

**AN INVESTIGATION OF ENERGY AND THERMAL  
PERFORMANCE OF A DOUBLE SKIN FAÇADE (DSF) FOR  
A TYPICAL OFFICE BUILDING IN KSA**

BY

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A Thesis Presented to the  
DEANSHIP OF GRADUATE STUDIES

**KING FAHD UNIVERSITY OF PETROLEUM & MINERALS**

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the  
Requirements for the Degree of

**MASTER OF SCIENCE**

In

**ARCHITECTURAL ENGINEERING**

**APRIL, 2020**

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

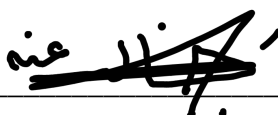
**DEANSHIP OF GRADUATE STUDIES**

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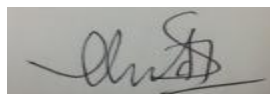
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Dedicated to  
My family for the love, support, and encouragement through the years

## **ACKNOWLEDGMENTS**

In the Name of Allah, the Most Beneficent, the Most Merciful. All the praises and thanks be to Allah, who blessed me and gave me the power to achieve success. Also, I wish to thank King Fahd University of Petroleum and Minerals, and all of its members who helped me and gave me the chance and support to finish this study.

I would also like to express my deepest appreciation toward my thesis advisor Dr. Daeung Kim for all of his guidance and support. Likewise, for all the committee members, including Dr. Muhammad Asif and Dr. Omar Asfour, for all the knowledge and all of the useful comments they shared in this study. Eventually, I am extremely thankful to my father, my mother, and all of my family for their support and encouragement.

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## **LIST OF ABBREVIATIONS**

|        |   |                                                        |
|--------|---|--------------------------------------------------------|
| DSF    | : | Double-Skin Façade                                     |
| IES VE | : | Integrated Environmental Solutions Virtual Environment |
| CFD    | : | Computational Fluid Dynamics                           |
| Daysim | : | Daylighting Simulation                                 |
| SEC    | : | Saudi Electricity Company                              |
| BBRI   | : | Belgian Building Research Institute                    |
| SSF    | : | Single-Skin Façade                                     |

## **ABSTRACT**

Full Name : Mostafa Mohammed Al-Qadoor  
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Façade (DSF) for a Typical Office Building in KSA  
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Date of Degree : May 2020

DSF applications are considered as a valuable solution in reducing energy consumption, although the climatic conditions can hugely influence the performance of . In cold countries such as in Europe, DSFs are mainly used due to maximizing solar gain, which plays a vital role in its performance. However, this study aims to find and define the optimum design characteristics of DSFs for office buildings under the climatic conditions of Saudi Arabia concerning thermal comfort and the reduction in annual energy consumption. For the purpose of this study, an existing office building was selected and modeled using IES VE simulation software, and an investigation of the factors that might influence the overall performance of DSFs was conducted. Results revealed that airflow inside the air cavity is found to be an essential aspect of DSFs design. Also, using a higher efficiency glazing element will help in reducing the annual energy consumption of the building. The optimum design characteristics for the climatic conditions of Saudi Arabia, which will help in reducing the heat gain and lowering energy consumption, were also discussed in this study.

## ملخص الرسالة

الاسم الكامل: مصطفى محمد القدور

عنوان الرسالة : بحث عن الأداء الحراري في الواجهات المزدوجة ومساعدتها في خفض الاستهلاك السنوي للطاقة في المباني المكتبية في المملكة العربية السعودية

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: ١٤٤١ هجري

تعتبر تطبيقات الواجهات المزدوجة حلاً قيماً في تقليل استهلاك المبنى للطاقة ، وتعد الظروف المناخية من أكثر العوامل تأثيراً على أداء الواجهات المزدوجة. في البلدان الباردة مثل أوروبا ، يتم استخدام الواجهات المزدوجة بشكل كبير وذلك لزيادة الطاقة الحرارية المكتسبة من الطاقة الشمسية والتي تلعب دوراً أساسياً في تخفيض استهلاك الطاقة في المبنى في المناخات الباردة. تهدف هذه الدراسة إلى إيجاد وتحديد خصائص التصميم المثلى للواجهات المزدوجة للمباني المكتبية في ظل الظروف المناخية للمملكة العربية السعودية بما يتعلق بتخفيض استهلاك الطاقة في المبنى وتوفير الراحة. للوصول الى غرض هذه الدراسة، تم اختيار مبنى مكتبي موجود في منطقة الظهران وتمت محاكاته باستخدام برنامج IES VE. وخلال هذه الدراسة تم اجراء اختبارات باستخدام برنامج المحاكاة على العوامل التي قد تؤثر على الأداء العام للواجهات المزدوجة. أوضحت نتائج الدراسة أن تدفق الهواء داخل التجويف الموجود في الواجهات المزدوجة يعد عاملاً أساسياً في التأثير على فعاليتها ويعد جانباً أساسياً في تصميم الواجهات المزدوجة. أيضاً ، أوضحت النتائج أن استخدام عناصر زجاجية ذات كفاءة عالية ستساعد في خفض الاستهلاك السنوي للطاقة في المبنى. كما تم مناقشة الخصائص المثلى للتصميم في ظل الظروف المناخية للمملكة العربية السعودية ، والتي ستساعد في الحد من اكتساب المبنى للحرارة وخفض الاستهلاك السنوي للطاقة في المبنى.

# **CHAPTER 1**

## **INTRODUCTION**

Nowadays, the focus towards reducing the energy consumption in buildings has become an important topic, and it is drawing more attention as the construction sector developing, whereas more high-rise buildings are being constructed. As in the modern days, the most desired attributes of buildings are lightness and transparency; this trend has been adopted by both architects and buildings designers (Colombo 2017). This type of pattern in buildings construction has led toward implementing a higher ratio of glazing elements in newly constructed buildings, especially office buildings. Therefore, a higher amount of energy will be consumed to maintain thermal comfort for internal spaces (Hien 2005). On the other hand, studies illustrate that 40-45% of buildings' total thermal load is transmitted through the envelope of the building; these percentages are depending on the amount of glazed areas (Hamza 2008). Therefore, the building's façade design is directly related to its ability to reduce the energy consumption in the building while maintaining thermal comfort for the building users (Alberto 2017). Therefore, to try and solve the concerns related to building efficiency and reduce the consumption of energy in buildings, an innovative solution called DSF arose in the construction world. This solution has been presented in the early years of the 20th century as a possible alternative to the traditional glazed facades to improve the building's thermal performance (Alberto 2017).

Architectures and building designers are adopting a DSF in the newly constructed buildings, especially high-raised buildings due to its “visual and aesthetic quality enhancement” and its capability of saving energy (Ghaffarianhoseini 2016). DSF could cover one part of the building façade or the whole façade, which sometimes will result in a fully glazed façade. DSF can help in maintaining thermal comfort and energy efficiency for the building as well as improving the

daylighting and indoor environment (Elarga 2015). Moreover, DSF acts like an envelope for the building, which consists of two layers of inner and outer glazed layer separated by an air cavity (Su, Ziyi 2017). The air cavity could be ventilated naturally or by using mechanical equipment. Since its located between the two transparent layers, it acts as an insulation barrier to prevent unwanted climatic impacts (Shameri 2011). However, the most common method used to ventilate DSF is natural ventilation which can be done by openings on the outer layer of DSF to allow air circulation, this method is easy to control, to operate and it can help in saving energy (Su, Ziyi 2017).

Compared to the single façade, buildings with DSF can be more sensitive to the outdoor climatic conditions owing to the larger glazed surfaces, due to this higher sensitivity a more comprehensive investigation on “transparency, solar gain, glare, daylight, view to the outside, ventilation and control strategy, heat loss, noise, and weather protection” is required (Hendriksen 2000). Furthermore, studies showed that DSF could preserve more heat in the wintertime, which will help in reducing heating loads also, it can help in lowering the internal heat gain in the summertime through optimizing air ventilation in the space between the two layers (Gratia 2007; Ghaffarianhoseini 2016).

Considering that DSFs were developed mainly for cold climatic conditions, most of the researchers consider cold and moderate climatic conditions for their works. On the other hand, works investigating the use of a DSF and their thermal performance in hot climates are limited, and most of them are based on simulation software. For instance, in 2009, Zhou carried out a study to investigate the effect of a DSF in the hot summer season of china. Zhou concluded that the DSF could be adapted as a solution even in the warm climates if the ventilation for the air cavity in the DSF was well designed. Also, in 2009 Chan investigated the effect of a DSF on the energy

performance of an office building located in Hong Kong. By using energy plus simulation software, Chan reported that saving around 26 % of the energy consumed due to cooling load annually can be saved comparing with a single-skin façade. Many researchers believe that with the proper design and ventilation, DSF can help in reducing the energy consumption due to cooling load in hot climates (Haase 2006; Zomorodian 2018; Hashemi 2010).

In the case of Saudi Arabia, which is generally classified as a hot climatic region, the building's façade becomes more critical as an energy consumption control element. The highest share of energy consumption in buildings in Saudi Arabia is due to HVAC systems, as it may consume around 60 % of the total energy (Al Rabghi 2004). In a recent report published by the Saudi Electricity Company (SEC), the percentage of the energy required for cooling has increased up to 70 % of the energy consumed in buildings (SEC 2014). Also, the studies showed that the building façade is responsible for transmitting around 40-45 % of the total thermal load of the building. Therefore, optimizing the building façade can help in reducing energy consumption significantly (Hamza 2008). Nowadays, buildings facades draw much attention in Saudi Arabia due to the growing number of newly constructed buildings to save more energy by adopting new façade strategies (Almaziad 2014).

Consequently, it is crucial to investigate the effect of using a DSF in buildings located in Saudi Arabia since studies showed that it could help in reducing the cooling load and thus reducing the energy consumption for the building (Larsen 2015; Zomorodian 2018). Therefore, in this study, IESVE simulation software will be used to investigate the effect of the DSF on thermal comfort and energy consumption of an office building located in Saudi Arabia. Energy performances of various alternatives of the DSF are analyzed to establish the optimum design characteristics for office buildings under the climatic conditions of Saudi Arabia. However, the outcomes of the

simulated building will be used as a base guideline for developing the design of a DSF in the climatic conditions of Saudi Arabia.

## **1.2 Goal**

This study aims toward finding and defining the optimum design characteristics of a DSF for office buildings under the climatic conditions of Saudi Arabia with reference to thermal comfort and reducing energy consumption.

## **1.3 Objectives**

To achieve the goal of this study, the following objectives will be met in this study:

1. Evaluate building envelope characteristics of office buildings in Saudi Arabia considering local climatic conditions.
2. Assess energy and thermal comfort performance of various design configurations of the DSF.
3. Establish the design guidelines of the DSF for office buildings considering the hot climatic conditions of Saudi Arabia.

## **1.4 Significance of the study:**

The outcomes of this study will redound to the benefits of future studies concerning DSF for better thermal comfort and more energy-efficient office buildings under similar climatic conditions of Saudi Arabia.

## **1.5 Scope and Limitation:**

This study is focusing on the effect that the DSF has on the thermal performance of the building as well as reducing the energy consumption due to cooling load in hot climates of Saudi Arabia. Other parameters or building components will not be changed or optimized and will be kept as its current states. In this study, the office building is located in the eastern province of Saudi Arabia; therefore, the Dhahran city weather data file will be used in the simulation process. The outcomes of the simulation process will be analyzed and will be limited only to the proposed office building, which consists of 10 floors as the base case. A comparative analysis will be conducted regarding different types of glasses, cavity width, and ventilation strategies to choose the best-case scenario.

## **1.6 Research Methodology:**

Defining and developing the optimum designing characteristics of the DSF for the proposed office building located in the Dhahran region is considered to be the primary goal of this study. Therefore, to achieve the goal of this research, three objectives need to be followed and fulfilled. For that purpose, the methodology of this study will be categorized into three main phases as described below:

### **1.6.1 Phase 1: Comprehensive Literature Review:**

In this phase of the methodology, a comprehensive review of related literature concerning the DSF will be conducted to obtain a clear understanding of the DSF. Information such as definitions, classifications, and design parameters will be collected and gathered from previous works regarding the DSF and will be discussed in this stage. Moreover, Various types and configurations of the DSF will be Identified, and their characteristics such as potential energy saving, thermal comfort, and area of application. Also, information on the performance of a DSF in Different

climatic conditions will be gathered mainly in hot climatic conditions similar to the climate of the proposed region in this research.

### **1.6.2 Phase 2: Modelling and Simulation of the Building:**

3D modeling of a 10-story office building using Integrated Environmental Solutions (IES VE) will be constructed considering hot climatic conditions for this research. After modeling the base case, different parameters such as cavity width, cavity depth, cavity height, various types of glazing materials, and different types of ventilation used in a DSF will be investigated. Integrated Environmental Solutions (IES VE) software will be used in this study, which is a useful design tool that helps in modeling and analyzing the building performance considering various options and outcomes. Therefore, the model of the building will be constructed using Integrated Environmental Solutions (IES VE) software to investigate different design options of the DSF. After running the simulation, a comparison between various design options of DSF energy performance and their impact on the building performance will be conducted.

### **1.6.3 Phase 3: Analysis and Discussion of the Results:**

After simulating all DSF design options, a detailed energy analysis will be made to select the most energy-efficient option. Also, in this stage, a cost-effective analysis regarding the design options will be conducted to choose the best-case scenario taking into consideration both energy performance and cost aspect. The results of this study will be used as an indicator of whether that DSF can be used in building with similar climatic conditions of the proposed building in this study. Also, a set of design guidelines for a DSF will be developed for a more comfortable indoor environment and more energy-efficient office buildings regarding the climatic conditions of Saudi Arabia.

## **CHAPTER 2**

### **LITERATURE REVIEWS**

#### **2.1 Theoretical Background:**

In recent projects, architects and designers tend to use high glazing facades, especially in commercial buildings owing to their low weight characteristics, higher daylighting possibility, and enhanced aesthetics (Ghaffarianhoseini 2016). However, most of the glasses used around the world were the single-layer glass; these types of glazing elements have significant weaknesses such as low thermal insulation and poor sound isolation (Jiru 2011; Ghaffarianhoseini 2016). Therefore, a DSF has been presented as a solution to overcome most of these problems, and it has been widely used due to its high energy savings potentials (Su, Ziyi 2017; Zomorodian 2018). Integrating the DSF in the building design could be beneficial in terms of energy savings and improving the thermal comfort for the users. Also, it has some drawbacks that should be taken into considerations (Alberto 2017).

The first use of a DSF in buildings goes back to 1903, a toy factory in Germany was designed by Richard Steiff. When he installed a curtain wall consisting of two layers of glass separated by an air cavity considering the cold weather and for enhancing the daylighting in the factory (Kalyanova 2008; Ghaffarianhoseini 2016). After that, in the year of 1904, Otto Wagner designed a double skin skylight when he was chosen to be the winner in a designing competition to design the Post Office Savings Bank in Austria (Kalyanova 2008). Even that DSF was mainly applied in European countries, the idea of using a DSF became more popular in both North American and Asian countries (Yellamraju 2004).

