Thermal Comfort Improvement for Atrium Building with Double Skin Skylight in the Mediterranean Climate

Refaa Y. M. Sokkar

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Architecture

Eastern Mediterranean University
January 2020
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Architecture.

Prof. Dr. Resmiye Alpar Atun
Chair, Department of Architecture

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Architecture.

Assoc. Prof. Dr. Halil Zafer Alibaba
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Halil Zafer Alibaba
2. Asst. Prof. Dr. Polat Hancer
3. Asst. Prof. Dr. Parastoo Pourvahidi

ABSTRACT

Recently, global awareness has been oriented toward sustainability and saving energy solutions based on passive strategies. Since thermal comfort has been considered the most important indicator for uses satisfaction, the achievement of this indoor condition relies on the building design. The atrium has been added to the building for its aesthetical, environmental, and economic benefits, the appropriate atrium design can advance the atrium thermal performance as well as the adjacent spaces' temperatures. However, inappropriate design decisions cause thermal discomfort and consequently, higher energy consumption.

Since the Mediterranean climate has diverse climatic conditions around the year, the central atrium with top-lit skylight is recommended, but in the summer period it can cause overheating, and since the insertion of shading elements shrinks the lighting performance, then the atrium skylight design is supposed to improve the thermal comfort without affecting the lighting level. Therefore, this study investigated the thermal performance in the atrium building by the use of double skin skylight.

This study aimed at improving the indoor thermal comfort for the spaces attached to a top-lit central atrium in the EMU main library building, by applying double skin skylight (DSS) to enhance the atrium thermal performance. The current research is designed with a quantitative approach. To accomplish the aim, the research used the computer simulations which were run with EDSLTas software (EDSL Tas, 2018) with the weather file of Gazimagusa city sequentially.

The study prepared various design strategies, different proposals were tested and compared in terms of indoor temperatures with reference to ASHRAE-55. The implementation of DSS achieved an average of 77% comfort working hours around the year with different opening percentages according to the outdoor conditions. Moreover, results show that changing the DSS glazing materials did not affect the thermal performance of the atrium.

Keywords: Atrium, Natural Ventilation, Thermal Comfort, Passive Design Strategy, Mediterranean Climate.

ÖZ

Son zamanlarda, küresel farkındalık pasif stratejilere dayalı olarak sürdürülebilirliğe ve enerji çözümlerinden tasarruf etmeye yöneliktir. Termal konfor kullanım memnuniyeti için en önemli gösterge olarak kabul edildiğinden, bu iç mekan koşulunun başarısı bina tasarımına dayanmaktadır. Atriyum, estetik, çevresel ve ekonomik yararları için binaya eklenmiştir, uygun atrium tasarımı, atriyum termal performansını ve bitişik alanların sıcaklıklarını artırabilir. Bununla birlikte, uygunsuz tasarım kararları termal rahatsızlığa ve sonuç olarak daha yüksek enerji tüketimine neden olur.

Akdeniz iklimi yıl boyunca çeşitli iklim koşullarına sahip olduğundan, en iyi aydınlatılmış tavan penceresine sahip merkezi atriyum tavsiye edilir, ancak yaz döneminde aşırı ısınmaya neden olabilir ve gölgeleme elemanlarının eklenmesi aydınlatma performansını düşürdüğü için atriyum çatı penceresi tasarımı aydınlatma seviyesini etkilemeden termal konforu artırması beklenmektedir. Bu nedenle, bu çalışma atriyum binasındaki termal performansı çift cidarlı ışıklık kullanarak araştırmıştır.

Bu çalışma, atriyum termal performansını arttırmak için çift cidarlı ışıklık (DSS) uygulayarak DAÜ ana kütüphane binasında üst aydınlatmalı merkezi atriyuma bağlı alanlar için iç mekan termal konforunu geliştirmeyi amaçlamıştır. Mevcut araştırma nicel bir yaklaşımla tasarlanmıştır. Bu amaca ulaşmak için araştırma, sırasıyla Gazimağusa kentinin hava durumu dosyası ile EDSLTas yazılımı (EDSL Tas, 2018) ile çalıştırılan bilgisayar simülasyonlarını kullandı.

Çalışma çeşitli tasarım stratejileri hazırlamış, farklı teklifler test edilmiş ve ASHRAE-55 referans alınarak iç ortam sıcaklıkları açısından karşılaştırılmıştır. DSS uygulaması, dış koşullara göre farklı açılış yüzdeleri ile yıl boyunca ortalama% 77 konfor çalışma saatine ulaşmıştır. Ayrıca, sonuçlar DSS cam malzemelerinin değiştirilmesinin atriyumun termal performansını etkilemediğini göstermektedir.

Anahtar Kelimeler: Atrium, Doğal Havalandırma, Termal Konfor, Pasif Tasarım Stratejisi, Akdeniz İklimi.

DEDICATION

To those, who believe in me…….

ACKNOWLEDGMENT

I would like to express my deepest gratitude to my supervisor Assoc. Prof. Dr. Halil Alibaba for his patience, knowledge, and encouragement during the work period. His valuable comments had directed me in the right way to accomplish this work.

I am also thankful for the examining committee Asst. Prof. Dr. Polat Hancer and Asst. Prof. Dr. Parastoo Pourvahidi for their valuable comments.

Lastly, I am forever thankful to my family and friends for their love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DSS	Double Skin Skylight
RS	Reading Space
SSS	Single Skin Skylight
WH	Working Hour

Chapter 1

INTRODUCTION

1.1 General Overview

Since the industrial revolution has begun, the construction sector has witnessed a vast change in construction materials. New buildings' techniques and construction technologies widened the implementation of glass surfaces. Since then, large transparent envelopes have been the prominent characteristic of modern and contemporary architecture. The wide use of these materials without paying attention to the impact they have on the internal environment created new problems in these environments, one of the major resulting problems is high heat transfer (Bahaj, James, & Jentsch, 2008). These indoor thermal problems have been treated by different mechanical and technological systems to adjust the indoor temperatures which cause high energy consumption (Tabesh & Sertyesilisik, 2016).

Recently, global awareness of the sustainability, and the increase of environmental interests and energy efficiency calls have been directed toward utilizing the building elements as well as passive techniques to reduce energy dependence and reserve comfort indoor environment simultaneously (Lee, Park, Yeo, & Kim, 2009; Tabesh & Sertyesilisik, 2016). Various studies emphasized the great role of passive strategies in enhancing the indoor environmental conditions of these spaces, the improvement of such conditions mainly relies on the architectural as well as the ventilation designs (Lau, Zhang, & Tao, 2019).

Thermal comfort as one of the indoor environmental conditions is considered the most important factor which affects the users' satisfaction (Frontczak & Wargocki, 2011), which directly affect their performance, users' performance regression can be explicitly noticed due to uncomfortable conditions and thermal discomfort, hence, many studies focus on this topic recently (Sarbu & Pacurar, 2015). For institutional buildings generally, and libraries, in particular, a comfortable environment is one of the main criteria of design success (Ibrahim, Baharun, Abdul Manan, & Abang Adenan, 2013).

On one hand, one of the most effective architectural passive solutions regarding thermal performance is the double skin envelope, which mainly benefits the addition of an extra layer to the original façade or roof to increase the indoor thermal acceptance (Abuseif & Gou, 2018; Barbosa & Ip, 2016; Barbosa, Ip, & Southall, 2015; Bianco, Diana, Manca, & Nardini, 2018; Omar, Joseph, Etienne, Damien, & Idriss, 2017), however, the applications of the double skin envelopes either in glazed facades or solid roofs have proved their efficiency in indoor thermal comfort enhancement, whereas double skin glazing roofs and double skin skylights have not been studied yet. On the other hand, naturally ventilated buildings showed a wider range of comfort indoor temperatures relative to mechanical ventilated buildings (Hien, Gabriela, Tan, & Jusuf, 2017; Omrani, Garcia-hansen, Capra, & Drogemuller, 2017).

Recently, atria buildings have received a popular acceptance in modern architecture especially in deep-plans and high-rise buildings due to their architectural, environmental, and economic beneficial features (Hung & Chow, 2001). A well-integrated atrium with the building spaces improves the indoor environment by enhancing the visual and thermal comfort, as well as saving energy (Baharvand, Hamdan, Ahmad, & Safikhani, 2013). Since natural ventilation is one of the most effective passive design strategies in the atrium, the optimum atrium design achieves the least energy consumption with the best indoor conditions (Hussain & Oosthuizen, 2012), where the optimum use of atrium benefits natural ventilation for reducing energy consumption.

Although the atrium could have different configurations, design-decisions are supposed to be taken concerning the function and the climatic conditions (Hussain & Oosthuizen, 2012). As the atrium has huge glazed boundaries with the exterior; indoor thermal performance is strongly affected by the outer climatic conditions which vary from one region to another, and thus it is supposed to be designed accordingly (Tabesh & Sertyesilisik, 2016).

Atria generally suit temperate and cold regions (Laouadi, Atif, & Galasiu, 2002; Moosavi, Mahyuddin, Ab Ghafar, & Azzam Ismail, 2014), while hot climates are challenging (Abdullah & Wang, 2012; Baharvand et al., 2013). It is worth to note that most studies were conducted in hot and tropical climates which receive intense solar radiation all the year where the side-lit atrium is mostly used (Ab Ghafar, Gadi, & Adam, 2019; Abdullah & Wang, 2012; Baharvand et al., 2013; Hussain & Oosthuizen, 2012; Moosavi, Ghafar, & Mahyuddin, 2016; Moosavi et al., 2014; Moosavi, Mahyuddin, & Ghafar, 2015; Moosavi, Mahyuddin, Ghafar, Zandi, & Bidi, 2018; Sunanda, Budiarto, & Budiarto, 2018; F. Wang & Abdullah, 2011), however, fewer studies focused on the atrium thermal performance in diverse climates (Douvlou & Pitts, 2000; Douvlou, 2004; Palma Rojas, 2013), as well as the cold ones (L. Wang, Huang, Qi, Xu, & Yuen, 2017).

According to koppen world climate classification, the Mediterranean climate has a noticeable variation between winter and summer temperatures (D. Chen & Chen, 2013). In the Mediterranean climate, atria can work effectively around the year, as winter temperatures are close to the cold regions where the atrium has proven its efficiency as a thermal buffer zone, while the summer-time can benefit the stack effect ventilation (Palma Rojas, 2013). Regarding the atrium type in this climate, the top-lit atrium has been considered the best choice for day-lighting especially in cloudy days compared with side-lit one, but overheating problems might occur during the cooling periods (Ahmed & Rasdi, 2000). Although the insertion of shading devices has been recommended in such climates as a solution to mitigate the excessive solar radiation during hot seasons, it also reduces the day-lighting level in both atrium and adjacent spaces (Douvlou & Pitts, 2000). On the other hand, utilizing the stack effect in the atrium by operating natural ventilation could overcome this problem (Baharvand et al., 2013).

As a result, a diverse climate like the Mediterranean has received fewer studies concerning the atrium glazed roofs design and its ventilation strategies roles in thermal performance, thus, atrium thermal performance under this climate still needs more exploration.

1.2 Research Problem Statement

Despite the fact that atrium has been added to the building design for its aesthetical, environmental, and economic benefits, its inefficient design can lead to thermal discomfort in the atrium as well as the adjacent spaces, thus high energy consumption due to the high reliance on mechanical systems to adjust the indoor temperatures (Aldawoud, 2013). Unfortunately, architects and designers do not take this into consideration while designing (Tabesh & Sertyesilisik, 2016). The pre-design evaluation of atrium design alternatives can predict the most influential parameters that affect the thermal performance atria buildings which help the designers to make the most appropriate decisions (Yasa, 2015).

Thermal discomfort which is caused by overheating is one of the most common problems in the Mediterranean atria during summer. In spite of the fact that shading devices mitigate the solar radiation in this diverse climate, it is not preferable to insert these devices due to the direct reduction of the penetrated lighting through the skylight (Douvlou & Pitts, 2000).

Since the top-lit atrium is mostly recommended in the Mediterranean climate (Ahmed & Rasdi, 2000), then the atrium skylight design is supposed to improve thermal comfort. Therefore, this study was conducted to develop the thermal performance in the atrium and the adjacent spaces by passive design strategies under the Mediterranean climate. Hence, it can be hypothesized that employing the double skin skylight (DSS) achieves comfort conditions around the year, which increases the benefit of the greenhouse effect during the heating period, while it enhances the stack effect incorporation with the appropriate scheduled natural ventilation in the cooling period.

1.3 Research Aims and Objectives

To achieve acceptable indoor thermal conditions in the buildings that use top-lit atria in the Mediterranean climate, this study aims at emphasizing the significance of developing double skin skylight DSS as a passive design strategy in atria buildings concerning thermal comfort, taking into consideration that appropriate design of DSS should achieve comfortable conditions to the whole spaces and provide the desired indoor conditions for the users.

To accomplish the main aim of this research, this study underlines the importance of double skin skylight DSS design in the atrium for achieving acceptable thermal conditions. Moreover, the study promotes the significance of utilizing natural ventilation as an example of passive design strategies. Therefore, adequate thermal comfort can be achieved for different spaces regardless of their orientation.

This study is supposed to answer the following questions:

- How does the implementation of Double Skin Skylight (DSS) affect the atrium building thermal performance in the Mediterranean climate? And how do the different glazing materials affect the indoor thermal conditions for this kind of skylights?
- Does the implementation of DSS improve the thermal comfort in the atrium' adjacent spaces around the year?
- How does the application of natural ventilation and DSS achieve acceptable operative temperatures of the reading spaces in the peak months?

1.4 Scope and Limitations

This study focuses on central atria with top-lit skylights in institutional buildings, the study concerning the atrium adjacent spaces which attached directly to the atrium, thus, in this research, ground and first floors which are not attached to the atrium space are excluded.

Moreover, the indoor conditions are only studied in terms of thermal comfort by defining the comfort operative temperatures based on the adaptive model in ASHRAE-

55 standard (ANSI/ASHRAE Standard 55, 2017) which is used for naturally ventilated spaces. Thus, mechanical ventilation is not studied.

1.5 Research Significance

This research aims to add a new application of double skin envelopes to central atria which mainly use top-lit skylights, using the climatic characteristics to improve the indoor thermal conditions with the minimum energy consumption. Therefore, the study employs the design of DSS in a central atrium for achieving acceptable indoor operative temperatures of the adjacent spaces attaching the atrium space as a passive design strategy in the Mediterranean climate, the main characteristic of this climate is represented by the fluctuated solar radiation around the year, thus, the diverse climatic characteristics can be employed around the year.

1.6 Research Methodology

To achieve the research objectives, the quantitative approach was used. The study employs a dynamic thermal simulation program to run sequential computer simulations for the aim of improving the indoor thermal conditions.

The data collection phase used the literature survey to find the related studies about the atrium and utilizing the building envelope in indoor thermal comfort by passive design strategies. Moreover, the initially proposed models as well as the ventilation operation schedules, were developed based on the related literature.

For the data analysis stage, firstly, sequential computer simulations with different scenarios were run by the use of EDSL Tas simulation software (EDSL Tas, 2018). Finally, simulation results were compared and discussed according to the adaptive model of ASHRAE-55 standard (ANSI/ASHRAE Standard 55, 2017).

Figure 1 outlines the research methodology, more details about the studied case of the main library in EMU will be elaborated in chapter three.

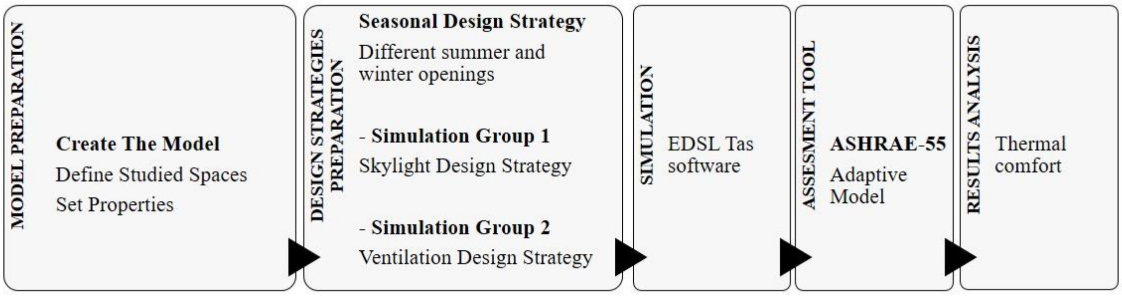


Figure 1: Research Methodology Outline. Developed by the author.

1.7 Research Design

The study is divided into four main chapters as Figure 2 shows:

- Chapter one presents the study introduction with a general overview of the thesis topic, aim and objectives of the study, the study scope and limitations, as well as the outline of the used methodology.
- Chapter two presents the previous literature about atria development and design, in addition to the implemented passive design strategies. The last part of the literature explains thermal comfort and its prediction models.
- Chapter three includes three sections; the first part explains the research methodology strategies, while the second part shows the computer simulation outcomes. The last part discusses the previous results and findings.
- Chapter four concludes the research chapters in addition to providing recommendations for further studies.

