mesh of 200K was tested using the case of blind angle 45 degrees. The overall first-order parameters are consistent with the mesh with 110K cells. Therefore the mesh of 110K cells was used for the simulations of all other blind angles.

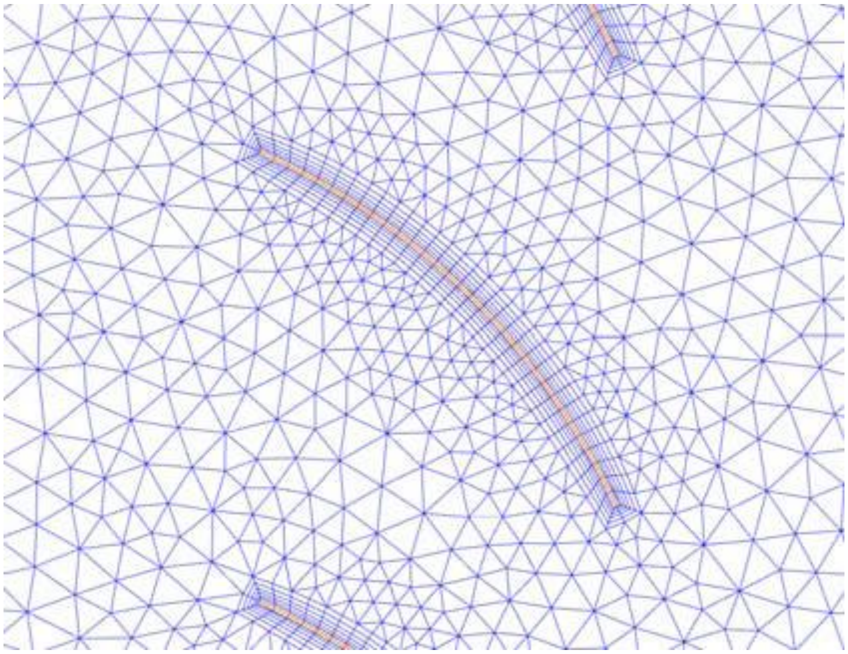


Figure 8.22 Mesh structures of the detailed mesh of one slat and its surrounding (Author).

Simulation Results

Figure 8.23 shows the temperatures distribution within the CFD with blind angle 45 degree. The thermal boundary layer of the domain next to the glazing/blind surfaces increases with the façade height. However, the thermal boundary layer is still very narrow at the top of the façade cavity, suggesting that the mixing within the domain due to natural convection is very weak.

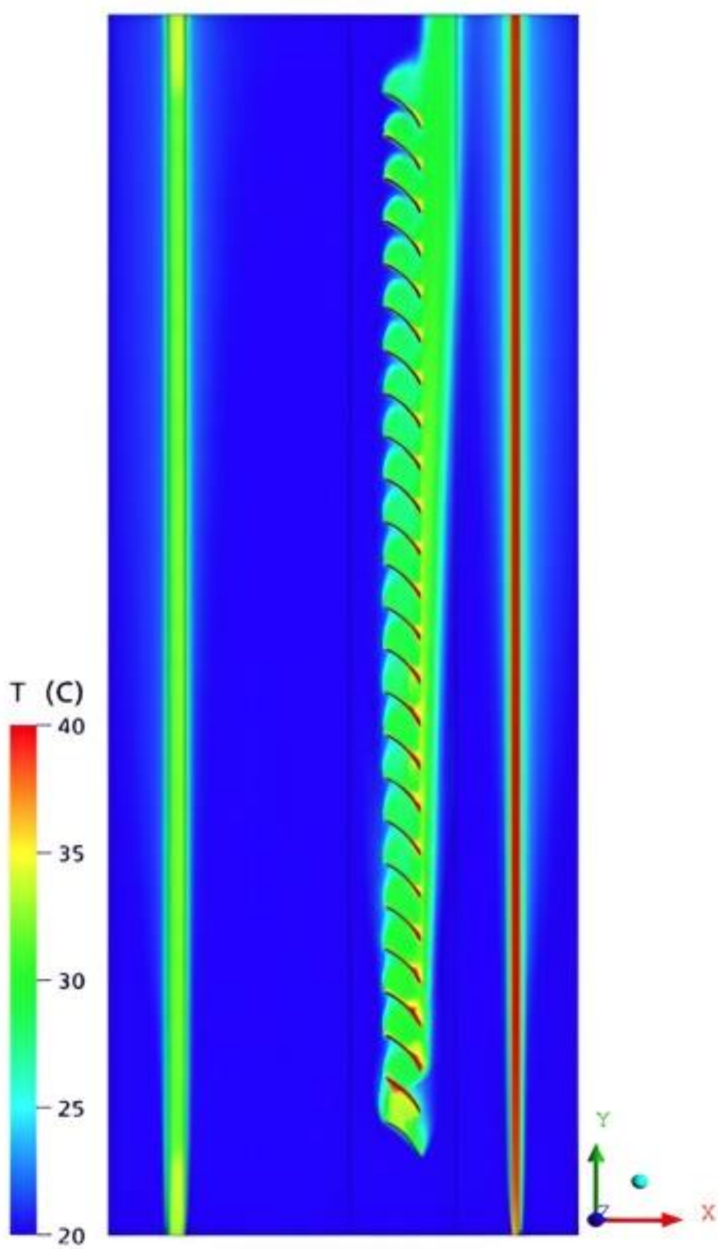


Figure 8.23 Temperature field with blinds of 45 degree (Author).

The temperature in the DSF's cavity with blind angles 0, 30, 45, 60, and 80 degrees is shown in figure 8.24. The difference in temperature of the double glazing due to the use of PMC blinds and the change in blind angles are clear. This indicates that the shading effects provided by the blinds are accurately represented in the heat transfer model and predict that the temperature of the double glazing can be substantially reduced, even when the blind angle is zero.

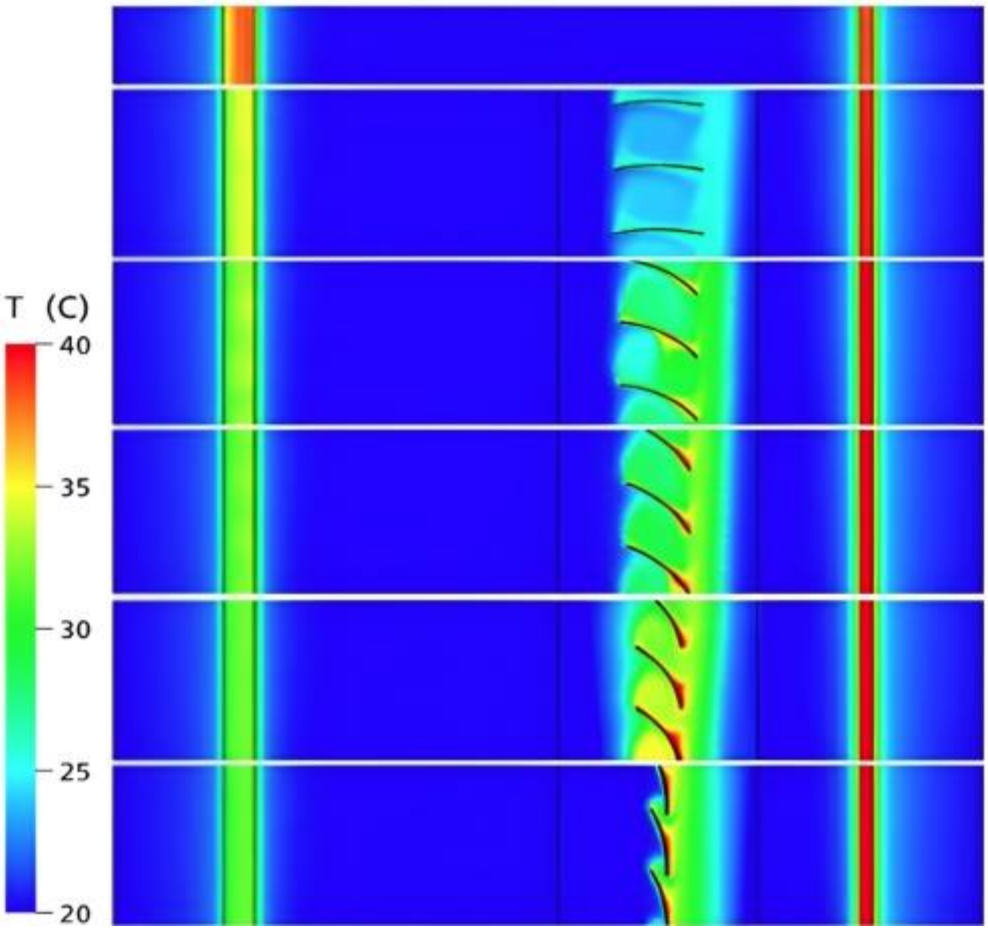


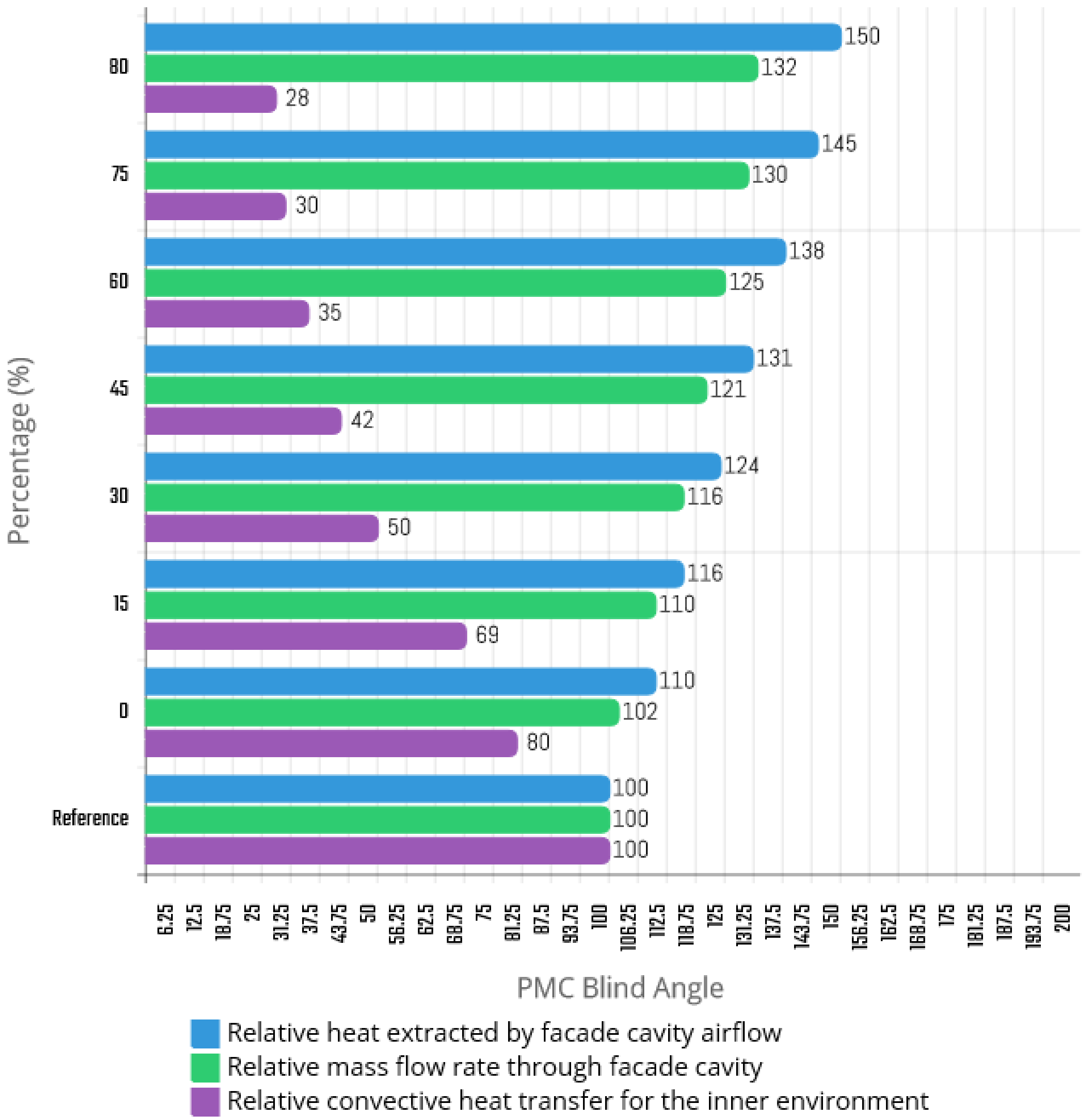
Figure 8.24 The temperature for cases with blinds for different slat angles (Author).

4) <u>Comparison of the optimum performance alternatives</u>

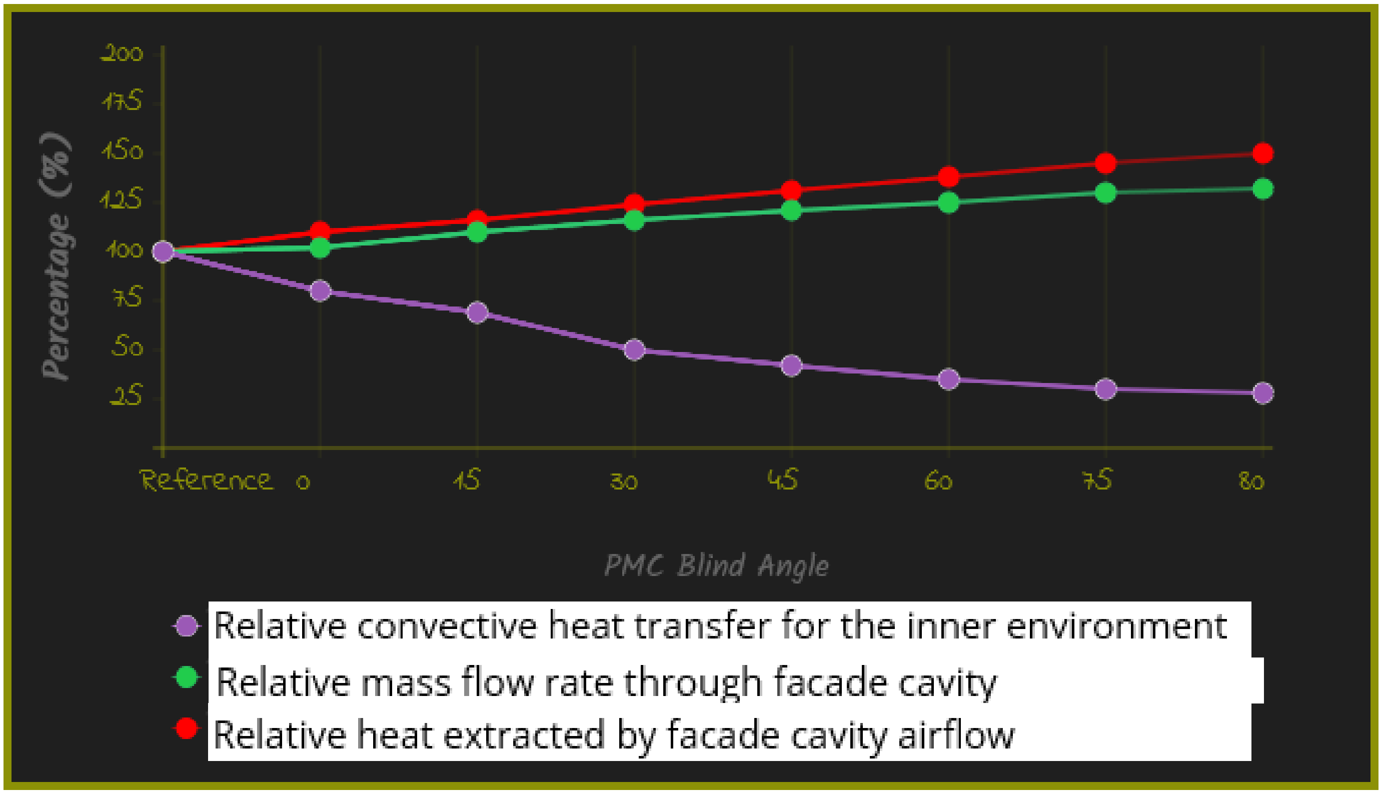
Several attempts and comparisons have been conducted, to optimize the convective heat transfer coefficients on the glazing surfaces by the different alternatives (materials, positions, shape, and angles). Graph 8.9 shows how the façade airflow rate and the convective heat transfer coefficient are affected by varying parameters using the case without blind as a reference. For a PMC blind angle of 80 degrees, the convective heat transfer for the inner environment due to solar radiation is only 28% of the heat transfers for the case without blinds. The mass flow rate through the façade cavity is enhanced up to 32% by increasing the blind angles to 80 degrees. This larger mass flow can potentially extract more excess heat through the cavity airflow.