However, many authors define DSF in various terms the following table 1 briefly shows some of the different DSF definitions:

Table 1DSF definitions

| Author                    | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (BBRI 2002)               | <i>“An active façade is a façade covering one or several stories constructed with multiple glazed skins. The skins can be air tighten or not. In this kind of façade, the air cavity situated between the skins is naturally or mechanically ventilated. The air cavity ventilation strategy may vary with the time. Devices and systems are generally integrated in order to improve the indoor climate with active or passive techniques. Most of the time such systems are managed in semi-automatic way via control systems”</i> |
| Harrison and Boake (2003) | <i>“essentially a pair of glass skins separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbers of permutations and combinations of both solid and diaphanous membranes”</i>                                                                                                      |
| Arons (2001)              | <i>“a façade that consists of two distinct planar elements that allows interior or exterior air to move through the system. This is sometimes referred to as a twin skin”</i>                                                                                                                                                                                                                                                                                                                                                        |

|                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Safer N (2005)</i>  | <i>“Double-skin façade is a special type of envelope, where a second (skin), usually a transparent glazing, is placed in front of a regular building façade”</i>                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <i>Compagno (2002)</i> | <i>“an arrangement with a glass skin in front of the actual building façade. Solar control devices are placed in the cavity between these two skins, which protects them from the influences of the weather and air pollution a factor of particular importance in high rise buildings or ones situated in the vicinity of busy roads”</i>                                                                                                                                                                                                                                                                |
| <i>Uttu (2001)</i>     | <i>“ a pair of glass skins separated by an air corridor (also called cavity or intermediate space) ranging in width from 20 cm to several meters. The glass skins may stretch over an entire structure or a portion of it. The main layer of glass, usually insulating, serves as part of a conventional structural wall or a curtain wall, while the additional layer, usually single glazing, is placed either in front of or behind the main glazing. The layers make the air space between them work to the building’s advantage primarily as insulation against temperature extremes and sound ”</i> |

## 2.2 Classification of DSF:

After conducting a literature review about the categorization of a DSF, many authors classified DSF into different classifications depending on many factors.



Figure 1 (Weill Cornell's Belfer Research Building) DSF example

, such as the construction of DSF, strategies of airflow in the space of DSF, airflow source, and compartmentalization of the intermediate space of DSF. According to Magali in his study published in 2001, Magali categorized the DSF into:

- 1) DSF covering more than one floor.
- 2) Per level DSF.

Magali stated that the difference between the two categories is that there is a partition fixed horizontally in the intermediate space per floor. Also, Magali divided them into four subcategories regarding airtightness of DSFs such as:

1. DSF covering more than one floor: is being divided into four subcategories:
  - a) The whole DSF is airtight.

- b) The outer part of the DSF is airtight, and the internal part is not airtight.
  - c) The internal part of the DSF is airtight, and the outer part is not airtight.
  - d) The whole DSF is not airtight.
2. Per floor DSF is being divided into four subcategories:
- a) The whole DSF is airtight.
  - b) The outer part of the DSF is airtight, and the internal part is not airtight.
  - c) The internal part of the DSF is airtight, and the outer part is not airtight.
  - d) The whole DSF is not airtight.

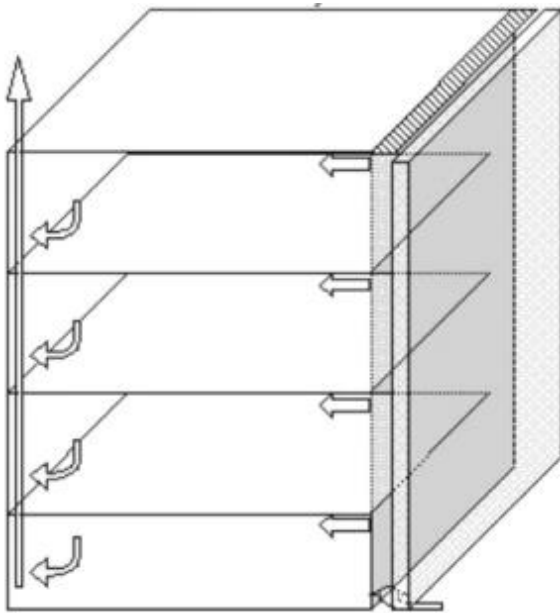


Figure 2 (Ghaffarianhoseini 2016) Double-skin façade covering more than one floor

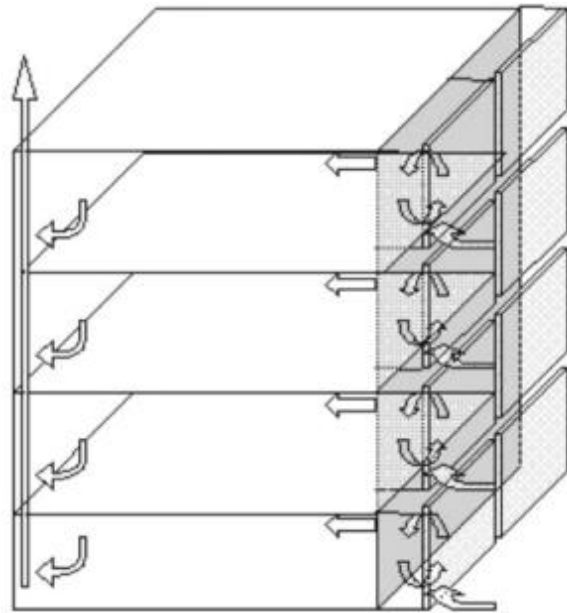


Figure 3 (Ghaffarianhoseini 2016) Double-skin façade per floor

Also, according to Battle McCarthy DSFs could be divided into five main categories depending on the configuration of the DSF and type of the ventilation system (Poirazis 2004; Yellamraju 2004; Ahmed 2016):

a) Closed Internal layer:

1. Mechanical ventilation for intermediate space.
2. Ventilated and serviced thermal flue.

b) Openable internal and external layers:

1. One-story height air cavity.
2. The air cavity covers the height of the entire building.

c) Openable internal layer: Mechanical ventilation with controllable outlet.

d) Closed air cavity:

1. For each floor.
2. Covers height of the entire building.

e) Sound wall:

1. Huge external cover.
2. Lightweight external cover.

On the other hand, according to Yazdizad in 2014, DSFs can be classified into three main categories depending on the type of ventilation used in the air cavity of the DSF. However, Yazdizad, in his study, stated that the ventilation could be natural ventilation or mechanical ventilation by using fans or other equipment; therefore, he divided them into:

1) Naturally ventilated: In this type of DSF, air flows according to the stack effect, which means that hot air will flow upward and will be replaced with cold air, as figure 5 illustrates.

2) Mechanically ventilated: In this type of DSF, air flows with the help of mechanical forces such as fans or other equipment, as figure 4 illustrates.

3) Mixed ventilated: This type is used when natural ventilation is not enough, then using mechanical equipment to make sure that space is appropriately ventilated.

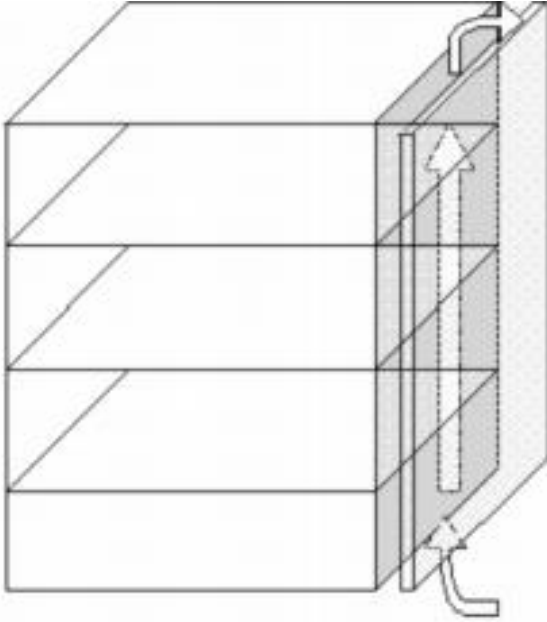


Figure 5 (Ghaffarianhoseini 2016)  
Natural ventilation

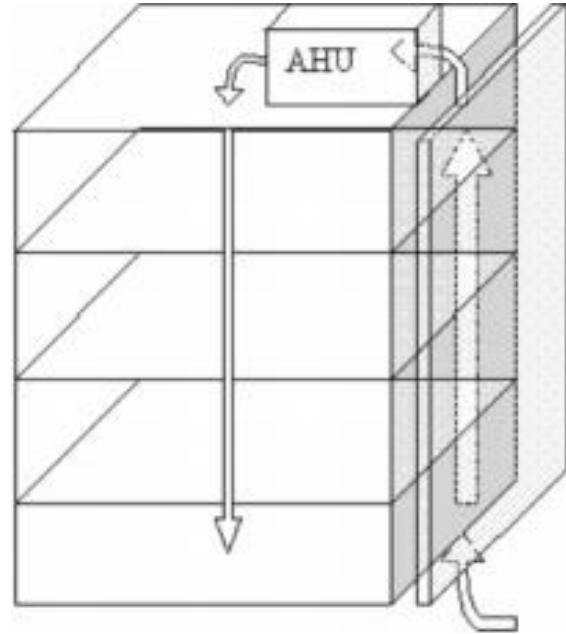


Figure 4 (Ghaffarianhoseini 2016)  
Mechanical ventilation

### 2.3 DSF design parameters

DSF components such as the intermediate space depth, materials of glazing layers, DSF structure, and DSF opening size have a considerable influence on the thermal performance of the building (Barbosa 2014). Barbosa, in his study in 2015, identified the design parameters of DSF as following:

Table 2 DSF design parameters

| Parameter               | Review                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Air Cavity depth        | <ul style="list-style-type: none"> <li>• Careful and proper design of the air cavity in a DSF can help in reducing energy consumption substantially (Barbosa 2014).</li> <li>• If the air cavity is not appropriately designed, this will lead to more energy consumption and an uncomfortable indoor environment (Rundle 2011).</li> <li>• Different design concept regarding the depth of the air cavity has been developed such as various depths of the air cavity, providing enough space for shading devices and providing accessible space for maintenance work (Pappas 2008).</li> <li>• Narrow air cavity is favored in the building, which uses air conditioning due to the stack effect that will help in reducing the heat transferred into the building, thus reducing energy consumption (Barbosa 2015).</li> </ul> |
| External layer material | <ul style="list-style-type: none"> <li>• Selecting the proper glazing material for the DSF external layer will help in reducing the energy consumption as well as providing a more comfortable indoor environment (Perez-Grande 2005; Manz 2014).</li> <li>• In the designing of a DSF, using a single glazed material for the external layer and double-glazed material for the internal layer is a common practice (Barbosa 2014).</li> <li>• In a naturally ventilated DSF using of single glazed material for the external layer will help in increasing the buoyancy effect by increasing the heat gain in the cavity (Perez-Grande 2005).</li> </ul>                                                                                                                                                                        |

|                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Structure of DSF | <ul style="list-style-type: none"> <li>• Structure or form of DSF can be divided into two main categories: 1- cover floor by floor 2- cover the whole building (Magali 2001).</li> <li>• The air cavity height has a significant influence on DSF performance, owing to its impact on the buoyancy effect.</li> <li>• According to previous studies, the air cavity that covers the whole building will help in saving more energy due to the increase in air ventilation and stack effect (Torres 2007; Rahmani 2012).</li> </ul> |
| Openings         | <ul style="list-style-type: none"> <li>• Airflow will be affected by the opening size, the bigger the opening, the more airflow will occur in the cavity (Barbosa 2015).</li> <li>• Bigger opening size at the upper part of the DSF will help in extract warm air from the air cavity (Rahmani 2012).</li> </ul>                                                                                                                                                                                                                  |

## 2.4 Previous studies:

In recent years, many works have discussed DSFs, and many researchers had investigated it, which contributed toward a better understanding. Many of the published papers and studies have been talking DSFs and how to implement it in new or renovated buildings and what design guidelines to follow. In 2016 Sanchez, conducted a comparative study to compare the conventional façade system (single-skin) with the DSF. Sanchez's goal was to design a more practical configuration for a DSF that may help in saving more energy as well as maintaining the thermal comfort level for the building users. He used in his study ANSYS Fluent software to investigate the effects of DSF in both summer and winter season with taking into consideration the impact of ventilation for the intermediate air space. The result of his study showed that in the winter season, ventilation is not preferable and will lead to more energy consumption. Therefore, vents should be kept closed on

the other hand, in summer he concluded that ventilation is an essential factor and will help to reduce the building's energy load; therefore, the vents should open.

Moreover, in 2005 Perez-Grande investigated the effect of a DSF with various glass properties, the results showed that a proper selection of the glazed layers that form the DSF would help in reducing the thermal load of the building. Also, in 2014 Manz investigated the effect of various glazing materials of the total solar energy transmitted to the building through a DSF by using a CFD simulation. The finding of the study demonstrated that the heat transferred through the glazing façade could be reduced by 2%, and the total solar energy transmitted can be reduced by 10 % when selecting the proper glass type.

After selecting the proper and suitable type of materials for glass layers of a DSF, selecting the ventilation type for the air cavity is advisable. According to Fallahi in 2010, he investigated the DSF's overall performance by using simulation software to assess the overall performance of the DSF. The result illustrated that using mechanical ventilation for the DSF could help in saving energy and decreasing the consumption of the building in summer from 21% - 26% and in winter from 41%-59%. Also, Hashemi in 2010 investigated the thermal behavior of a DSF for a building in a hot arid climate by monitoring the building for two weeks and by using simulation software. The result of Hashemi's study showed that the DSF could help in lowering the cooling load with the proper ventilation design of the air cavity as well as using other methods such as night ventilation. Another study carried out by Nasrollahi in 2015, which was concerning the performance of a DSF in a building and how efficiently it can function under hot and dry climatic conditions. By using Computational Fluid Dynamics (CFD) software, Nasrollahi found that a DSF could be used in hot climatic conditions by increasing the velocity of airflow in the intermediate space of the DSF.

In recent years many studies have been considering DSF as a valuable option even for hot climatic conditions, and many researchers started to investigate the effect of adopting such strategy in buildings. For instance, Zomorodian, in 2018, analyzed the energy consumption of a DSF in a hot and dry climate for an office building located in Tehran, Iran. Zomorodian's goal was to find the optimum design configuration by the use of simulation software. Zomorodian stated that around 14.8 % of energy consumption could be saved by implementing a DSF. Also, in 2008 Hamza conducted a comparative study concerning the cooling load by comparing the SSF with various configurations of DSF hot arid climates. By using a simulation software called integrated environmental solutions IESVE, the result showed that around 30 % reduction in cooling load could be achieved with a DSF. Larsen carried out a study in 2015 regarding the DSF considering the Mediterranean climatic conditions for a building located in Argentina during summer and spring seasons. However, the study results showed that a well-designed DSF would help in saving energy even during sunny climates.

On more recent studies, Abdultawab, in 2019, in his paper studied the efficiency of DSF in controlling heat gain under the climatic conditions of Malaysia. Depending on the result of his study Abdultawab stated that the DSF was proven to be effective in controlling the heat gain from the building façade. Another study conducted by Yoon (2019) when he studied DSF system thermal performance in a residential building located in Seoul. In his research, Yoon used simulation software to measure the energy savings in the building after adding the DSF. Since the study was conducted in Seoul, which has a dominant heating climate, the main focus was the amount of saving in heating energy. The result showed that around 30 % of heating energy could be saved in residential buildings by installing a DSF system. Kim (2019) investigated the DSF system impact on both thermal performance and daylighting levels in an office building located in

Daejeon, South Korea. In his study, Kim used two simulation software to measure the thermal performance and daylighting level, energy plus software, and Daysim software. In his results, Kim stated that after simulating the building with a DSF system savings of 40% of heating energy, 2% of cooling energy, and 5% of the building's total loads could be achieved. Previous studies showed that there is a potential saving in the energy consumed by the building when implementing DSF.

Moreover, using different types of materials and different design guidelines can result in more savings, or it could lead to a catastrophic situation regarding energy consumption. Little work has been published regarding using a DSF in climate conditions similar to the climatic conditions of Saudi Arabia. Therefore, the current study investigates the DSF performance in an office building located in a hot climatic region of Saudi Arabia. After analyzing different DSF alternatives, and choosing the best possible DSF design scenario, a set of design guidelines will be developed.