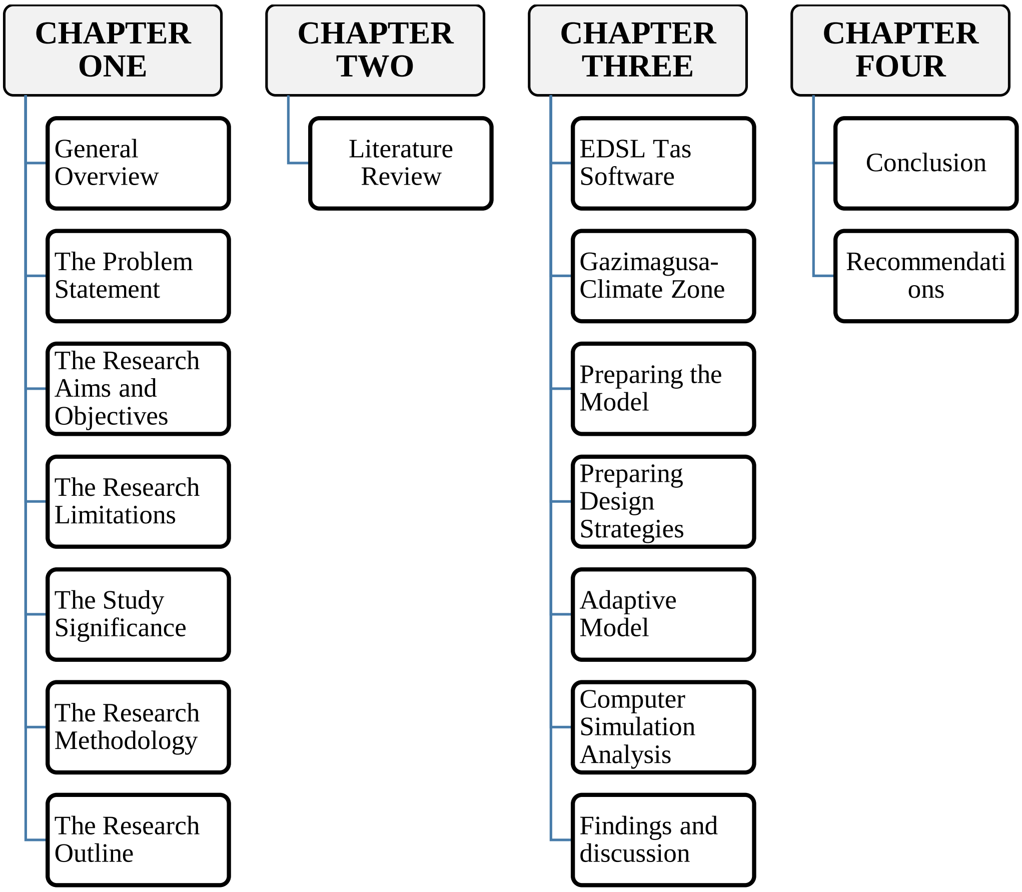


Figure 2: Research Design. Developed by the author.

Chapter 2

LITERATURE REVIEW

This chapter presents the related literature about this research topic of thermal comfort in the atrium in three sections. The first part explains atria and the main important titles, the second part includes passive design strategies and focuses on natural ventilation as well as the ventilated envelopes, while the third part defines thermal comfort and its prediction models. This chapter aims at providing a comprehensive idea about the atrium and its design principles as well as defining thermal comfort. The last part of this chapter summarizes the previous sections and how the three titles are related to each other's, moreover, it provides a theoretical framework to explain the study's development.

2.1 Atria

To have a deep understanding of atria and how these buildings are affected and influenced by the whole context. This section presents a comprehensive overview of the atrium since the initial stages, and how this space has been developed and interacted within the building itself and the surrounding environment which led to the form, performance and function modifications accordingly. Moreover, various aspects related to the atrium will be presented in this study to develop a systematic framework that forms the guidance outline for proposals' design.

2.1.1 Atrium Definition

Micheal Bendar (1986) (as cited in Douvlou, 2004) defined the contemporary atrium in his book *The new atrium* as *"a centroidal, interior, daylit space, which organizes a* *building".* The concept of centrality dominates this definition, where if the space takes a centeral place within the plan and expanding vertically then it will have a great role in the organization of the building.

As a term, the atrium was used for the first time to represent the unroofed central courtyard in the ancient roman house (Hung & Chow, 2001). *"A 'courtyard" is a space within a building or between buildings that is open to the sky"* (Douvlou, 2004). For Nasrollahi, Abdolahzadeh & Litkohi (2015)*"Atrium refers to an open interior space that can be potentially related to an exterior environment".*

Covered courtyard nowadays is called an atrium. Atria in modern architecture are covered spaces with glass and sometimes with one or more glazed facades, the borders of these atria could be the adjacent spaces walls or it could directly connect to the exterior with glazed walls (Douvlou, 2004; Pitts, 2013). Different definitions agreed to consider atrium space as a large multi-storey addition to the building with one or more transparent envelope (Rundle, Lightstone, Oosthuizen, Karava, & Mouriki, 2011; Hien et al., 2017), this space connects adjacent spaces to each other (Moosavi et al., 2016), as well as emphasizes the social interaction between users of this attractive space in non-residential buildings (Moosavi et al., 2015).

In other words, the atrium is a glazed boundary between interior and exterior that allows sun lighting to enter, the access of the environmental conditions as solar radiation and ventilation through this layer greatly impacts the indoor environmental conditions for the atrium space (Palma Rojas, 2013). The emergence of the early atrium in modern architecture is related to temperate climates, later on, it has been used in different regions regardless of the cultural or climatic considerations (Moosavi et al., 2015).

To summarize, in spite of using different terms and descriptions for this space, the main characteristics of the atrium is defined by the produced indoor conditions as a result of the exterior environment via this barrier, which confirms the importance of realizing the relationship between all these aspects to obtain the suitable indoor environment.

2.1.2 History of Atrium

The first use of atrium was in ancient Greece and Rome in the form of uncovered central space which is connected to a huge entrance and semi-public covered space (Nasrollahi et al., 2015), where construction was limited to timber and masonry, then it was expanded to Arab traditional architecture as a huge courtyard space (Hung & Chow, 2001). As a result of the industrial revolution in the 19th century and the new construction materials which started to be manufactured and used, these courtyards have been sheltered from harsh climatic conditions with glass and iron frames (Douvlou, 2004).

In literature, modern atrium development is divided into Early 19th century, late 19th century, Early 20th century and Late 20th century (Hung & Chow, 2001).

Early 19th century atrium appeared in 1806 when the architect John Nash evolved the new roof construction technology for *the picture gallery at Attingham Park, Shropshire* by the use of glass and iron to be as the first modern atrium simultaneously with the emergence of greenhouses that gathering solar energy via their transparent envelope (Hung & Chow, 2001). The innovation of new techniques like blinds, shutters, and insulation in addition to improving glass properties had inspired the designers to develop huge transparent spaces utilizing the atrium buildings concept. This inspiration had been noticed in the buildings with huge, high, lighted and transparent spaces like railway stations and exhibitions, the construction of the Crystal Palace exhibition in London which is also known as the great exhibition in 1851 represents a good example of these technologies implementation (Douvlou, 2004).

The new atrium saw the light in Chicago, the United States in the Late 19th century (1886) when Burnham and Root's Rookery atrium was converted from a conventional light well to a covered sun-lighted commercial street with two levels. The integration between a multi-storey buildings with the original atrium form was arranged in the early 20th century by Frank Lloyd Wright in 1905, he presented the concept of central major top-lit space in a gift shop (1949) in San Francisco and Guggenheim Museum in New York (1959) (Hung & Chow, 2001).

As a result of the technological construction's development new high level atria within skyscrapers had been formed. Afterword, 1968 has witnessed atrium return in the form of central covered court in the Hyatt Regency in Atlanta by John Portman where the architect aimed to create a living social space. These attractive spaces have been a vital component in different buildings like shopping malls, office buildings, and hotels. This leap in the late 20th century represented the rebirth for the new atrium as a unique structure with different design alternatives (Hung & Chow, 2001).

Nowadays, the atrium plays an important role in connecting complex functions together with reserving the main concept of being a great enclosed naturally-lighted space (Douvlou, 2004).

2.1.3 Atrium Benefits and Roles

To emphasize the great role of atrium buildings in sustainability, Sharples & Bensalem, (2001) mentioned the early use of atria in ancient roman architecture for the purpose of permitting daylight in and ejecting fire smokes out. In modern architecture, atria were not only utilized as buffer zones to enhance adjacent spaces microclimates but also they worked as active spaces as well (Liang, Kong, Cao, Zheng, & Yang, 2019). Recently, with the increased global concern towards climate change and intensive attempts to design adapted buildings, atria have received great attention in this regard (Ab Ghafar et al., 2019).

Since the initial implementation as a central space in ancient roman architecture; atrium has great environmental benefits which allow natural lighting getting into indoor spaces and driving fire smokes out (Li et al., 2014), besides providing the inner spaces with natural ventilation (Ab Ghafar et al., 2019; Moosavi et al., 2016), this major space was the main communal component for all surrounding spaces (Douvlou, 2004).

Regarding natural lighting and ventilation, new atrium keeps providing the previous primary benefits that related to conventional atrium form as well as considering this spacious void as a charming architectural component that is mainly used for aesthetic purposes (Aram & Alibaba, 2019; Aldawoud, 2013). Designing this space as a monumental and catchy area includes the insertion of attractive features regardless of the suitability to their context or sustainability considerations. Well-designed atria buildings proved their efficiency in energy saving by gathering adequate solar heating and reducing artificial lighting (Baharvand et al., 2013).

Although the study of Göçer, Tavil, & Özkan, (2006) considered atrium as a buffer zone which is flexibly changed according to the building function, atria benefit is not limited to its own space as a thermal barrier region improving the quality of the interior environment, but also adjacent spaces greatly influenced by their performance (Su, 2017). While some studies emphasized on enhancing thermal comfort in atrium spaces in many climates (Baharvand et al., 2013), other researches confirmed that the thermal performance of these spaces cannot be expected (Aldawoud, 2013).

The transparent properties of atria envelopes serve filtration and protection from undesired external climatic conditions like wind or rain with remaining the visual contact between outside and inside and utilizing fresh air and sunshine (Aram & Alibaba, 2019; Baharvand et al., 2013). This makes atrium to be a promising intermediate environment that reforms unwanted climatic factors to beneficial indoor conditions which can be achieved by the employment of passive techniques (Parker, Wood, 2013).

From another point of view, the atrium has been considered as an important social interactive space (Modirrousta & Boostani, 2016), it could be used as a circulation in different levels as well (Baharvand et al., 2013). Moreover, Pitts, (2013) considered atria as one of the transition spaces which has an important role in urban context design and directing users of these spaces. The use of atria expanded to have an impact on urban design, by converting large outdoor spaces into covered interactive ones and that gave the atrium much attention in and dominance as well as its importance in street-line formation.

Although atrium design usually starts with the initial stages, it’s also can be added to old buildings as well in conservation, thus, this addition saves the antique impression of these buildings and revitalizes the leftover spaces in-between simultaneously by originating a new interactive environment (Najafabadi & Alibaba, 2013). This integration surprisingly enriches social, cultural and economic life.

2.1.4 Atrium Design Parameters

The importance of atrium design parameters refers to their influence on indoor environmental conditions which will consequently affect the energy consumption (Aldawoud, 2013), the best indoor natural environment with minimum energy the most successful atrium design (Hussain & Oosthuizen, 2012), these indoor environmental conditions are represented in ventilation, daylighting, thermal behavior and indoor air quality (L. Wang, Huang, Qi, Xu, & Yuen, 2017; Laouadi et al., 2002). This assures the importance of applying a comprehensive study to fulfill the maximum advantages of atrium regarding the whole indoor environmental conditions as well as energy saving for both cooling and heating seasons (Laouadi et al., 2002; Ab Ghafar et al., 2019).

Since the atrium is one of the most effective strategies to benefit daylighting and heat gain, there are various sets of parameters that control these two aspects (Galal, 2019). Therefore, these parameters strongly rely on diverse climatic conditions (Baharvand et al., 2013), and as a result, both form and function play an important role in atrium performance for a specific climate (Ab Ghafar et al., 2019; L. Wang et al., 2017).

These wide sets of atrium design parameters can be categorized into four groups which are mainly related to building geometrical characteristics, materials physical characteristics, ventilation strategy and shading (L. Wang et al., 2017; Hussain & Oosthuizen, 2012).

2.1.4.1 Building Geometrical Characteristics

Regarding atria: building geometrical characteristics are including the atrium geometrical form, orientation, adjacent spaces features, atrium type, roof openings, glazing area (L. Wang et al., 2017; Laouadi et al., 2002), ceiling height (Fini & Moosavi, 2016), atrium shape, skylight form and orientation related to the sun and the well index (Ab Ghafar et al., 2019; Galal, 2019) in addition to the atrium proportions (Modirrousta & Boostani, 2016; Aldawoud, 2013). Fenestration features like openings position, number, shape and dimensions also powerfully contribute in the atrium performance (Fini & Moosavi, 2016).

2.1.4.1.1 Atrium Forms and Orientation

In terms of design, modern atria have diverse and complex geometries, and each one of these forms is acting differently under specific climatic conditions (Ab Ghafar et al., 2019; L. Wang et al., 2017), the atrium position within the building is considering as an influential factor in energy performance (Fini & Moosavi, 2016) as well as the adjacent spaces performance (Laouadi et al., 2002), whereas the selection of this form based on design considerations and spaces functions (Hussain & Oosthuizen, 2012) all these criteria should be related to the climatic conditions (Fini & Moosavi, 2016).

In spite of the infinite number of atria designs it can be classified to four main forms based on the surrounding sides of the atrium space (Baharvand et al., 2013), these forms are centralized or closed form, open-sided or semi-enclosed form, linear form and attached form (Modirrousta & Boostani, 2016; Douvlou, 2004).

The centralized or closed atrium is surrounded by the building spaces and defined with the edges of these spaces, in this kind of atria the only source of daylight is the glass roof. In the open-sided atrium which also called semi-enclosed it has one, two or three fully or partially glazing sides, this atrium is sitting within the building with one exterior side, the roof in this form could be glass or open. Linear atrium is occupying an intermediate place between two masses, the atrium may include circulation, and roof and end sides are consisting of glass. The last form of atrium is the attached one which is connected to the building in one side, with three exterior surfaces (Modirrousta & Boostani, 2016). Figure 3 shows the atrium general forms.

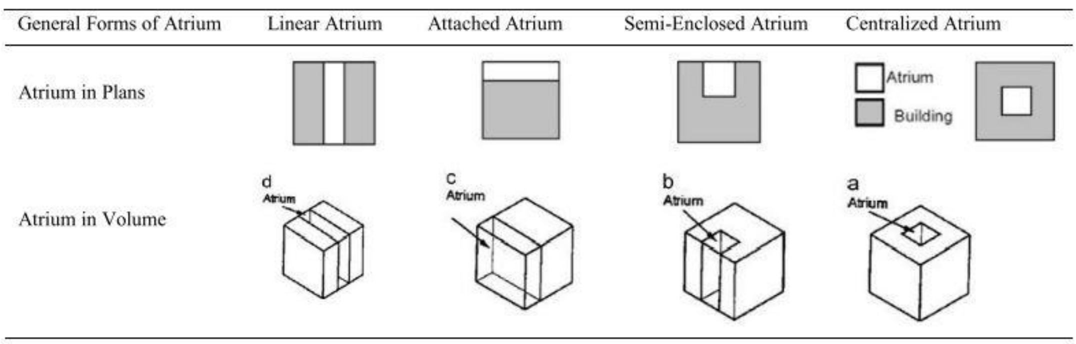


Figure 3: Atrium General Forms. Source: (Modirrousta & Boostani, 2016).

In case of deep plans or design limitations of applying southern atrium, Modirrousta and Boostani, (2016) suggested that the centralized form of atrium will be an appropriate solution, while (Fini & Moosavi, 2016) asserted that the most appropriate forms for hot regions are linear and closed atria as these two forms reducing the heat transfer while attached form fits temperate climates. Furthermore, for the purpose of energy consuming: Ab Ghafar and others, (2019) tested one sided atrium in different orientations under tropical climate, and concluded that southern atrium performed the worst whereas northern oriented atrium performed the best for the four directions.

Surprisingly, most studies focused on tropical and hot climates, while diverse climates like the Mediterranean was not covered enough.

On the other hand, for the same form of the atrium, different results will be obtained with changing the proportions of the space which is represented with length, width and height (Aldawoud, 2013), as well as modifying the opening or enclosure to adjacent spaces (Laouadi et al., 2002). Moreover, changing the atrium orientation remarkably affects the thermal performance for the same form (Ab Ghafar et al., 2019).

Changing the atrium ratio which is represented with the relationship between the height and the width of the atrium space H/W noticeably affects air velocity and as a result will affect the atrium thermal performance. According to Su (2017), as the H/W ratio in the atrium is small, the air speed will increase and consequently ventilation will reduce the humidity and air temperature, these indicators express the thermal behavior of the space which determines the users' comfort as well.