Result (2)

For a PMC blind angle of 80 degrees with high slops comparatively and close to external glass skin, the convective heat transfer for the inner environment due to solar radiation is only 28% of the heat transfers for the case without blinds.



Graph 8.9 the optimum performance alternatives in comparison with the reference case without a blind (Author).



Graph 8.9 the optimum performance alternatives in comparison with the reference case without a blind (Author).

The mobile shading system remains horizontal (open) in winter time, to provide the building with the maximum possible solar radiation, which penetrate through the façade of the building, specifically due to lower height of sun at this time of the year. This system becomes more efficient as it is associated with multiple reflection of opaque surface of shading system.

8.3.2 Facade Orientation

Common wisdom about orienting buildings in hot-dry climates is that thermal performance is heavily influenced by orientation of the facade where different facade techniques could be used according to orientation due to the direct solar radiation intensities in hot arid areas.

1) <u>Input</u>

A series of angles was proposed which form a right angle (a 90-degree angle) confined between east and south directions. For the simulation purpose, a series of angles (10, 20, 30, 40, 50, 60, 70, and 80 degrees) have been tested, to determine the optimum angle and the overhang length, which provide optimum facade shading, as shown in the Figure below.

Table 8.11 The orientation alternatives.

Building Height	Orientation Angles	Overhang Length
10-story	10-80 degree confined between east and south directions	0.5 to 2m

2) Simulation process

In this section, the facade orientation was tested to reduce the direct solar radiation intensities using Grasshopper and DIVE software.

Simulations results agree with the common wisdom of orienting buildings in hot-dry climates. The thermal performance is heavily influenced by orientation of the facade where different facade techniques could be used according to orientation. Due to the direct solar radiation intensities in hot arid areas, the East and West orientations are to be avoided as much as possible, while the North orientation provides the least heat gains.

Result (3)

According to simulation results, An orientation slightly east of south (typically 15° east of south) is expected more effective in Al-Khartoum city, because in this way the western façade absorbs lesser sun heats in the summer (as shown in fig 8.25). The eastern facade is exposed to the sun's rays only from sunrise to noon. The walls cool down considerably by evening, making this exposure more suitable for bedrooms than the western exposure.

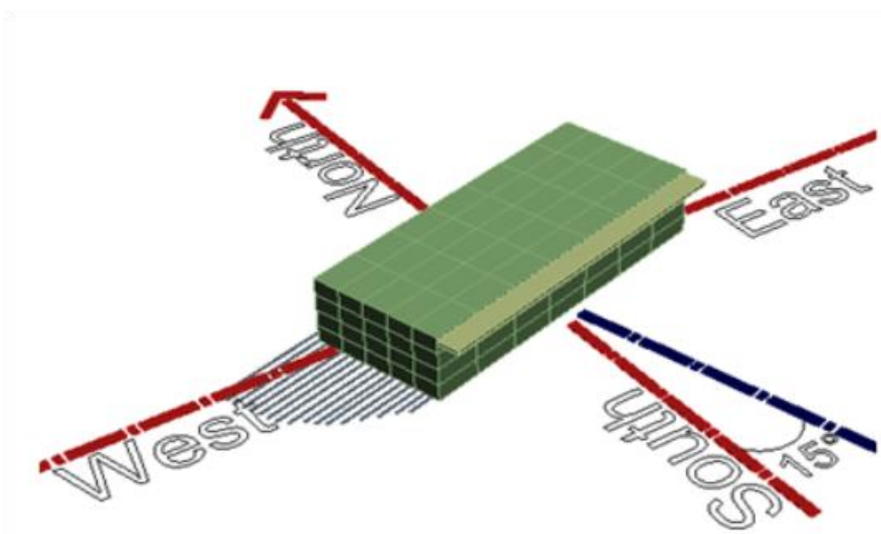


Figure 8.25 Building orientations relative to South-north axis to reduce convective heat transfer (Author).

8.3.3 Glazing properties

This investigation adopts an analytical approach using dynamic simulation software. In this section, a comparative analysis of convective heat transfer on a clear glass base case is compared against three possible changes to the physical properties of the external layer of the double-skin facade.

1) **<u>Simulation process</u>**

A dynamic thermal performance software Rhinoceros (Rhinoceros, version 5.1) and DIVE plug-in was used to test the external surface of the double-skin facade by using three different glass performance properties responding to clear, tinted, and reflective glazing. The reflective glazing properties are also chosen to be selective to increase daylight penetration. Properties of glass used for the double skin facades are stated in Table 8.12.

Table 8.12 Glazing properties for the outer leaf of the double-skin facade

	Exterior leaf glazing type		
	Clear glazing (Base case)	Body tinted green	Reflective glazing active blue
U-value (W/m2K)	5.6	5.6	5.6
Solar coefficient (SC)	0.85	0.59	0.27
g-Value	0.87	0.51	0.42
Thickness (mm)	10	10	10
Transmittance (%)	73	35	21
Reflection (%)	7	5	12
Absorption (%)	20	60	67

2) Simulation Results

Simulation results indicate that a reflective double-skin facade can achieve better energy savings than a single skin with reflective glazing. For glazing of the outer leaf, reducing the solar coefficient of glazing from 0.85 to 0.27 equivalent to changing the glazing properties from clear to reflective coated glass achieved major reductions in heat transfer on all orientations (as shown in figure 8.26). Therefore, it qualifies to be considered as the benchmark double-skin strategy for improving thermal performance.

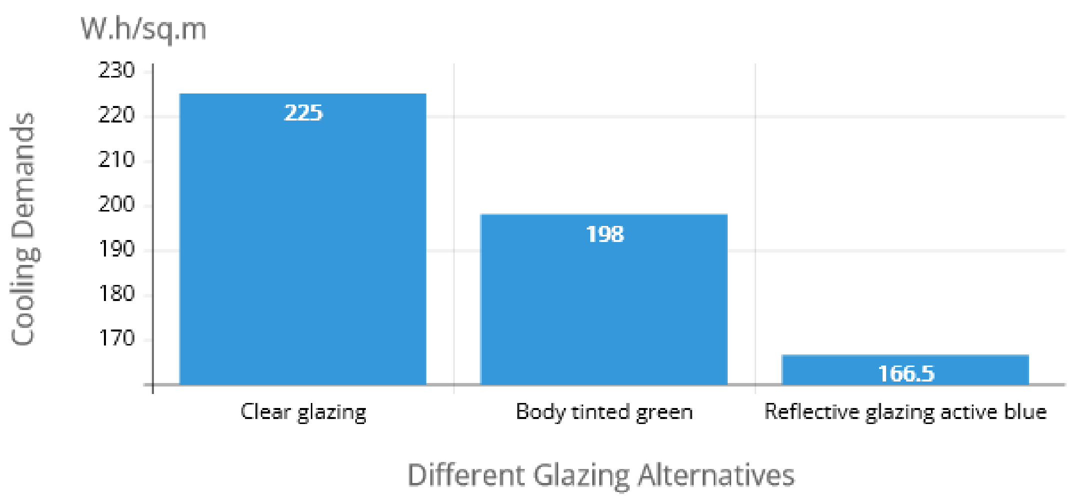


Figure 8.26 Comparison between different glazing alternatives in peak summer cooling demands.

Result (4)

Table 8.12 summarizes the cooling demand for the w in comparison with the clear glazing as a base case (BC). The total cooling load has been reduced by 12% in the Body tinted green glazing and by almost 26% in the Reflective glazing active blue.

Table 8.13 Comparison between Clear (BC), Body tinted green and Reflective glazing.

	Clear glazing (Base case)	Body tinted green	Cooling loads (%)	Reflective glazing active blue	Cooling loads (%)
South Zone	225	198	-12%	166.5	-26%

8.4 Conclusion

While there is a great deal of interest in transparent buildings in current architecture, larger areas of glazing area results in weaker envelope performance, and higher cooling and heating demands. The advent of the double-skin facade is a response to these problems. In this chapter, an investigation about the third hypothesis has been opened, which is interested in how to improve the thermal performance level by applying the two techniques (airflow promotion and convective heat transfer reduction).

First, the airflow promotion technique which is interested in studying the behavior of natural ventilation in a combined DSF configuration has been studied. The first stage of simulation of the combined shaft-corridor DSF was carried out on seven-story stack to investigate the thermal behavior of this combined design facade and evaluate the thermal performance. This will become the base case for variables studies. CFD was used to simulate turbulent airflow. In order to verify the results, the precise approach of the CFD model depends on the boundary conditions-settings accuracy. CFD models were used to determine velocities at various points on the reference building for wind velocity of 5 m/s based on the weather data. Based on airflow modeling of the combined shaft-corridor DSF, it was found that the stack encourages buoyancy and induces air movement. Convective forces inside the cavity could be used to promote air extraction from the room, although it is needed to promote air movement within the room to release the excess heat. The CFD results appear to confirm the design's effectiveness in two ways. First, the airflow follows the ceiling and exits through the chimney openings, which suggests that the cool night air will effectively draw the heat out of the ceiling slab. The second outcome of the airflow staying near the ceiling is the avoidance of high air velocities in the occupied zone during the day. The main driving forces in the cavity are buoyancy and wind pressure.

The results have shown that the combined shaft-corridor DSF has a possibility of improving the thermal performance through natural ventilation technique in a hot-dry climate. In the second stage, the studies in optimizing the configurations of the DSF system have lead to the construct of an improved system for use in a hot-dry climate of Al-Khartoum. Some of the important findings are tabulated below:

a) A DSF system with openings vs. cavity depth (shaft height constant). As the opening size increased, the performance improved with the same cavity depth.

In order to get the same results in thermal performance, as the cavity depth is decreased, the opening size should be increased.

b) A DSF system with the opening size vs. shaft height (cavity depth constant). Increasing the shaft height improved the thermal performance and as the shaft height increases the opening size needs to increase to provide the same results.
c) DSF system cavity depth vs. shaft height (opening size constant). As the shaft height increases, the cavity depth should be decreased with a constant opening size to provide the same results.

Secondly, the convective heat transfer technique was tested. Where, several attempts and comparisons have been conducted, to optimize the convective heat transfer coefficients on the glazing surfaces by the different alternatives (materials, positions, shape, and angles). Results show how the façade airflow rate and the convective heat transfer coefficient are affected by varying parameters using the case without blind as a reference. For a PMC blind angle of 80 degrees, the convective heat transfer for the inner environment due to solar radiation is only 28% of the heat transfers for the case without blinds. The mass flow rate through the façade cavity is enhanced up to 32% by increasing the blind angles to 80 degrees. This larger mass flow can potentially extract more excess heat through the cavity airflow. The simulation results also present, an orientation slightly east of south (typically 15° east of south) is expected more effective in Al-Khartoum city, because in this way the western façade absorbs lesser sun heats in the summer. The eastern facade is exposed to the sun's rays only from sunrise to noon. As to glazing properties, the simulation results indicate that a reflective double-skin facade can achieve better performance improvements than a single skin with reflective glazing. For glazing of the outer leaf, reducing the solar coefficient of glazing from 0.85 to 0.27 equivalent to changing the glazing properties from clear to reflective coated glass achieved major reductions in heat transfer on all orientations. Therefore, it qualifies to be considered as the benchmark double-skin strategy for improving thermal performance.

This chapter concluded that the combined shaft-corridor DSF has a possibility of improving the thermal performance level by applying the two techniques (Airflow promotion and Convective heat transfer reduction) in a hot-dry climate of Al-Khartoum. This result matched the third hypothesis posed in the introduction of this research.

Chapter Nine
Conclusions, Recommendations, and Future Works

9.1. Introduction

The building envelope plays an important role in improving thermal performance, which is considered the boundary between an internal and external environment and center to the thermal exchange operations between them. several architectural malpractices in buildings to improve the aesthetic aspects are led to substantially weakened the thermal performance of buildings envelopes. The development of an intelligent envelope system is one of the more promising responses to this problem.

The aim of this research is to investigate how existing envelope techniques design can be developed to improve the thermal performance of buildings in hot climates. This chapter presents the conclusion to this research and details how effective would the integration of different building envelope techniques be for performance improvement of buildings by following an intelligence as a means which to give an integration property of those techniques the ability to improve the thermal performance. The research aim and objectives are answered in this chapter detailing how each is satisfied. Discoveries from previous chapters are described detailing major findings of this research. The original contribution to new knowledge is also justified.

9.2Methodology Design

This part reviews the methodology used to find out the results of the research. The research started out by studying the concept of thermal performance, intelligent envelopes, Performance improvement techniques, and the effect of these techniques on thermal performance in multi-story buildings. The tools used for research tasks are Energyplue, Computational fluid dynamics (CFD), and Rhino, Grasshopper software, and DIVA plug-in. Several tests and comparisons of the different variables had been made to achieve the optimized and most effective alternatives that maximum thermal performance when integrated the building envelope techniques and then will be detailed it's to form a platform for new design guidelines.

Different methods are used in this research depending on the nature of each stage of analysis. That includes a theoretical analytical method and analytical-practical method of the building envelope techniques and the thermal simulation processes, respectively.

9.3 Review of Objectives

This section completes a review of the research objectives set out in section 1.3 (chapter 1). Each one identifies if goals are achieved identifying significant issues.

As required by objective 1, comprehensive literature was completed (chapters 2 and 3) for performance improvement techniques including the studies identifying how these are currently incorporated within buildings. The main conclusions from literature review show that minimal research has been completed for evaluating performance improvement for envelope systems and highlights these have been reviewed temperature reduction with only a small number showing basic analysis regarding thermal performance improvement (quantitative data). This identifies that further research scope for investigating potential performance improvement for each building envelope element .

Also as required by objective 2 about the thermal performance evaluation tools, the main conclusions show how to select and use suitable simulation software in the early design stages to improve the thermal performance of buildings, especially those software that is available in Sudan. There are also limited design tools available which leave scope for performance evaluation tools development.

Objective 3 was completed by the development of a theoretical building base case model. This is realized via buildings model using all available software and verified against performance benchmarks, as detailed in Chapter 5.

Objective 4 evaluates the thermal performance by applying the two techniques that arrived at in chapter 6 (airflow promotion and convective heat transfer reduction).

- First, the airflow promotion technique which is interested in studying the behavior of natural ventilation in a combined DSF configuration has been studied. CFD was used to simulate turbulent airflow of the combined shaft-corridor DSF to investigate the thermal behavior of this combined design facade and evaluate the thermal performance. This will become the base case for the variables studies.
- Secondly, the convective heat transfer technique was tested. Several attempts and comparisons have been conducted, to optimize the convective heat transfer coefficients on the glazing surfaces by the different alternatives (materials, positions, shape, and angles).

9.4 Test of Hypotheses

Following completion of this research, tests of the hypothesis are completed below:

- ***Hypothesis 1***: The simulation results showed (Chapter 7, Table 7.5), the cooling loads of shaft and corridor DSF types in comparison with the well-designed single-skin façade (WSS). These results agree with the first hypothesis that the double-skin facades provide significant thermal performance only when compared to poor construction and poor insulation standards in single-skin facades.

- ***Hypothesis 2***: As shown in the results in Chapter 7, using methods developed (chapter 6), the cooling demand of each month for the double-skin facade alternatives were reduced in comparison with the base case single skin (BC). Therefore, this agrees with the second hypothesis that the proposed configuration that combines both shaft and corridor types led to improve thermal performance in the hot-dry climate of Khartoum.

- ***Hypothesis 3***: As shown in the simulation results in Chapter 8, The combined shaft-corridor DSF has a possibility of improving the thermal performance level by applying the two techniques (Airflow promotion and Convective heat transfer reduction) in a hot-dry climate of Al-Khartoum. This result matched the third hypothesis posed in the introduction of this research.

9.5 Main Research Findings

The main findings from this research are as follows:

1) The simulation results showed (Table 7.5), the cooling loads were increased by 0.09% in the shaft type and decreased by 1.9% in the corridor type in comparison with the well-designed single-skin façade (WSS). This is due to the low direct solar radiation reflection properties of clear glazing.

2) A proposed of combines both shaft and corridor types led to improve thermal performance in the hot-dry climate of Khartoum by taking the advantages and avoiding the disadvantages of both types. Where, the cooling stacks allow for further ventilation on hot, stagnant, summer days so the building always remains within reasonable temperature levels.
3) CFD simulation results have shown that the combined shaft-corridor DSF has a possibility of improving thermal performance by providing acceptable internal temperatures through a natural ventilation strategy in the hot-summer climate of Khartoum.
4) The studies in optimizing the configurations of the DSF system have led to construct of an improved system by promoting airflow. Some of the important findings are tabulated below:

    a) A DSF system with openings vs. cavity depth (shaft height constant). As the opening size increased, the performance improved with the same cavity depth. In order to get the same results in thermal performance, as the cavity depth is decreased, the opening size should be increased.
    b) A DSF system with the opening size vs. shaft height (cavity depth constant). Increasing the shaft height improved the thermal performance and as the shaft height increases the opening size needs to increase to provide the same results.
    c) DSF system cavity depth vs. shaft height (opening size constant). As the shaft height increases, the cavity depth should be decreased with a constant opening size to provide the same results.