## **CHAPTER 3**

### **METHODOLOGY**

The purpose of the present study is to find and define the best designing characteristics for DSF office buildings. Also, taking into consideration the climatic conditions of Saudi Arabia, specifically the Dhahran region concerning thermal comfort and reducing energy consumption. By using simulation software, various types and configurations of a DSF can be studied, and the annual energy consumption can be predicted for each scenario. Therefore, by using IES VE software, the building as it is current state will be modeled and simulated as the base case model taking into consideration different parameters in the proposed building, such as the shape of the building, envelop layers, and their materials. The results which will be taken from this model simulation will be used in the comparison process to choose the best-case scenario from various simulations. Though, different DSF configurations will be applied to the base case model of the proposed building to investigate their impact on the building performance. However, simulation results for different configurations of the DSF will help in determining the optimum selection for variables such as means of ventilation, envelope related aspects, and glazing materials used in both interior and an exterior layer of the DSF. Also, the results will help in showing if using a DSF for an office building in Saudi Arabia will have any energy-saving potentials.

#### **3.1 Description of the proposed office building:**

In order to evaluate the performance of the DSF under the climatic conditions of Saudi Arabia, IESVE software was used to model an office building located in the Dhahran region. The office building will be divided into four perimeter zones (North, East, South, and West) and a central zone (core zone), as shown in figure 6 below.

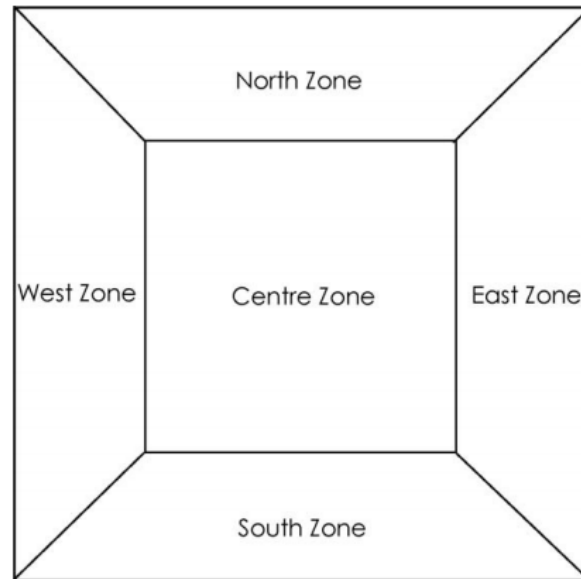


Figure 6 (Chan 2009) Zones of the building

The office building is located in Saudi Arabia in the region of Dhahran, with approximately 6250 square meters floor area and designed with an SSF with around 60% window to wall ratio to provide the best view for occupants as shown in figure 7.

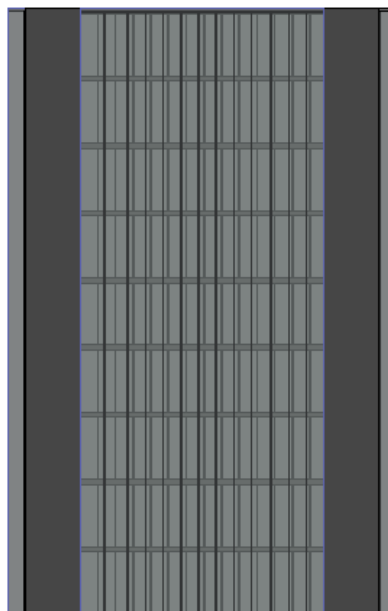


Figure 7 Building elevation

After investigating the reference height for office buildings in Dhahran city through literature review, the outcomes showed that the reference height is around ten floors as following:

Table 3 No. of floors literature review

| <b>Literature</b>                                                                                                                          | <b>No. of floors</b> |
|--------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| <i>“Energy performance and economic viability of nano aerogel glazing and nano vacuum insulation panel in multi-story office building”</i> | 10                   |
| <i>“Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates”</i>             | 11                   |
| <i>“Impact of external shading strategy on energy performance of multi-story hotel building in hot-humid climate”</i>                      | 10                   |
| <i>“Unmanned Aerial Vehicles Application in Building Envelope Thermal Energy Assessment in Saudi Arabia”</i>                               | 13                   |
| <i>“Energy-efficient window design through the integration of daylighting and artificial lighting in office buildings”</i>                 | 10                   |
| <i>“Energy savings due to daylight and artificial lighting integration in office buildings in hot climate”</i>                             | 10                   |
| <i>“An Approach to Select Ideal Window Area in Office Buildings: Modeling and Simulation”</i>                                              | 10                   |

Also, depending on a survey made by (Al-Ashwal 2008), the results showed that the number of floors for an office building in the city of Dhahran is usually in the range of 4-10 floors height. Also, the results showed that the most common shape for the office building envelop in Dhahran city is either rectangular shape (45%) or square shape (40%). Therefore, considering the previous literature, an office building consist of 10 floors is chosen for this research.

However, the floor-to-floor height is 3.8 m, while the height of the glazing material on the outer facade is 3.4 m. The indoor air temperature for the HVAC systems was designed as follows; for heating and cooling, the setpoint temperatures were designed to range between 18-24 °C in summer. For winter season from 21-26 °C for the duration of occupant presence (from 8:00 a.m. to 5:00 p.m.) and the value of setback temperature was 16 °C and 30 °C and the seasonal heating and cooling system CoP is 1.35. The intended building functions for six days a week from 8:00 a.m. to 5:00 p.m., all around the year. Other parameters, such as occupant density for the office zones it was set to 0.120 (person/m<sup>2</sup>). For the central zone (stairway and elevators) 0.110 (person/m<sup>2</sup>) .also for the density of the internal heat gain, it was set to 12 W/m<sup>2</sup> for the workplace equipment and 8 W/m<sup>2</sup> for the lighting equipment.

### **3.2 Building Envelope Information:**

In this part of the research, buildings envelop system will be provided as taken from the building contractor. The information will describe the construction and details of walls, roofs, windows, and floors.

### 3.2.1 Walls:

The building walls system has the following layers from the external to the internal: 1- dense plaster 2- medium weight concrete brick 3- insulation layer 4- medium weight concrete brick 5- lightweight finishing (plaster). Wall total thickness is 280 mm and the U-value for this wall is 0.466 W/m<sup>2</sup> K. the two layers of concrete block in the wall are having the same thickness, on the other hand, the plaster thickness varies. Figure 8 shows a section for the wall with the layers.

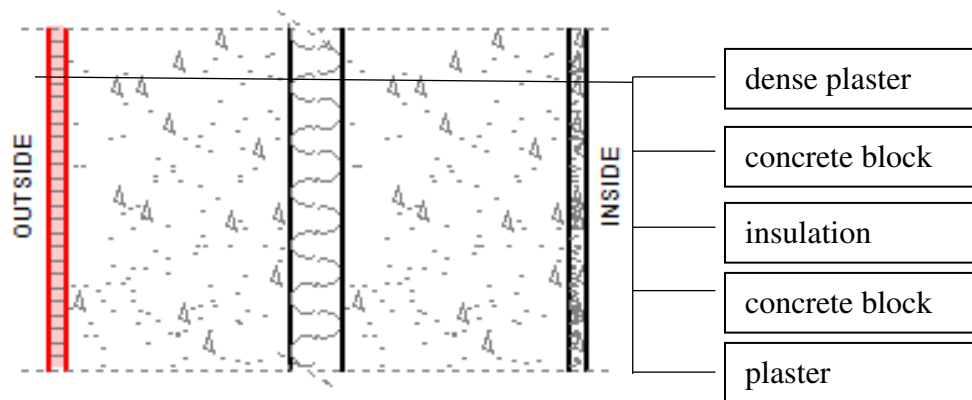


Figure 8 Wall section

### 3.2.2 Roof:

The roof construction for the intended building consists of the following layers from the outer surface to the inner surface: 1- concrete tiles for roof 2- polyethylene (high density) 3- roof insulation layer 4- bitumen layer 5- a layer of cement screed 6- dense concrete (reinforced). The roof thickness is around 400 mm, and the U-value for the roof is equal to 0.540 W/m<sup>2</sup> K, as shown in figure 9.

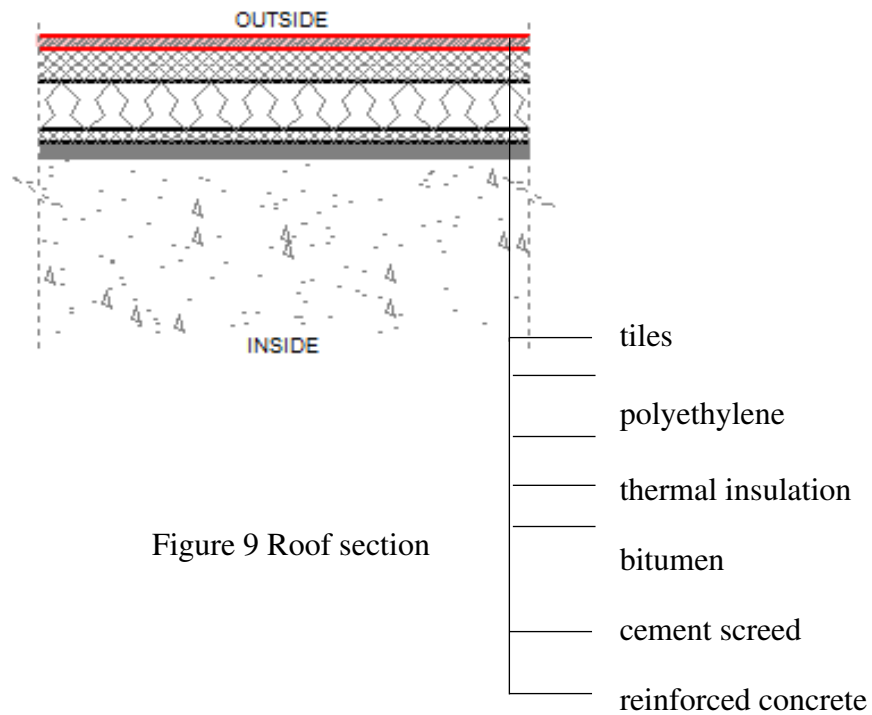


Figure 9 Roof section

### 3.2.3 Windows:

The glazing system of the building consists of a sliding (operable) panel and fixed glass type framed with a frame made of aluminum material without thermal break. These glazed panels consist of double-glazed layers with an air layer in between them. The glazing layers are clear, and their thickness varies; however, the thickness for the glazing is 24 mm, and the U-value equals 2.71 W/m<sup>2</sup> K. figure 10 shows the section for the window system.

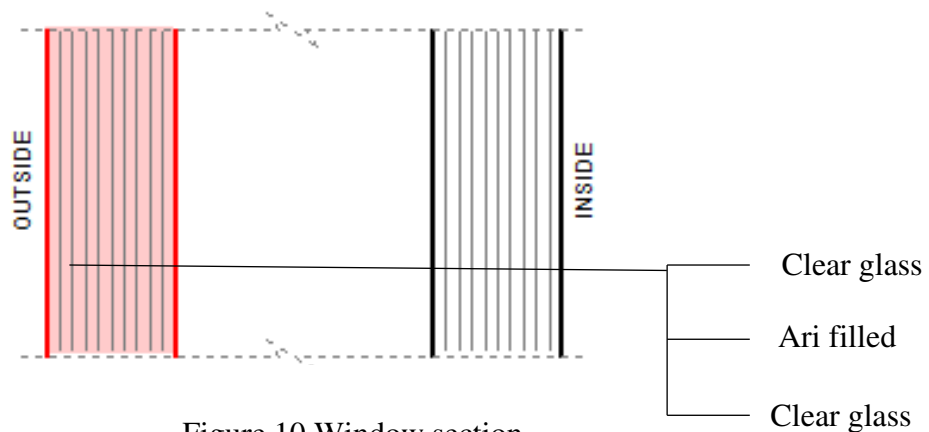
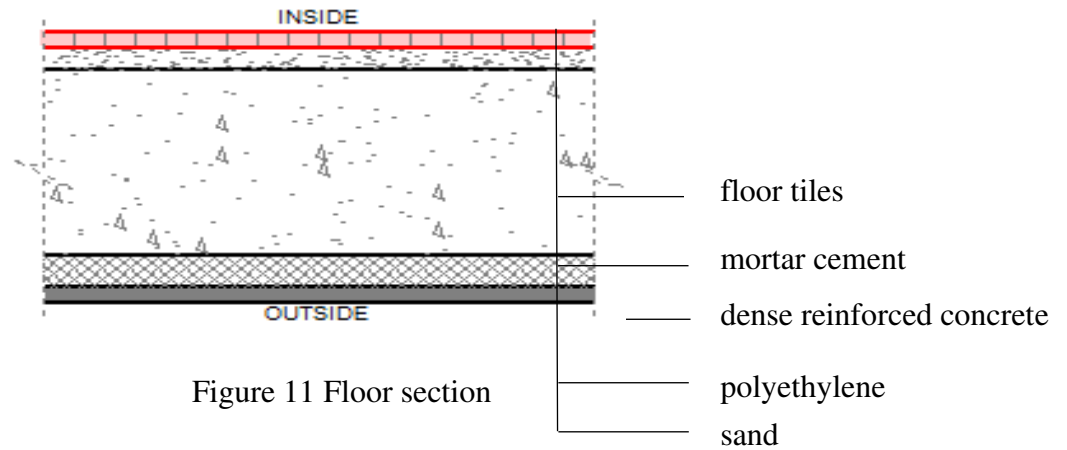


Figure 10 Window section

### 3.2.4 Floor:

The flooring system of the building has the following specifications: 1- floor tiles 2-layer of mortar cement 3- dense reinforced concrete 4- polyethylene (high density) layer 5- a layer of sand with a U-value of 0.842 W/m<sup>2</sup>-K as shown in figure 11.



### 3.2.5 Building Features:

Table 4 Building description and weather parameters

| Characteristics /<br>Specification | Description of the building.                        |
|------------------------------------|-----------------------------------------------------|
| Location                           | Dhahran region 26.27 N latitude, 50.15 E longitude. |
| Orientation                        | North                                               |
| Floor to Floor                     | 3.8m                                                |
| Occupancy Density                  | 0.120 (person/m <sup>2</sup> )                      |

|                  |                                                                                                                                           |
|------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Area             | 6250 m <sup>2</sup>                                                                                                                       |
| WWR              | 60%                                                                                                                                       |
| Weather File and | Dhahran weather data file:2012                                                                                                            |
| RH               | 60% RH                                                                                                                                    |
| Exterior Walls   | Dense plaster+ concrete block + thermal insulation sandwiched + plaster (280 mm)                                                          |
| Roof             | Concrete tiles + high density polyethylene + thermal insulation + bitumen felt/sheet + cement screed + dense reinforced concrete (400 mm) |
| Occupancy        | 0.120 (person/m <sup>2</sup> )                                                                                                            |
| HVAC System Type | Variable air volume (VAV)                                                                                                                 |

### 3.2.6 Technical data of the office building case:

Table 5 Technical data

|                      |                           |
|----------------------|---------------------------|
| <b>Wall</b>          |                           |
| WWR                  | 60 %                      |
| Walls U-value        | 0.466 W/m <sup>2</sup> -K |
| Wall absorptance     | 0.65                      |
| <b>Internal load</b> |                           |
| Equipment load       | 12 W/m <sup>2</sup>       |

|                            |                                    |
|----------------------------|------------------------------------|
| Lighting load              | 8 W/m <sup>2</sup>                 |
| Occupant density           | 0.120 (person/m <sup>2</sup> )     |
| <b>Temperature setting</b> |                                    |
| Inside temperature setting | 18-24 for summer, 21-26 for winter |

### 3.3 Dhahran Climate:

The climatic region of Dhahran is described to be hot and humid in summer seasons and cold in winter seasons, and the coordinates for Dhahran city are 26°16'N as latitude, 50°10'E longitude. The temperature could reach a temperature higher than 50 °C in the summer season, with a high level of humidity range from 85-100 RH percent. However, Dhahran city has one of the highest dew point temperatures with 35 °C recorded in the year of 2003 in July, and the temperature of the air was around 42 °C with a heating index of 78 °C (Gandhidasan 2010). Dhahran city has another record in Saudi Arabia by recording the highest temperature during a rainfall compared to other cities in Saudi Arabia in the period from November until May (ABUBAKAR 2015). However, the dust storm also has its impact on the weather of Dhahran city due to some seasonal wind in the first months of the summer season (ABUBAKAR 2015).