2.1.4.1.2 Atrium Roofs and Skylights

Since the energy exchange of the building is controlled by the envelope (Sozer, 2010), studies emphasized the importance of the roof as a dominant building envelope which controls about two-thirds of the total energy performance (C. Liu et al., 2016), and this returns to the fact that it is the most exposer element to sun radiation which causes heat accumulation and consequently higher indoor temperatures (Roslan, Halipah, et al., 2016).

In the case of skylights; building thermal performance is directly affected by their design alternatives (Abuseif & Gou, 2018) where modifying roof form can enhance the atrium performance (Abdullah & Wang, 2012). However, unchecked design parameters that correlating to interior thermal comfort will lead to excessive heat gain and convert the space to a greenhouse (Al-Obaidi, Ismail, & Rahman, 2014).

Interestingly, atria roofs and skylights are classified into many categories, the most common classification is according to their geometry, as these roofs could be flat, pitched with different inclination angles, curved or other configurations (Ab Ghafar et al., 2019; Douvlou, 2004) the variation of these forms is resulted of that each form works differently in a specific climate and so the best form for one climate might be the worst for another.

However, changing the roof form in some cases may not have considerable effects, so the selection process of the roof geometry should consider an inclusive study relative to other parameters (Abuseif & Gou, 2018). In this regard, Laouadi et al., (2002) tested various roof forms in the cold climate of Canada and concluded that pitched skylight roof improves solar heat gain for different types of atria in winter, while it slightly affects the performance in summer.

Another classification for atria roofs is top-lit and side-lit roofs (Baharvand et al., 2013) or a mix of both (Hussain & Oosthuizen, 2012), which depends on the openings' position. An example of the adaptive design of skylight with climatic conditions, the side-lit atrium was proposed as an alternative for the top-lit in tropical climate (L. Wang et al., 2017; Baharvand et al., 2013).

To study the effect of different roofs solutions in tropical climate Abdullah and Wang, (2012) examined two top-lit and side-lit roofs alternatives with other ventilation strategies, they define cooling loads, mean radiant temperature and air temperature inside the building as an indicators for thermal comfort evaluation and they concluded that the side-lit roof is more favorable . Another study was conducted by Baharvand et al., (2013) in the same topic in Malaysia, results showed that using the side-lit in such tropical climate decreased indoor temperature and improved the pattern of airflow whilst top-lit increased air velocity at the openings.

2.1.4.1.3 Atrium Fenestration and Openings Design

Openings design is a key role to achieve optimum natural ventilation since it controls air entry and exit to and from the space, different characteristics define this performance and affect the airflow, these properties include openings size, window to wall ratio (WWR), distance between inlets and outlets and position (Aflaki, Mahyuddin, & Mahmoud, 2015). For atria: the design of these openings size, openings number, arrangement and distance between openings strongly affect the airflow inside atrium space and adjacent areas which will consequently achieve thermal comfort (Mirrahimi et al., 2016).

To predict whether natural ventilation can be an effective way to improve thermal comfort in a side-lit atrium building: Wang and Abdullah, (2011) tested the airflow and temperature differences within atrium by changing openings sizes ratio and arrangement, results indicated that the greater inlet to outlet ratio >1 produces best thermal comfort, these results are obtained due to the fact that the smaller inlets decrease the air pressure at the outlets and cause air speed reduction. On the other hand, increasing the ratio of the outlets enhances the air pressure, the produced ventilation reduces the indoor air temperature, whereas using the same sizes for inlets and outlets and changing the openings arrangement and shape did not improve thermal conditions for the atrium and adjacent spaces. Li et al., (2014) highlighted that the air exchange within the atrium is caused by the pressure difference between inlets and outlets rather than the openings’ sizes, in other words, air will flow out from the low-pressure openings.

Moreover, another study was conducted by Abdullah and Wang, (2012) revealed that in spite of that large inlets and outlets at the lower and higher levels respectively reduced air temperature in users spaces it’s also decreased the upper part temperature and consequently affected the air stratifications which created mixed indoor air.

For the inlets’ size, Su (2017) confirmed the importance of increasing the inlets’ size rather than the outlets to improve the atrium natural ventilation. About the same concept: Moosavi et al., (2015) studied a stack flue assisted atrium in a tropical climate, and suggested >15 as a ratio for inlets to outlets to optimize the atrium cooling process and enhancing stack effect by blocking reverse air movement.

To conclude, a greater inlet to outlet ratio should be considered as the most influential factor for naturally ventilated spaces. Most of the given results are related to side-lit atria under tropical climates where generally top-lit atrium is not preferable, whilst top-lit atrium was not tested even in different climatic conditions.

2.1.4.2 Materials Physical Characteristics

Another significant design parameter of atria is building materials properties; material characteristics for the building elements like walls, floors, ceilings, roofs, frames and transparent panes for windows and skylights are greatly impact the building environment (Ab Ghafar et al., 2019; Galal, 2019).

For skylights and glazing surfaces; inappropriate glazing materials will generate an undesired indoor conditions which will be caused by excessive heat transfer for both summer and winter (Al-Obaidi, Ismail, & Rahman, 2014) or glare (Aldawoud, 2013) that consequently affecting energy consumption, so this emphasizes the importance of following a comprehensive and systematic study in the initial stages of design (L. Wang et al., 2017).

Optical and thermal properties of glazing material are the dominant influencers in the indoor environment for both lighting and thermal performance (Al-Obaidi, Ismail, & Rahman, 2014). Therefore, providing the desired day-lighting simultaneously with mitigating heat transfer are the reference criteria for glazing surfaces' selection (Sunanda et al., 2018).

To conclude, the selection criteria of building material should be based on their thermal mass which strongly will affect the building's thermal performance and energy consumption.

2.1.4.2.1 Thermal Properties

As the heat gained through glass affects indoor air temperature then there are two main characteristics indicate glass efficiency; the first one is the solar heat gain coefficient SHGC which defines the solar radiation passing through the glazing pane by absorption and transmission and heats inner spaces (Hussain & Oosthuizen, 2012), this coefficient is expressed with a number ranges between 0-1, whilst the second one is the U-value that represents the conductivity or the thermal heat transfer factor of these transparent panes (Laouadi et al., 2002).

Both SHGC and U-value determine the amount of heat flux and consequently the thermal behavior (Galal, 2019). Logically, mitigating the heat flux minimizes energy consumption, for this, Abuseif and Gou (2018) recommended the integration of shading devices or reflective materials with low U-value skylights.

In addition to common types of glass; compound types of glass with different materials that have specific thermal properties could also be used to get a better performance like argon-filled glazing (Sunanda et al., 2018) and silicon-aerogel (Yang et al., 2019). Phase change material which is known with PCM enhances the thermal performance with its storing thermal capacity (C. Liu, Bian, Zhang, Li, & Liu, 2018; C. Liu et al., 2016).

2.1.4.2.2 Visual Properties

visual comfort is based on a specific group of environmental tools of assessment which related to international standards like LEED and BREEAM, these parameters are glare control, appropriate daylight, views quality and internal and external lighting level control (Galal, 2019).

Light evaluation considers light quantity and distribution that is basically measured with illumination level and daylight factor, these factors are recommended by European standards depending on space activities, for instance; the recommended lluminance level in atrium ranges between 50-200 lux (Sunanda et al., 2018) while reading function spaces as libraries requires 300 lux and 2-5% for illuminance and daylight factor respectively, to define the visual properties; appropriate visible light transmittance VT is the determinant factor for glazing openings (Galal, 2019). Large areas of glass need low thermal and visible coefficients (Al-Obaidi, Ismail, & Rahman, 2014). Thus, in hot climates lower SGHC, U-values are required (Raji, Tenpierik, & Dobbelsteen, 2016).

To summarize, materials properties selection strongly based on space function and characteristics like fenestration area and position, each space requires specific design considerations.

To conclude the previous sections; having a comprehensive architectural and systematic thinking is produced by creating relationships between different variables, these variables are: influenced, design and affected variables which represent climate, building materials and occupants' comfort respectively (Al-Obaidi, Ismail, & Abdul Rahman, 2014). Figure 4 correlates the relation between climates as an independent variable and hot it controls the skylight design which produces the indirect loads, this frame emphasizes the importance of these variables in design decisions. Thus, this map obviously formulates a theoretical and systematic outline that should be followed.

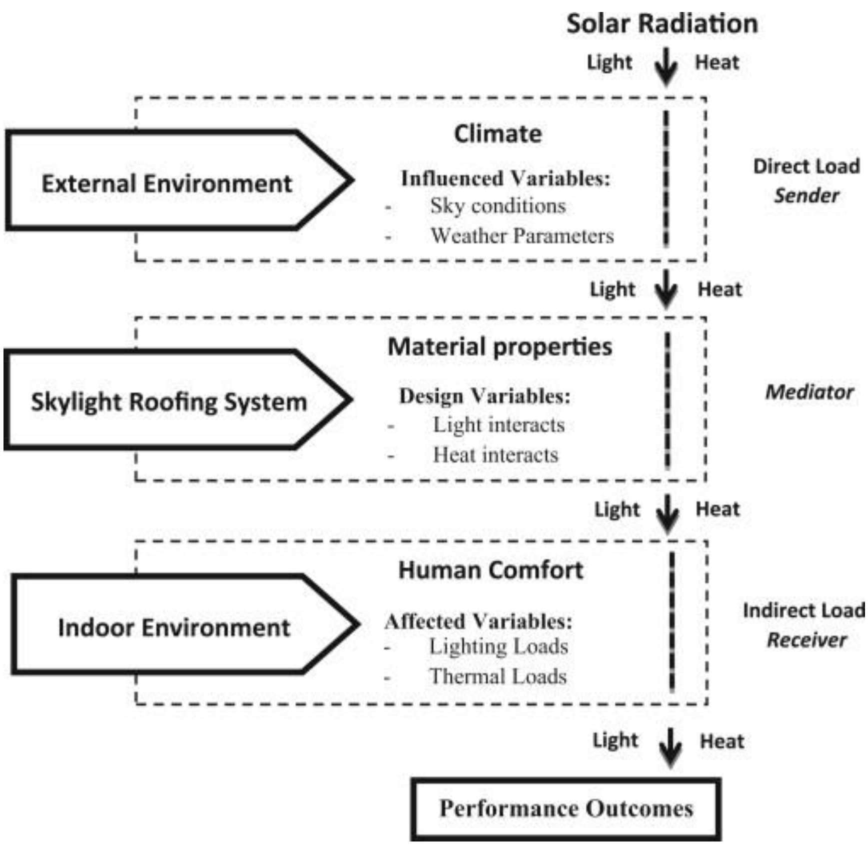


Figure 4: Skylight Design Approach. Source: (Al-Obaidi, Ismail, & Abdul Rahman, 2014).

2.1.4.3 Ventilation Strategies in Atrium

In atria, there are two main driving forces that create natural ventilation which are buoyancy force and wind force, natural ventilation in atrium space mainly occur due to buoyancy driven force as Figure 5 illustrates, but outdoor winds may affect, enhance or oppose this force (Gan, 2010), to have a better understanding of ventilation process in atrium buildings, further explanation of natural ventilation forces in section 2.2.1.

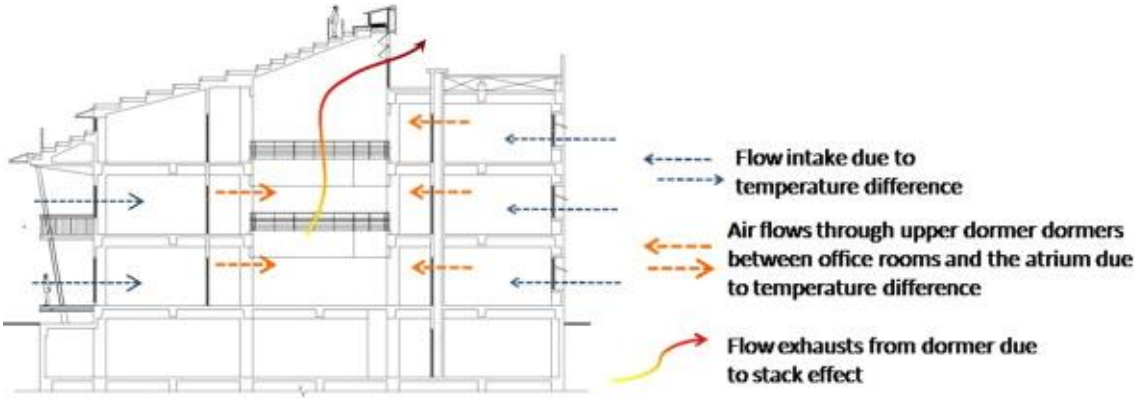


Figure 5: General Ventilation Concept of The Atrium. Source: (P. Liu, Lin, & Chou, 2009)

As a conclusion for the above, after expressing the atrium design parameters' categories it can be clearly noticed that all parameters strongly affected by external conditions as well as each other, and influencing the outcome as a result. Thus, obtaining more accurate results necessitates checking a wider set of design parameters.

2.1.5 Atrium Design Factors

Basically, external variables which are represented with climate is the determinant factor for designing atria (Fini & Moosavi, 2016), these variables are temperature, solar radiation, and wind (Moosavi et al., 2014). Various climatic regions harvest different amounts of solar radiation according to their latitudes and longitudes (Ab Ghafar et al., 2019) and thus obtaining the optimum atrium design requires elaborated testing for all design parameters to control the internal variables and getting desired results.

Furthermore, the position of atrium building within the urban context plays a great role in this regard as the surrounding buildings may increase the sheltering and thus the ventilation performance will be affected which emphasize the importance of utilizing the atrium roof to create temperature differences and pressure gradient (Sharples & Bensalem, 2001).

Moosavi et al., (2014) correlated the atrium design parameters and variables, in addition to the expected results based on the measured data as it is seen in Figure 6.

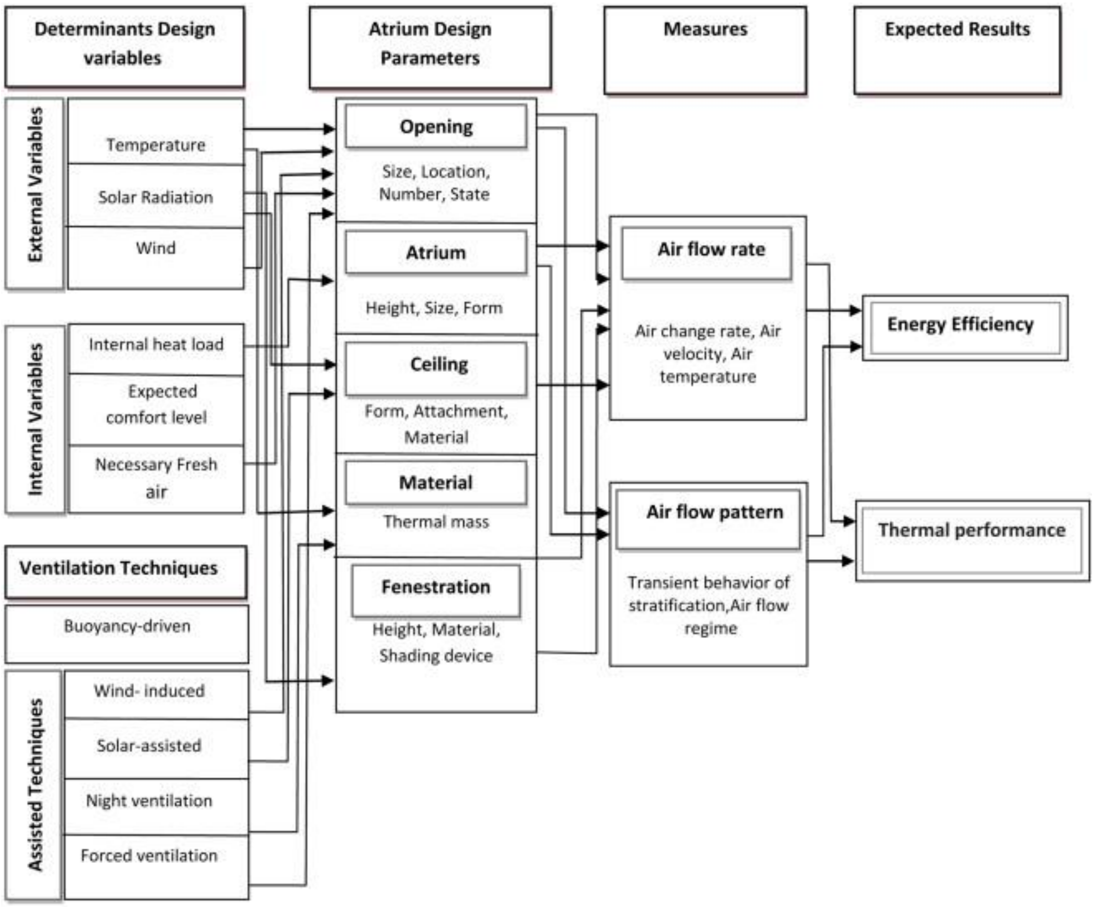


Figure 6: Atrium Design Parameters and Variables. Source: (Moosavi et al., 2014)

2.1.6 Atrium Thermal Phenomena

Mainly, two natural phenomena occur in the atrium which directly influence the thermal behavior and energy consuming in atria, namely the greenhouse effect and the stack effect. In general, these two effects can be considered as heating and cooling strategies in the atrium.