5) Results show how the façade airflow rate and the convective heat transfer coefficient are affected by varying parameters using the case without blind as a reference. Some of the important findings are tabulated below:

   a) For a PMC blind angle of 80 degrees, the convective heat transfer for the inner environment due to solar radiation is only 28% of the heat transfers for the case without blinds. The mass flow rate through the façade cavity is enhanced up to 32% by increasing the blind angles to 80 degrees. This larger mass flow can potentially extract more excess heat through the cavity airflow.
   b) An orientation slightly east of south (typically 15° east of south) is expected more effective in Al-Khartoum city, because in this way the western façade absorbs lesser sun heats in the summer (Figure 8.25). The eastern facade is exposed to the sun's rays only from sunrise to noon.
   c) As to glazing properties, the simulation results indicate that a reflective double-skin facade can achieve better performance improvement than a single-skin with reflective glazing. For glazing of the outer leaf, reducing the solar coefficient of glazing from 0.85 to 0.27 equivalent to changing the glazing properties from clear to reflective coated glass achieved major reductions in heat transfer on all orientations. Therefore, it qualifies to be considered as the benchmark double-skin strategy for improving thermal performance.

6) And according to the numerical analysis, the overall thermal performance value of an intelligent envelope system has been improved by 38.65%.

7) Research methodology set out in Figure 5.1 is proven in chapters 7 and 8 can be applied to the construction industry in order to evaluate the thermal performance improvements by using simulation software.

9.6 Justification of Original Contribution to Knowledge

There are limited simplified design and calculation tools available for the building envelope techniques. In a practical sense, architects and building services engineers in Sudan do not have a lot of design tools or skills available to enable an accelerated assessment for implementation of these techniques. At later design stages, these techniques are ruled out (omitted) from the design process, as benefits cannot be fully understood or assessed. These intelligent systems are highly complex and relying on marginally predictable external environmental conditions. This makes designs complex, expensive and high risk, especially when attempting to guarantee buildings thermal performance for hot-dry climates.

9.7 Recommendations for future work

Regarding the complexity of analyzing the building envelope techniques, a few assumptions have been made and limitations are acknowledged. Following are some of the research areas that were not in the scope of this study, which might be addressed in the future to improve the thermal performance in multi-story buildings :

First, in addition to the whole building thermal simulation, measurements on the actual model is highly recommended. The results and findings from the research needed to be validated directly with experimental results. This shortcoming could be overcome to some extend by installing full size experimental model in Al-Khartoum climate and monitor the experimental results for a specific period of time. Due to the time and cost constraints for the research, the simulation tools have been used to study the different variables in terms of performance improvement .

Second, the research has looked at overall performance through different parameters such as air temperature and air velocity to achieve optimized thermal performance. Other issues associated with facade systems such as day lighting and condensation, are not within the scope of this research. In addition, the local discomfort has not been investigated within this research .

Third, this study has not looked at different internal partitions‘ positions. The internal airflow patterns would be affected based on different layout spaces that can be investigated to point out the stagnant points and thermal comfort conditions. In other words, the influence of geometrical characteristics on airflows can be investigated and presented as a guideline for architects. The next recommendation is to consider the integration of other technologies such as phase change materials, PV, and aerogel transparent insulation to the DSF system. Some research has been done in the integration of PV and DSF for low-rise buildings. However, further work need to be done in a hot-dry climate.

It was hypothesized that the combined shaft-corridor DSF would show significant improvements in terms of enhancing the airflow. This is promising for the combined shaft-corridor DSF in its ability to improve the thermal performance. Furthermore, it is necessary to investigate the energy life cycle and economic analysis, which are the ultimate tools in assessing DSF impact on a global scale. Further, it is useful to identify the importance of other parameters such as control strategies-dashboard system that may validate and monitor the actual building performance. Last but not least, the incorporation of nighttime ventilation to the DSF system has been addressed in the literature. However, the impact of nighttime ventilation on thermal performance has not been investigated in this study.

9.8 Final note

The development of new technology plays a major role in response to thermal performance issues. To that end, resources must be used wisely, while new ways of generating energy are being developed. Performance must be improved and more types of sustainable techniques should be incorporated. Technology and architecture integration to face the challenge of the future is promising in its ability to improve the thermal performance.

One of the famous quotes of the Egyptian architect Hassan Fathy of all time is

"As an architect, as long as I have the ability and means to comfort the people, God never forgives me to raise the temperature inside the building by 17 degree on purpose".

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APPENDIX A: Simulation software

Table (1) some commonly used building simulation tools for energy modeling.

Simulation Tools	General Description
TRNSYS[1]	TRNSYS is a simulation program primarily used in the fields of renewable energy engineering and building simulation for passive as well as active solar design. TRNSYS is a commercial software package developed at the University of Wisconsin. One of its original applications was to perform dynamic simulation of the behaviour of a solar hot water system for a typical meteorological year so that the long-term cost savings of such a system could be ascertained.
TRACE[2]	TRACE is divided into four distinct calculation phases: Design, System, Equipment and Economics. During the Design Phase the program first calculates building heat gains for conduction through building surfaces as well as heat gains from people, lights, and appliances and impact of ventilation and infiltration. Finally, the program sizes all coils and air handlers based on these maximum loads. During the System Phase, the dynamic response of the building is simulated for an 8760-hour (or reduced) year by combining room load profiles with the characteristics of the selected airside system to predict the load imposed on the equipment.
TAS[3]	Tas is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems. The main module is Tas Building Designer, which performs dynamic building simulation with integrated natural and forced airflow. It has a 3D graphics based geometry input that includes a CAD link. Tas Systems is a HVAC systems/controls simulator, which may be directly coupled with the building simulator. It performs automatic airflow and plant sizing and total energy demand. The third module, Tas Ambiens, is a robust and simple to use 2D CFD package which produces a cross section of micro climate variation in a space. Tas combines dynamic thermal simulation of the building structure with natural ventilation calculations which include advanced control functions on aperture opening and the ability to simulate complex mixed mode systems. The software has heating and cooling plant sizing procedures, which include optimum start

SUNREL[4]	SUNREL is an hourly building energy simulation program that aids in the design of small energy efficient buildings where the loads are dominated by the dynamic interactions between the building's envelope, its environment, and its occupants. SUNREL has a simplified multizone nodal airflow algorithm that can be used to calculate infiltration and natural ventilation. Windows can be modeled by one of two methods. Users can enter exact optical interactions of windows with identical layers of clear or tinted glass and no coatings on the layers. Thermal properties are modeled with a fixed U-value and fixed surface coefficients. For the second method, a user imports data from Window 4 or 5. SUNREL only models idealized HVAC equipment. The equipment and loads calculations are solved simultaneously, and the equipment capacities can be set to unlimited. Fans move a schedulable fixed amount of air between zones or from outside.
Power-Domus[5]	PowerDomus is a whole-building simulation tool for analysis of both thermal comfort and energy use. It has been developed to model coupled heat and moisture transfer in buildings when subjected to any kind of climate conditions, i.e., considering both vapor diffusion and capillary migration. Its models predict temperature and moisture content profiles within multi-layer walls for any time step and temperature and relative humidity for each zone. PowerDomus allows users to visualize the sun path and inter-buildings shading effects and provides reports with graphical results of zone temperature and relative humidity, PMV and PPD, thermal loads statistics, temperature and moisture content within user-selectable walls/roofs, surface vapor fluxes and daily-integrated moisture sorption/ desorption capacity.
HEED[6]	The objective of HEED is to combine a single-zone simulation engine with an user-friendly interface. It is intended for use at the very beginning of the design process, when most of the decisions are made that ultimately impact the energy performance of envelope-dominated buildings. HEED requires just four project inputs: floor area, number of stories, location (zip code), and building type. An expert system uses this information to design two base case buildings: scheme 1 meets California’s Title 24 Energy Code, and a scheme 2 which is 30% more energy efficient. HEED automatically manages up to 9 schemes for up to 25 different projects.

HAP[7]	Hourly Analysis Program (HAP) provides two tools in one package: sizing commercial HVAC systems and simulating hourly building energy performance to derive annual energy use and energy costs. Input data and results from system design calculations can be used directly in energy studies. HAP is designed for the practicing engineer, to facilitate the efficient day-to-day work of estimating loads, designing systems and evaluating energy performance. Tabular and graphical output reports provide both summaries of and detailed information about building, system and equipment performance. HAP is suitable for a wide range of new design and retrofit applications. It provides extensive features for configuring and controlling air-side HVAC systems and terminal equipment. Part-load performance models are provided for split DX units, packaged DX units, heat pumps, chillers and cooling towers. Hydronic loops can be simulated with primary-only and primary/secondary configurations, using constant speed or variable speed pumps.
IES (VE)[8]	The IES <Virtual Environment> (IES <VE>) is an integrated suite of applications linked by a common user interface and a single integrated data model. <Virtual Environment> modules include: • ModelIT – geometry creation and editing • ApacheCalc – loads analysis • ApacheSim – thermal • MacroFlo – natural ventilation • Apache HVAC – component based HVAC • SunCast – shading visualisation and analysis • MicroFlo – 3D computational fluid dynamics • FlucsPro/Radiance – lighting design • DEFT – model optimisation • LifeCycle – life-cycle energy and cost analysis • Simulex – building evacuation
IDA ICE[9]	IDA Indoor Climate and Energy (IDA ICE) is based on a general simulation platform for modular systems, IDA Simulation Environment. Physical systems from several domains are in IDA described using symbolic equations, stated in either or both of the simulation languages Neutral Model Format (NMF) or Model ica. IDA ICE offers separated but integrated user interfaces to different user categories: • Wizard interfaces lead the user through the steps of building a model for a specific type of study. The Internet browser based IDA Room wizard calculates cooling and heating load.

ESP-r[10]	ESP is a general purpose, multi-domain building thermal, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow—simulation environment which has been under development for more than 25 years. It follows the pattern of `simulation follows description` where additional technical domain solvers are invoked as the building and system description evolves. Users control the complexity of the geometric, environmental control and operations to match the requirements of particular projects. It supports an explicit energy balance in each zone and at each surface.. ESP-r is distributed under a GPL license. The web site also includes an extensive publications list, example models, source code, tutorials and resources for developers.
eQUEST[11]	eQUEST is a easy to use building energy use analysis tool which provides high quality results by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module with an enhanced DOE-2.2- derived building energy use simulation program. The building creation wizard walks a user through the process of creating a building model. Within eQUEST, DOE-2.2 performs an hourly simulation of the building based on walls, windows, glass, people, plug loads, and ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices. eQUEST allows users to create multiple simulations and view the alternative results in side-by-side graphics. It offers energy cost estimating, daylighting and lighting system control, and automatic implementation of energy efficiency measures (by selecting preferred measures from a list).
EnergyPlus[12]	EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E. It is a simulation engine with input and output of text files. Loads calculated (by a heat balance engine) at a user-specified time step (15- minute default) are passed to the building systems simulation module at the same time step. The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response. This integrated solution provides more accurate space temperature prediction—crucial for system and plant sizing, occupant comfort and occupant health calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

Energy-10[13]	Energy-10 was designed to facilitate the analysis of buildings early in the design process with a focus on providing a comprehensive tool suited to the designteam environment for smaller buildings. Rapid presentation of reference and low-energy cases is the hallmarks of Energy-10. Since Energy-10 evaluates one or two thermal zones, it is most suitable for smaller, 10,000 ft2 (1000 m2) or less, simpler, commercial and residential buildings. Energy-10 takes a baseline simulation and automatically applies a number of predefined strategies ranging from building envelope (insulation, glazing, shading, thermal mass, etc.) and system efficiency options (HVAC, lighting, daylighting, solar service hot water and integrated photovoltaic electricity generation). Full life-cycle costing is an integral part of the software.
Energy Express[14]	Energy Express is a design tool, created by CSIRO, for estimating energy consumption and cost at the design stage. The user interface allows fast and accurate model creation and manipulation. Energy Express includes a dynamic multi-zone heat transfer model coupled to an integrated HVAC model so that zone temperatures are impacted by any HVAC shortcomings. Energy Express for Architects provides graphic geometry input and editing, multiple report viewing, comparison of alternative designs and results, simplified HVAC model, and detailed online help. Energy Express for Engineers provides those capabilities along with peak load estimating, and detailed HVAC model, graphic editing of air handling system and thermal plant layouts.
Ener-Win[15]	Ener-Win, originally developed at Texas A&M University, simulates hourly energy consumption in buildings, including annual and monthly energy consumption, peak demand charges, peak heating and cooling loads, solar heating fraction through glazing, daylighting contribution, and a life-cycle cost analysis. Design data, tabulated by zones, also show duct sizes and electric power requirements. The Ener-Win software is composed of several modules — an interface module, a weather data retrieval module, a sketching module, and an energy simulation module. The interface module includes a rudimentary building sketching interface. Ener-Win requires only three basic inputs: (1) the building type, (2) the building’s location, and (3) the building’s geometrical data.

ECOTECT[16]	Ecotect is a highly visual architectural design and analysis tool that links a comprehensive 3D modeler with a wide range of performance analysis functions covering thermal, energy, lighting, shading, acoustics and cost aspects. Whilst its modelling and analysis capabilities can handle geometry of any size and complexity, its main advantage is a focus on feedback at the earliest stages of the building design process. In addition to standard graph and table-based reports, analysis results can be mapped over building surfaces or displayed directly within the spaces. This includes visualisation of volumetric and spatial analysis results, including imported 3D CFD data. Real-time animation features are provided along with interactive acoustic and solar raytracing that updates in real time with changes to building geometry and material properties.
DOE-2.1E[17]	DOE-2.1E predicts the hourly energy use and energy cost of a building given hourly weather information, a building geometric and HVAC description, and utility rate structure. DOE-2.1E has one subprogram for translation of input (BDL Processor), and four simulation subprograms (LOADS, SYSTEMS, PLANT and ECON). LOADS, SYSTEMS and PLANT are executed in sequence, with the output of LOADS becoming the input of SYSTEMS, etc. The output then becomes the input to ECONOMICS. Each of the simulation subprograms also produces printed reports of the results of its calculations.
DeST[18]	DeST (Designer's Simulation Toolkits) allows detailed analysis of building thermal processes and HVAC system performance. DeST comprises a number of different modules for handling different functions: Medpha (weather data), VentPlus (natural ventilation), Bshadow (external shading), Lighting (lighting), and CABD (CAD interface). BAS (Building Analysis & Simulation) performs hourly calculations for indoor air temperatures and cooling/heating loads for buildings up to 1000 rooms.
BSim[19]	BSim provides user-friendly simulation of detailed, combined hygrothermal simulations of buildings and constructions. The package comprise several modules: SimView (graphic editor), tsbi5 (building simulation), SimLight (daylight), XSun (direct sunlight and shadowing), SimPV (photovoltaic power), NatVent (natural ventilation) and SimDxf (from CAD). BSim has been used extensively over the past 20 years, previously under the name tsbi3. Today BSim is the most commonly used tool in Denmark, and with increasing interest abroad, for energy design of buildings and for moisture analysis.

BLAST[20]	The Building Loads Analysis and System Thermodynamics (BLAST) system predicts energy consumption and energy system performance and cost in buildings. BLAST contains three major subprograms: Space Loads Prediction, Air System Simulation, and Central Plant. Prediction computes hourly space loads given hourly weather data and building construction and operation details using a radiant, convective, and conductive heat balance for all surfaces and a heat balance of the room air. This includes transmission loads, solar loads, internal heat gains, infiltration loads, and the temperature control strategy used to maintain the space temperature.

1. ^ http:// trnsys.com (retrieved 4May2007).
2. ^ http://tranecds.com (retrieved 23November2004).
3. ^ http://edsl.net (retrieved 13May2005).
4. ^ http:// nrel.gov/buildings/sunrel (retrieved 7November2004).
5. ^ http://edsl.net (retrieved 13May2005).
6. ^ http://pucpr.br/lst (retrieved 11june2005).
7. ^ http://aud.ucla.edu/heed (retrieved 2 January2005).
8. ^ http://commercial.carrier.com (retrieved 26February2004).
9. ^ http:// iesve.com (retrieved 10December2004).
10. ^ http:// equa.se/ice.com (retrieved 2December2005).
11. ^ http:// esru.strath.ac.uk/Programs/ESP-r.htm (retrieved 16 February2005).
12. ^ http:// doe2.com/equest (retrieved 14 February2005).
13. ^ http://energyplus.gov (retrieved 27April2005).
14. ^ http:// nrel.gov/buildings/energy10 (retrieved 8June2005).
15. ^ http://ee.hearne.com.au (retrieved 2February2005).
16. ^ http://members.cox.net/enerwin (retrieved 13June2005).
17. ^ http:// ecotect.com.au (retrieved 25April2005).
18. ^ http://simulationresearch.lbl.gov (retrieved 20September2003).
19. ^ http:// bsim.dk (retrieved 5April2004).
20. ^ http:// bso.uiuc.edu/BLAST (retrieved 12June2005).