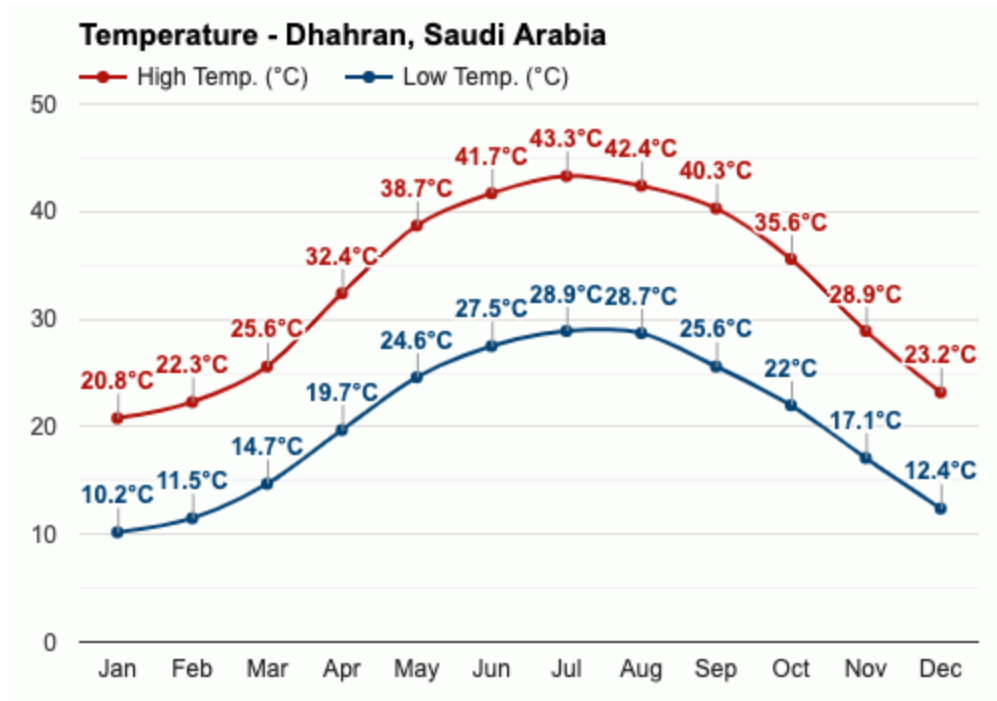


Figure 12 (d.o.o., Yu 2020) Average temperature of Dhahran city, Saudi Arabia

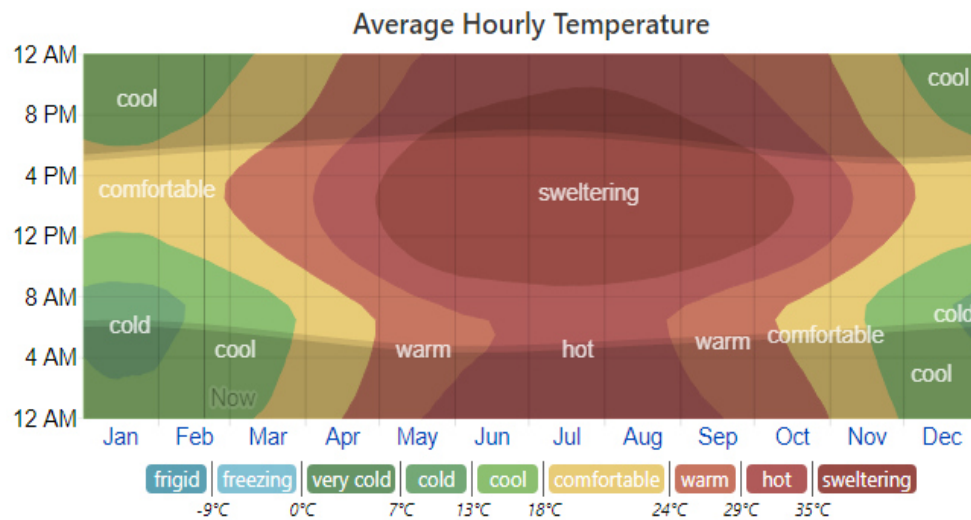


Figure 13 (Weather Spark 2020)The average hourly temperature

### 3.4 Simulation scenarios:

The base model of the proposed building will be tested as to its current state as an SSF building without implementing a DSF system, as shown in figure 14.

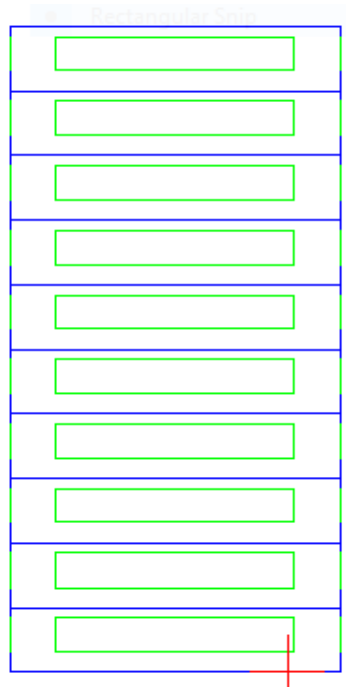


Figure 14 single skin façade (Base case)

However, various configurations of the DSF will be simulated and investigated using IES VE software, as shown in figure 15 below.

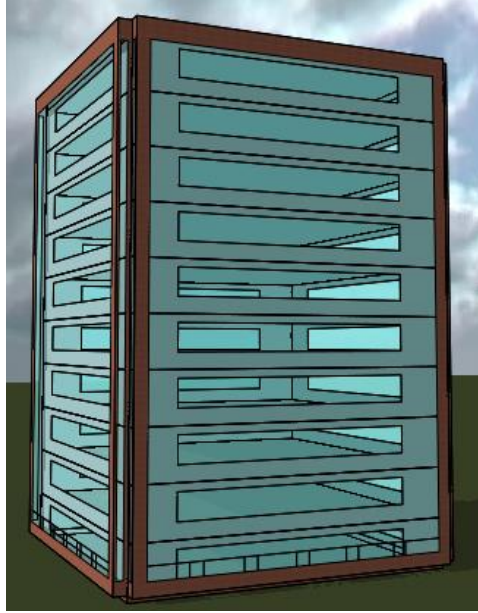


Figure 15 The building with double skin façade

The parameters that will define the various configuration of the DSF will include the effect of DSF geometry, airflow path within the DSF, the width of the air cavity, type of the glazing material of DSF.

### 3.4.1 DSF geometry

Façade geometry has a huge impact on the amount of heat transferred to the inside of the building and on the efficiency of the air cavity ventilation. Therefore, the transmitted solar radiation of facades with geometry such as Corridor or Multi-Storey facades, will show a different effect from other facades such as the Shaft-Box or Box-window types. Moreover, geometries with an extended air cavity that covers more than one floor without horizontal dividers, and due to the stack effect, the airflow inside the cavity will be higher. “The greater the distance, the greater the airflow rate through the cavity” (Alberto 2017). Therefore, for the purpose of this study, the geometry of Multi-Storey facades for a DSF will be investigated.

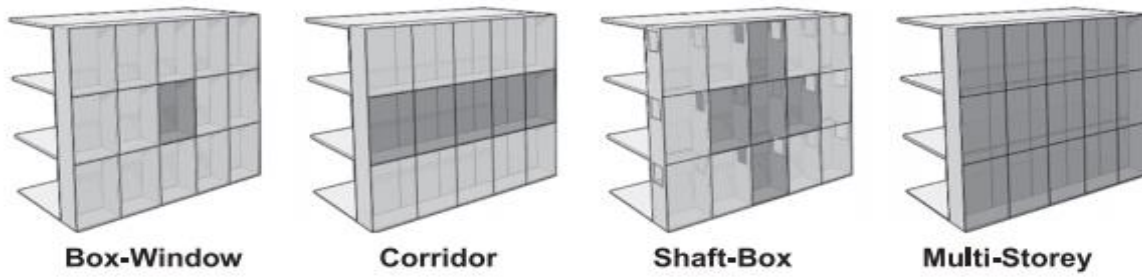


Figure 16 (Alberto 2017) DSFs geometry types.

### 3.4.2 Airflow path

Ventilating the air cavity can help in saving more energy, therefore various airflow paths as simulated. However, the exterior conditions can be a determining factor in deciding the airflow path direction. Also, the geometry of the DSF can affect the ventilation in the air cavity.

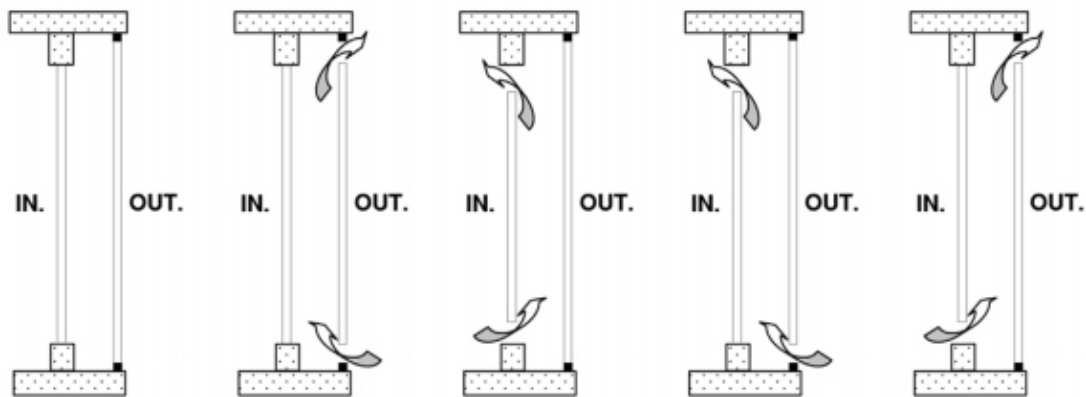


Figure 17 (Alberto 2017) Airflow path in DSFs

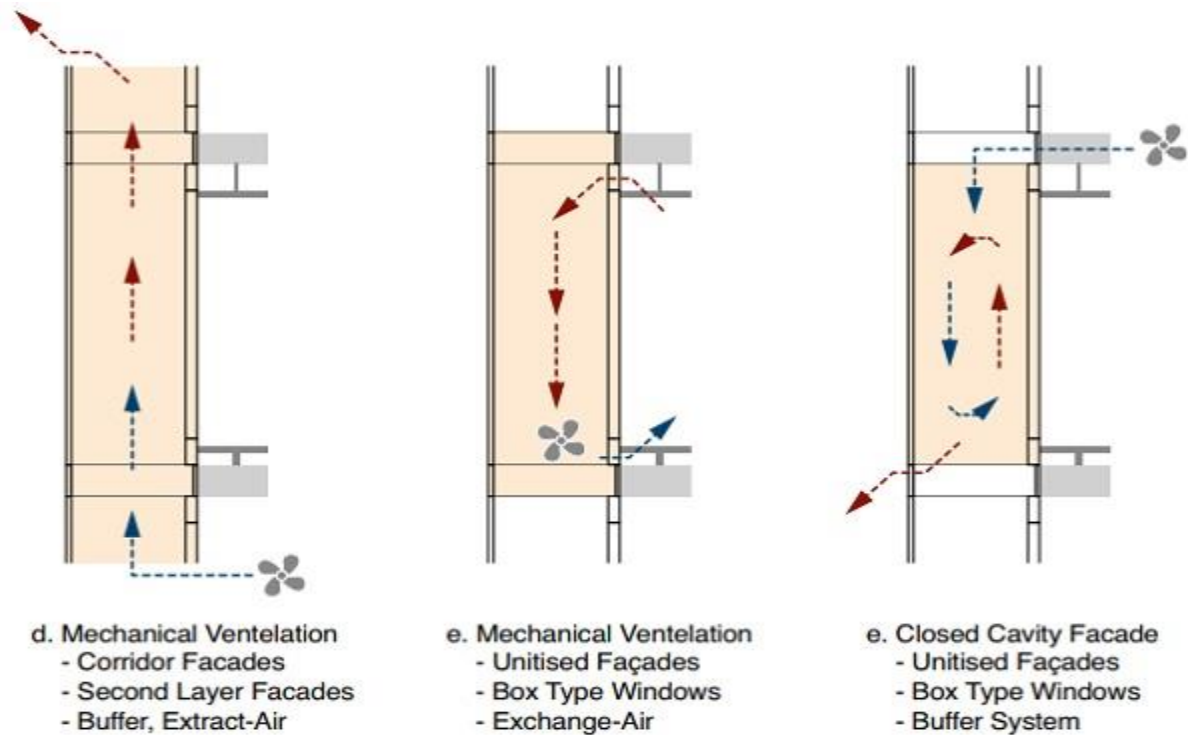


Figure 18 (Schmid 2019) Airflow path with different ventilation in DSFs

### 3.4.3 Air Cavity width

The heat transfer coefficient values will be affected by the air cavity width, which will impact the air temperature inside the building. Also, the air velocity will be affected when changing the air cavity width; therefore, a proper design of the air cavity width will help in the energy-saving process.

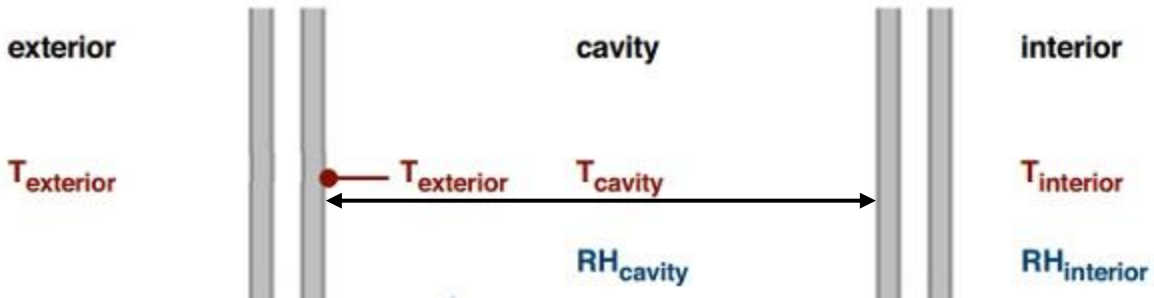


Figure 19 Air Cavity width

### 3.4.4 Type of glazing

Many studies regarding the DSF are considering the glazing layer to be single glazed material for the outer layer and an insulated glazed layer for the internal layer such as (double, Low-E, and solar control) (Gratia 2007, Yuan 2006, Haase 2009, Hashemi 2010). Therefore, in this study, the impact of different glazing materials of a DSF will be investigated to choose the best glazing material. The main focus will be on the thermal performance of the glazing material in the DSF and investigate their effect on the energy-saving process. Therefore, various types of glazing materials with different properties such as emissivity ( $\epsilon$ ), conductance ( $k$ ), U-value, and SHGC will be investigated.