2.1.6.1 Greenhouse Effect

Basically the greenhouse effect is produced in spaces with transparent envelopes when the solar radiation with short-waves penetrates glass and heats internal materials, heated up material then reradiate long-waves which cannot pass back through the glass to outside, thus heat is trapped inside the atrium and increases the air temperature (Najafabadi & Alibaba, 2013).

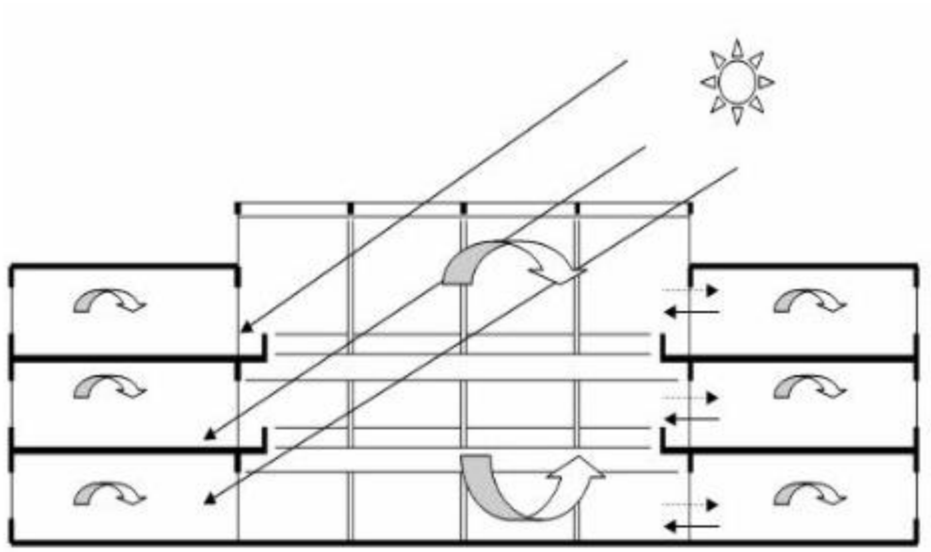


Figure 7: Greenhouse Effect in Atrium During Winter. Source: (Göçer et al., 2006).

Interestingly, Figure 7 shows that this effect can be beneficial during the heating season in moderate climates, as an example; the Mediterranean climate can benefit this effect as it keeps the interior space as well as the adjacent spaces warm. Whereas, this effect considered a problem in the cooling season due to overheating and not being able to extract this heat. To overcome this issue; glazing surfaces' characteristics like absorption and re-radiation should be carefully chosen as well as the ratio of the transparent surface (Douvlou, 2004).

The benefit of the greenhouse effect is considered as one of the most passive heating strategies which mainly gather the solar heat and trap it to keep the building warm for a longer time, moreover, this spaces could be provided with greenery elements like plants which use the high temperatures for growing, additionally, the benefit of the heated air in these spaces is not limited to the space itself, it also provides the surrounding spaces with the heated air to improve the thermal comfort for the mentioned period. Mostly, the insertion of the greenhouse spaces takes the southern orientation to maximize the solar gathering, in some cases, these space can have interior and exterior parts within the building, the other type of this space be in the form of inner central space with the glazed roof (Modirrousta & Boostani, 2016).

2.1.6.2 Stack Effect

Figure 8 explains the principle mechanism of the stack effect, it is also called Buoyancy-driven effect, which is based on the vertical air movement resulted by temperature differences, with the existence of lower and upper openings air rises up and pulls colder air from outside via the lower inlets which is caused by pressure differences as well (Grabe, Svoboda, & Bäumler, 2014). This technique is greatly beneficial for atria natural ventilation to extract heated air (Liang et al., 2019), since the atrium is extended vertically, the air temperature will be higher at the upper part of the space, the insertion of inlets have to be at the lower levels while the outlets located at the top part. Outer airflow over the upper openings will create pressure differences and improve the suction (Douvlou, 2004).

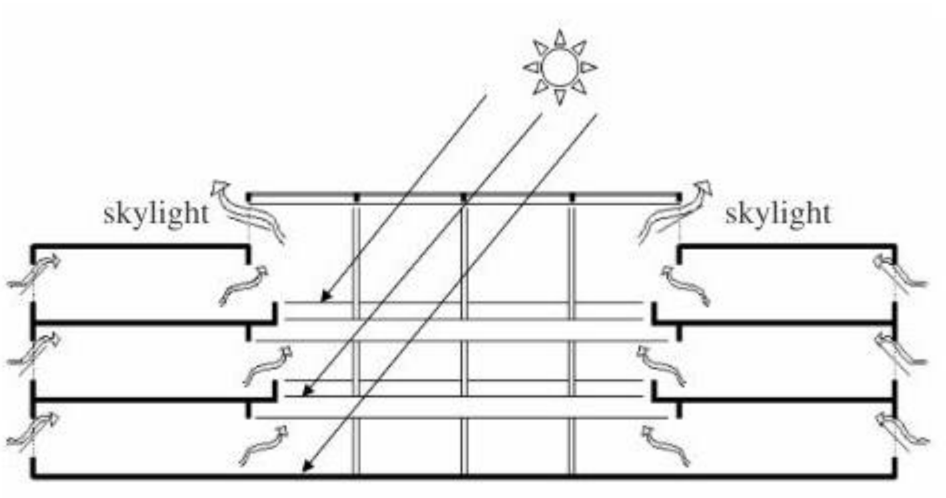


Figure 8: Stack Effect in Atrium During Summer. Source: (Göçer et al., 2006).

To sum up, both of these effects can be a problem or a solution with respect to climatic conditions, this strongly depends on design decisions and alternatives.

2.1.7 Atrium Thermal Performance

Beside the whole benefits which were mentioned in the previous sections, atrium thermal performance is considered as the most significant aim for these spaces, this importance returns to its capacity in adjusting internal conditions for the space itself as well as the adjacent spaces, the main goal behind using atria in ancient architecture was totally environmental, while it was employed in modern architecture for aesthetic, lighting as well as protection.

Lately, re-attention to the sustainability of buildings highlighted the atrium energy-saving potential. This potential comes from the atrium capability of hiring architectural elements for obtaining users' comfort with the help of natural resources. Moreover, a proper design for atrium strongly affects energy performance for this buffer zone by mitigating and sometimes eliminating the use of mechanical equipment (Douvlou, 2004).

However, regarding the atrium skylight form design, (Douvlou, 2004) conducted a parametric study of atrium design parameters to predict the thermal performance under the Mediterranean climate, the results concluded that central atrium is mostly recommended for this climate, moreover, the flat roof as well as the vaulted roof, have the same undesired indoor thermal conditions without the insertion of shading elements. Regarding the appropriate glazing materials, the study emphasized the importance of combining different glass like low-e, reflective, and clear glass materials to achieve the best thermal performance. Furthermore, different ventilation rates by changing the openings' size are supposed to be adapted during winter and summer to obtain the desired indoor conditions. A previous study was conducted by Douvlou and Pitts (2000) confirmed that the insertion of the shading elements for the atrium in this climate will reduce the natural lighting in the atrium as well as the surrounding spaces.

A study was conducted by Palma Rojas (2013) assumed that atria in the Mediterranean climate can work effectively around the year, as winter temperatures are close to the cold regions where the atrium has proven its efficiency as a thermal buffer zone, while the summer-time can benefit night ventilation. Moreover, the study confirmed that atria in the Mediterranean climate consume a high level of cooling energy due to the thermal discomfort in such spaces. A simulation was produced by Tas software to improve energy saving by a set of design suggestions including changing glazing materials, ventilation systems, and shading systems. Results indicate that more than two-thirds of energy saving can be achieved by the use of double glazing with fully atrium shading, and operating ventilation during day and night. Regardless of the cooling energy saving achievement, with the implementation of shading elements then the visual comfort can be affected.

To emphasize the importance of employing ventilation passive strategies in heat reduction in the atrium, Moosavi et al. (2015) tested different passive strategies in a four-storey atrium with a southern glazed façade, in addition to a slightly tilted roof glazed to the east. The study confirmed the efficient role of natural ventilation in indoor temperature and humidity level reduction. Moreover, the best results were obtained when the whole inlets on the lower floors were opened simultaneously with partially opened outlets in the upper level, the atrium benefit both cross and stack ventilation for indoor temperature improvement. In spite of the thermal comfort improvement in the atrium space, the effect of these strategies on the adjacent offices was not clear.

Interestingly, concerning thermal comfort in a simple atrium, Hussain and Oosthuizen (2012) examined how buoyancy-driven natural ventilation in the atrium can be improved by solar radiation in two steps. Firstly, testing different atrium configurations where the results showed that the atrium with solar chimney recorded the best results regarding indoor temperatures and airflow. Moreover, for this configuration, another set of design iterations were tested to predict the thermal comfort in the form of PMV and PPD outcomes. It worth to be mentioned that this study was tested under steady outdoor conditions, thus, in case of diverse climatic conditions, thermal comfort cannot be predicted.

On the other hand, to define the optimum energy-efficient atrium geometry; Aldawoud (2013) studied how the atrium forms and proportions affect its thermal performance in different climatic regions in the USA, the findings confirmed that extended atrium shape consumes more energy due to the high exposure to exterior conditions.

Confirming the significant role of solar energy in atrium buildings, Modirrousta and Boostani (2016) study asserted that atrium design factors strongly affect the atrium thermal and visual behavior, it's also emphasized the efficient role of the atrium as a passive element by confirming the visual comfort and natural ventilation as well as the gathering function.

To achieve the desired indoor conditions in atria, Ab Ghafar and others (2019) assumed a comprehensive relationship between the climatic solar characteristics and the atrium thermal behavior, thus the skylight design and materials are supposed to take the glazing materials properties and climate in consideration. Consequently, the study asserted that initial study should be conducted to predict the thermal performance of the atrium, where inappropriate atrium design leads to excessive indoor heating and high energy consumption, for this purpose, the study conducted sequential simulations and concluded that the atrium skylight design strongly affected by the solar radiation, moreover, various climatic conditions result in different cooling and heating energy loads for the same atrium design, whereas for the same climate, changing the skylight angle, design, and orientation also affected energy consumption. The results also revealed that the central atrium consumes the minimum heating and cooling loads. Regarding the orientation and the angle, the study confirmed that in the tropical climate the northern and the more inclined skylight consume less energy, moreover, the curved roof with one-sided northern skylight was recommended for such climate. Whereas these outcomes cannot be generalized for other climatic regions with different weather characteristics.

Regarding the materials' characteristics, and the impact of top glazing atrium materials on the visual and thermal behavior, Galal (2019) concluded that the glazing materials characteristics like SHGC, DST, U-Factor, and VT show the material performance, moreover, the study recommended the low-e glass for the best thermal performance.

The atrium proportions affect the thermal behavior significantly, where the less height to width ratio increases the air movement between the atrium and the adjacent spaces, which consequently enhances the indoor thermal comfort (Su, 2017).

Moreover, by operating natural ventilation in a lateral western atrium integrated with double skin façade DSF system, thermal performance had been improved and thus energy consumption was mitigated significantly during cooling season, taking in consideration the optimum design for openings' positions and sizes (Tanaka, Okumiya, Tanaka, Young, & Watanabe, 2009).

2.2 Passive Design Strategies

Studies declared that buildings' HVAC systems consume a great amount of building energy (Chenari, Carrilho, & Gameiro, 2016) simultaneously with the increased global concerns about sustainability. Thus, the concept of benefit passive design strategies was highlighted which mainly based on the replacement of ambient energy sources instead of the paid ones like electricity, these resources cover natural ventilation, daylight and solar energy . (URL 1 :"Sustainable Building design at Autodesk Sustainable Building Design ," 2018)

Passive cooling building term is used to characterize the architectural design that responds to climate and create convenient indoor space conditions utilizing natural resources, and also it could be a description for the technique that protects indoor space from exterior heat flux as well as extracts inner heat out (Aflaki et al., 2015). The major attention is paid for the inner space comfort is due to the considerable impact of this environment on users' health (Chenari et al., 2016), both physical and psychological wellness ought to be the guideline of space designing (Lau et al., 2019). There are many techniques that can be applied as a passive design strategies, but this section mainly focuses on natural ventilation and ventilated building envelope, Jomehzadeh (2017) summarized the passive cooling techniques in buildings as Figure 9 shows.

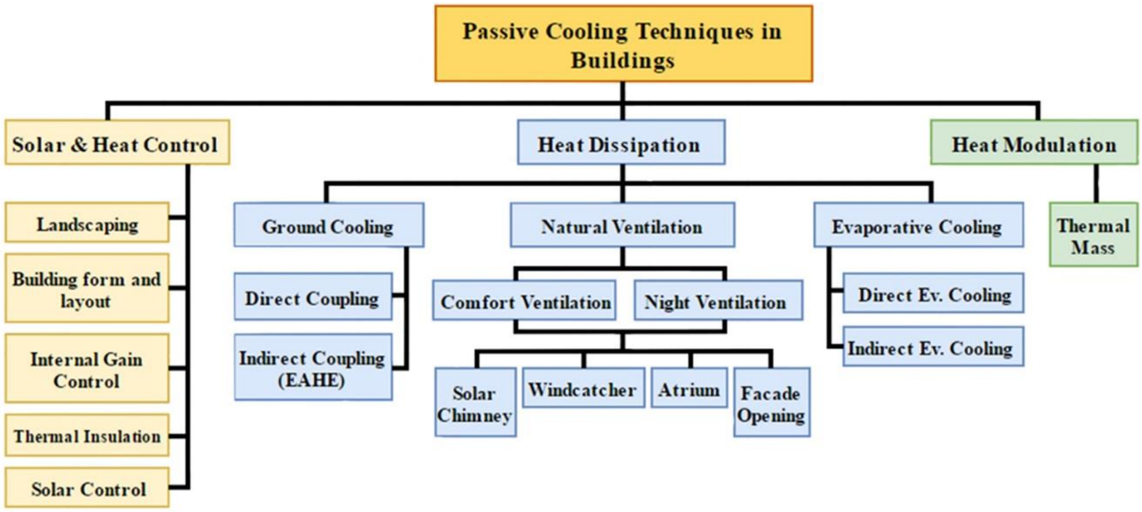


Figure 9: Cooling Techniques in Buildings. Source: (Jomehzadeh et al., 2017).

2.2.1 Natural Ventilation

In general, there are three ventilation strategies in spaces which are: mechanical ventilation, hybrid ventilation, and natural ventilation. Recently, attention has been directed towards passive strategies to minimize energy consumption, by utilizing natural resources like wind and solar radiation (Moosavi et al., 2015). Regarding this, natural ventilation has proved its efficiency in minimizing energy consumption and CO_2 emissions produced by HVAC systems' operation (Chenari et al., 2016), as well as improving indoor air quality and thermal comfort (Omrani, Garcia-hansen, Capra, & Drogemuller, 2017; Jomehzadeh et al., 2017). On the other hand, utilizing natural ventilation efficiently is supposed to be designed according to the exterior climatic conditions which vary from one region to another (Y. Chen, Tong, & Malkawi, 2017).

Natural ventilation (NV) basically depends on natural air movement between indoor and outdoor, thus designing this movement is one of the influential strategies that enhances indoor conditions as well as decreases energy consumption (Chenari et al., 2016).

The improvement of indoor environment includes providing fresh air that achieves appropriate air quality beside controlling indoor temperature to prevent overheating and thus improving occupants' thermal comfort (Jomehzadeh et al., 2017), these ventilation rates differ from one objective to another where thermal comfort, in general, requires higher rates than indoor air quality. In this regard hybrid systems of natural ventilation which is aided by fans could be beneficial (Fini & Moosavi, 2016).

Mainly, natural ventilation is produced by wind effect and buoyancy effect; pressure differences created by wind direction with respect to the building openings positions whereas temperature and height variations between air entries and exits make buoyancy effect (Aflaki et al., 2015).

Many aspects affect natural ventilation performance; ventilation mode, openings design, area, building orientation and openings to wall ratio, the most influential feature is the ventilation mode (Omrani et al., 2017). Ventilation modes define the air movement inside the space by placing inlets and outlets to get the desired design, it can be single-sided, cross ventilation or stack effect (Chenari et al., 2016).

2.2.1.1 Wind Effect

Wind effect causes by pressure differences, when it blows on a building it creates positive pressure in the windward direction that faces the wind, a negative pressure then be created in the leeward side of the building that establishes a suction force, these pressure differences allow fresh air to enter the building.

Two wind driven ventilation types are produced by wind effect: single sided and cross ventilation, in single sided ventilation openings are placed in the same side, whereas cross ventilation openings are set on opposite sides (Shetabivash, 2015). In case of high wind speed, then pressure differences will be increased and this enhances spaces ventilation. To understand the wind forces mechanism, Bangalee, Lin, and Miau (2012) analyzed the total flow pattern in and outside the building, this analysis provided wider explanation about how windows distribution affect airflow and define air inlets and outlets, while positioning openings in the windward and leeward specify air entrances and exits respectively that agrees with pressure principles, single-sided windows work as air inlet and outlet at the same time. Figure 10 illustrates the wind driven ventilation.