Table (2) shows Comparison between simulation programs according to general characteristics of simulation model and internal zone thermal loads calculation.

	TRNSYS	**TRACE**	**Tas**	**SUNREL**	**Power Domus**	**HEED**	**HAP**	**IES (VE)**	**IDA ICE**	**ESP-r**
Calculation of thermal loads										
Depended on Temperature	X		X	X	X	X		X	X	X
Depended on Air flow	E		X			X		X		X
Dependent on surface heat coefficient from				X	X			X		E
User-defined coefficients (constants and equation)	X		X	X	X	X		X	R	E
Calculation the Internal thermal mass	X	X	X		P	X		X	X	X
Automatic design day calculations for sizing										
Dry-Blub temperature		X	X			X	X	X	X	
Relative humidity		X	X				X	X	X	
Maximum and minimum thermal comfort for occupants		X	X			X	X	X	X	
Calculate thethermal comfort for occupants	X	X	X				X	X	X	

Table (3) shows Comparison between simulation programs according to general characteristics of simulation model and internal zone thermal loads calculation.

	eQUEST	**Energy Plus**	**Energy-10**	**Energy Express**	**Ener-Win**	**Ecotect**	**DOE-2.1E**	**DeST**	**BSim**	**BLAST**
Calculation of thermal loads										
Depended on Temperature		X		P					X	X
Depended on Air flow		P		X						X
Dependent on surface heat coefficient from		E								
User-defined coefficients (constants and equation)		X				X	X	X	X	
Calculation the Internal thermal mass	X	X	X	X	X	X	X	X	X	X
Automatic design day calculations for sizing										
Dry-Blub temperature	X	X	X	X	X	X	X	X	X	X
Relative humidity	X	X		X	X		X	X		
Maximum and minimum thermal comfort for occupants	X	X		X	X		X	X		
Calculate thethermal comfort for occupants								X		

Table (4) shows Comparison between simulation programs according to external zones thermal loads, design of building envelope and daylighting.

	TRNSYS	TRACE	Tas	SUNREL	Power Domus	HEED	HAP	IES (VE)	IDA ICE	ESP-r
Climate data input for study zone										
-BLAST/TARP		X								
-DOE-2		X								
-MoWiTT		X								X
-ASHRAE simple		X	X			X		X		
-Ito. Kimura. And Oka correlation									X	X
Calculation of thermal loads for external zones	X	X	X		X			X	X	X
Effect of solar radiation			X	P				X	X	X
Transfer heat by Convection	X	P	X	X				X	X	X
Calculate daylighting	X				P			X		X

Table (5) shows Comparison between simulation programs according to external zones thermal loads, design of building envelope and daylighting.

	eQUEST	**Energy Plus**	**Energy 10**	**Energy Express**	**Ener-Win**	**Ecotect**	**DOE 2.1E**	**DeST**	**BSim**	**BLAST**
Climate data input for study zone										
-BLAST/TARP		X								X
-DOE-2	X	X					X			
-MoWiTT		X								
-ASHRAE simple	X	X	X		X					X
-Ito. Kimura. And Oka correlation										
Calculation of thermal loads for external zones		X						X		
Effect of solar radiation		X						X		
Transfer heat by Convection		X						X		
Calculate daylighting		X				X		P		

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

Table (6) shows comparison between simulation programs from aspect of ventilation calculation and Air flow through zones.

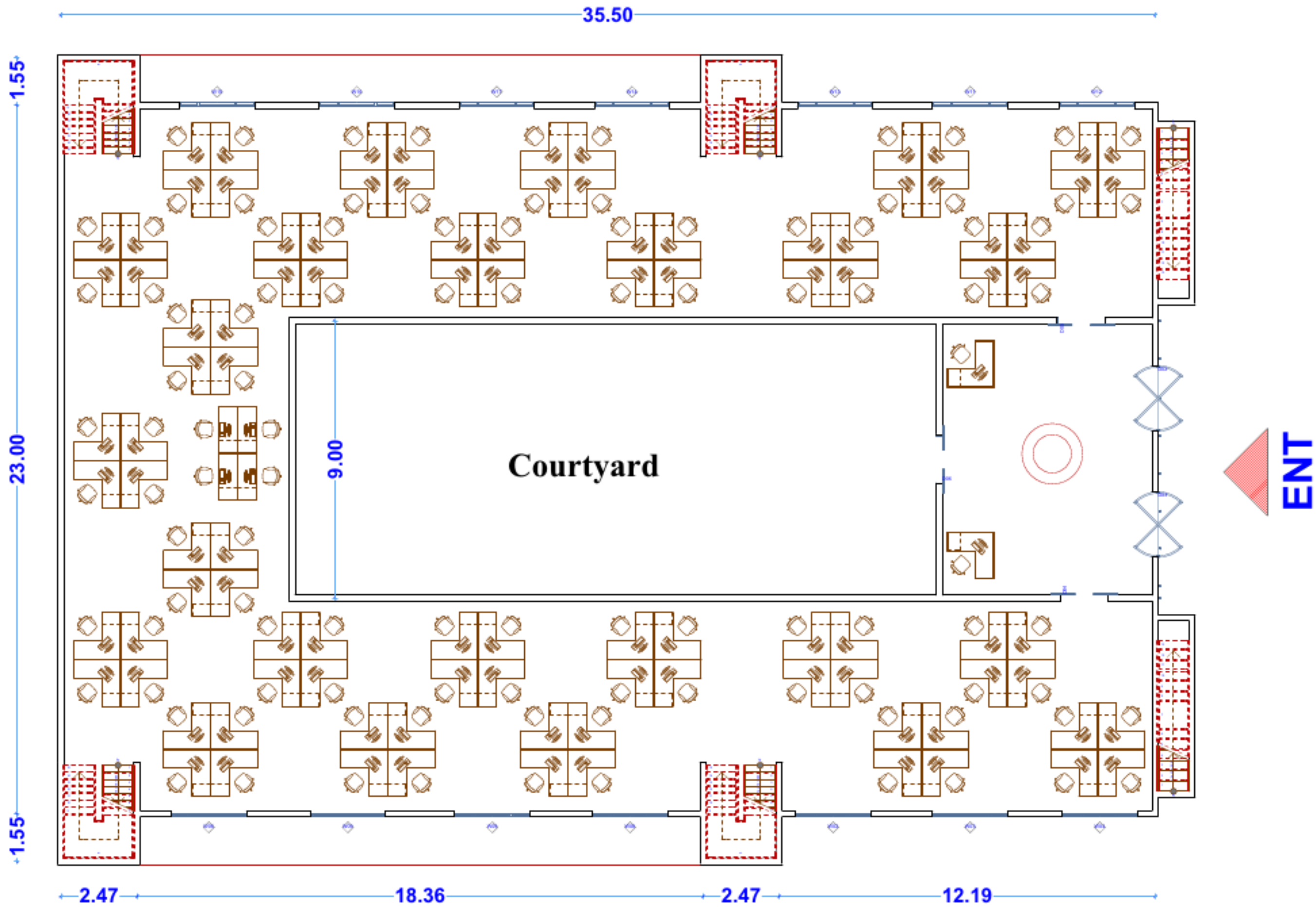
	TRNSYS	TRACE	Tas	SUNREL	Power Domus	HEED	HAP	IES (VE)	IDA ICE	ESP-r
Calculate the ventilation infiltration in single zone	X	X	X	X	X	X	X	X	X	X
Automatic calculation of wind pressure coefficient			X	X				X		
Calculate the natural ventilation	O		X	X	X			X	X	X
Calculate the ventilation infiltration inmultizone	O		X	X				X	X	X
Integrating natural and artificial ventilation	O		X		X			X	X	I
Control window opening based on zone or external conditions	O			X	P			X		X
Displacement Ventilation control	O		X					X	X	X
Control of CFD										E

Table (7) shows comparison between simulation programs from aspect of ventilation calculation and Air flow through zones.

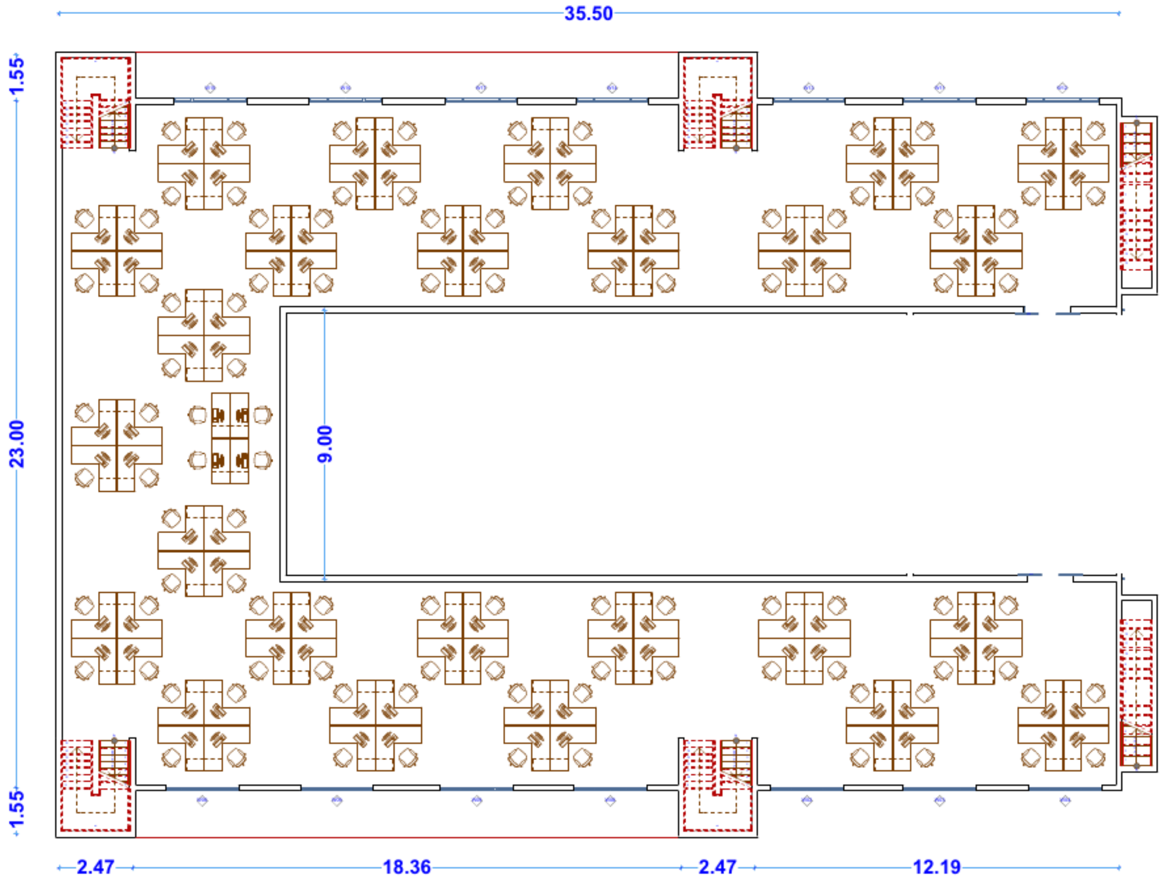
	eQUEST	Energy Plus	Energy 10	Energy Express	Ener-Win	Ecotect	DOE 2.1E	DeST	BSim	BLAST
Calculate the ventilation infiltration in single zone	X	X	X	X	X	X	X	X	X	X
Automatic calculation of wind pressure coefficient		P						P	X	
Calculate the natural ventilation	P	X						P	X	
Calculate the ventilation infiltration inmultizone		X						P	X	
Integrating natural and artificial ventilation					X			P	X	
Control window opening based on zone or external conditions		X			X			X		
Displacement Ventilation control		X								
Control of CFD								X		

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

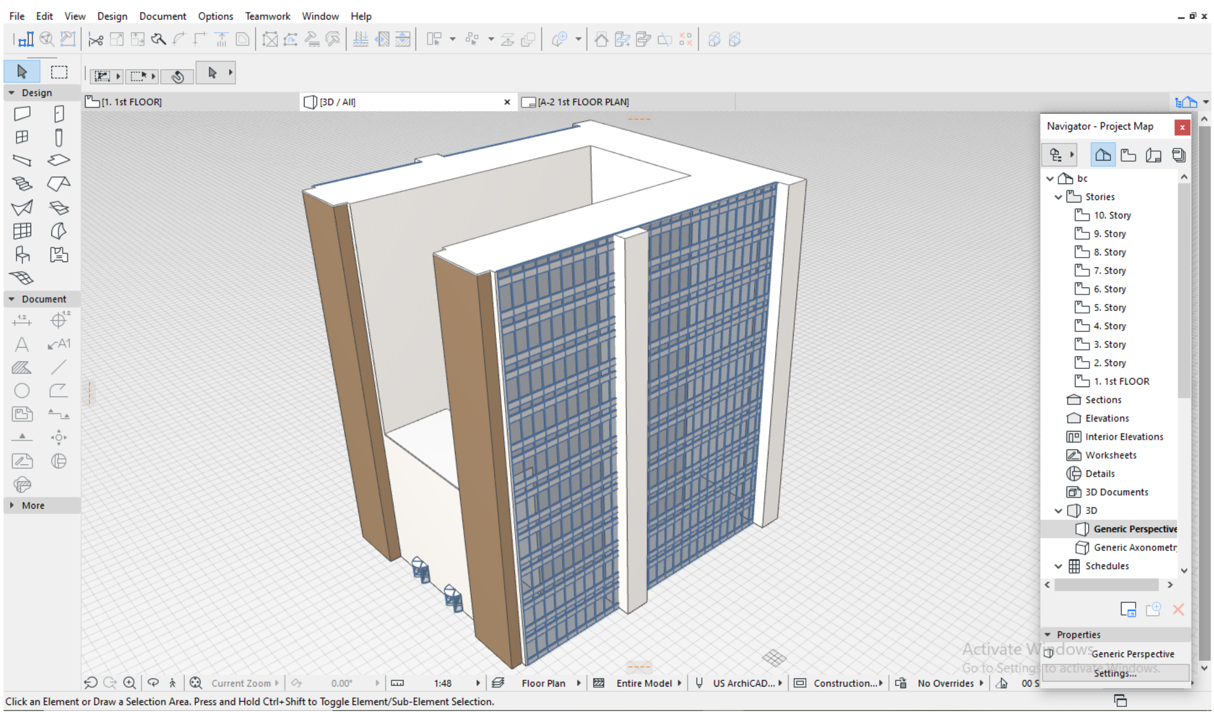
APPENDIX B: Base case office building Drawings



Ground floor: total floor area for the number of working places (only office rooms) is 15.4 m^2 /occupant.

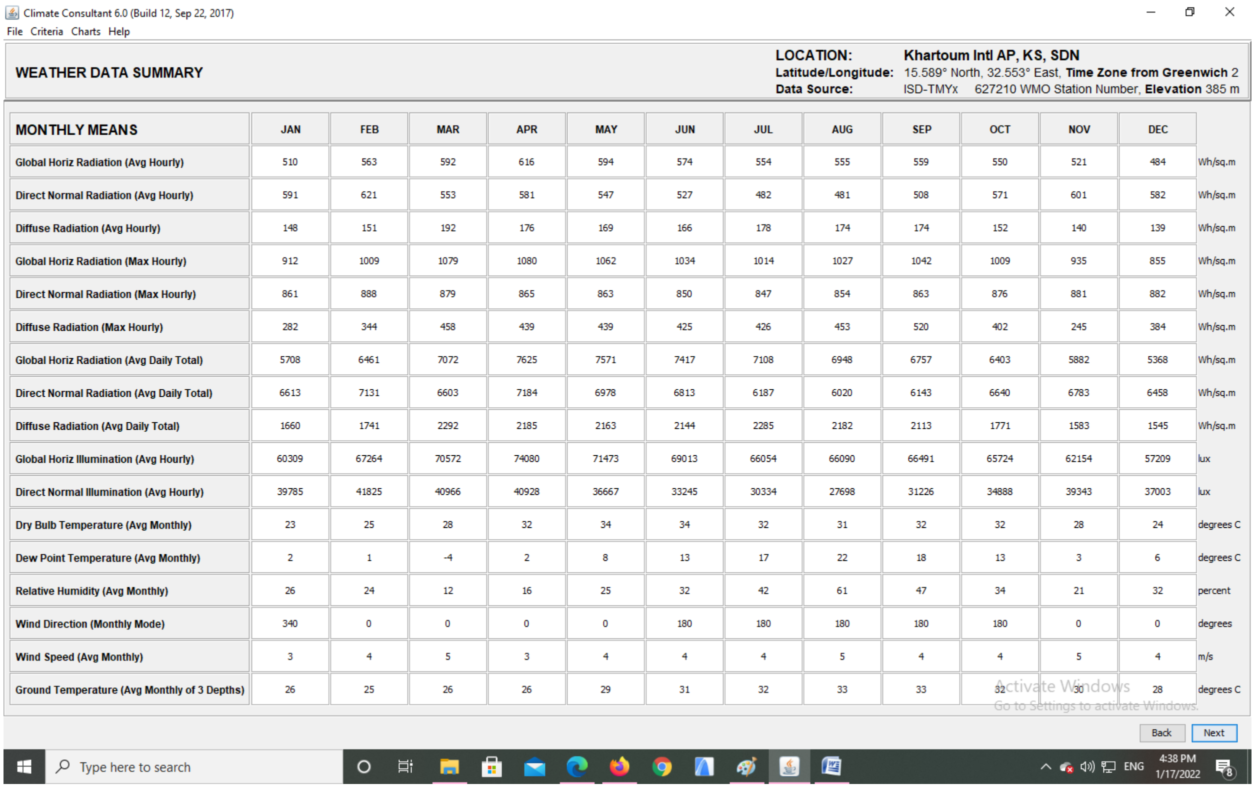


Typical floor plan (fifth-tenth floor).