### 3.4.5 Energy Simulation Software:

IESVE is an integrated building simulation tool that provides the user with a single data model and a common interface to link various applications. This program gives a detailed report of building performance and different system designs, enabling the user to optimize performances based on energy use and indoor comfort. Virtual environment (VE) modules use an integrated analysis platform, including geometry editing, solar analysis, thermal analysis, daylight analysis, natural ventilation analysis, and HVAC system simulation. (IESVE2011).

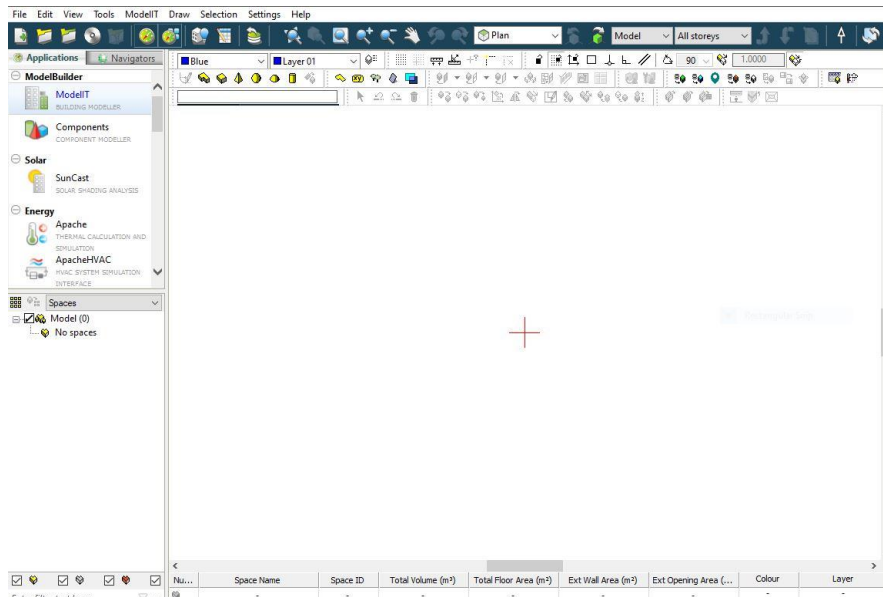


Figure 20 IES VE interface

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 optimization) -LifeCycle (life-cycle energy and cost analysis) -Simulex (building evacuation)

## **CHAPTER 4**

### **RESULTS AND DISCUSSION**

#### **4.1 Overview**

The effect of the DSF on a typical office building located in KSA regarding energy and thermal performance is Investigated to define the optimum design characteristics for a DSF. Therefore, energy simulation had been done on the base case for the office building as a single skin façade. Energy consumption and Thermal Performance is investigated by simulating the office building in IES VE software. However, in this chapter, the work is being focused on the simulation process of energy consumption, which is associated with different scenarios that have been mentioned in Chapter 3. Different DSF configurations have been simulated to observe how the total energy consumption was affected. By using simulation software, investigating different DSF configurations to see how they will affect the energy consumption caused is possible.

The planned outcomes of the simulations were as follows

- 1-Gaining a clear understanding of the impact that the DSF will have on the overall energy consumption for the office building by taking into consideration different scenarios for the DSF.
- 2- Determine and define the best configuration for the DSF and their contribution toward energy saving.

## 4.2 Building Overall performance:

The office building in its current state as an SSF has been simulated to calculate the energy consumption and overall performance throughout the whole year, as shown in figure 22 below.

The results showed that the building consumes around 1,838.1MWh as the Yearly Total Energy Consumption and has about 294.1kWh/m<sup>2</sup> EUI.

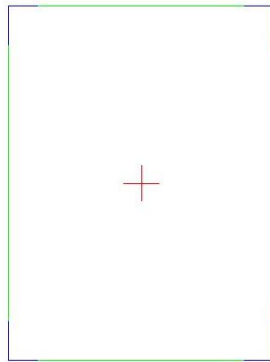


Figure 21 Base case

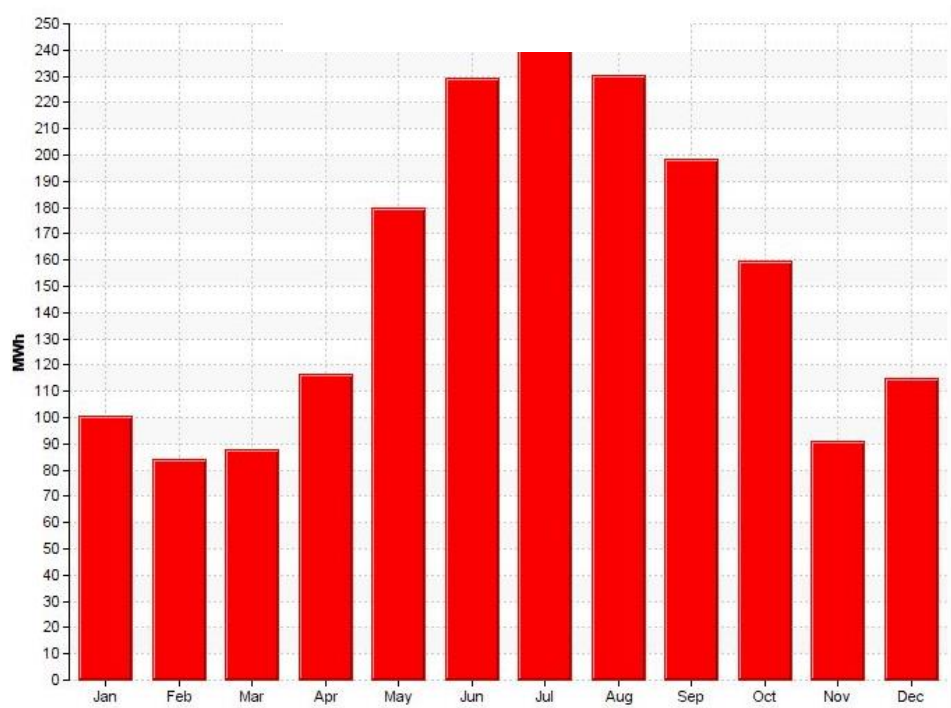


Figure 22 Monthly energy consumption around the whole year

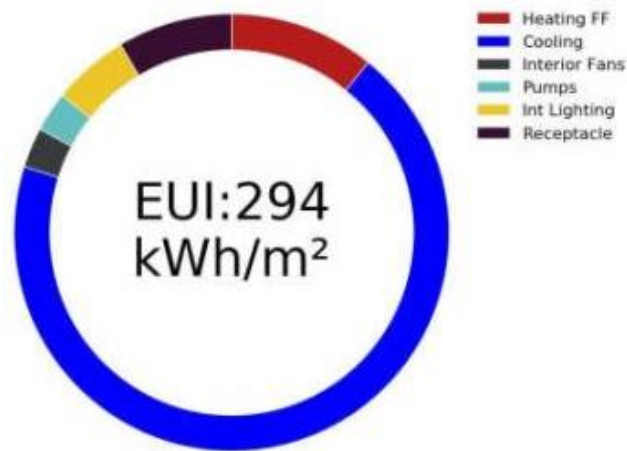


Figure 23 EUI for the base case

Unfortunately, KSA does not have a benchmarking database to be used as a baseline to compare the result to it. Therefore, in this study, the data trend report from the ENERGY STAR Portfolio Manager program published by the U.S. Environmental Protection Agency will be used for the comparison purpose. The Data Trend report has a database of EUI for office buildings, which will be applied as a standard for the office building in this study. In the latest Data Trend report, the median for EUI is equal to 184 kBtu/ft<sup>2</sup>, which equals 580.3 Kwh/m<sup>2</sup> (DataTrend, 2015).

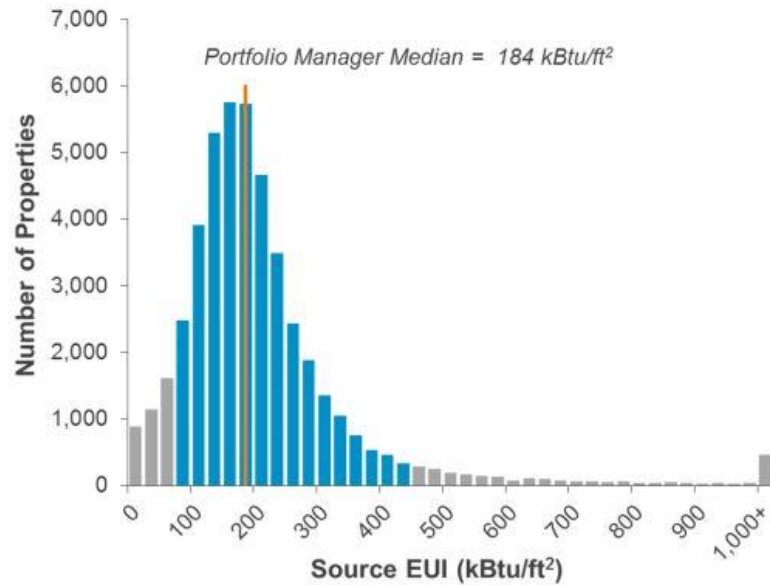


Figure 24 DataTrend 2015 report

However, simulation results for the office building show that EUI is falling in the range of energy consumption for office buildings according to the Data Trend report. However, the results showed that the air conditioning system has the lion share of energy consumption, mainly due to the cooling load. Simulation outcomes indicate how electricity consumption varies around the year and which month consumes more, as shown in figure 25 below.

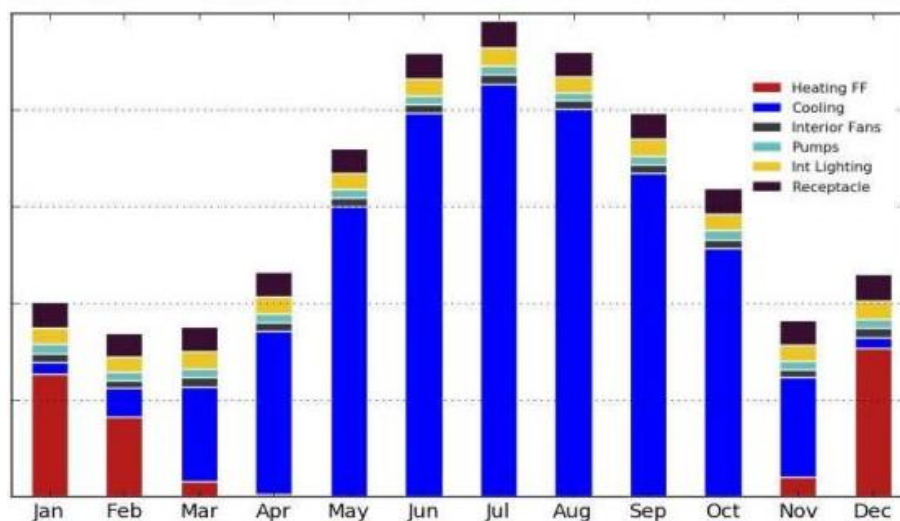


Figure 25 Monthly energy consumption

### 4.3 DSF performance:

After simulating the office building to measure its performance without a DSF, various scenarios and configurations of a DSF will be simulated to investigate their impact on the overall building performance. After conducting the simulation on different DSF scenarios in IES VE simulation software, then changes in the building performance regarding energy consumption will be discussed. However, the HVAC system represents the most significant part of the building's annual energy consumption; therefore, the result will differ when the impact on cooling, heating, and mechanical ventilation is substantial.

#### 4.3.1 Airflow effect:

To investigate the impact that airflow has on the DSF performance, two scenarios of airflow will be discussed. The first one will be when the airflow path is fully closed, and the second scenario will be when the airflow path is fully ventilated.

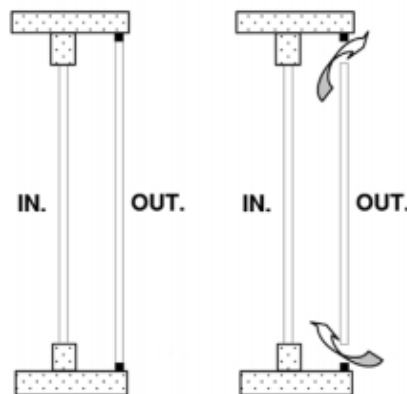


Figure 26 (Alberto 2017) Airflow path scenarios

#### 4.3.1.1 Closed airflow path:

In this scenario, a DSF had been implemented for the building with 1 m width, double-glazed windows with air gap (U-value =2.71w/m<sup>2</sup> k), and closed airflow path.

| Openable Area % | Equivalent Orifice Area (% of Gross) | Crack Flow Co-efficient (l/(s·m·Pa <sup>0.6</sup> )) | Crack Length (% of Opening Perimeter) | Opening Threshold (°C) | Degree of Opening |
|-----------------|--------------------------------------|------------------------------------------------------|---------------------------------------|------------------------|-------------------|
| 95.00           | 95.000                               | 0.15                                                 | 0.000                                 | 0.00                   | off continuously  |

Figure 27 Closed air flow path

Simulation results showed that adding a DSF with 1 m width and a closed airflow path has an impact on the annual energy consumption by 1.436 %. The yearly energy consumption decreased from 1,838.1MWh to 1,811.7MWh, and the EUI decreased from 294.1 kWh/m<sup>2</sup> to 290 kWh/m<sup>2</sup>.

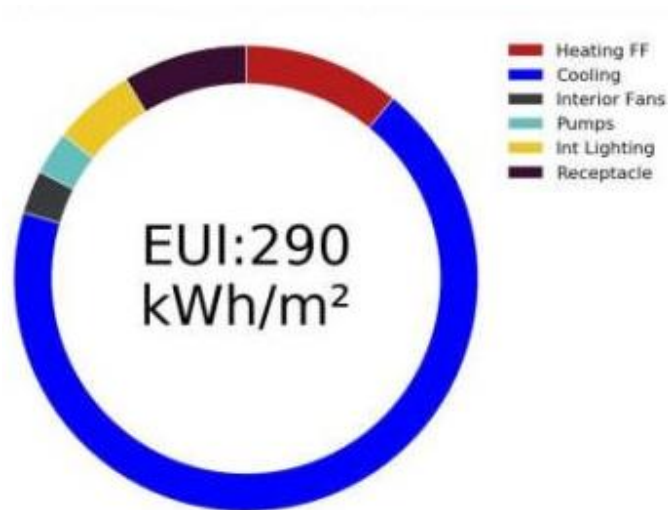


Figure 28 EUI for double skin façade with closed air flow

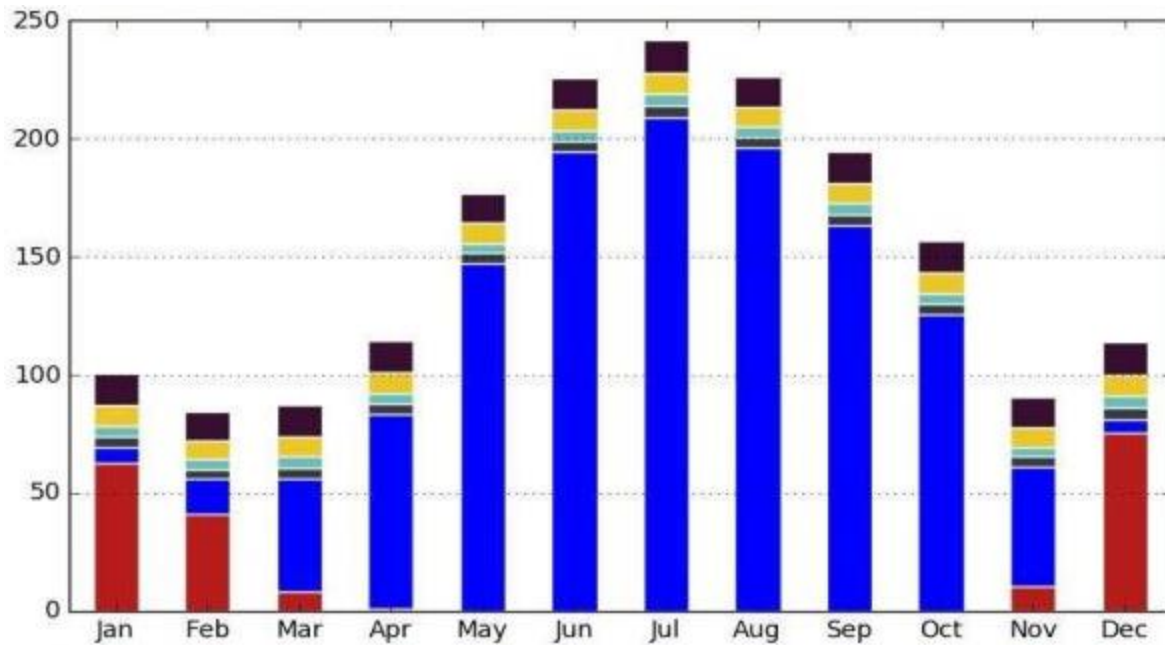


Figure 29 Monthly energy consumption for DSF with closed airflow

#### 4.3.1.2 Open airflow path:

In this scenario, the same configuration of a DSF had been implemented for the building with changing only the airflow path to be fully ventilated airflow path.

| Openable Area % | Equivalent Office Area (% of Gross) | Crack Flow Co-efficient ( $l/(s \cdot m \cdot Pa^{0.6})$ ) | Crack Length (% of Opening Perimeter) | Opening Threshold ( $^{\circ}C$ ) | Degree of Opening |
|-----------------|-------------------------------------|------------------------------------------------------------|---------------------------------------|-----------------------------------|-------------------|
| 95.00           | 95.000                              | 0.15                                                       | 0.000                                 | 0.00                              | on continuously   |

Figure 30 Open air flow path

The outcomes revealed that fully open-air flow path has an impact on the annual energy consumption of 4.83%. The result showed a decrease in the annual energy consumption from

1,838.1MWh to 1,749.3 MWh, and the EUI decreased from 294.1 kWh/m<sup>2</sup> to 280 kWh/m<sup>2</sup> when compare it to the single skin facade.