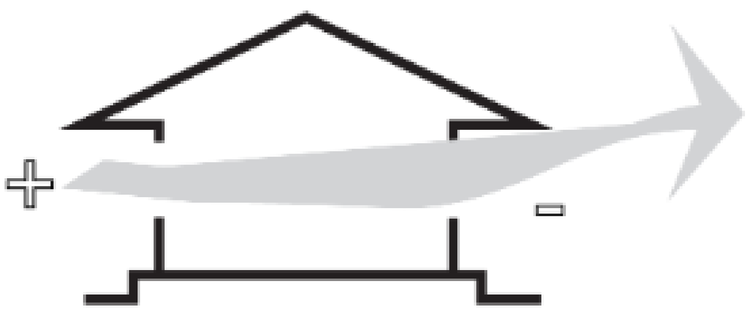


Figure 10: Wind Effect Principle Work. Source: (Faggianelli et al., 2013)

2.2.1.2 Stack Effect

Stack effect apparently drives fresh air in lower levels without the existence of wind forces which produces a steady air movement as it can be seen in Figure 11, moreover, the continuous air circulation significantly mitigates humidity (Moosavi et al., 2015). Even though wind catchers benefit the stack effect, it will not be effective in the absence of outer airflow (Jomehzadeh et al., 2017).

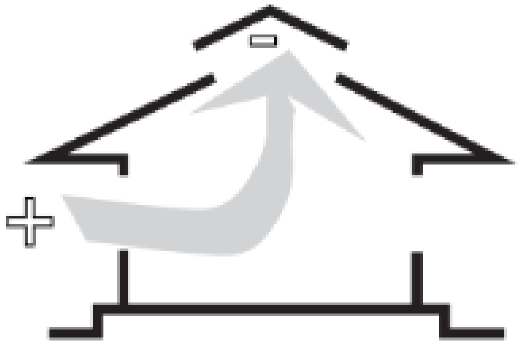


Figure 11: Stack Effect Principle Work. Source: (Faggianelli et al., 2013)

Fenestration plays the key role of flow rate in atria as well, and so to obtain the optimum effect, inlets and outlets must be set precisely, in this regard, Ji and Cook (2005) highlighted that using the same size of inlets for different levels reduces the airflow and this returns to the fact that when the height of floor increases the pressure will be decreased, and so, using larger openings in the upper floors to enhance flow rate could be effective. From another point of view, Abdullah and Wang (2012) asserted that extending atrium height over the last level is essential to avoid hot air returning to the upper floors and thus improve thermal comfort as hot air will be trapped away from occupants' spaces. Moreover, in their study, they also emphasized the importance of computer simulation in the atrium thermal performance prediction that gives the chance for the designers to test different design parameters, and thus helping them to select a suitable design for the optimum thermal comfort performance.

The definition of air inlets and outlets facilitate controlling airflow and thus makes space ventilation predictable. As it can be clearly noticed that openings design is an important factor where location, size, area and shape strongly affect the natural ventilation process. Changing inlets and outlets sizes creating pressure differences. Figure 12 clarifies the ventilation pattern in the atrium as it was prepared by Moosavi (2014).

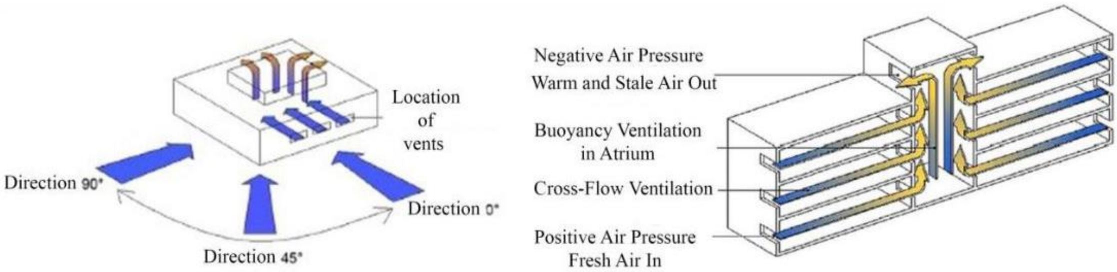


Figure 12: Wind Effect and Airflow Patterns of Ventilation Process in Atrium.
Source: (Moosavi et al., 2014).

2.2.2 Natural Ventilation For Cooling as A Passive Design Strategy

The beneficial level on natural ventilation greatly depends on climate; where hot climate might need one or more passive or active strategies to reduce the use of mechanical systems, while cold climate regions employ natural ventilation to provide indoor air quality for spaces as there is no or minimal need for cooling in summer. Moderate as well as humid climates' buildings are considered the most recipient of natural ventilation for thermal comfort (Santamouris, 2012, p. 141).

Considering climatic conditions which differ from one region to another is the key role of utilizing this technique. In hot climates; as NV is one of the most favorable passive cooling strategies (Omrani et al., 2017), studies confirmed that this strategy can be effectively utilized in Mediterranean climate (Y. Chen et al., 2017), even though, the application of this strategy should be carefully designed and tested in preliminary stages of building design to avoid undesired results like heat (Aflaki et al., 2015).

In other words; decision making should mainly achieve an optimum design of controlling exchanged air rate according to the indoor needs with eliminating heat gain during summer and reducing heat loss in winter (Modirrousta & Boostani, 2016).

Utilizing natural ventilation as a passive technique can be applied mainly in:

* **Building components/ systems**: this strategy includes the addition of wind tower (ventilation towers) as a specific component to improve stack effect combined with wind effect in some cases, moreover, the windows in the elevations may contribute in this process where these components integrated with the building structure and utilizing natural forces.

*** Operational principle:** in general, ventilation is based on the use of natural ventilation to cool down the building during the day, while this strategy depends on eliminating heat during the night, applying all day ventilation has a great potential in decreasing temperature in summer (Al-tamimi, 2015).

*** Cooling effectiveness:** in some cases, using natural ventilation cooling alone cannot be enough, that leads to combine natural and mechanical which called hybrid or mixed mode ventilation (Santamouris, 2012).

The benefit of NV in thermal comfort enhancement as a cooling tool can be achieved by direct and indirect ways; direct by cooling down the occupants and indirect by decreasing the building masses' temperature during night ventilation (Chenari et al., 2016).

Ventilation towers: it's also called chimney, this building component enhances natural driving forces and it's widely used in new low-energy strategies (Santamouris, 2012). It could be in a way of a thermal chimney, solar chimney or wind chimney, this part explains these elements on details.

Thermal chimney: The solar chimney or thermal chimney is defined by the position of this tower. Thermal chimney principle work depends on generating buoyancy forces as a result of vertical temperature differences that makes hot air with light density moves up and colder air with heavy density enters from envelope openings which enhances cross ventilation within the space, the advantage of using solar chimney is represented with its ability of retaining of heated air far away from space users (Santamouris, 2012). whereas solar chimney is basically added to the south side of the building to gather heat, this type greatly beneficial during summer to improve ventilation, amazingly this chimney creates a passive cooling ventilation (Chenari et al., 2016), improvement of this chimney performance can be achieved by combining it with other features like water as it was used in ancient roman architecture (Nugroho, 2009). Figure 13 explains the principle work of solar chimney.

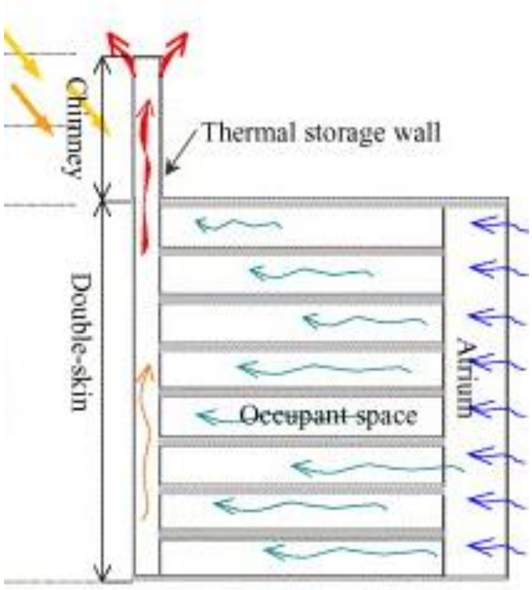


Figure 13: Solar Chimney Principle Work. Source: (Ding, Hasemi, & Yamada, 2005)

Wind chimney: These towers greatly utilize wind pressure differences which are generated by air moving around blocks, and usually these elements are placed higher than the buildings. There are two major types of these chimneys which are: the wind catcher, which has inlets and outlets with positive and negative pressures respectively within the same element, whilst the outlet type depends on suction force at the exhaust openings in leeward side with the help of buoyancy forces inside the building (Santamouris, 2012), this also works in case of low air speed so the tower works as a chimney.

Another alternative for this type is inlet type that catches air from by the upper inlet and extracts it by another building outlet, this mostly used in regions with one direction air (Jomehzadeh et al., 2017).

To explain that; when the indoor air temperature is higher than the outdoor then interior hot air with low density will rise up to be exhausted by the leeward outlet, this extraction creates pressure differences inside the building and pulls the colder air with higher density from the windward inlet (Jomehzadeh et al., 2017).

In spite of utilizing wind catchers as a passive cooling technique, it might be integrated with other strategies for heating purposes as well, the great influence of wind speed must be taken in consideration (Abuseif & Gou, 2018) which enhances their performance, this integration will be beneficial in regions with hot summer and cold winter.

The importance of this design clearly appears in the buildings that cannot benefit buoyancy effect alone to improve their thermal comfort, thus, achieving it requires associating wind catcher with their design (Z. R. Li et al., 2014).

2.2.2.1 Night Ventilation

Night ventilation is considered as one of the most effective strategies of saving energy as well as improving indoor thermal comfort, this strategy can be applied in both mechanical and natural way, moderate climates like Mediterranean climate has the ability to operate natural night ventilation to achieve better thermal comfort. The mechanism of this strategy is based on the fact that air temperature cools down during the night. Solid materials have a high thermal mass which represents the solar heat storage ability of these materials during day and re-radiate it during the night, and thus; utilizing this cooler airflow helps the solid parts of the building to get rid of the re-radiated heat (Z. Wang, Yi, & Gao, 2009). It's worth mentioning that material density controls the thermal mass; where heavy construction like concrete has higher thermal mass than light elements like wood. Thus, operating night ventilation is recommended to decrease buildings' indoor temperatures.

2.2.3 Double Skin Envelopes

According to Mirrahimi et al., (2016) the main function of the building envelope is to define and protect the interior spaces from the exterior conditions. Therefore, it works as an external barrier to the indoor environment as well as provides comfort (Mirrahimi et al., 2016). The external climatic conditions must be the prominent factor in the envelope design-decision (Al-Obaidi, Ismail, & Abdul Rahman, 2014). Architects and designers attempt to overcome the undesired thermal effects of huge transparent building envelopes by adding an extra layer of glass. The second layer proved to be efficient in improving the thermal performance within different environments, and this efficiency varies depending on the climatic conditions in which they are used (Barbosa et al., 2015).

Lately, double skin envelopes and ventilated building envelopes (roofs and facades) have been considered as one of the promising applications for heat reduction and energy consumption, this development was a response to the global calling of implementing passive cooling strategies for temperature reduction as well as energy saving (Ciampi, Leccese, & Tuoni, 2003), since that time, scholars have investigated these envelopes widely to obtain deep understanding of this technique so that will help them to optimize their performance. Hot climates in particular, utilize the ventilated structures substantially (Gagliano, Patania, Nocera, Ferlito, & Galesi, 2012).

This section includes an explanation for the principle work of these envelopes and how do these strategies influence the internal conditions of spaces.

2.2.3.1 Double Skin Roof

Building envelope generally and roofs, in particular, affect indoor thermal conditions since they have direct exposure to solar radiation (Roslan, Ibrahim, Affandi, & Mohd

Nawi, Mohd NasrunBaharun, 2016; Abuseif & Gou, 2018), thus conventional roofs, transparent roofs, and skylights receive different amounts of heat according to the climatic conditions as well as the materials' properties (Al-Obaidi, Ismail, & Abdul Rahman, 2014). Moreover, these roofs cannot save indoor spaces temperatures during heating seasons. This high impact of roofs on indoor thermal conditions sheds light on improving roof performance. Lately, studies called attention to improve roofing design techniques (Abuseif & Gou, 2018) as well as integrate passive design strategies like ventilated roofs, skylights, and double roofs (Mirrahimi et al., 2016) to overcome the problems of heat gain and loss.

A double skin roof has been considered as one of the most influential methods for convective and conductive heat transfer reduction (Chang, Chiang, & Lai, 2008), in spite of that double skin roofs are strongly recommended in hot climates, these roofs have not been tested in diverse climatic regions.

The main concept of the double skin roof, which is known also with the ventilated roof is the air movement in the cavity (Roslan, Halipah, et al., 2016) which is formed between the original roof and the extra layer (Omar et al., 2017), this cavity isolates the inner layer by delaying temperature transfer (D. Li, Zheng, Liu, Qi, & Liu, 2016) while the extra layer protects the original roof from direct solar radiation (Zingre, Wan, Tong, et al., 2015), furthermore, the thermal performance of this roof strongly depends on the materials as well as the roof shape (Omar et al., 2017).Whereas the gap could be ventilated by both stack and wind effect which have been mentioned earlier, and because both of these effects are not stable; then the thermal performance of this gap is unsteady (Abuseif & Gou, 2018).

Decreasing the spaces temperatures basically occurs due to heat flux reduction and heat mitigation by the airflow (Gagliano et al., 2012), especially the upper floors and attics needs an adequate ventilated gap between the conventional roof and the added layer, appropriate floor proportions are also considered to be the most influential parameters in heat transfer mitigation (Roslan, Halipah, et al., 2016). Moreover, roof material properties are other influencers that significantly affect the heat flux, as an example; the outer layer is supposed to be reflective and absorptive (Abuseif & Gou, 2018). Furthermore, Roof slope, inlets, and outlets sizes and cavity thickness are also indicated to be crucial parameters (Lee et al., 2009). Although D. Li et al. (2016) study addressed the cavity thickness as a key design role for ventilated roofs, it's also confirmed that different climatic conditions strongly affect the final output.

Regarding the efficiency of double skin roof; Zingre, Wan, Wong, Toh, and Lee (2015) research results indicated that developed kinds of double roofs have a crucial impact on heat gain reduction more than other cooling roof techniques, moreover, the study confirmed the applicability of double skin roof in different climatic regions. Furthermore, the ventilated roof in hot climates could shorten the energy consumption to the half (Gagliano et al., 2012).

To achieve indoor thermal comfort, Roslan, Ibrahim, et al. (2016) suggested employing ventilated roofs as a passive design strategy for mitigating the heat flux from outside as well as extracting the hot air from the buildings. The determination of the optimum roof cavity dimensions directly affects the air speed and movement, moreover, the combination of adequate air cavity and appropriate roof inclination minimizes heat flux through the roof (Roslan, Halipah, et al., 2016).

To indicate the most crucial aspect affecting the heat flux within an inclined naturally ventilated roof: Tong and Li (2014) conducted a parametric study, the outcomes showed that the tilting angle and cavity width have less impact than the reflection and conduction properties of the two roofs' layers on heat transfer.

Double skin roofs can be implemented in residential buildings, for this purpose, Omar et al. (2017) tested the impact of inserting an external layer for a slightly inclined roof, results revealed 50% energy saving, moreover, with insulating the internal roof layer; energy consumption decreased to reach one-fifth of the conventional roof consumption. However, the results were obtained in terms of energy consumption, thus the indoor thermal conditions had not been explained.

All the pre-mentioned studies were conducted and performed with solid roofs for the aim of cooling, while other types of roofs like transparent roofs and skylights have not been studied adequately, moreover, while the main point of these roofs was delaying heat gain, winter period performance for these roofs is not clear.

2.2.3.2 Double Skin Façade

Double skin façade or as it is known DSF is an architectural element which has been added to full glazing skin with a cavity between the two layers that isolates the indoor spaces from the outer conditions (Barbosa et al., 2015). This element plays a great role in the energy performance of the building. DSF components are outer and inner skins of glass with a cavity in between. The cavity ranges between 20cm up to 2m depth, and it could be ventilated mechanically, naturally or mixed mode (Alibaba & Ozdeniz, 2016), the inner skin could be either glass as it was mentioned before or solid with specific window to wall ratio WWR (Barbosa et al., 2015).

The mechanism of DSF is to collect or get rid of solar radiation in the cavity which is absorbed by glazing layers of the envelope (Zhou & Chen, 2010). The first use of DSF was in a commercial building in Europe which showed better performance due to the cold weather, but this performance was less effective in hotter climate because of the great heat gain in the southern facade which increased the importance of adding shading devices. These shading devices differ from plants to metal or concrete slides with dark colors (Barbosa et al., 2015). Furthermore, in hot regions, the insertion of shading devices in the cavity can improve the thermal performance for DSF (Zhou & Chen, 2010).

DSF was categorized in different ways, one of these categories is according to the cavity ventilation type, which might be naturally, mechanically or mixed mode, the other classification is the ventilation mode; that represents the air movement from and to the cavity, which could be outdoor air curtain, indoor air curtain, air supply, air exhaust or air buffer (Dickson, 2004).