3D view of the modeled proportion of the single-skin facade in Revit software.

APPENDIX C: Weather data file



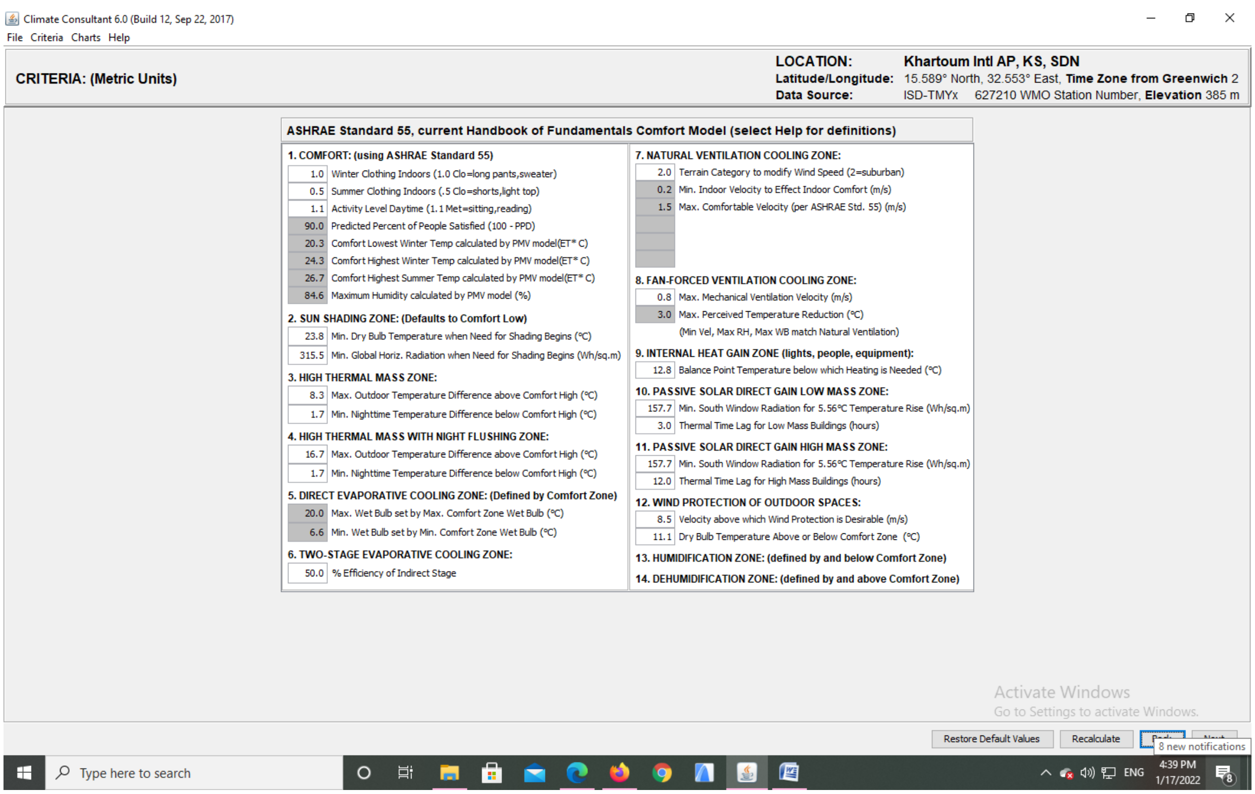
Climate Consultant 6.0 (Build 12, Sep 22, 2017)

File Criteria Charts Help

WEATHER DATA SUMMARY

LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, **Time Zone from Greenwich** 2
Data Source: ISD-TMYx 627210 WMO Station Number, **Elevation** 385 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	510	563	592	616	594	574	554	555	559	550	521	484	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	591	621	553	581	547	527	482	481	508	571	601	582	Wh/sq.m
Diffuse Radiation (Avg Hourly)	148	151	192	176	169	166	178	174	174	152	140	139	Wh/sq.m
Global Horiz Radiation (Max Hourly)	912	1009	1079	1080	1062	1034	1014	1027	1042	1009	935	855	Wh/sq.m
Direct Normal Radiation (Max Hourly)	861	888	879	865	863	850	847	854	863	876	881	882	Wh/sq.m
Diffuse Radiation (Max Hourly)	282	344	458	439	439	425	426	453	520	402	245	384	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	5708	6461	7072	7625	7571	7417	7108	6948	6757	6403	5882	5368	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	6613	7131	6603	7184	6978	6813	6187	6020	6143	6640	6783	6458	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1660	1741	2292	2185	2163	2144	2285	2182	2113	1771	1583	1545	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	60309	67264	70572	74080	71473	69013	66054	66090	66491	65724	62154	57209	lux
Direct Normal Illumination (Avg Hourly)	39785	41825	40966	40928	36667	33245	30334	27698	31226	34888	39343	37003	lux
Dry Bulb Temperature (Avg Monthly)	23	25	28	32	34	34	32	31	32	32	28	24	degrees C
Dew Point Temperature (Avg Monthly)	2	1	-4	2	8	13	17	22	18	13	3	6	degrees C
Relative Humidity (Avg Monthly)	26	24	12	16	25	32	42	61	47	34	21	32	percent
Wind Direction (Monthly Mode)	340	0	0	0	0	180	180	180	180	180	0	0	degrees
Wind Speed (Avg Monthly)	3	4	5	3	4	4	4	5	4	4	5	4	m/s
Ground Temperature (Avg Monthly of 3 Depths)	26	25	26	26	29	31	32	33	33	32	30	28	degrees C



Climate Consultant 6.0 (Build 12, Sep 22, 2017)

File Criteria Charts Help

CRITERIA: (Metric Units)

LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, **Time Zone from Greenwich** 2
Data Source: ISD-TMYx 627210 WMO Station Number, **Elevation** 385 m

ASHRAE Standard 55, current Handbook of Fundamentals Comfort Model (select Help for definitions)

1. COMFORT: (using ASHRAE Standard 55)
- 1.0 Winter Clothing Indoors (1.0 Clo=long pants,sweater)
- 0.5 Summer Clothing Indoors (.5 Clo=shorts,light top)
- 1.1 Activity Level Daytime (1.1 Met=sitting,reading)
- 90.0 Predicted Percent of People Satisfied (100 - PPD)
- 20.3 Comfort Lowest Winter Temp calculated by PMV model(ET* C)
- 24.3 Comfort Highest Winter Temp calculated by PMV model(ET* C)
- 26.7 Comfort Highest Summer Temp calculated by PMV model(ET* C)
- 84.6 Maximum Humidity calculated by PMV model (%)

2. SUN SHADING ZONE: (Defaults to Comfort Low)
- 23.8 Min. Dry Bulb Temperature when Need for Shading Begins (°C)
- 315.5 Min. Global Horiz. Radiation when Need for Shading Begins (Wh/sq.m)

3. HIGH THERMAL MASS ZONE:
- 8.3 Max. Outdoor Temperature Difference above Comfort High (°C)
- 1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

4. HIGH THERMAL MASS WITH NIGHT FLUSHING ZONE:
- 16.7 Max. Outdoor Temperature Difference above Comfort High (°C)
- 1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

5. DIRECT EVAPORATIVE COOLING ZONE: (Defined by Comfort Zone)
- 20.0 Max. Wet Bulb set by Max. Comfort Zone Wet Bulb (°C)
- 6.6 Min. Wet Bulb set by Min. Comfort Zone Wet Bulb (°C)

6. TWO-STAGE EVAPORATIVE COOLING ZONE:
- 50.0 % Efficiency of Indirect Stage

7. NATURAL VENTILATION COOLING ZONE:
- 2.0 Terrain Category to modify Wind Speed (2=suburban)
- 0.2 Min. Indoor Velocity to Effect Indoor Comfort (m/s)
- 1.5 Max. Comfortable Velocity (per ASHRAE Std. 55) (m/s)

8. FAN-FORCED VENTILATION COOLING ZONE:
- 0.8 Max. Mechanical Ventilation Velocity (m/s)
- 3.0 Max. Perceived Temperature Reduction (°C)
- (Min Vel, Max RH, Max WB match Natural Ventilation)

9. INTERNAL HEAT GAIN ZONE (lights, people, equipment):
- 12.8 Balance Point Temperature below which Heating is Needed (°C)

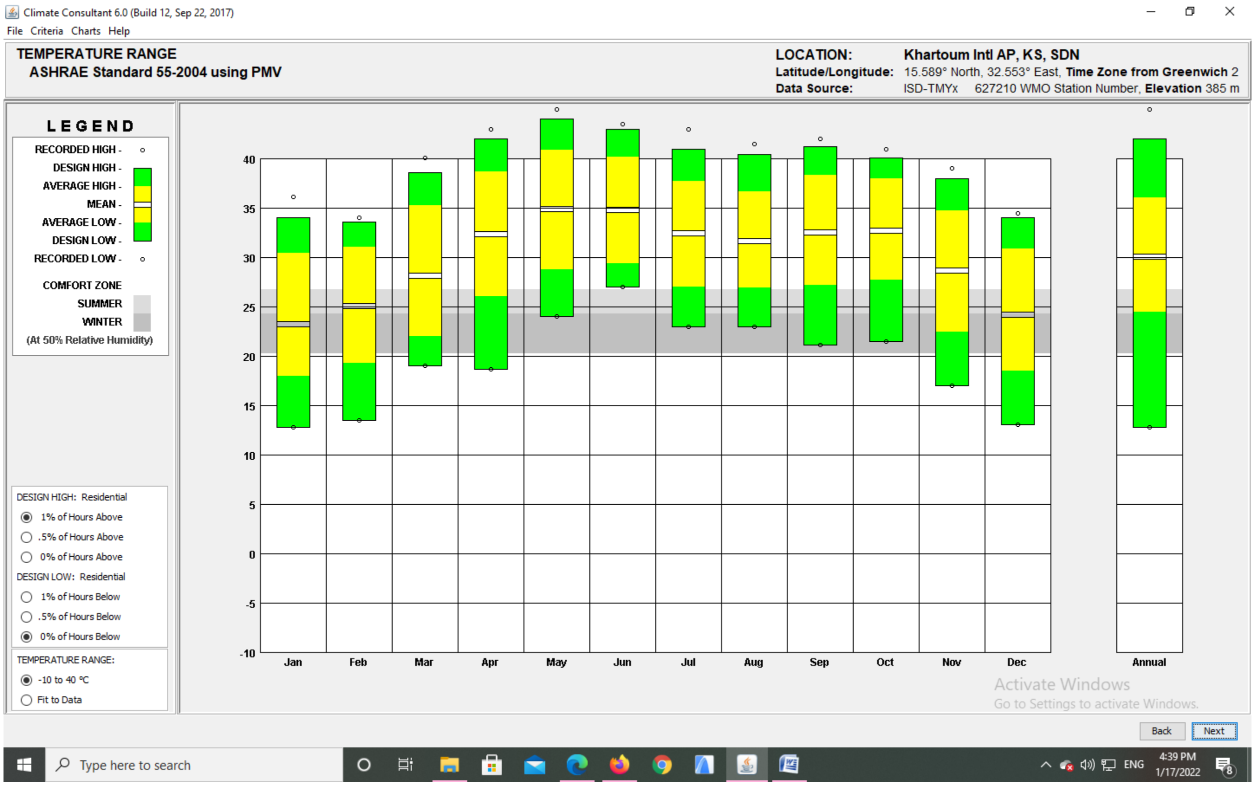
10. PASSIVE SOLAR DIRECT GAIN LOW MASS ZONE:
- 157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
- 3.0 Thermal Time Lag for Low Mass Buildings (hours)

11. PASSIVE SOLAR DIRECT GAIN HIGH MASS ZONE:
- 157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
- 12.0 Thermal Time Lag for High Mass Buildings (hours)

12. WIND PROTECTION OF OUTDOOR SPACES:
- 8.5 Velocity above which Wind Protection is Desirable (m/s)
- 11.1 Dry Bulb Temperature Above or Below Comfort Zone (°C)