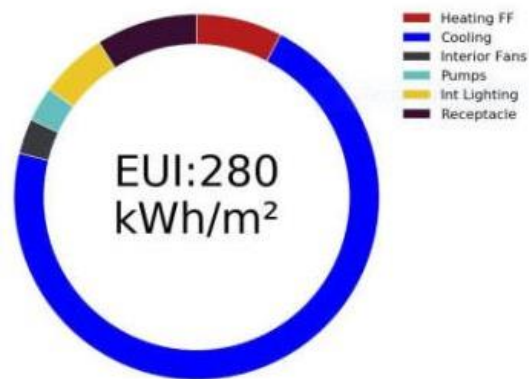


Figure 31 EUI for double skin façade with open air flow

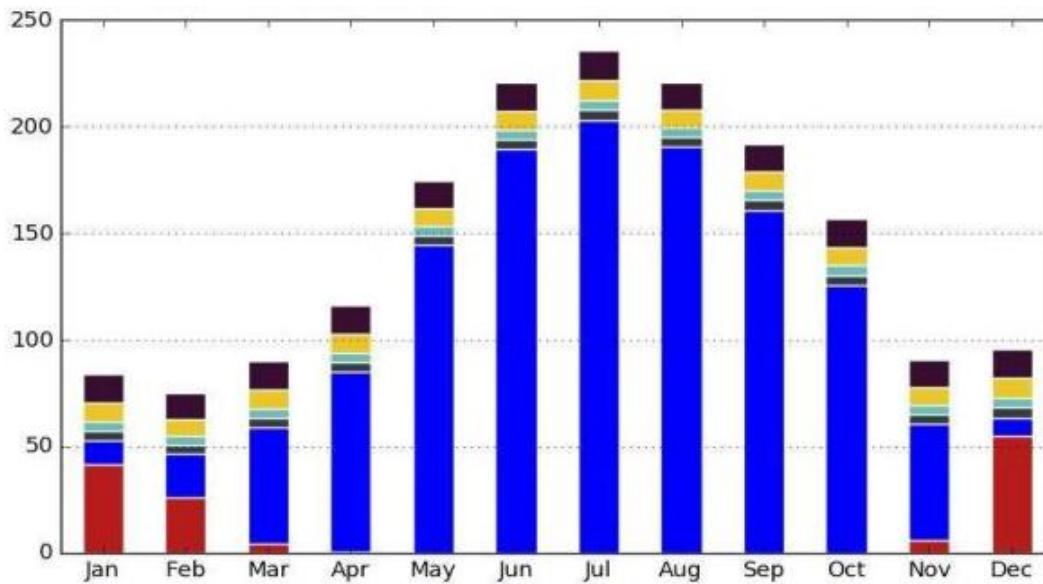


Figure 32 Monthly energy consumption for double skin façade with closed air flow

The result showed that the open airflow path could result in more energy saving compared to a closed airflow path. The outcomes demonstrated that airflow path configuration affects the cooling load for the building, especially in June, July, and August.

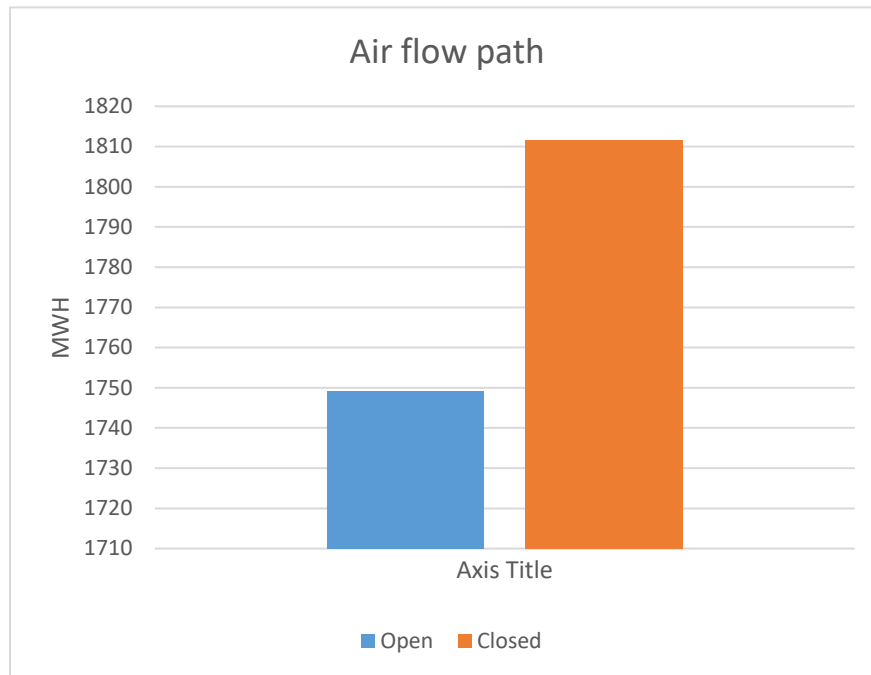


Figure 33 Comparison between air flow path scenarios

#### 4.3.2 Air Cavity width:

To investigate and understand the effect of the air cavity, the simulation process regarding the air cavity width will be divided into two main categories. The first one is investigating the impact of increasing the air cavity width while the airflow path is closed and the second one when it is open. The Air cavity width effect on the DSF overall performance was assessed by simulating Different width of 1m, 1.5m, and 2 m. After simulating the base case for the building as a single skin façade, a DSF with an air cavity width of 1 m is being investigated. However, the impact of the air cavity

on the performance of the DSF will be studied while the airflow path is open, and when it is closed, as shown in the graph below.

Table 6 Air Cavity width impact

| Air cavity width | Airflow path |            | Saving |        |
|------------------|--------------|------------|--------|--------|
|                  | open         | Closed     | Closed | Open   |
| <b>1 m</b>       | 1749.3 MWH   | 1811.7 MWH | 1.44 % | 4.83 % |
| <b>1.5 m</b>     | 1750.6 MWH   | 1810.9 MWH | 1.48 % | 4.76 % |
| <b>2 m</b>       | 1752.2 MWH   | 1810.8 MWH | 1.49 % | 4.67 % |

The result showed that adding a DSF system with 1 m width will have an impact of 1.436 %. Also, it would help in decreasing the annual energy consumption from 1,838.1MWh to 1,811.7 MWh when the airflow path being closed. Also, the result showed that when the airflow path is open, the annual energy consumption will drop to 1749.3 MWH. On the other hand, increasing the width of the air cavity to 1.5 m will help in reducing the annual energy consumption to 1810.9 MWH when the airflow path is closed and to 1750.6 MWH when it is open. Moreover, increasing the width for the air cavity to 2 m will result in a change in the annual energy consumption to 1810.8 MWH when the airflow path is closed and reduce it more to 1752.2 MWH when the airflow path is open.

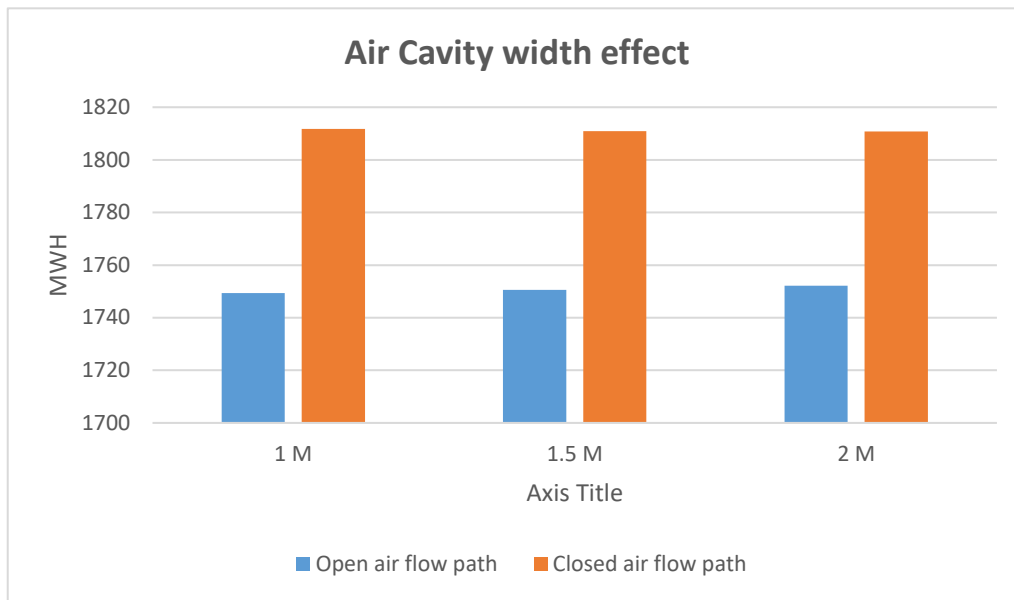


Figure 34 Comparasion of Air Cavity width

#### 4.3.3 Glazing:

Glazing elements of a DSF provide a visual connection; also, they have an impact on the annual energy consumption. Therefore, different glazing types of DSF affect the energy consumed by the building. For example, the higher the amount of sunlight can enter the space, the less artificial light is needed during the day. One of the most critical properties of glazing elements is the U-value, which has a massive impact on the energy consumption of a building. U-value, which is also known as thermal conductance, can be defined as “a measure of how well the window conducts heat”. Therefore, to study the impact of the glazing elements on DSF performance, three types of glazing with different U-value had been simulated. Table 7 below shows the variety of glazing elements in this study and their properties.

Table 7 Glazing types

| Glazing type                        | Thermal properties                                                                      |
|-------------------------------------|-----------------------------------------------------------------------------------------|
| Double glass clear with air cavity  | $U\text{-value} = 2.71 \text{ w/m}^2 \text{ k}$<br>$SHGC = 0.704$<br>$T_{vis} = 0.786$  |
| Double glass (Low e) with Argon gas | $U\text{-value} = 1.608 \text{ w/m}^2 \text{ k}$<br>$SHGC = 0.431$<br>$T_{vis} = 0.639$ |
| Double glass (Low e) with Xenon gas | $U\text{-value} = 1.15 \text{ w/m}^2 \text{ k}$<br>$SHGC = 0.3930$<br>$T_{vis} = 0.55$  |

The result for the first case of the Double glass clear with air cavity showed that the annual energy consumption would decrease to 1,811.7 MWh and the EUI to 290 kWh/m<sup>2</sup>. The second glazing element type Double glass (Low e) with Argon gas with a U-value of 1.608 w/m<sup>2</sup> k showed a fall in the annual energy consumption to 1778.1 MWh. On the other hand, Double glass (Low e) with Xenon gas with a U-value of 1.15 w/m<sup>2</sup> k resulted in more savings in the annual energy consumption to 1775.1 MWh.

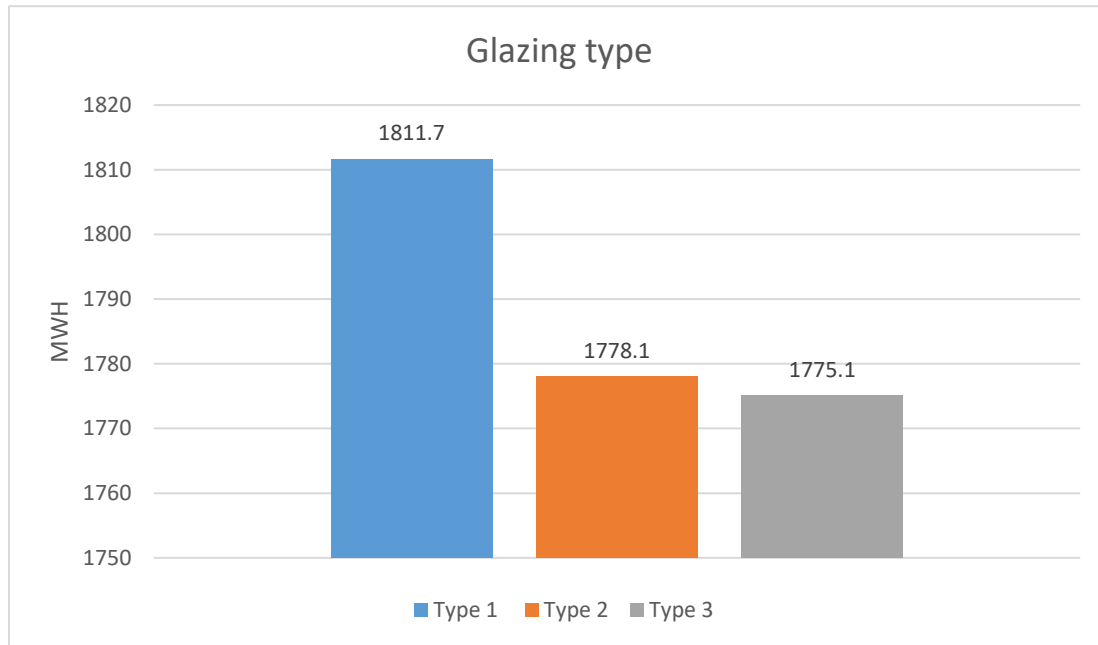


Figure 35 Comparison between glazing types

The

previous results were simulated with a 1 m air cavity width for the DSF and a closed airflow path. Therefore, for more understanding of the effect of glazing elements on the DSF performance, more simulation scenarios had been done, as shown in Table 8 below.