For the configurations classification; many types of DSF that were developed can be applied to the buildings such as shaft-box window, multi-e double skin façade, corridor façade and box-window façade (Alibaba & Ozdeniz, 2016). Building energy consumption connected strongly with the indoor thermal performance of the building envelope which directly affects the solar heat gain and thermal heat transfer, and it is highly affected by the location and the seasonal climates (Zhou & Chen, 2010).

DSF can be applied to different glazing spaces, hence, (Yasa, 2015) tested naturally ventilated atrium with DSF in terms of thermal performance in Turkey, the study discussed the outcomes in the form of PMV and PPD values, moreover, the study confirmed that the air speed was higher in the narrower cavity. Winter results proved the DSF atrium thermal efficiency due to the higher air temperatures in the cavity.

Since the DSF performance varies from one climatic region to other, Alberto et al. (2017) conducted a parametric study under mild European climates to define the effect of these parameters on the building behavior, the results concluded that airflow is the most influential factor in building energy performance, moreover, the multi-storey DSF configuration reduced one-third energy consumption.

2.3 Thermal Comfort

Fundamentally, buildings were initiated by humans for the purpose of sheltering from the harsh outer environment. Whereas this shelter has been developed through time with the implementation of new materials and forms then these spaces have witnessed some undesirable internal conditions. As previously mentioned, the building design as well as the construction materials will define the indoor conditions. On the other hand, people spend most of their time in these spaces and they are directly interacting with and have been affected by the indoor environment, so these spaces ought to provide a healthy physiological and psychological atmosphere. To evaluate the indoor environment; thermal comfort has been addressed as the most important indicator compared with visual and acoustic comfort to decide the occupants convenient level (Frontczak & Wargocki, 2011).

Recently, users' comfort has been received much more attention, the international standard ASHRAE defines thermal comfort with "that condition of mind that expresses satisfaction with the thermal environment". This statement needs elaborated design and study to be achieved where thermal environment includes not only the thermal comfort but also air quality and other indicators like humidity, and thus it can be concluded that thermal comfort is one aspect of the thermal environment. Undoubtedly, satisfaction is a relative concept and thus thermal comfort of any spaces cannot be defined with a constant value, however, space is considered comfort when the majority of space occupants are thermally satisfied.

2.3.1 ASHRAE-55 Standard

Mainly, this standard is considered as a reference that deals with the study of the interacting personal and environmental factors to obtain agreeable thermal environmental conditions for most of healthy users of the space with more than 15 minutes, whereas non-thermal environmental factors such as air quality, acoustics, or illumination that could affect the comfort or health does not consider in this standard.

To obtain a thermally comfort space means the absence of being hot or cold, in other words it is obtained by a neutrality state (Douvlou, 2004). To determine the acceptable thermal comfort there are six different variables, four are related to the physical environment which represented with air temperature, radiant temperature, air speed and humidity. The other two variables are represented the human factors with the metabolic rate and clothing insulation, all of these factors could be changeable with time. According to Fanger (1972) (as sited in Douvlou, 2004)) gender also affects comfort as women need higher temperatures to feel warm more than men.

With the wide variation of climatic conditions and as four of the thermal factors are related to the climate then as a result thermal comfort for each region will be variable accordingly.

2.3.1.1 Thermal Comfort Scales

2.3.1.1.1 Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD)

To measure the thermal satisfaction of spaces, (1970) Professor Fanger developed a seven-points scale that ranges from -3 as too cold to reach 3 as too hot, 0 is the neutrality state of thermal comfort, this gradient has been used to express the thermal feelings which was later confirmed by ASHRAE as a representative, these scales are Predicted Mean Vote (PMV) and Predicted Percent Dissatisfaction (PPD) and both of them are considered as a static approach which are mainly based on heat balance studies (López-Pérez, Flores-Prieto, & Ríos-Rojas, 2019).

PMV basically predicts the comfort vote that could be a result of specific climatic conditions and a certain human activity with clothes, this index express a group of people within a space. Whereas PPD is an extension of PMV prediction as a proportional value of the dissatisfied occupants with that environmental conditions (Douvlou, 2004).

2.3.1.1.2 The Adaptive Thermal Comfort Approach

People's thermal comfort can be influenced by various sets of factors like personal differences, social, cultural and other different factors. While the defined thermal comfort is represented with the persons' mind sensation, then the thermal comfort cannot be stable because of the unstable mental state. Different activities as well as changing clothing, opening or closing the windows all of these behaviors will affect comfort. Thus we cannot define thermal comfort with a static standard (Mirrahimi et al., 2016).

Basically, as the main concept of the adaptive approach is defined by the ability of human body of exchanging its temperature with the surroundings to achieve balance, then this gives the opportunity to obtain a wider range of the thermal comfort more than the given values in PMV and PPD prediction method, on the other hand, studies confirmed that naturally ventilated spaces show wider range of acceptable temperatures more than the spaces with AC systems (Lau et al., 2019).Therefore, this method is used for predicting thermal comfort in buildings with natural ventilation strategies (Hien et al., 2017).

To conclude, the adaptive model according to ASHRAE is that model relates acceptable interior temperatures ranges to outer climatic conditions, this model, in general, is used only for naturally ventilated spaces that follow a set of criteria that supposed to meet all together. These criteria are summarized with no use for mechanical systems, metabolic range of occupants between 1.0-1.3 met, the prevailing outdoor temperature between 10 C to 33.5 C and the ability of users to adapt their clothes to the indoor and/or outdoor thermal conditions with the range of 0.5 to 1.0 clo. Moreover, studies revealed that occupants in hot and humid climates generally thermally comfortable even in higher temperatures than the ones were mentioned in different standards (López-Pérez et al., 2019).

Figure14 summarizes the theoretical framework which will be used for this study based on the previous literature, which aims at improving the central atrium thermal performance with passive design strategies, including the employment of double skin skylight as a ventilated envelope incorporation with different natural ventilation strategies to achieve wider range of indoor thermal comfort.

PASSIVE DESIGN STRATEGIES

Natural Ventilation

Utilizing natural ventilation efficiently ***is supposed to be designed according to the exterior climatic conditions*** which are vary from one region to another *(Y. Chen, Tong, & Malkawi, 2017)*. Mainly, natural ventilation is produced by ***wind effect*** and ***buoyancy effect*** *(Aflaki et al., 2015)*.

Night Ventilation

Moderate climates like the Mediterranean has the ability of ***exploiting natural night ventilation to achieve better thermal comfort*** *(Z. Wang, Yi, & Gao, 2009)*.

Ventilated Building Envelops

Hot climates in particular, utilize the ventilated structures substantially *(Gagliano, Patania, Nocera, Ferlito, & Galesi, 2012)*. Architects and designers attempt to ***overcome the undesired thermal effects*** of huge transparent building envelopes ***by adding an extra layer of glass*** *(Barbosa et al., 2015)*.

Double Skin Roof:** ***The main concept of the double skin roof is the air movement in the cavity *(Roslan, Halipah, et al., 2016)*

Double skin façade:** ***The mechanism of DSF is to collect or get rid of solar radiation in the cavity which is absorbed by glazing layers of the envelope *(Zhou & Chen, 2010)* ***the air speed was higher in the narrower cavity*** *(Yasa, 2015)*

ATRIA

Design Factors

External variables which is represented with ***climate*** is ***the determinant factor for designing atria*** *(Fini & Moosavi, 2016)*, these variables are ***temperature***, ***solar radiation*** and ***wind*** *(Moosavi et al., 2014)*.

Atrium Thermal Phenomena

Greenhouse effect: ***Mediterranean climate*** can benefit this effect as it ***keeps the interior*** space as well as the adjacent ***spaces warm*** *(Douvlou, 2004)*.

The stack effect: This technique is greatly ***beneficial for atria natural ventilation to extract heated air*** *(Liang et al., 2019)*.

Design Parameters

Building geometrical characteristics

Atrium Forms and orientation: the atrium ***position*** within the building is an influential factor in energy performance. The centralized atrium is surrounded with building spaces, in this kind of atria the only ***source of daylight is the glass roof.*** *(Fini & Moosavi, 2016)*.

Atrium roofs and skylights*:* In case of skylights; building ***thermal performance*** is directly affected by their design alternatives *(Abuseif & Gou, 2018)*.

Atrium Fenestration and Openings design*: Openings design is a key role* to achieve optimum natural ventilation since it controls air entry and exit to and from the space *(Aflaki, Mahyuddin, & Mahmoud, 2015)*. Increasing the inlets size rather than the outlets to improve the atrium natural ventilation *(Su, 2017)*

Materials physical characteristics

Optical and thermal properties of glazing material are the dominant influencers on indoor environment for both lighting and thermal performance *(Al-Obaidi, Ismail, & Rahman, 2014)*.

Both ***SHGC and U-value*** determine the amount of heat flux and consequently the thermal behavior *(Galal, 2019)*.

ATRIUM THERMAL COMFORT IN MEDITERRANEAN CLIMATE

Natural ventilation has an efficient role of in ***indoor temperature*** and humidity ***level reduction*** *(Moosavi et al. 2015)*

In ***the Mediterranean climate*** the ***atrium*** can work effectively ***around the year***, as ***winter*** temperatures are close to the cold regions where the atrium has proven its efficiency ***as a thermal buffer zone***, while the ***summer-time can benefit night ventilation*** *(Palma Rojas 2013)*

the ***skylight design and materials*** are supposed to take the ***glazing materials properties*** and ***climate*** in consideration *(Ab Ghafar et al., 2019)*.

Glazing materials characteristics (SHGC and ***U-Factor)*** show the material performance, recommending the ***low-e glass for the best thermal performance*** *(Galal, 2019)*

THERMAL COMFORT

ASHRAE-55 Standard

To evaluate the indoor environment; ***thermal comfort*** has been addressed as ***the most important indicator*** compared with visual and acoustic comfort to ***decide the occupants convenient level*** *(Frontczak & Wargocki, 2011)*.

The international standard ***ASHRAE*** defines thermal comfort with ***"that condition of mind that expresses satisfaction with the thermal environment".***

Thermal comfort scales

(PMV) and (PPD)

(PMV) is a seven-point scale that ranges from ***-3 as too cold to reach 3 as too hot,*** 0 is the neutrality state of thermal comfort. Both of them are considered as a ***static approach*** which are mainly based on heat balance studies *(López-Pérez, Flores Prieto, & Ríos-Rojas, 2019)*.

The Adaptive Thermal Comfort

The main concept of the adaptive approach is defined by the ***ability of human body of exchanging its temperature with the surroundings to achieve balance,*** this method is used for predicting thermal comfort in buildings ***with natural ventilation strategies*** *(Ilhen et al., 2017)*.

Figure 14: Research Theoretical Framework. Developed by the author.

Chapter 3

PROPOSED MODEL

This section of the study includes the research methodology as well as the research outcomes and discussion. The first part of this chapter explains the methodology development and tools, while the second part presents the produced results by the simulation for the selected building by EDSL Tas software (EDSL Tas, 2018), which provides hourly results for each zone around the year. Finally, the third part discusses the outputs and compares these results with refer to ASHRAE-55 standard (ANSI/ASHRAE Standard 55, 2017). In this study different groups models of a naturally ventilated building were simulated where the variables selection based on the related previous literature; two seasonal scenarios compare the existing building with different alternatives of double skin skylight (DSS) by the changing in the cavity outer openings ratio and the DSS glazing materials, as well as operating different ventilation strategies. This study was performed for the aim of improving the thermal behavior for indoor spaces regarding these variables.

To fulfill this purpose; five different percentages of DSS apertures openings in addition to the existing building with single skylight (SS) were examined around the year. The total monthly working hours were calculated according to the library schedule for weekdays and weekends from 9:00 am to 10:00 pm and from 10:00 am to 8:00 pm respectively which recorded a total of 4796 WH, then the number of comfort working hours were calculated, the results are presented in the form of monthly percentage of thermally comfort working hours to the total monthly working hours (WH) for the different building spaces in both 80% and 90% acceptability limits according to the standard. Table 1 shows the monthly working hours of the library. Findings are discussed and compared seasonally to predict the possibility of improving thermal comfort for adjacent spaces of a centralized atrium with top-lit skylight by changing the cavity openings percentages in these specific climatic conditions.

Table 1: Monthly Working Hours of Ozay Oral Library. Developed by the author.

Months	January	February	March	April	May	June	July	August	September	October	November	December	Yearly
WH	408	368	407	393	410	393	407	410	390	410	396	404	4796

Thermal comfort evaluation for indoor environments is based on the acceptable limits of ASHARE-55 standard (ANSI/ASHRAE Standard 55, 2017) for naturally ventilated spaces where there is no use of mechanical heating or cooling. This standard considers outdoor temperature, air speed, and indoor operative temperature.

3.1 EDSL Tas Software

This study used EDSL Tas 9.4.4 simulation software tool (EDSL Tas, 2018), this software package has 3D modeler, Tas building simulator, and results reviewer in addition to other applications, and hence this program is used for analyzing environmental performance it has a high capability to perform hourly dynamic thermal simulation for complex buildings.

3.2 Gazimagusa-North Cyprus Climate Zone

Köppen climate classification mentioned North Cyprus as a Mediterranean climate with Csa classification (D. Chen & Chen, 2013). According to this classification; the first two letters Cs represent Mild Temperate with Dry Summer while the third letter a refers to the hot summer category with summer temperature ≥ +22 °C. As the city of Gazimagusa locates on the eastern coast of the island the weather in such coastal cities has high temperatures and relative humidity with an average yearly temperature of 19.3 °C. (Source: URL 2). Figure 15 illustrates the world map according Köppen climate classification.

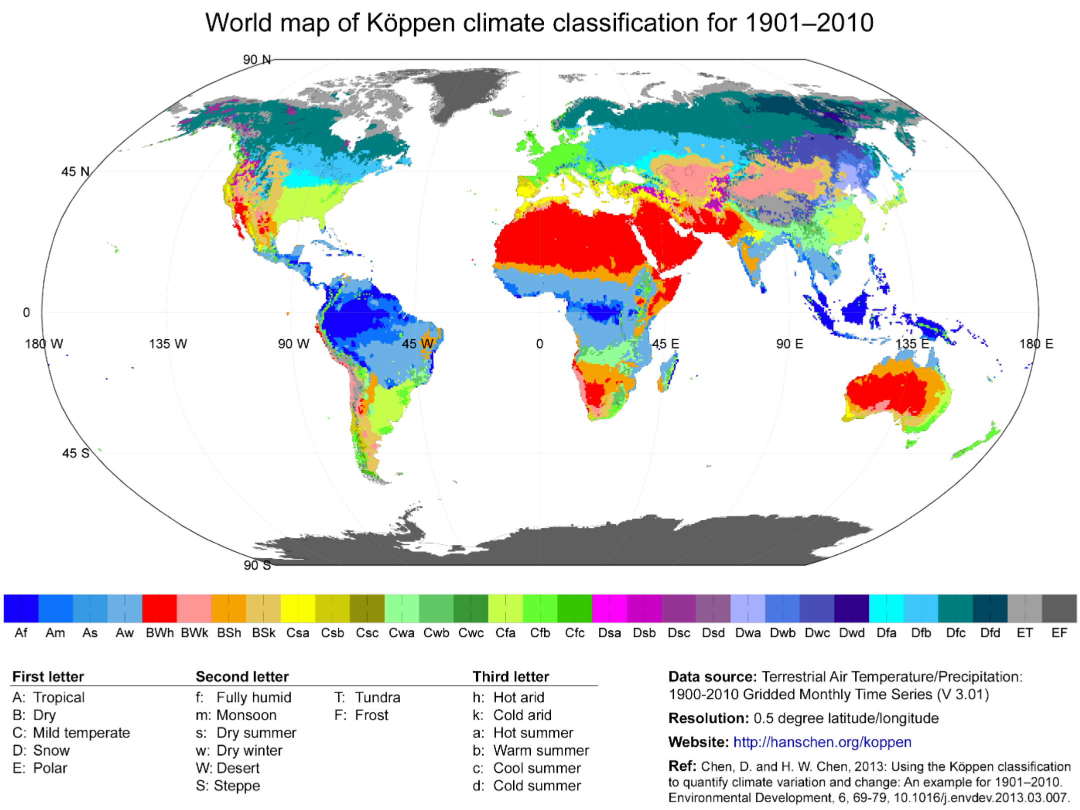


Figure 15: Köppen World Map Climate Classification. Source: (Chen, & Chen, 2013).

The weather data calculations and average monthly temperatures of this study used climate consultant 6.0 software. Table 2 shows the monthly average temperature and wind speed for Gazimagusa city.

Table 2: Monthly Average Temperature and Wind Speed for Gazimagusa City.
Source: Climate Consultant 6.0 Software

WEATHER DATA SUMMARY

LOCATION: **Famagusta, FA, CYP**
Latitude/Longitude: 35.133° North, 33.933° East, **Time Zone from Greenwich** 2
Data Source: ISD-TMYx 175400 WMO Station Number, **Elevation** 0 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Dry Bulb Temperature (Avg Monthly)	12	13	15	17	21	25	28	28	26	22	17	14	degrees C
Relative Humidity (Avg Monthly)	69	67	72	65	65	66	67	67	66	63	62	62	percent
Wind Direction (Monthly Mode)	250	40	240	200	210	120	200	200	240	250	50	20	degrees
Wind Speed (Avg Monthly)	4	4	3	3	3	3	3	3	2	3	4	4	m/s

3.3 Proposed Model

After reviewing the literature, occupants' thermal comfort strongly depends on design decisions, some of these decisions are related to the building characteristics itself while other decisions include the utilization of passive strategies, and thus; the appropriate design of these two techniques controls the indoor thermal comfort.