13. HUMIDIFICATION ZONE: (defined by and below Comfort Zone)

14. DEHUMIDIFICATION ZONE: (defined by and above Comfort Zone)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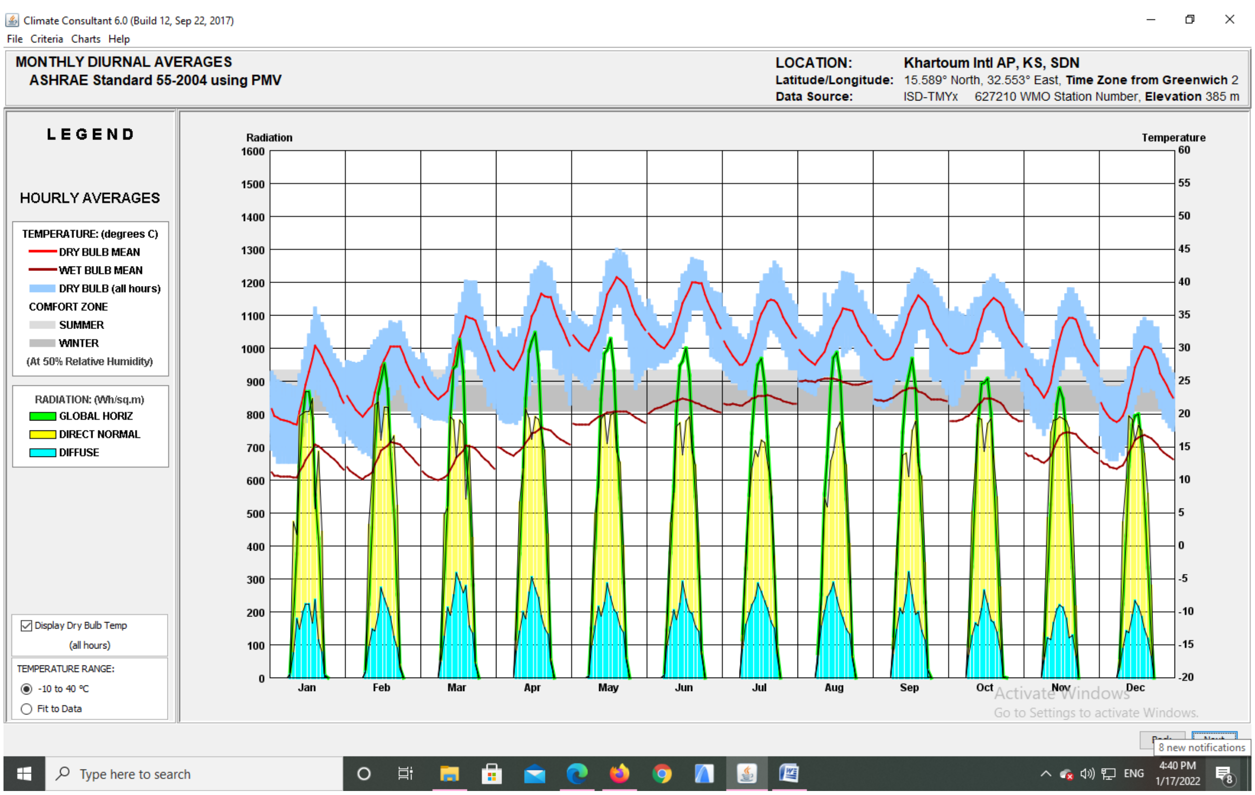
TEMPERATURE RANGE
ASHRAE Standard 55-2004 using PMV
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
RECORDED HIGH -
DESIGN HIGH -
AVERAGE HIGH -
MEAN -
AVERAGE LOW -
DESIGN LOW -
RECORDED LOW -
COMFORT ZONE
SUMMER
WINTER
(At 50% Relative Humidity)
DESIGN HIGH: Residential
1% of Hours Above
.5% of Hours Above
0% of Hours Above
DESIGN LOW: Residential
1% of Hours Below
.5% of Hours Below
0% of Hours Below
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Annual
Back Next
Type here to search
4:39 PM
1/17/2022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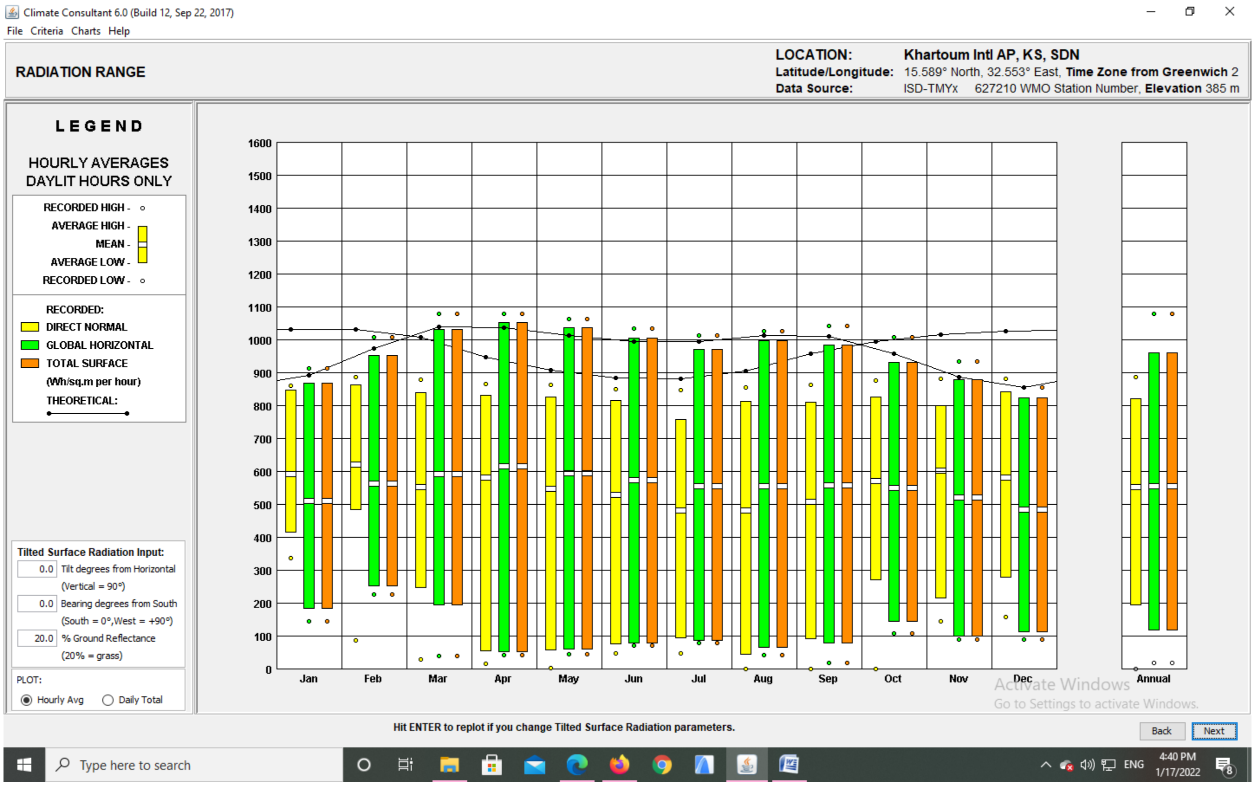
MONTHLY DIURNAL AVERAGES
ASHRAE Standard 55-2004 using PMV
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
HOURLY AVERAGES
TEMPERATURE: (degrees C)
DRY BULB MEAN
WET BULB MEAN
DRY BULB (all hours)
COMFORT ZONE
SUMMER
WINTER
(At 50% Relative Humidity)
RADIATION: (Wh/sq.m)
GLOBAL HORIZ
DIRECT NORMAL
DIFFUSE
Display Dry Bulb Temp (all hours)
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Radiation
Temperature
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
8 new notifications
Type here to search
4:40 PM
1/17/2022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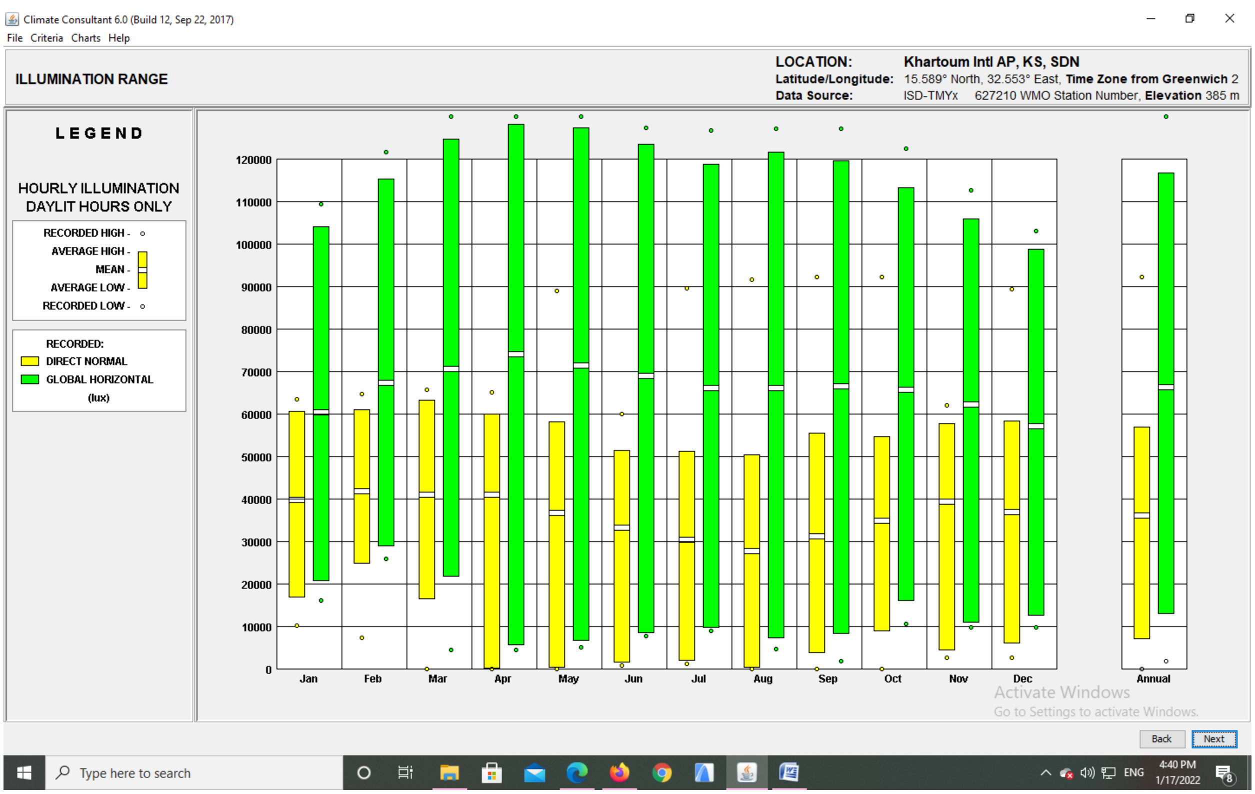
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
HOURLY AVERAGES DAYLIT HOURS ONLY
RECORDED HIGH
AVERAGE HIGH
MEAN
AVERAGE LOW
RECORDED LOW
RECORDED:
DIRECT NORMAL
GLOBAL HORIZONTAL
TOTAL SURFACE
(Wh/sq.m per hour)
THEORETICAL:
Tilted Surface Radiation Input:
0.0 Tilt degrees from Horizontal (Vertical = 90°)
0.0 Bearing degrees from South (South = 0°, West = +90°)
20.0 % Ground Reflectance (20% = grass)
PLOT: Hourly Avg Daily Total
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Annual
Hit ENTER to replot if you change Tilted Surface Radiation parameters.
Back Next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Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
HOURLY ILLUMINATION DAYLIT HOURS ONLY
RECORDED HIGH
AVERAGE HIGH
MEAN
AVERAGE LOW
RECORDED LOW
RECORDED:
DIRECT NORMAL
GLOBAL HORIZONTAL
(lux)
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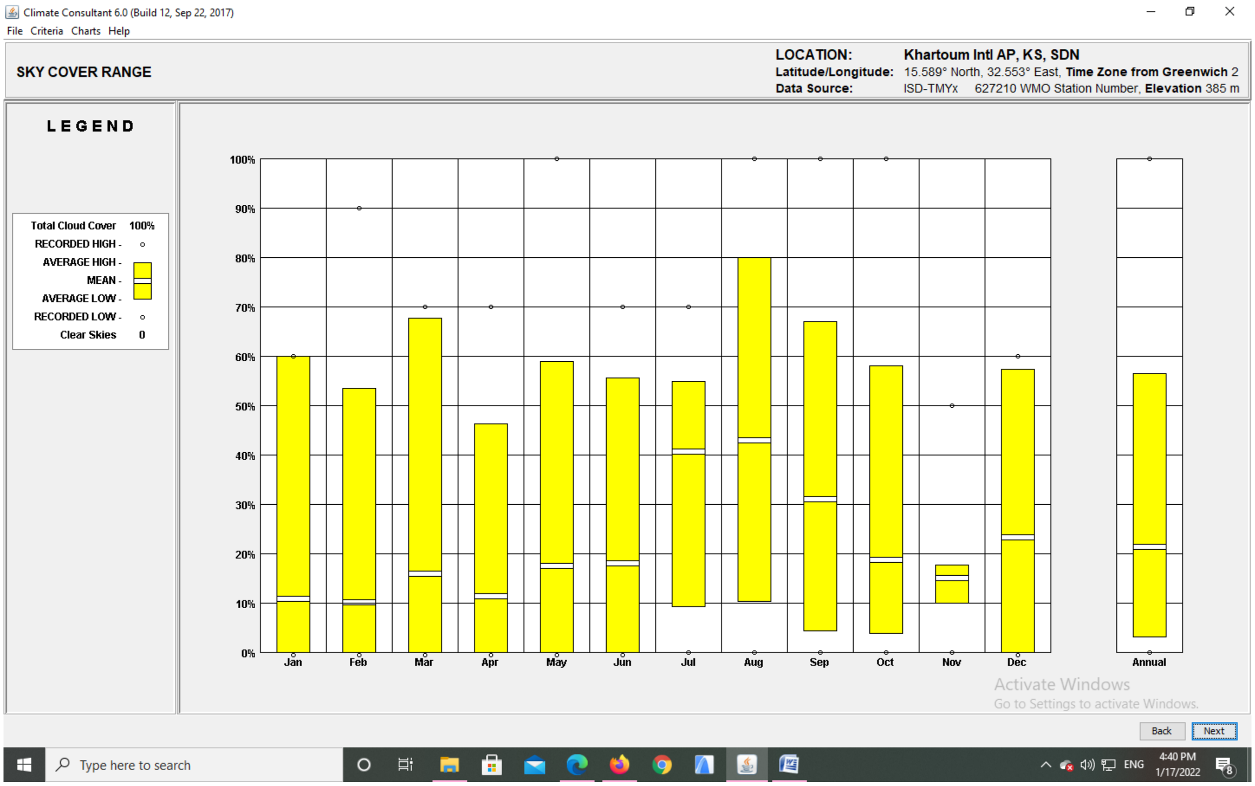
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Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
Total Cloud Cover 100%
RECORDED HIGH -
AVERAGE HIGH -
MEAN -
AVERAGE LOW -
RECORDED LOW -
Clear Skies 0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Annual
Back Next
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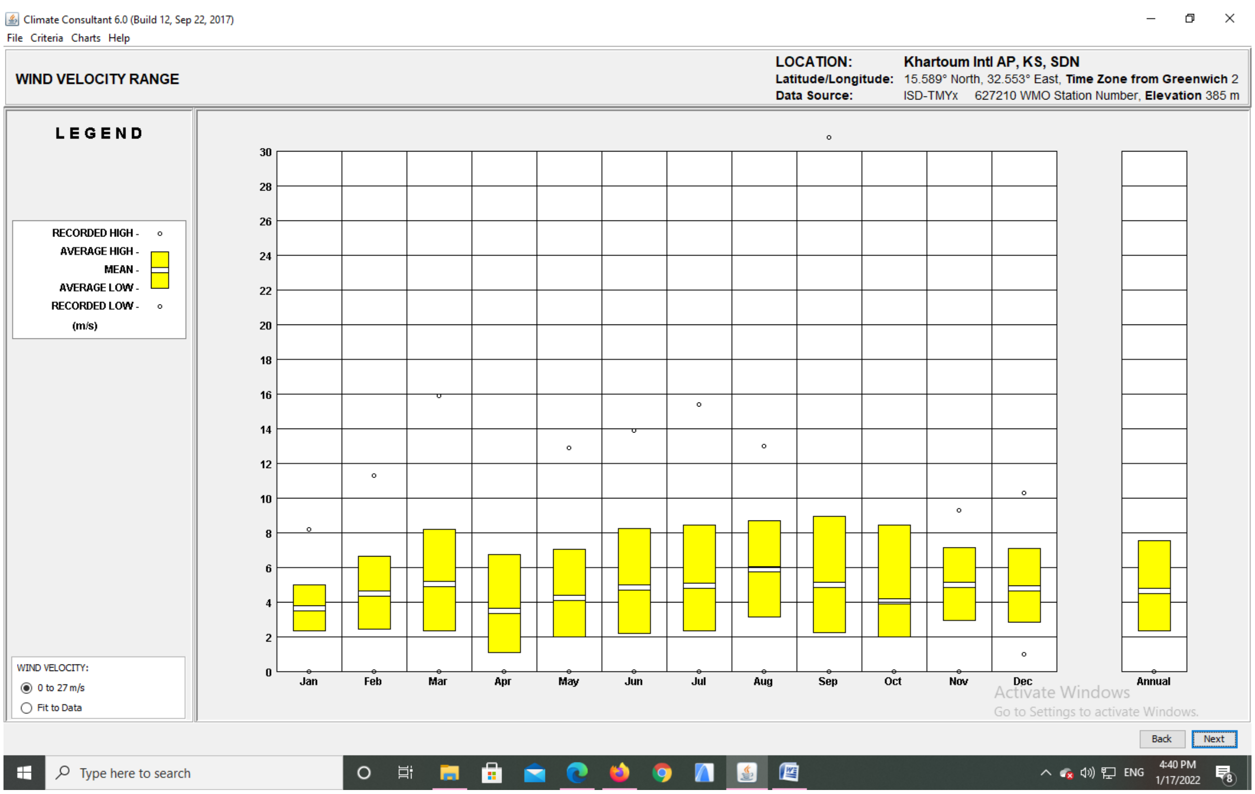
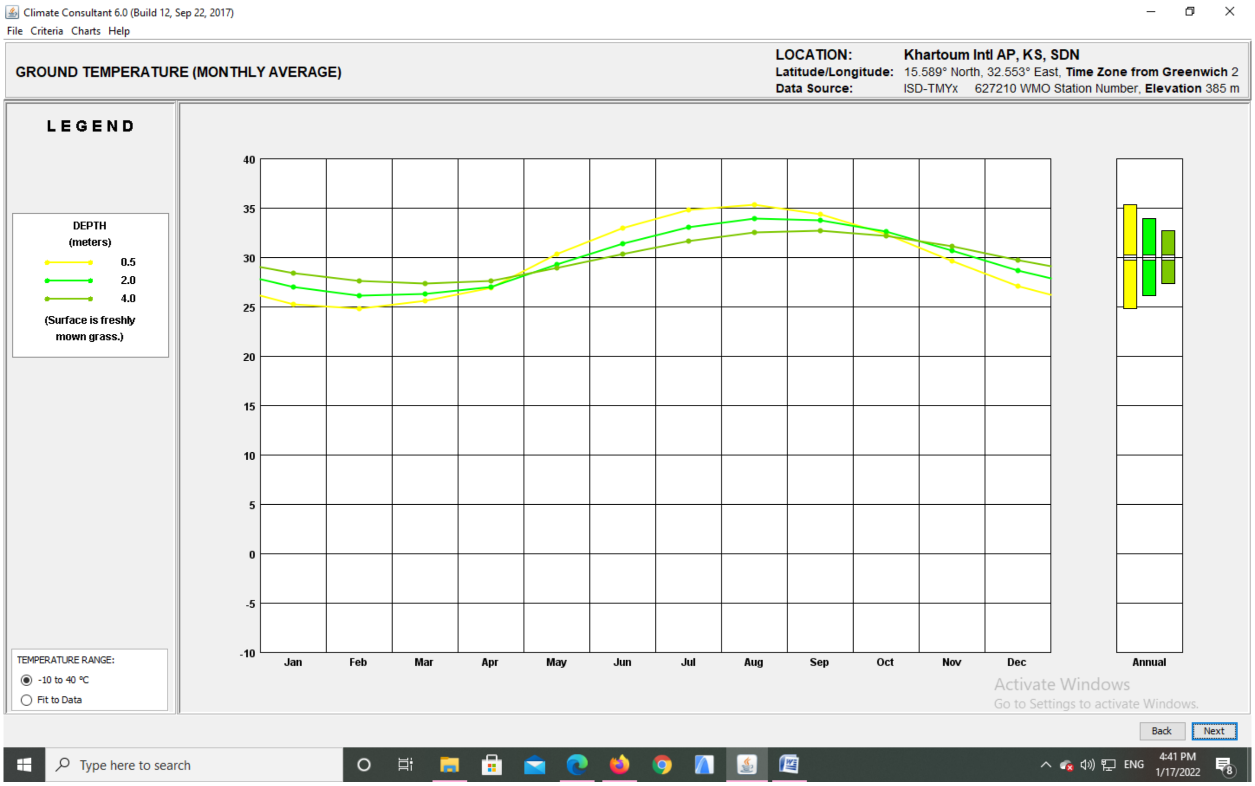
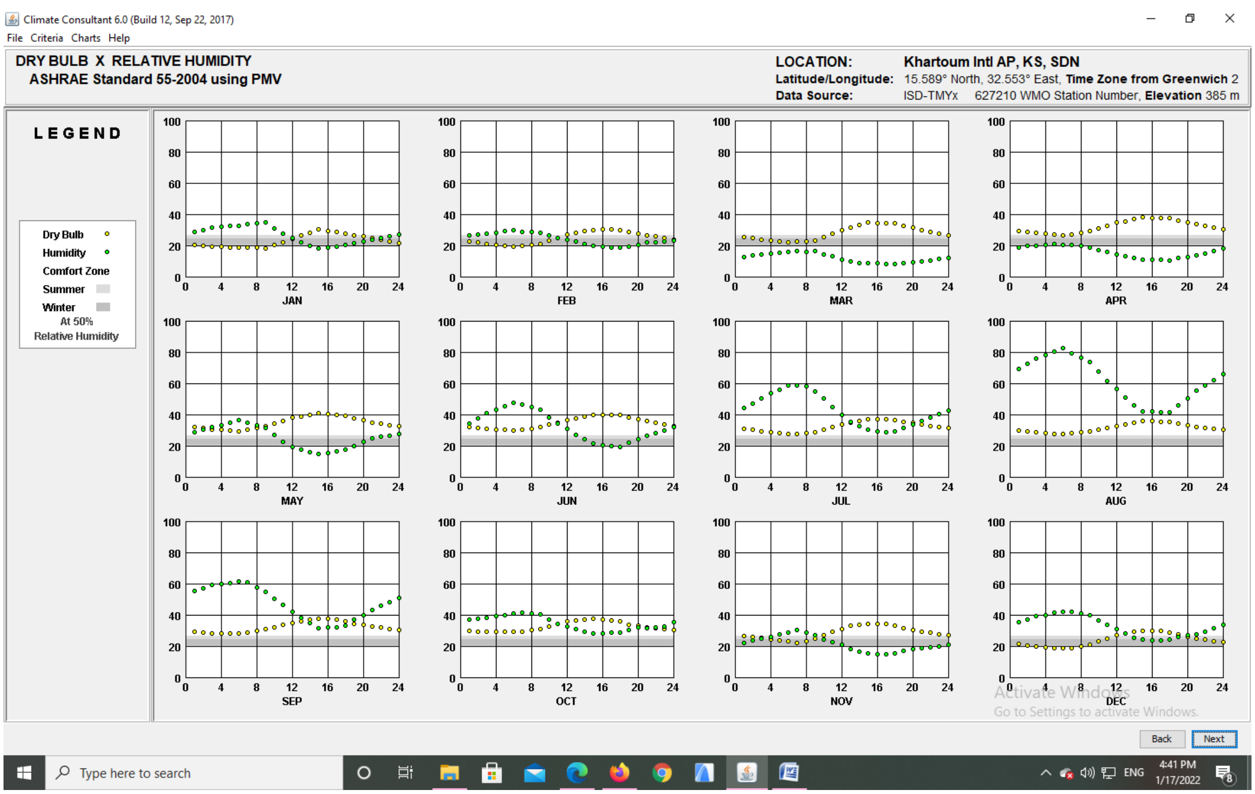
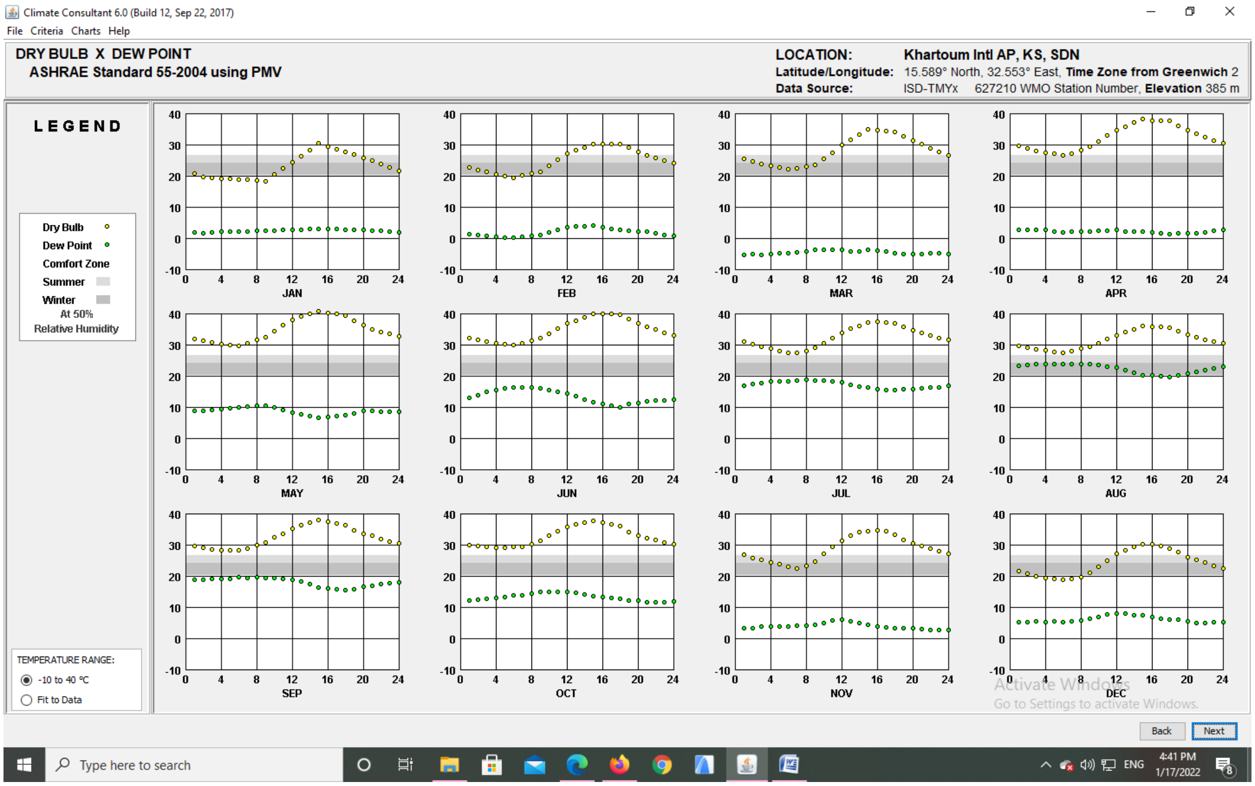
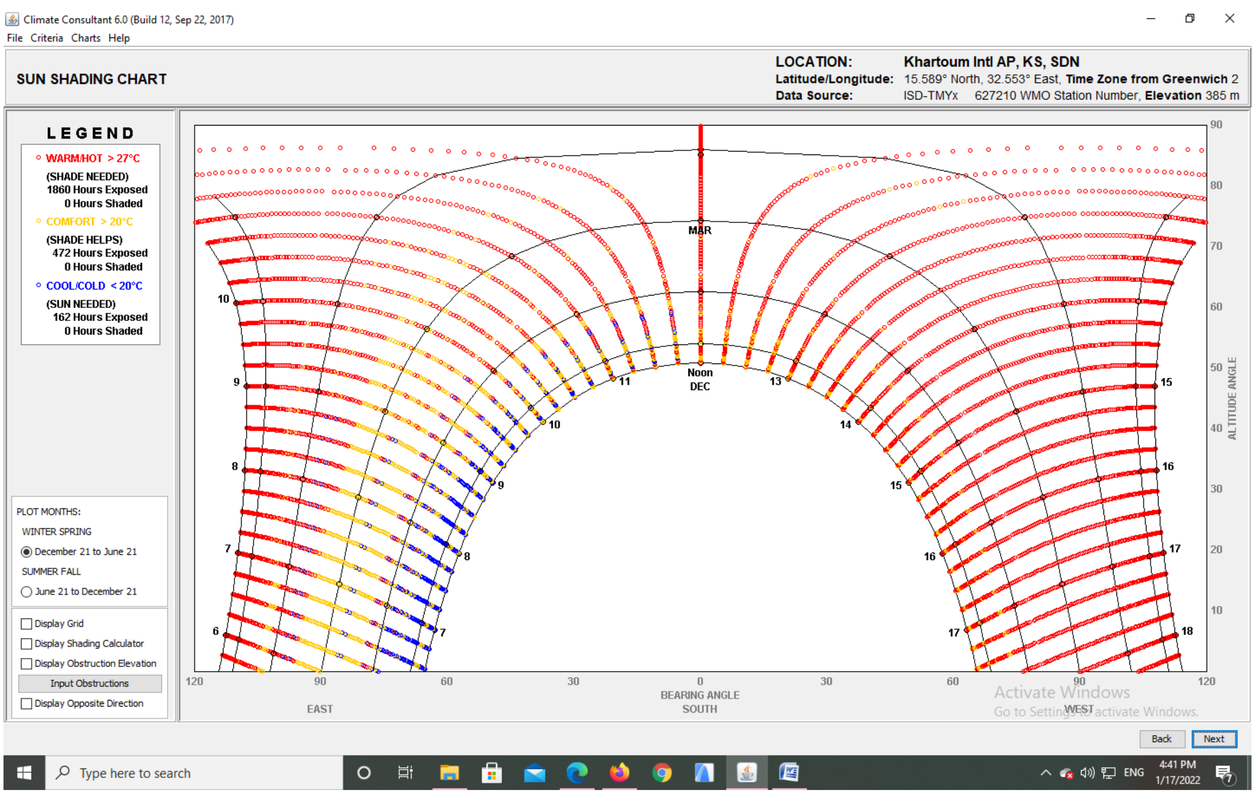
ENG 4:40 PM 1/17/2022