Table 8 Simulation results

| Case | Configurations                      | Result                                                       |
|------|-------------------------------------|--------------------------------------------------------------|
| 1    | Air cavity width = 1m               | Annual energy consumption = 1749.3 MWH<br>EUI = 279.9 KWH/m2 |
|      | Double glass clear with air cavity  |                                                              |
|      | U-value=2.71w/m2 k                  |                                                              |
|      | Open air flow path                  |                                                              |
| 2    | Air cavity width = 1m               | Annual energy consumption = 1686.0 MWH<br>EUI = 269.8 KWH/m2 |
|      | Double glass (Low e) with Argon gas |                                                              |
|      | U-value=1.608 w/m2 k                |                                                              |

|   |                                                                                                                            |                                                                          |
|---|----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
|   | Open air flow path                                                                                                         |                                                                          |
| 3 | Air cavity width = 1m<br>Double glass (Low e) with Xenon gas<br>U-value = 1.15 w/m <sup>2</sup> k<br>Open air flow path    | Annual energy consumption = 1675.3 MWH<br>EUI = 268.0 KWH/m <sup>2</sup> |
| 4 | Air cavity width = 1.5m<br>Double glass clear with air cavity<br>U-value = 2.71 w/m <sup>2</sup> k<br>Open air flow path   | Annual energy consumption = 1750.6 MWH<br>EUI = 280.1 KWH/m <sup>2</sup> |
| 5 | Air cavity width = 1.5m<br>Double glass (Low e) with Argon gas<br>U-value = 1.608 w/m <sup>2</sup> k<br>Open air flow path | Annual energy consumption = 1745.7 MWH<br>EUI = 279.3 KWH/m <sup>2</sup> |
| 6 | Air cavity width = 1.5m<br>Double glass (Low e) with Xenon gas<br>U-value = 1.15 w/m <sup>2</sup> k<br>Open air flow path  | Annual energy consumption = 1669.2 MWH<br>EUI = 267.1 KWH/m <sup>2</sup> |
| 7 | Air cavity width = 2m<br>Double glass clear with air cavity<br>U-value = 2.71 w/m <sup>2</sup> k<br>Open air flow path     | Annual energy consumption = 1752.2 MWH<br>EUI = 280.4 KWH/m <sup>2</sup> |
| 8 | Air cavity width = 2m<br>Double glass (Low e) with Argon gas<br>U-value = 1.608 w/m <sup>2</sup> k<br>Open air flow path   | Annual energy consumption = 1680.9 MWH<br>EUI = 268.9 KWH/m <sup>2</sup> |
| 9 | Air cavity width = 2m<br>Double glass (Low e) with Xenon gas                                                               | Annual energy consumption = 1672.7 MWH                                   |

|    |                                                                                                                 |                                                                 |
|----|-----------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
|    | U-value =1.15 w/m2 k<br>Open air flow path                                                                      | EUI = 267.6 KWH/m2                                              |
| 10 | Air cavity width = 1.5m<br>Double glass clear with air cavity<br>U-value=2.71w/m2 k<br>closed air flow path     | Annual energy consumption =<br>1810.9 MWH<br>EUI = 289.7 KWH/m2 |
| 11 | Air cavity width = 1.5m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m2 k<br>closed air flow path  | Annual energy consumption =<br>1777.2 MWH<br>EUI = 284.4 KWH/m2 |
| 12 | Air cavity width = 1.5m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m2 k<br>closed air flow path  | Annual energy consumption =<br>1774.1 MWH<br>EUI = 283.9 KWH/m2 |
| 13 | Air cavity width = 2m<br>Double glass clear with air cavity<br>U-value=2.71w/m2 k<br>closed air flow path       | Annual energy consumption =<br>1810.8 MWH<br>EUI = 289.7 KWH/m2 |
| 14 | Air cavity width = 2m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m2 k<br>closed air flow path    | Annual energy consumption =<br>1776.4 MWH<br>EUI = 284.2 KWH/m2 |
| 15 | Air cavity width = 2m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15<br>w/m2 k<br>closed air flow path | Annual energy consumption =<br>1773.2 MWH<br>EUI = 283.7 KWH/m2 |

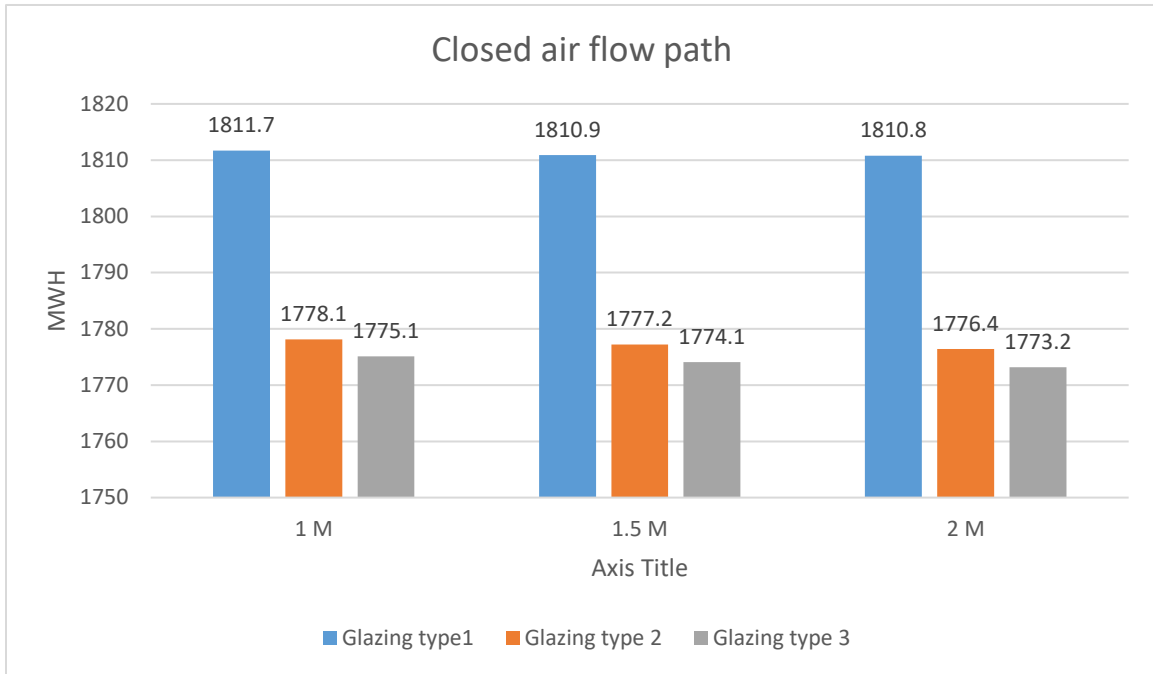


Figure 36 Comparison between cases with closed air flow path

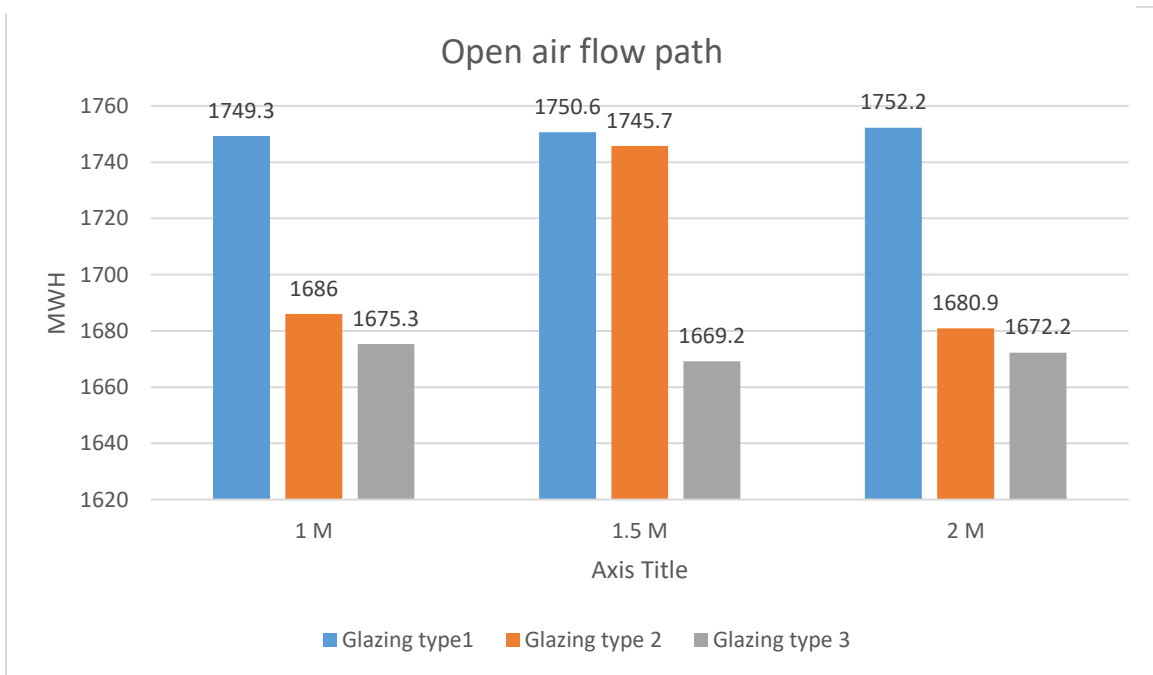


Figure 37 Comparison between cases with open air flow path

#### 4.4 Economic evaluation:

The economic aspect of evaluating the effectiveness of adopting a DSF is considered to be massively important. For this study, a simple payback period method will be used to analyze the feasibility of implementing a DSF and choosing the most feasible option. Cost and prices for DSF per unit area are taken from local contractors and other studies about the DSF, as shown in Table 9 below.

Table 9 Cost for DSF

| Material                              | Cost SR               |
|---------------------------------------|-----------------------|
| Installation cost                     | SR 120/m <sup>2</sup> |
| Electricity cost                      | 0.20/ kWh             |
| Double glass clear with an air cavity | 140/m <sup>2</sup>    |
| Double glass (Low e) with Argon gas   | 210/m <sup>2</sup>    |
| Double glass (Low e) with Xenon gas   | 350/m <sup>2</sup>    |

Table 10 Economic evaluation for DSF scenarios

| Configuration                      | price(SR) | Saving (SR) | pay-back(years) |
|------------------------------------|-----------|-------------|-----------------|
| Air cavity width = 1m              |           |             |                 |
| Double glass clear with air cavity | 2320472   | 5280        | 439.5           |
| U-value=2.71w/m <sup>2</sup> k     |           |             |                 |

|                                                                                                              |         |       |       |
|--------------------------------------------------------------------------------------------------------------|---------|-------|-------|
| Closed air flow path                                                                                         |         |       |       |
| Air cavity width = 1m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m2 k<br>Closed air flow path | 2532152 | 12000 | 211.0 |
| Air cavity width = 1m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m2 k<br>Closed air flow path | 2955512 | 12600 | 234.6 |
| Air cavity width = 1m<br>Double glass clear with air cavity<br>U-value=2.71w/m2 k<br>Open air flow path      | 2320472 | 17760 | 130.7 |
| Air cavity width = 1m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m2 k<br>Open air flow path   | 2532152 | 30420 | 83.2  |
| Air cavity width = 1m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m2 k<br>Open air flow path   | 2955512 | 32560 | 90.8  |
| Air cavity width = 1.5m<br>Double glass clear with air cavity<br>U-value=2.71w/m2 k<br>closed air flow path  | 2356952 | 17500 | 134.7 |
| Air cavity width = 1.5m<br>Double glass (Low e) with Argon gas                                               | 2568632 | 18480 | 139.0 |

|                                                                                                                            |         |       |       |
|----------------------------------------------------------------------------------------------------------------------------|---------|-------|-------|
| U-value=1.608 w/m <sup>2</sup> k<br>closed air flow path                                                                   |         |       |       |
| Air cavity width = 1.5m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m <sup>2</sup> k<br>closed air flow path | 2991992 | 33780 | 88.6  |
| Air cavity width = 1.5m<br>Double glass clear with air cavity<br>U-value=2.71w/m <sup>2</sup> k<br>Open air flow path      | 2356952 | 5440  | 433.3 |
| Air cavity width = 1.5m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m <sup>2</sup> k<br>Open air flow path   | 2568632 | 12180 | 210.9 |
| Air cavity width = 1.5m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m <sup>2</sup> k<br>Open air flow path   | 2991992 | 12800 | 233.7 |
| Air cavity width = 2m<br>Double glass clear with an air cavity<br>U-value=2.71w/m <sup>2</sup> k<br>Open air flow path     | 2393432 | 17180 | 139.3 |
| Air cavity width = 2m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m <sup>2</sup> k<br>Open air flow path     | 2605112 | 31440 | 82.9  |
| Air cavity width = 2m                                                                                                      | 3028472 | 33080 | 91.5  |

|                                                                                                                          |         |       |       |
|--------------------------------------------------------------------------------------------------------------------------|---------|-------|-------|
| Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m <sup>2</sup> k<br>Open air flow path                            |         |       |       |
| Air cavity width = 2m<br>Double glass clear with an air cavity<br>U-value=2.71w/m <sup>2</sup> k<br>Closed air flow path | 2393432 | 5460  | 438.4 |
| Air cavity width = 2m<br>Double glass (Low e) with Argon gas<br>U-value=1.608 w/m <sup>2</sup> k<br>Closed air flow path | 2605112 | 12340 | 211.1 |
| Air cavity width = 2m<br>Double glass (Low e) with Xenon gas<br>U-value =1.15 w/m <sup>2</sup> k<br>Closed air flow path | 3028472 | 12980 | 233.3 |

From table 10 above, the best option from an economic point of view is a DSF with 2 m air cavity width, double glass (Low e) Argon gas filled with a U-value of 1.608 w/m<sup>2</sup>k, and open-air flow path. However, the average life span for a DSF is around 50 years, and the simple payback period for this scenario is estimated to be approximately 82.9 years; therefore, it is considered to be infeasible economically (Fung 2017).

## **CHAPTER 5**

### **CONCLUSION**

A DSF can help in reducing the heat gain in buildings and help in reducing the annual energy consumption compared to the conventional façade system. Therefore, to investigate the DSF impact on the building's overall performance, an office building with a DSF was modeled using IES VE software using climatic data for the Dhahran region. The result showed that installing a DSF with double clear glass with an air layer will help in reducing the annual energy consumption by 4.83 compared to the conventional single-skin façade. Also, the simulation results for various scenarios showed that this saving percentage could go higher when the DSF is adequately designed. The highest saving percentage among all simulation scenarios was 9.19 % for DSF with 1.5m as air cavity width and double glass (Low e) with xenon gas. However, the saving in the annual energy consumption is clear statistically, but in terms of the payback period, all simulated scenarios were found to be infeasible as they exceeded the average life span for the DSF, which is around 50 years (Fung 2017). The shortest payback period found was 82.9 years for DSF with 2m air cavity width and double glass (Low e) with argon gas.

DSFs were designed and developed to be used in Europe, mainly for their advantages that help in reducing energy consumption for cold climates by increasing the solar heat gain, which will help in reducing heating energy. However, using a DSF in warm climates could have some disadvantages, such as overheating inside the air cavity if the system is not designed well. This overheating could lead to more energy consumption due to the increase in the cooling load. Many constraints may affect the performance of the DSF, and it should be taken into consideration in the early design stages, such as climatic conditions, building users, and how many hours the building

is being occupied. This study shows that the design of a DSF should be redefined, considering more parameters, and a more extensive range of materials should be considered.

## **5.1 Outcomes from the simulation:**

From the simulation results, the following can be seen:

### **5.1.1 Effect of airflow inside the cavity of DSF**

The results show that the airflow can affect the overall performance of the façade and on the building of annual energy consumption. The results showed that:

- DSF with closed airflow passage has little effect on the annual energy consumption of the office building by 1.44 % only.
- Natural ventilation can help in reducing the annual energy consumption for the office building by 4.83 % compared to the base case.