To serve the study main goal of improving the thermal comfort for the reading spaces: the first step tests the existing building thermal performance by applying two different seasonal design strategies to evaluate the current design, these strategies define the operational schedule for the building and the DSS openings according to the outdoor climatic conditions. Later on, two groups of design parameters will be tested sequentially, the first group is related to the DSS design parameters which include the cavity openings and the material selection respectively, the worst case in both summer and winter periods will be tested. The second group of parameters is related to natural ventilation, which is represented in operating night ventilation and changing the inlets openings.

Building description: The studied case is the main Library of EMU in Gazimagusa city, the main entrance places in the north-east side of the building at the ground level. The building consists of four floors with square plan of 40.9 m x 40.9 m, in addition to the entrance; the ground level includes the administration spaces, whereas the first floor has studying rooms and auditorium entrance hall, other service facilities are distributed in both floors in addition to the auditorium that occupies the central parts of these two floors. Second and third floors mainly contain an atrium that is surrounded with open reading spaces, a staircase extends from the ground to the third floor.

The library was built with the common building materials in Cyprus; the external walls were built with 20 cm brick, while the internal partitions were built with 15 cm bricks, concrete slabs were used for both floors and roofs. For windows and glazed facades: a 6 mm single clear glass is used for curtain walls skylight, and windows. Table 3 shows the physical and thermal properties of the used building materials in opaque and transparent elements.

Table 3: Physical And Thermal Properties for The Building Materials in Opaque and Transparent Elements. Developed by the Author.

Building Element	**Material**	**Thickness** (mm)	**U-Value** (W/m²·°C)
External Wall	Plaster- Brick- Plaster	200	1.6
Internal Partition	Plaster- Brick- Plaster	150	1.86
Floor	Plaster- Concrete Slab- Plaster	250	1.84
Roof			
Atrium Roof	Clear Glass	6	5.68
Curtain Wall			
Windows			

3.3.1 Studied Zones Description

To have a comprehensive overview of the thermal behavior of the applied strategies (changing the outer openings percentages of the atrium double skin skylight and applying natural ventilation) a group of reading zones that are adjacent to the atrium space was tested to improve the indoor thermal comfort of these spaces.

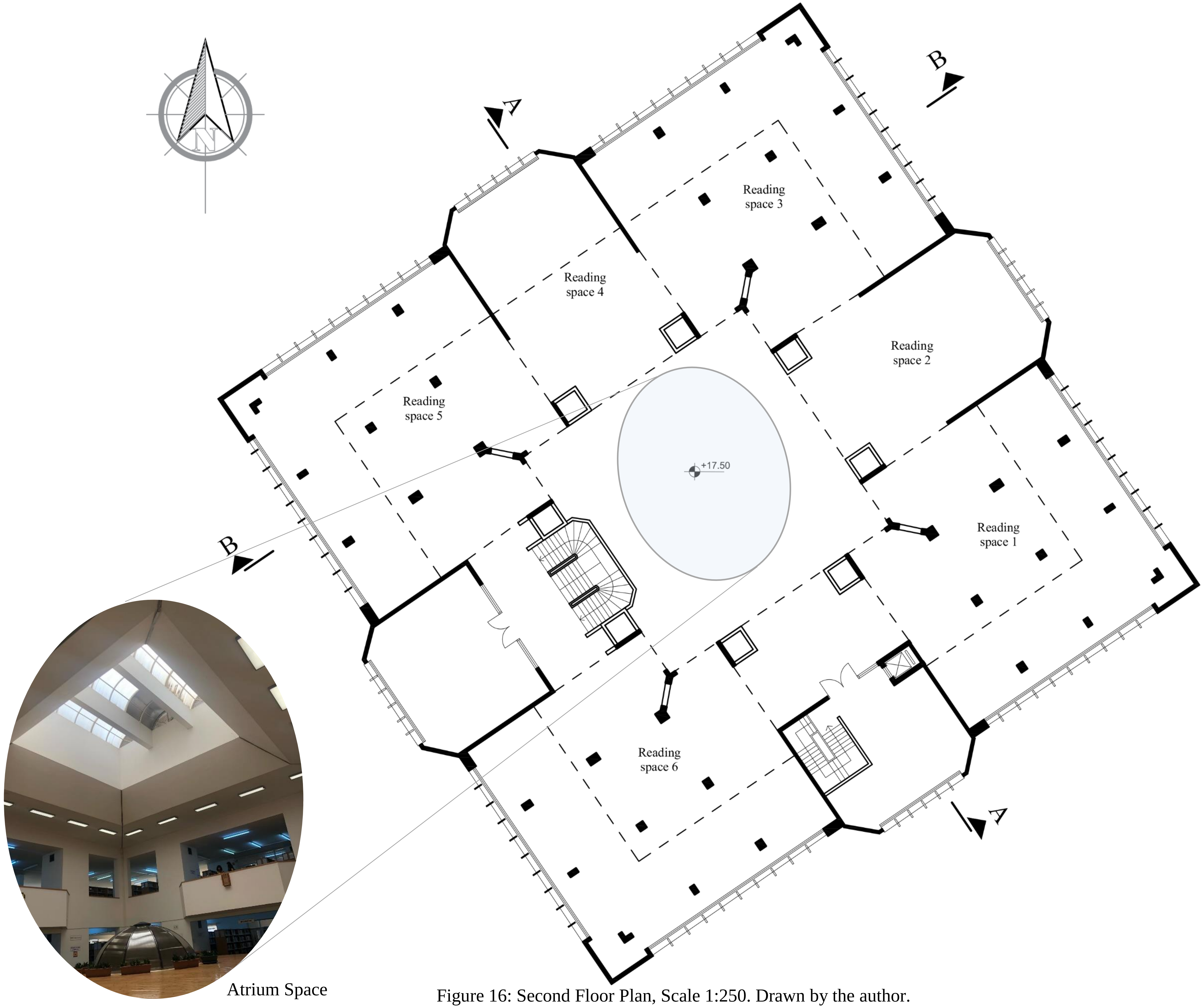
The 12 tested reading spaces are set in the second and the third floors of Ozay Oral Library- Eastern Mediterranean University in North Cyprus**.** Table 4 defines the spaces areas, orientation, and properties.

The atrium space locates in the middle of a square floor plan with dimensions 15.2 m x 15.2 m at the second floor level with 7.15 m height and 3.15 m light well. Moreover, the atrium is lighted by a top-lit skylight. Figures 16 and 17 define the zonal plans of the second and third floors of the library, and Figure 18 illustrates the sections and elevations.

Building windows: For the vertical openings (inlets), the second floor has 80 openable windows with dimensions 1.1 m x1.5 m for each window in groups of 10 windows in each exterior elevation for the open spaces, moreover, a total number of 12 windows were divided in two groups of 6 windows in the solid exterior facades of the semi-opened spaces with dimensions 0.9 m x 1.5 m for each window.

Table 4: Definitions, Orientation, Areas and Properties for the Studied Reading Spaces. Developed by the author.

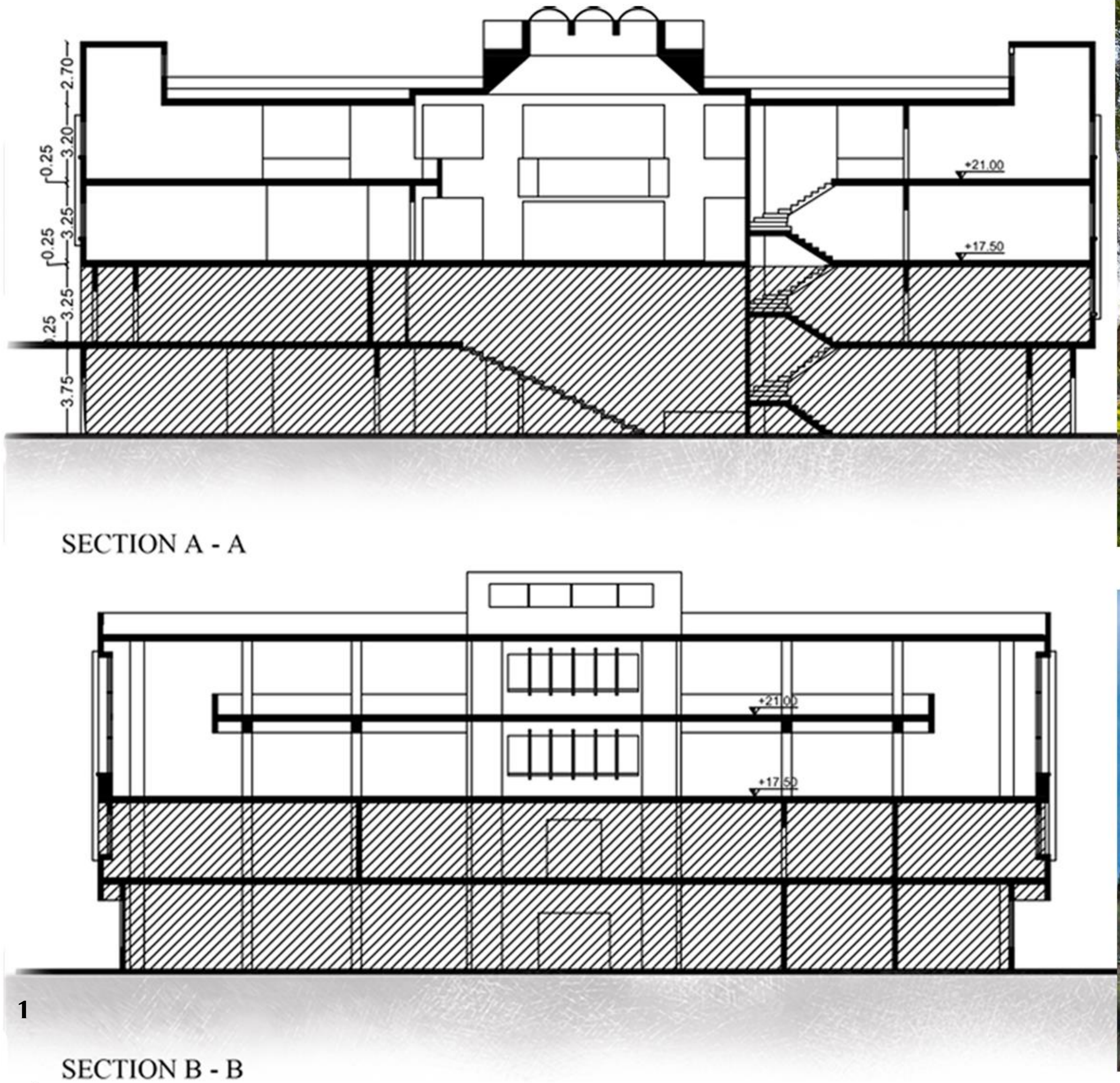
Space definition	***Space Orientation and Floor***	***Area m^2***	***Space Properties***
Reading Space 1	East/ Second Floor	224.2	*Both exterior facades are glazed *Openable windows at 1m height *Open spaces
Reading Space 3	North/ Second Floor	224.2	
Reading Space 5	West/ Second Floor	224.2	
Reading Space 6	South/ Second Floor	224.2	
Reading Space 7	East/ Third Floor	106.4	*4.25 m recess from exterior facades *Open spaces * 1m edge height from the floor level
Reading Space 8	North/ Third Floor	106.4	
Reading Space 10	West/ Third Floor	106.4	
Reading Space 11	South/ Third Floor	106.4	
Reading Space 2	North-East/ Second Floor	108	*Semi-open Spaces *Solid exterior facades with openable windows at 1m height
Reading Space 4	North-West/ Second Floor	108	
Reading Space 9	North-West/ Third Floor	122.3	
Reading Space 12	North-East/ Third Floor	122.3	



Atrium Space

Figure 16: Second Floor Plan, Scale 1:250. Drawn by the author.

Figure 17: Third Floor Plan, Scale 1:250. Drawn by the author.



1

2

3

Figure 18: 1: Sections, Scale 1:250. Drawn by the author. 2: South-East Elevation. 3: North-West Elevation. Source: URL 3

3.4 Preparing Design Strategies

3.4.1 Seasonal Design Strategy

This strategy was selected seasonally based on the outdoor climatic conditions which basically control the openings percentage according to the outdoor temperatures. During winter, while the outer temperature is low, then opening the side windows will not improve the indoor temperature, for that; the building windows were opened with 1%. For this study, the winter period is divided into two intervals; from the beginning of January to the end of April and from October till the end of December. Figure 19 shows winter openings strategy.

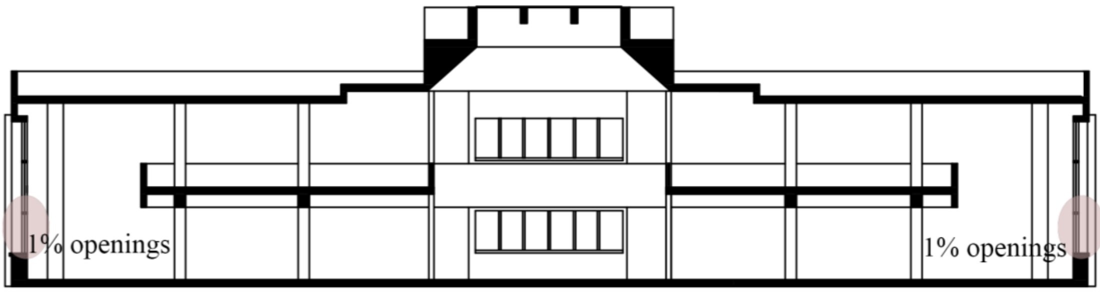


Figure 19: Seasonal Strategy, Wintertime. Developed by the author.

During summer, opening the windows enhances air entry to the building, the arrangement of these openings defines the airflow inside the building, in this study; initially, the building side windows were opened with 10% during the WH for weekdays and weekends from 9:00 am to 10:00 pm and from 10:00 am to 8:00 pm respectively as Figure 20 presents. In this study, the summer period extends from the beginning of May till the end of October, this schedule creates a total area of 13.2 m^2 for air openings.

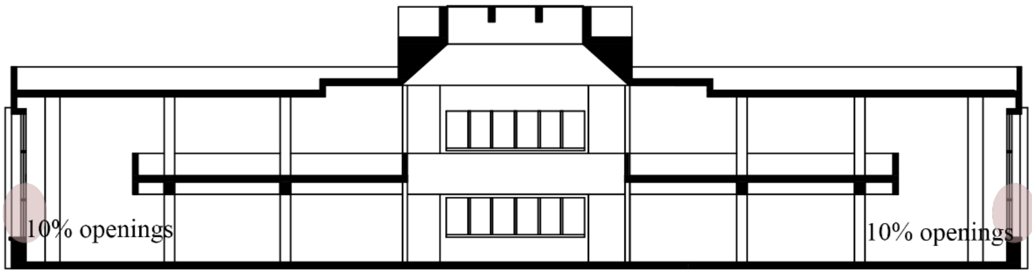


Figure 20: Seasonal Strategy, Summertime. Developed by the author.

3.4.2 Double Skin Skylight (DSS) Design Strategy

In this step, the DSS was applied and tested in two consequent simulations. The first group tested changing the DSS windows openings, the selection of this stage depended on the diverse thermal phenomena of the atrium which benefit the greenhouse effect in winter and the stack effect in summer. The existing skylight consists of three vaults, but in this study, these three vaults were replaced with one flat single glass roof, the replacement decision based on the following reasons: according to Douvlou (2004) study results in Mediterranean climate asserted that both flat and curved roofs have the same performance regarding the intensive penetrated solar radiation especially during summer without shading devices, but the use of shading elements strongly affects the visual performance for the inner spaces particularly in deep plans (Douvlou, 2004). The second reason behind using flat skylight refers to the construction cost, where a simple flat roof costs less than a vaulted one. DSS design parameters involve the air cavity width between the two glazed layers, the cavity openings, and glazing material properties selection.

Cavity design: Basically, an extra glazed layer was inserted above the original skylight to form a cavity between the two glazed layers, this gap aims to heat the upper air which stimulates the air extraction from the upper openings during summer.

Moreover, in wintertime the hated air insulates the external climatic conditions. Regarding the previous studies the narrower the cavity is, the greater airflow, thus a 35 cm cavity width was selected for this study.

Cavity fenestration design: Vertical openings (external outlets) with the dimensions 0.25 m x 5.9 m for each one are placed in the four sides of the cavity height, the first part of this study follows different scenarios for the opening percentage of these windows based on the seasonal scenarios.

For the horizontal openings (outlets), the interior glazing layer of DSS has three openings of 1.3 m x 2.0 m at the height of 10.3 m from the second-floor level, the existence of these openings aims the extraction of the hot air from the atrium space to the cavity. The total area of 7.8 m^2 for air outlets, the initial ratio between inlets and outlets was determined based on the literature recommendations.