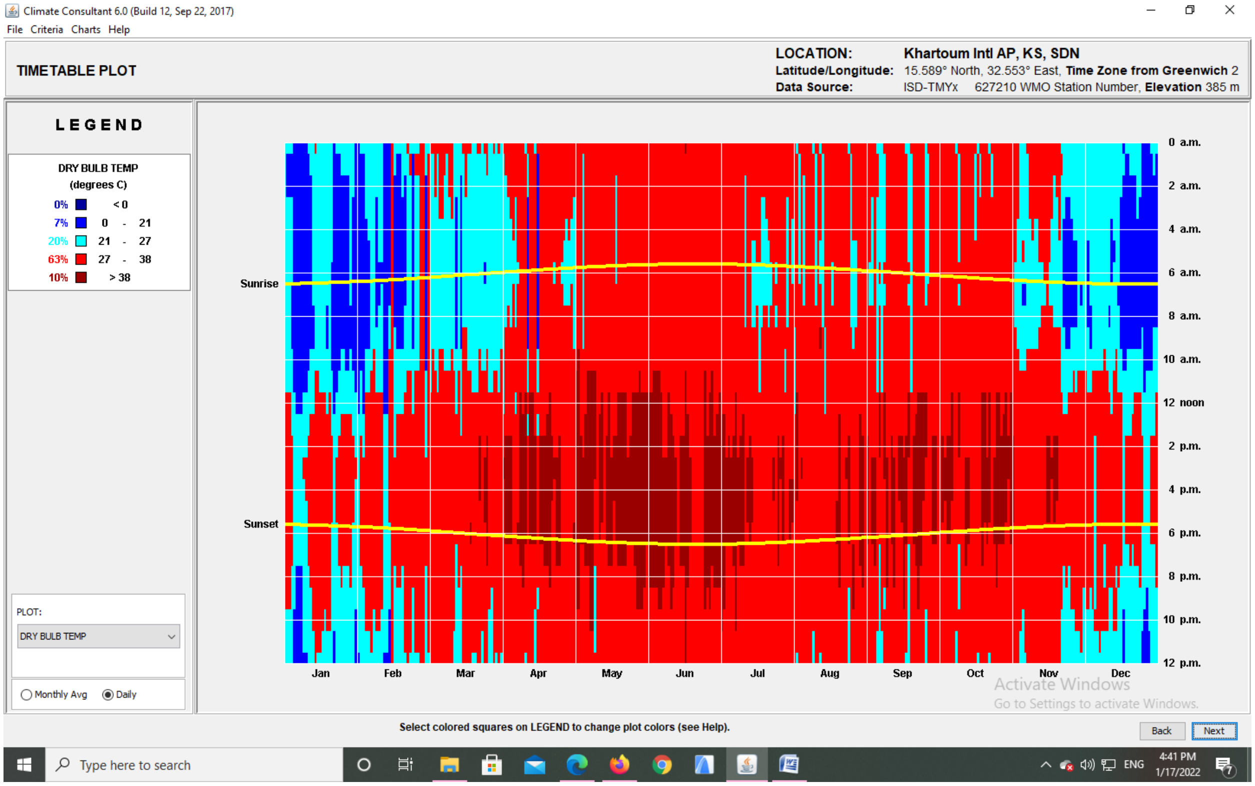

Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
WIND VELOCITY RANGE
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
RECORDED HIGH -
AVERAGE HIGH -
MEAN -
AVERAGE LOW -
RECORDED LOW -
(m/s)
WIND VELOCITY:
0 to 27 m/s
Fit to Data
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Annual
Back Next
Type here to search
ENG 4:40 PM 1/17/2022

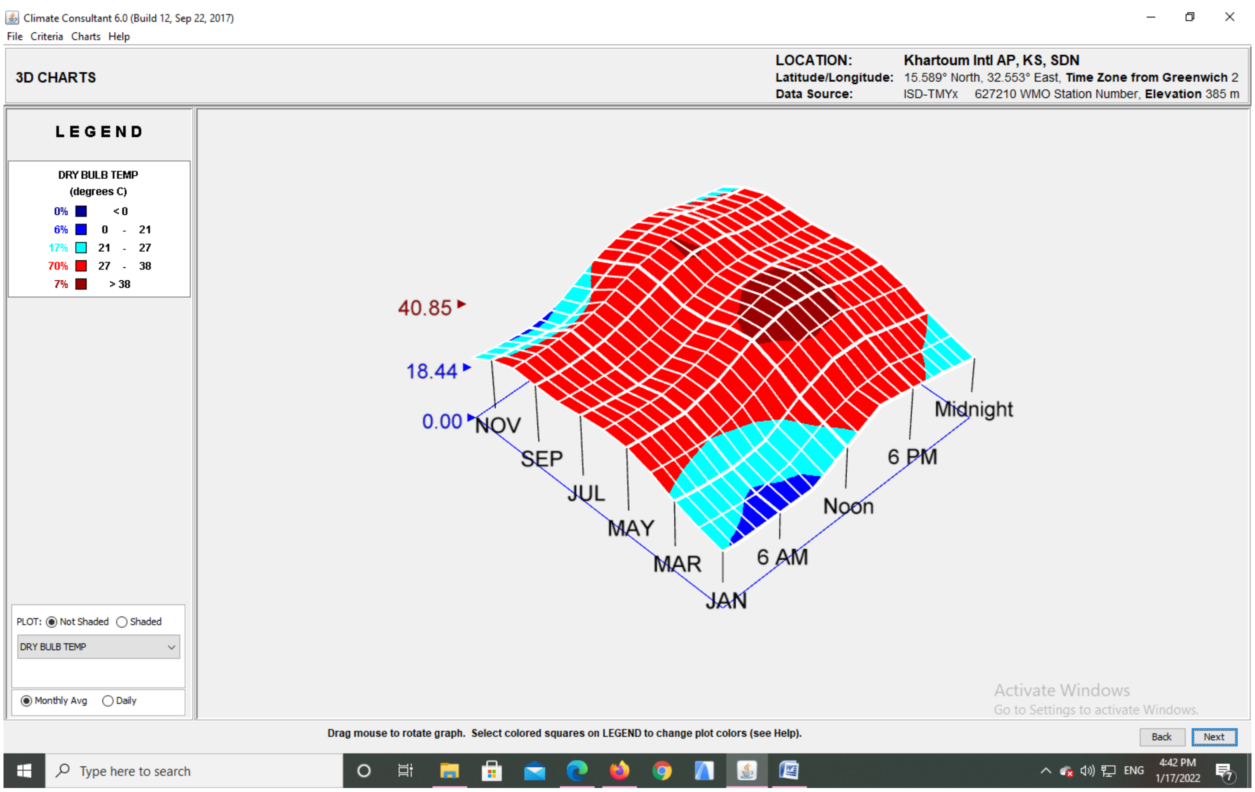

Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
GROUND TEMPERATURE (MONTHLY AVERAGE)
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
DEPTH (meters)
0.5
2.0
4.0
(Surface is freshly mown grass.)
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Annual
Back
Next
Type here to search
4:41 PM
1/17/2022