### **5.1.2 Effect of the air cavity width**

The outcomes showed that the width of the air cavity has an impact on building performance and energy consumption. The results showed that:

- DSF with only 1 m widths has little effect on the annual energy consumption of the office building by 1.44 % if the airflow path is closed and 4.83 if it is open.
- Air cavity width of 1.5 m, the saving percentage that DSF will provide is 1.48 % with closed airflow path and 4.76 % when it is open.
- Changing the width of the air cavity to 2 m will result in a saving of 1.49 % when the airflow path is closed and 4.67 when it is open.

The results revealed that when changing the air cavity width with keeping the airflow path closed, the saving percentage will go up by a minimal amount. When the airflow path is open, and natural ventilation is used to ventilate the air cavity, the saving percentage goes down as the air cavity width increases.

### **5.1.3 Effect of glazing type:**

From the results, it was found that implementing a higher efficiency glazing will result in more saving percentage. The lower the U-value that a glazing type has, the higher the saving in the annual energy consumption; therefore, it should be adequately designed. The results showed the following:

- Using double clear glass with a U-value of 2.71 w/m<sup>2</sup> k will help in reducing the annual energy consumption by 1.44 % compared to the base case. When combined with other options such as open airflow path, the percentage of saving will go higher to 4.83 %, and with 1.5 m air cavity width, the conservation percentage will go up to 8.27 %.
- The second glazing type was double glass (Low e) with argon gas with a U-value of 1.608 w/m<sup>2</sup> k, and it will help in reducing the energy consumption by 3.26 % compared to the base case. When combined with other options such as an open airflow path, the percentage of savings will go higher to 8.27 %.
- The third glazing type was double glass (Low e) with xenon gas with a U-value of 1.15 w/m<sup>2</sup> k it helped in reducing the annual energy consumption by 3.43 % compared to the base case.
- The results showed improvement and an increase in the saving percentage as the glazing type has lower U-value.

## 5.2 Design Guidelines:

In this study, a number of the parameters that might affect the performance of the DSF was investigated. The outcomes of this study helped in identifying some essential and critical problems that may influence the overall performance of a DSF. Therefore the Design Parameters are as the following:

- 1- Airflow path: The DSF should be designed to allow ventilation to pass through the air cavity. Ventilation can be beneficial at times when the temperature outside the building is at a comfortable and acceptable level, which may help in reducing the energy consumption by allowing the air to enter inside the building. Also, in the summer season, allowing ventilation to circulate in the air cavity will help in removing the trapped heat inside the hole.

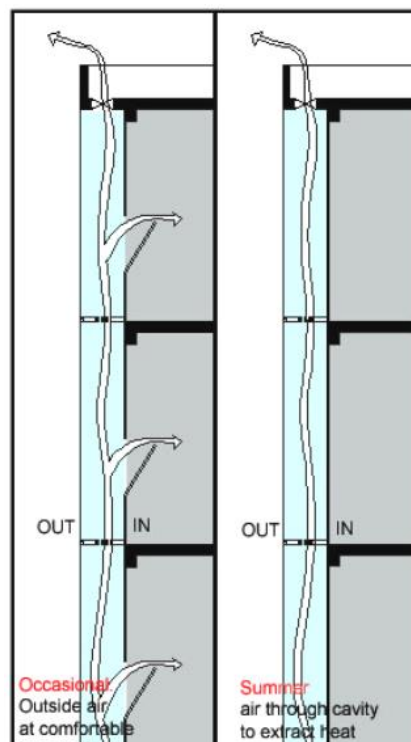


Figure 38 (Yellamraju 2004) Air flow path design

- 2- Glazing Material: Determining the glazing elements Ratio in a DSF system is as vital as determining the type of glazing elements to be used, therefore minimizing the ratio of glazed elements can help in saving energy. Also, the lower the U-value a glazing type has, the more saving can be achieved, but also the cost for glazing element should be studied to determine the feasibility of it.
- 3- Air cavity: Regarding the depth of the air cavity, there is various configuration such as continuous air cavity which was adopted in this study. The width of the air cavity can be decided concerning the available space for the DSF by taking into consideration the space needed for maintenance works. Some studies suggested using shading devices installed in the air cavity to help in reducing the annual energy consumption of the building.

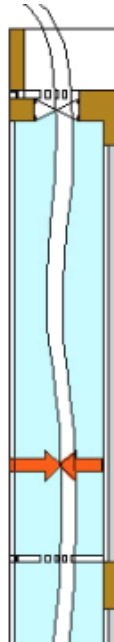


Figure 39 (Yellamraju 2004) Air cavity

## REFERENCES:

1. Alberto, Andre, Nuno MM Ramos, and Ricardo MSF Almeida. "Parametric study of double skin facades performance in mild climate countries." *Journal of Building Engineering* 12 (2017): 87-98.
2. Hamza, Neveen. "Double versus single skin facades in hot arid areas." *Energy and buildings* 40.3 (2008): 240-248.
3. Su, Ziyi, Xiaofeng Li, and Fei Xue. "Double skin façade optimization design for different climate zones in China." *Solar Energy* 155 (2017): 281-290.
4. Ghaffarianhoseini, Ali, et al. "Exploring the advantages and challenges of double-skin façades (DSFs)." *Renewable and Sustainable Energy Reviews* 60 (2016): 1052-1065.
5. Shameri, M. A., et al. "Perspectives of double skin façade systems in buildings and energy saving." *Renewable and Sustainable Energy Reviews* 15.3 (2011): 1468-1475.
6. Elarga, Hagar, Michele De Carli, and Angelo Zarrella. "A simplified mathematical model for transient simulation of thermal performance and energy assessment for active facades." *Energy and Buildings* 104 (2015): 97-107.
7. Haase, M., and A. Amato. "Design considerations for double skin facades in hot and humid climates." (2006).
8. Hendriksen, Ole J., et al. "Double skin façade fashion or a step towards sustainable buildings." *Proceedings of ISES, Eurosun 2000* (2000).
9. Gratia, Elisabeth, and André De Herde. "Greenhouse effect in double skin facade." *Energy and buildings* 39.2 (2007): 199-211.
10. Jiru, Teshome Edae, Yong-X. Tao, and Fariborz Haghighat. "Airflow and heat transfer in double skin facades." *Energy and Buildings* 43.10 (2011): 2760-2766.

11. Al- Al-Rabghi, Omar M., and Mohammed M. Akyurt. "A survey of energy efficient strategies for effective air conditioning." *Energy conversion and management* 45.11-12 (2004): 1643-1654.
12. Schmid, F. C., Stefan Marinitsch, and Martien Teich. "Double Skin Facades: Characteristics and Challenges for an Advanced Building Skin." *Świat Szkła* 24 (2019).
13. d.o.o., Yu. "Dammam, Saudi Arabia - Detailed Climate Information And Monthly Weather Forecast | Weather Atlas". *Weather Atlas*, 2020, <https://www.weather-atlas.com/en/saudi-arabia/dammam-climate>.
14. Weather Spark "Average Weather In Dhahran, Saudi Arabia, Year Round". *Weatherspark.Com*, 2020, <https://weatherspark.com/y/104950/Average-Weather-in-Dhahran-Saudi-Arabia-Year-Round>.
15. Chan, A. L. S., et al. "Investigation on energy performance of double skin façade in Hong Kong." *Energy and buildings* 41.11 (2009): 1135-1142.
16. "Weill Cornell's Belfer Research Building". *Urban Green Council*, 2020, <https://www.urbangreencouncil.org/content/events/weill-cornells-belfer-research-building>.
17. Hien, Wong Nyuk, et al. "Effects of double glazed facade on energy consumption, thermal comfort and condensation for a typical office building in Singapore." *Energy and Buildings* 37.6 (2005): 563-572.
18. Colombo, Elia, et al. "Design of a glazed double-façade by means of coupled CFD and building performance simulation." *Energy Procedia* 122 (2017): 355-360.

19. Zomorodian, Zahra S., and Mohammad Tahsildoost. "Energy and carbon analysis of double-skin façades in the hot and dry climate." *Journal of cleaner production* 197 (2018): 85-96.
20. Kalyanova, Olena. Double-skin facade: modelling and experimental investigations of thermal performance. Diss. Department of Civil Engineering, Aalborg University, 2008.
21. Yellamraju, Vijaya. Evaluation and design of double-skin facades for office buildings in hot climates. Diss. Texas A&M University, 2004.
22. Arons, Daniel MM. Properties and applications of double-skin building facades. Diss. Massachusetts Institute of Technology, 2000.
23. Harrison, Kate, and T. Meyer-Boake. "The tectonics of the environmental skin." University of Waterloo, School of Architecture (2003).
24. Compagno, A. "Intelligent Glass Facades (5th revised and updated edition)." (2002).
25. Uuttu, Sini. "Study of current structures in double-skin facades." Helsinki University of Technology, Department of civil and environmental engineering laboratory of steel structures (2001).
26. Belgian Building Research Institute (BBRI). "a better understanding of conceptual and operational aspects of activefacades." Department of Building Physics, Indoor Climate and Building Services, Belgian Building Research Institute. (2002).
27. Safer N, Woloszyn M, Roux JJ. Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin façade equipped with a venetian blind. *Solar Energy* 2005; 79:193–203.
28. Yazdizad, Arash, Firooze Rezaei, and Foad Faizi. "Classification of double-skin façade and their function to reduce energy consumption and create sustainability in buildings."

2nd international congress on structure, Architecture and Urban Development, Tabriz, Iran.  
2014.

29. Poirazis, Harris. "Double-skin façades for office buildings." Holland: Lund Institute of Technology (2004).
30. Ahmed, Mostafa MS, et al. "Double-skin façade : the state of art on building energy efficiency." *Journal of Clean Energy Technologies* 4.1 (2016): 84-89.
31. Yoon, Yeo Beom, et al. "Performance analysis of a double-skin façade system installed at different floor levels of high-rise apartment building." *Journal of Building Engineering* 26 (2019): 100900.
32. Almaziad, Faris, Ashraf, Noman " Effects of facade on the energy performance of Education Building in Saudi Arabia " (2014).
33. Barbosa, Sabrina, and Kenneth Ip. "Perspectives of double-skin façades for naturally ventilated buildings: A review." *Renewable and Sustainable Energy Reviews* 40 (2014): 1019-1029.
34. Rundle, C. A., et al. "Validation of computational fluid dynamics simulations for atria geometries." *Building and Environment* 46.7 (2011): 1343-1353.
35. Pappas, Alexandra, and Zhiqiang Zhai. "Numerical investigation on thermal performance and correlations of double-skin façade with buoyancy-driven airflow." *Energy and Buildings* 40.4 (2008): 466-475.
36. Boake, Terri Meyer, et al. "Understanding the General Principles of the Double-skin façade System." Associate Professor & School of Architecture, University of Waterloo (2003)

37. Barbosa, Sabrina, Kenneth Ip, and Ryan Southall. "Thermal comfort in naturally ventilated buildings with double-skin façade under tropical climate conditions: The influence of key design parameters." *Energy and Buildings* 109 (2015): 397-406.
38. Torres, Mauricio, et al. "Double skin facades-Cavity and Exterior openings Dimensions for Saving energy on Mediterranean climate." *Building Simulation*. Vol. 26. No. 1. 2007.
39. Rahmani, Behzad, Mohd Zin Kandar, and Parisa Rahmani. "How double-skin façade air-gap sizes effect on lowering solar heat gain in tropical climate." *World Applied Sciences Journal* 18.6 (2012): 774-778.
40. Sanchez, E., et al. "Influence of natural ventilation due to buoyancy and heat transfer in the energy efficiency of a double skin facade building." *Energy for Sustainable Development* 33 (2016): 139-148.
41. Perez-Grande, Isabel, Jose Meseguer, and Gustavo Alonso. "Influence of glass properties on the performance of double-glazed facades." *Applied Thermal Engineering* 25.17-18 (2005): 3163-3175.
42. Fallahi, Ali, Fariborz Haghighat, and Hafsa Elsadi. "Energy performance assessment of double-skin façade with thermal mass." *Energy and Buildings* 42.9 (2010): 1499-1509.
43. Manz, Heinrich. "Total solar energy transmittance of glass double façades with free convection." *Energy and buildings* 36.2 (2004): 127-136.
44. Nasrollahi, Nazanin, and Majid Salehi. "Performance enhancement of double skin facades in hot and dry climates using wind parameters." *Renewable energy* 83 (2015): 1-12.
45. Hashemi, N., R. Fayaz, and M. Sarshar. "Thermal behaviour of a ventilated double skin facade in hot arid climate." *Energy and Buildings* 42.10 (2010): 1823-1832.

46. Larsen, Silvana Flores, Luis Rengifo, and Celina Filippín. "Double skin glazed façades in sunny Mediterranean climates." *Energy and Buildings* 102 (2015): 18-31.
47. Qahtan, Abdultawab M. "Thermal performance of a double-skin façade exposed to direct solar radiation in the tropical climate of Malaysia: A case study." *Case Studies in Thermal Engineering* 14 (2019): 100419.
48. Kim, Dongsu, et al. "Comparative investigation on building energy performance of double skin facade with interior or exterior slat blinds." *Journal of Building Engineering* 20 (2018): 411-423.
49. Mujeebu, Muhammad Abdul, Noman Ashraf, and Abdulkarim Alsuwayigh. "Energy performance and economic viability of nano aerogel glazing and nano vacuum insulation panel in multi-story office building." *Energy* 113 (2016): 949-956.
50. Fasi, Mohammed Abdul, and Ismail Mohammad Budaiwi. "Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates." *Energy and Buildings* 108 (2015): 307-316.
51. Alhuwayil, Waleed Khalid, Muhammad Abdul Mujeebu, and Ali Mohammed M. Algarny. "Impact of external shading strategy on energy performance of multi-story hotel building in hot-humid climate." *Energy* 169 (2019): 1166-1174.
52. Youssef, Ayman, et al. "Unmanned Aerial Vehicles Application in Building Envelope Thermal Energy Assessment in Saudi Arabia." *ASHRAE Transactions* 125.2 (2019): 450-458.
53. Al-Ashwal, Nagib. *ENERGY-EFFICIENT WINDOW DESIGN THROUGH THE INTEGRATION OF DAYLIGHTING AND ARTIFICIAL LIGHTING IN OFFICE BUILDINGS*. Diss. King Fahd University of Petroleum and Minerals, 2008.

54. Al-Ashwal, Nagib T., and Ismail M. Budaiwi. "Energy savings due to daylight and artificial lighting integration in office buildings in hot climate." *International Journal of Energy and Environment* 2.6 (2011): 999-1012.
55. Al-Ashwal, Najib Taher, and Ismail Mohammed Budaiwi. "An Approach to Select Ideal Window Area in Office Buildings: Modeling and Simulation." (2014).
56. Saudi Electricity Company (SEC) Electrical Data (2014) <https://www.se.com.sa/en-us/Pages/ElectricalData.aspx>.
57. Fung, Siu Fung, and Lin Lu. "Thermal performance analysis on different types of glazing of public rental housing in Hong Kong." *Procedia Engineering* 205 (2017): 794-801.
58. Taleb, Hanan M., and Alan George Antony. "Assessing different glazing to achieve better lighting performance of office buildings in the United Arab Emirates (UAE)." *Journal of Building Engineering* 28 (2020): 101034.
59. Energy Star Portfolio Manager DataTrends (2015), "Energy Use in Offices" [https://www.energystar.gov/sites/default/files/tools/DataTrends\\_Office\\_20150129.pdf](https://www.energystar.gov/sites/default/files/tools/DataTrends_Office_20150129.pdf)

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