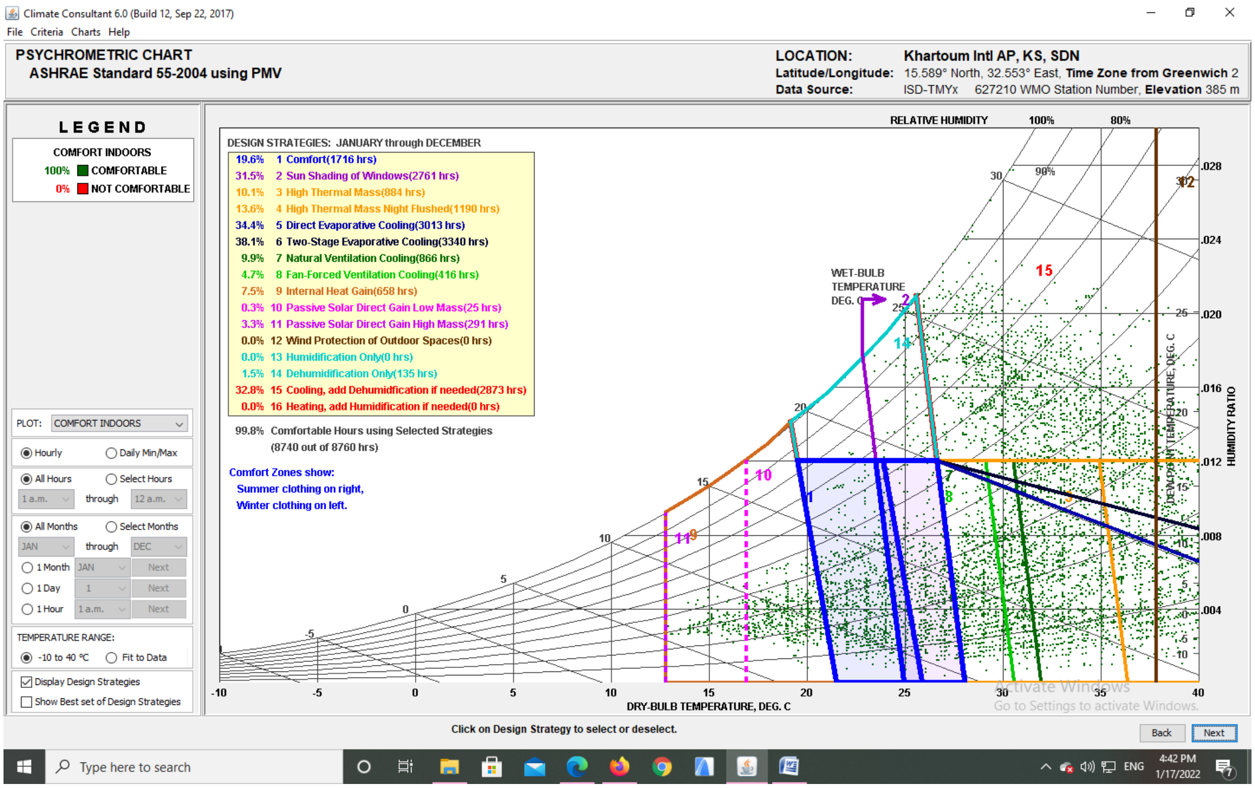

Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
DRY BULB X RELATIVE HUMIDITY
ASHRAE Standard 55-2004 using PMV
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
Dry Bulb
Humidity
Comfort Zone
Summer
Winter
At 50% Relative Humidity
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Back
Next
Type here to search
4:41 PM
1/17/2022

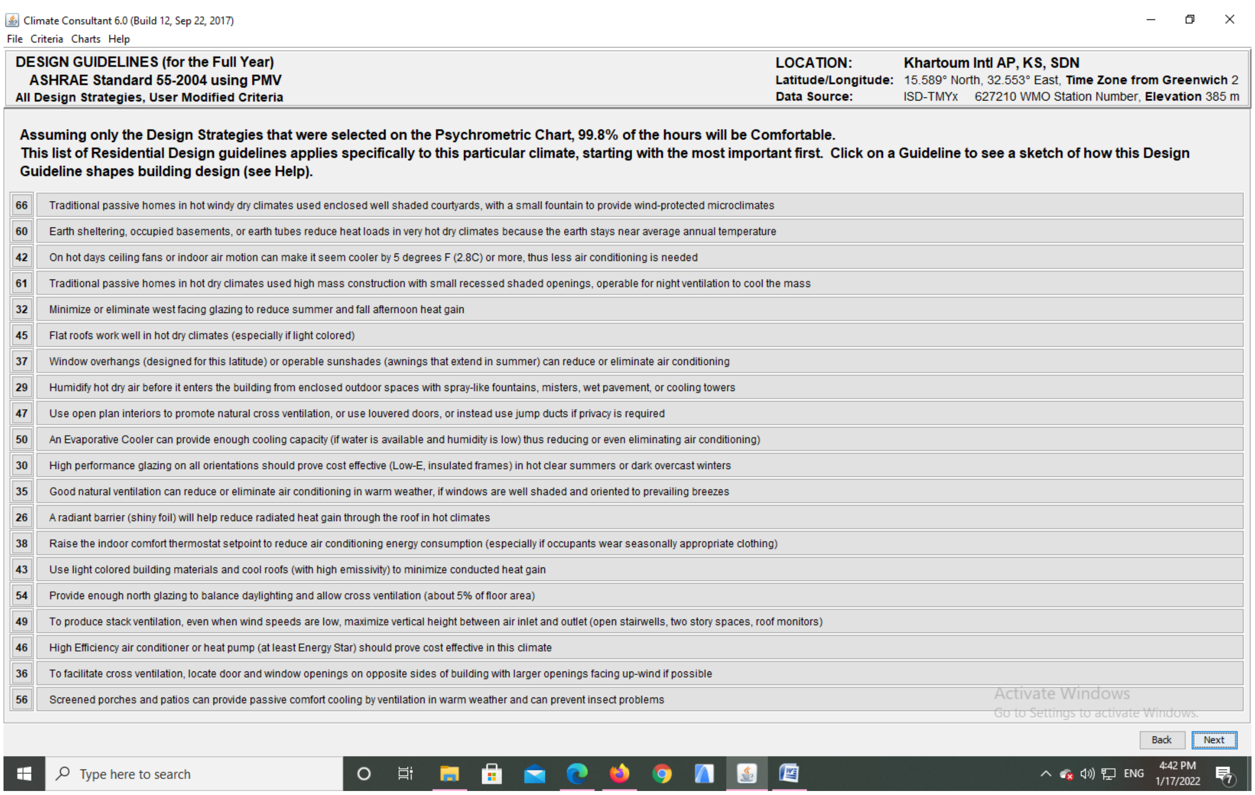

Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
DRY BULB X DEW POINT
ASHRAE Standard 55-2004 using PMV
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
Dry Bulb
Dew Point
Comfort Zone
Summer
Winter
At 50% Relative Humidity
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Back
Next


Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
SUN SHADING CHART
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
1860 Hours Exposed
0 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
472 Hours Exposed
0 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
162 Hours Exposed
0 Hours Shaded
MAR
Noon
DEC
ALTITUDE ANGLE
BEARING ANGLE
EAST
SOUTH
WEST
PLOT MONTHS:
WINTER SPRING
December 21 to June 21
SUMMER FALL
June 21 to December 21
Display Grid
Display Shading Calculator
Display Obstruction Elevation
Input Obstructions
Display Opposite Direction
Back
Next


Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
TIMETABLE PLOT
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
DRY BULB TEMP
(degrees C)
0% < 0
7% 0 - 21
20% 21 - 27
63% 27 - 38
10% > 38
Sunrise
Sunset
0 a.m.
2 a.m.
4 a.m.
6 a.m.
8 a.m.
10 a.m.
12 noon
2 p.m.
4 p.m.
6 p.m.
8 p.m.
10 p.m.
12 p.m.
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
PLOT:
DRY BULB TEMP
Monthly Avg
Daily
Activate Windows
Go to Settings to activate Windows.
Select colored squares on LEGEND to change plot colors (see Help).
Back
Next
Type here to search
ENG
4:41 PM
1/17/2022


Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
3D CHARTS
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
DRY BULB TEMP
(degrees C)
0% < 0
6% 0 - 21
17% 21 - 27
70% 27 - 38
7% > 38
40.85
18.44
0.00
NOV
SEP
JUL
MAY
MAR
JAN
Midnight
6 PM
Noon
6 AM
PLOT: Not Shaded Shaded
DRY BULB TEMP
Monthly Avg
Daily
Activate Windows
Go to Settings to activate Windows.
Drag mouse to rotate graph. Select colored squares on LEGEND to change plot colors (see Help).
Back
Next
Type here to search
ENG
4:42 PM
1/17/2022





Climate Consultant 6.0 (Build 12, Sep 22, 2017)

File Criteria Charts Help

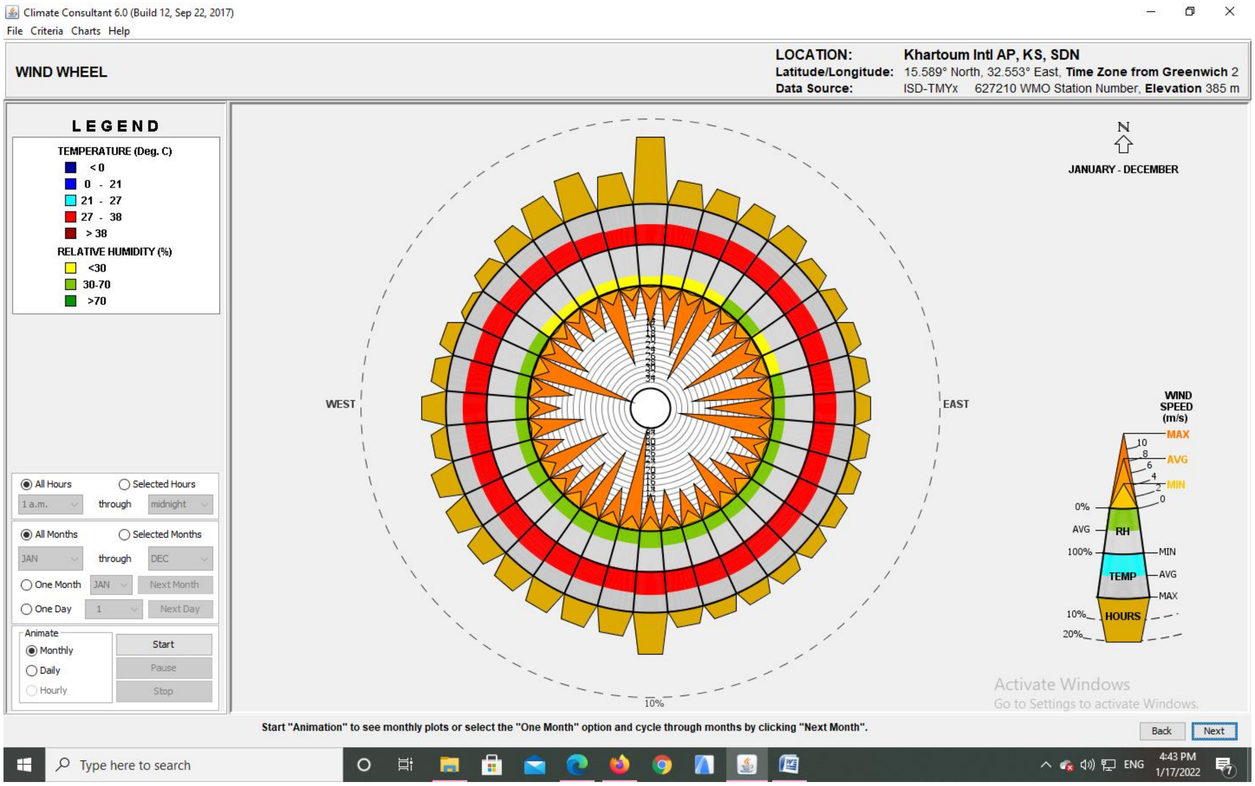
DESIGN GUIDELINES (for the Full Year)
ASHRAE Standard 55-2004 using PMV
All Design Strategies, User Modified Criteria

LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, **Time Zone from Greenwich** 2
Data Source: ISD-TMYx 627210 WMO Station Number, **Elevation** 385 m

Assuming only the Design Strategies that were selected on the Psychrometric Chart, 99.8% of the hours will be Comfortable.
This list of Residential Design guidelines applies specifically to this particular climate, starting with the most important first. Click on a Guideline to see a sketch of how this Design Guideline shapes building design (see Help).

66	Traditional passive homes in hot windy dry climates used enclosed well shaded courtyards, with a small fountain to provide wind-protected microclimates
60	Earth sheltering, occupied basements, or earth tubes reduce heat loads in very hot dry climates because the earth stays near average annual temperature
42	On hot days ceiling fans or indoor air motion can make it seem cooler by 5 degrees F (2.8C) or more, thus less air conditioning is needed
61	Traditional passive homes in hot dry climates used high mass construction with small recessed shaded openings, operable for night ventilation to cool the mass
32	Minimize or eliminate west facing glazing to reduce summer and fall afternoon heat gain
45	Flat roofs work well in hot dry climates (especially if light colored)
37	Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning
29	Humidify hot dry air before it enters the building from enclosed outdoor spaces with spray-like fountains, misters, wet pavement, or cooling towers
47	Use open plan interiors to promote natural cross ventilation, or use louvered doors, or instead use jump ducts if privacy is required
50	An Evaporative Cooler can provide enough cooling capacity (if water is available and humidity is low) thus reducing or even eliminating air conditioning)
30	High performance glazing on all orientations should prove cost effective (Low-E, insulated frames) in hot clear summers or dark overcast winters
35	Good natural ventilation can reduce or eliminate air conditioning in warm weather, if windows are well shaded and oriented to prevailing breezes
26	A radiant barrier (shiny foil) will help reduce radiated heat gain through the roof in hot climates
38	Raise the indoor comfort thermostat setpoint to reduce air conditioning energy consumption (especially if occupants wear seasonally appropriate clothing)
43	Use light colored building materials and cool roofs (with high emissivity) to minimize conducted heat gain
54	Provide enough north glazing to balance daylighting and allow cross ventilation (about 5% of floor area)
49	To produce stack ventilation, even when wind speeds are low, maximize vertical height between air inlet and outlet (open stairwells, two story spaces, roof monitors)
46	High Efficiency air conditioner or heat pump (at least Energy Star) should prove cost effective in this climate
36	To facilitate cross ventilation, locate door and window openings on opposite sides of building with larger openings facing up-wind if possible
56	Screened porches and patios can provide passive comfort cooling by ventilation in warm weather and can prevent insect problems

Back Next



Climate Consultant 6.0 (Build 12, Sep 22, 2017)
File Criteria Charts Help
WIND WHEEL
LOCATION: Khartoum Intl AP, KS, SDN
Latitude/Longitude: 15.589° North, 32.553° East, Time Zone from Greenwich 2
Data Source: ISD-TMYx 627210 WMO Station Number, Elevation 385 m
LEGEND
TEMPERATURE (Deg. C)
< 0
0 - 21
21 - 27
27 - 38
> 38
RELATIVE HUMIDITY (%)
<30
30-70
>70
All Hours
Selected Hours
1 a.m. through midnight
All Months
Selected Months
JAN through DEC
One Month JAN Next Month
One Day 1 Next Day
Animate
Monthly
Daily
Hourly
Start
Pause
Stop
N
JANUARY - DECEMBER
WEST
EAST
10%
WIND SPEED (m/s)
MAX
AVG
MIN
10
8
6
4
2
0
0%
AVG
100%
RH
MIN
TEMP
AVG
MAX
10%
20%
HOURS
Activate Windows
Go to Settings to activate Windows.
Start "Animation" to see monthly plots or select the "One Month" option and cycle through months by clicking "Next Month".
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Next
Type here to search
ENG
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1/17/2022