The cavity openings are set 0% for fully closed openings for the wintertime, whereas 25%, 50%, 75%, and 100% for fully opened cavity openings during day and night, the selection of this openings depend on the outdoor climatic condition. Figure 21 shows the DSS cavity windows.

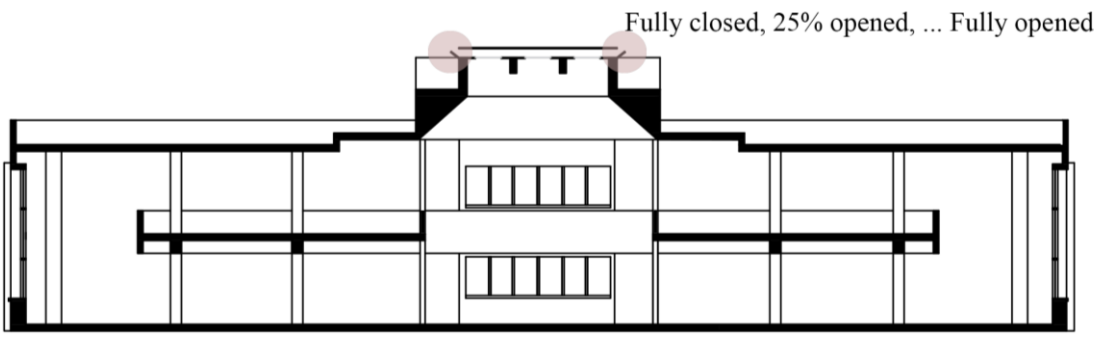


Figure 21: Cavity Fenestration. Developed by the author.

DSS material selection: Regarding the glazing material selection for the climatic characteristics which is represented by hot summer for Gazimagusa, the previous studies recommended the glass with low U-values, for this reason, the selected layer of glass mainly was chosen according to this value. Table 5 shows the properties for the Low-e glass material.

Table 5: Glass Material Properties. (EDSL Tas, 2018)

Low-e Glass	4mm clear glass-16mm air-4mm low-e glass	U Value ($W/m^2 \cdot °C$) 1.538

Four different scenarios for the tested materials will be designed as it is presented in Table 6 and Figure 22. The first scenario presents the existing building which uses Low-e glass in the outer DSS layer with clear glass for the inner one, the second scenario uses Low-e glass for the inner layer of DSS and clear glass for the outer one, the third scenario applies Low-e for both external and internal layers, and the fourth scenario uses the default clear glass for both layers.

Table 6: Materials Changing Scenarios. Developed by the author.

	Inner DSS glass Layer	**Outer DSS glass Layer**
Scenario 1	Clear Glass	Low-e Glass
Scenario 2	Low-e Glass	Clear Glass
Scenario 3	Low-e Glass	Low-e Glass
Scenario 4	Clear Glass	Clear Glass

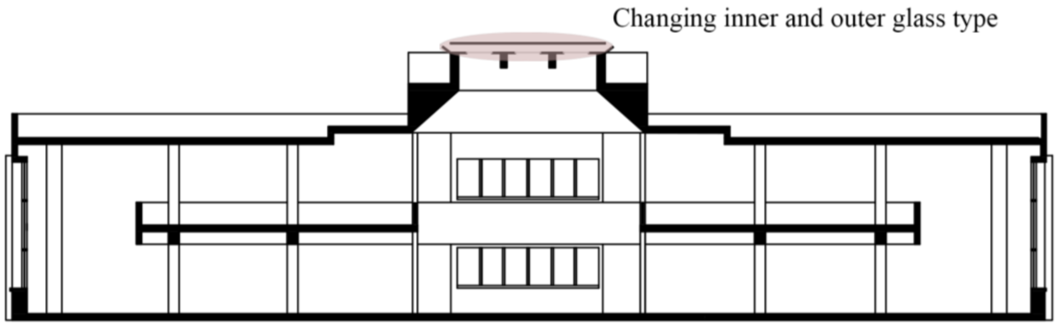


Figure 22: DSS Materials Design. Developed by the author.

3.4.3 Ventilation Strategy

In spite of the total dependence on mechanical systems for cooling and heating during summer and winter respectively to obtain thermal comfort; utilizing passive strategies as natural ventilation could provide a promising chance to achieve thermal comfort by enhancing the heated air trapping or extraction in the DSS' cavity during winter and summer respectively.

Natural ventilation is considered one of the most effective ways to enhance indoor thermal comfort, and whereas fenestration causes the air movement inside the building, so to benefit natural ventilation: controlling the apertures opening percentages will control this flow and consequently affect the indoor environment.

Night ventilation strategy: since the previous studies proved the efficient role of night ventilation in indoor temperatures decreasing in the Mediterranean climate, this study tested the efficiency of operating night ventilation beside the day ventilation. Based on the previous simulation results, in this stage: the best model of the previous design was examined by operating all day ventilation, which utilizes natural ventilation during day and night. The findings were compared between the same case with and without night ventilation to define the effect of operating day and night ventilation.

Building fenestration design: increasing the ratio between the inlets and the outlets improves the indoor thermal comfort which is caused by the high pressure differences, hence that, this strategy was chosen. The last simulation group in this step was run based on the previous simulation results, the best model from the previous simulation was tested by changing the inlets openings' percentage as Figure 23 illustrates, two proposals of the inlets openings: 50% and 100% building openings were tested.

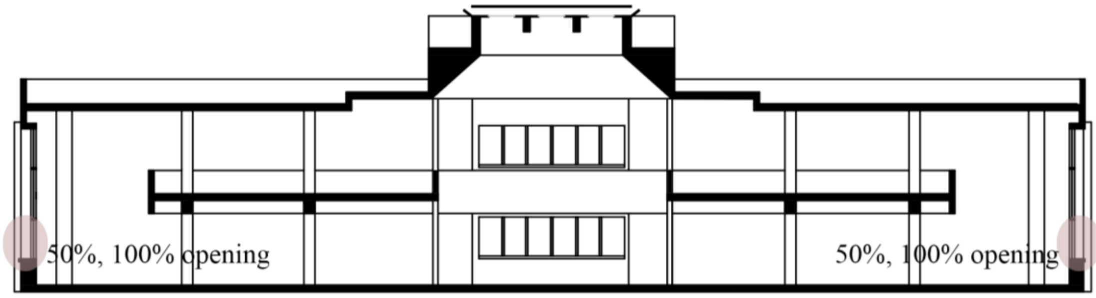


Figure 23: Building Fenestration Design. Developed by the author.

To summarize the previous part, Table 7 and Figure 24 display the research design strategies, and the methodology strategies flowchart.

Table 7: Research Design Strategies. Developed by the author

Winter period proposal	Simulation Group 1 DSS Design	Cavity Fenestration
Summer period proposal		DSS Material
	Simulation Group 2 Ventilation Design	Night Ventilation
		Building Fenestration Design

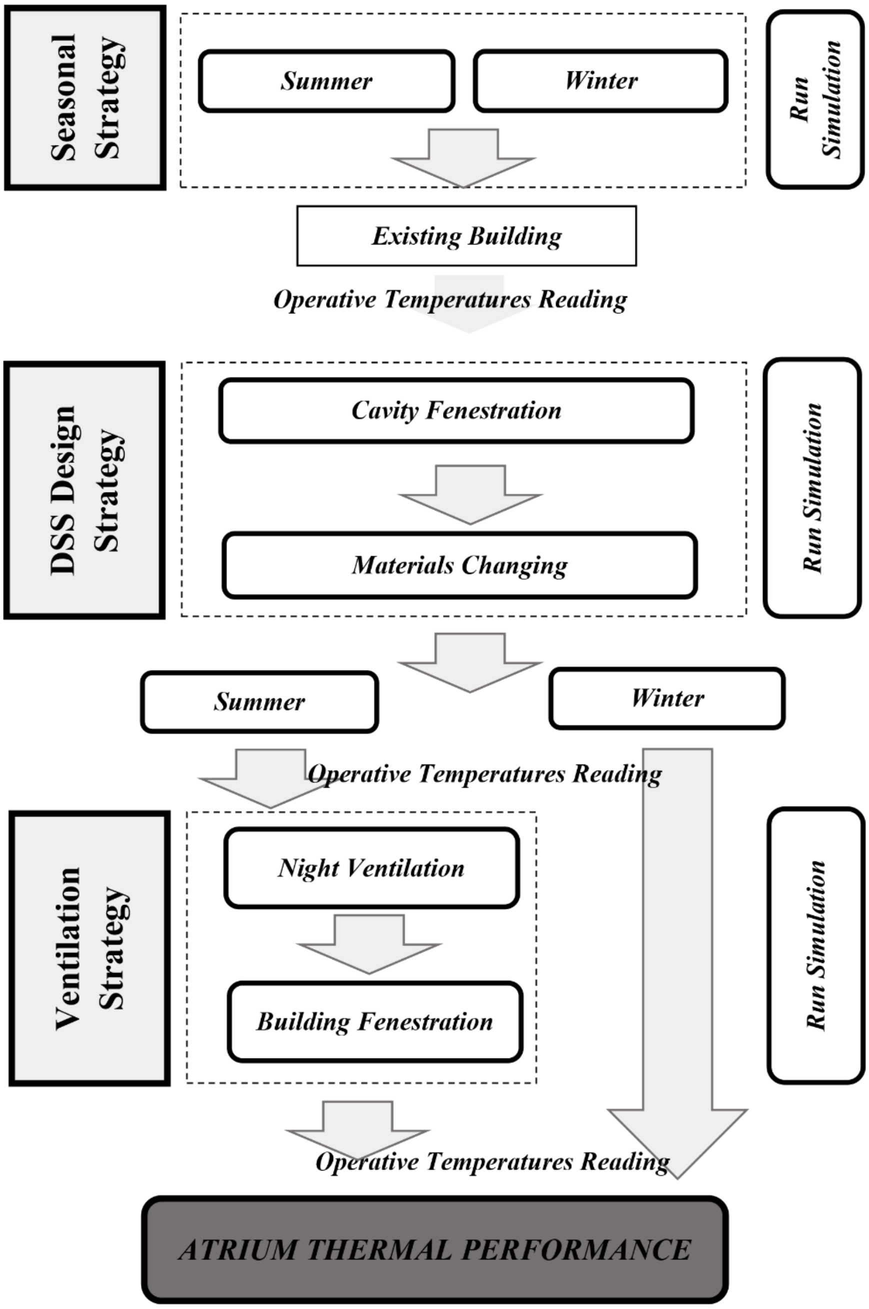


Figure 24: Research Methodology Flowchart. Developed by the author.

3.5 Adaptive Thermal Comfort Standard ASHRAE-55

This standard is considered in the thermal comfort evaluation for the reading spaces based on the following reasons; the prevailing mean outdoor temperature ranges greater than10°C and less than 33 °C. The proposed spaces are naturally ventilated without using any mechanical heating or cooling. Occupants who use the spaces not less than 15 minutes have metabolic rates range between 1.0-1.3 met. Moreover, they are free to adapt their clothing to the indoor or/and outdoor temperatures within the range of 0.5-1.0 clo.

The acceptable indoor operative temperature according to ASHRAE-55 standard (ANSI/ASHRAE Standard 55, 2017) is defined by Figure 25, which uses the 80% acceptability limits from the equations;

Upper 80% acceptability limit (°C) = 0.31 $t_{pma\ (out)}$ + 21.3

Lower 80% acceptability limit (°C) = 0.31 $t_{pma\ (out)}$ + 14.3

These limits are used when the air speed less than 0.3 m/s or when the indoor operative temperature is lower than 25 °C even if the wind speed more than the accepted limit.

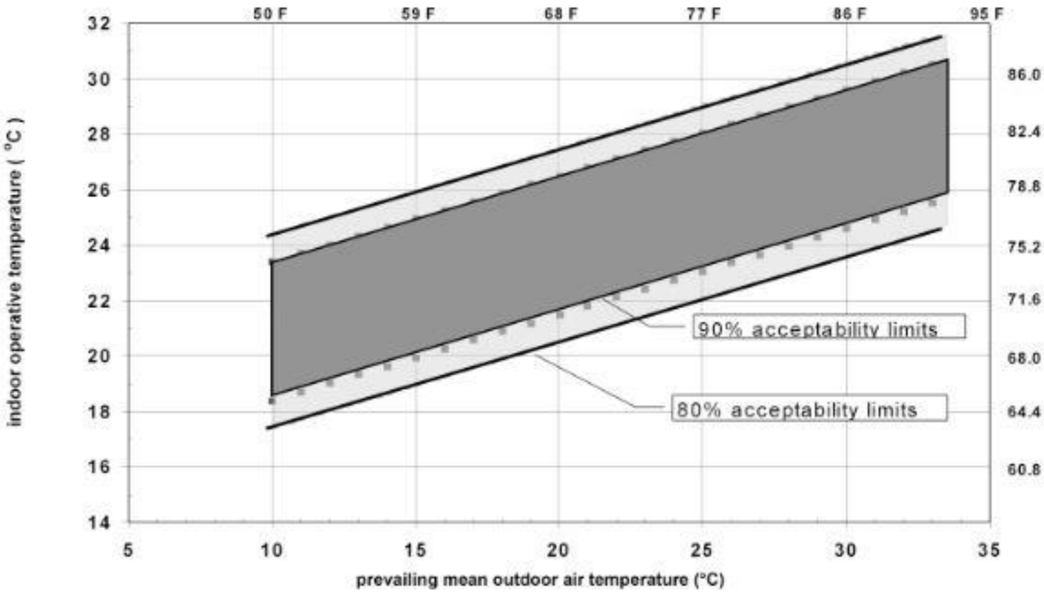


Figure 25: Adaptive Chart for The Acceptable Operative Temperatures Ranges for Naturally Ventilated Spaces, When Wind Speed < 0.3 m/s. Source: (ANSI/ASHRAE Standard 55, 2017)

In case of air speed more than 0.3 m/s and the average operative temperature more than 25 °C then the upper acceptability limit will be increased according to table 8.

Table 8: Increasing the Upper Acceptable Operative Temperature Resulting From Increasing Air Speed Above 0.3 m/s. Source: (ANSI/ASHRAE Standard 55, 2017)

Average Air Speed(V_a) 0.6 m/s	Average Air Speed(V_a) 0.9 m/s	Average Air Speed(V_a) 1.2 m/s
1.2 °C	1.8 °C	2.2 °C

Table 9 presents the average monthly temperatures and wind speed during the year in Gazimagusa with the 80% and 90% acceptability maximum and minimum operative temperatures.

Table 9: Gazimagusa Average Monthly Temperatures, Wind Speed During the Year, The 80% and 90% Acceptability Max And Min Operative Temperatures. Developed by the author.

Months	Monthly Temp °C	Average Operative Temp °C	Average wind speed m/s	80% Accept Temp °C		90% Accept Temp °C	
				Min	Max	Min	Max
January	12	17	4	18.0	25.0	19.0	24.0
February	13	19	4	18.3	25.3	19.3	24.3
March	15	21	3	19.0	26.0	20.0	25.0
April	17	23	3	19.6	26.6	20.6	25.6
May	21	27	3	20.8	30.0	21.8	29.0
June	25	32	3	22.1	31.3	23.1	30.3
July	28	34	3	23.0	32.2	24.0	31.2
August	28	33	3	23.0	32.2	24.0	31.2
September	26	31	2	22.4	31.6	23.4	30.6
October	22	27	3	21.1	30.3	22.1	29.3
November	17	23	4	19.6	26.6	20.6	25.6
December	14	20	4	18.6	25.6	19.6	24.6

Note: the highlighted cells represent the winter period

3.6 Computer Simulation Findings

The researcher used Ozay Oral Library which locates in Eastern Mediterranean University campus in North Cyprus, this selection based on the aim of this study which attempts to improve the indoor thermal comfort for the atrium adjacent spaces by the implementation of DSS, where the library reading spaces in both second and third floors connect to a central top-lit atrium which offers the opportunity to benefit the connection between these spaces to create a considerable air movement inside the building.

As the thermal comfort one of the most important factors that affect the users' performance especially in educational buildings, this study highlights the possibilities of achieving this comfort by using passive design strategies. In this study, computer simulations were run to evaluate the thermal effect of implementing a double skin skylight atrium with different openings percentages on the adjacent reading spaces for the second and third floors of the library building.

The whole building was modeled with the TAS 3D modeler for defining the studied zones, by generating a simulation, the second step was obtained as a form of building simulator were building physical characteristics, weather file, calendar, interior conditions as well as the operational properties were set. The last step was generated by the results viewer production, where the studied output is obtained in tabular and graphical data for the whole year.

The following sections describe three groups of simulation scenarios for winter and summer periods respectively, all scenarios have the same external parameters. Moreover, there are no shading elements.

3.6.1 Simulation Group 1

In this group two design parameters which are related to the DSS design were tested, which are the cavity openings percentage and the DSS glazing materials respectively. The library with its current design features was simulated in different scenarios; the winter scenario is defined by 1% façade openings for the whole second floor windows, while the second floor windows were opened with 10% during the summertime.

3.6.1.1 Cavity Fenestration Design Simulation

Winter period: For both with and without DSS scenarios, the simulation was run for the whole building which has the same characteristics and second floor openings percentage with the value of 1% during winter- from January to April and from November to December. To examine the thermal behavior of DSS an extra layer of low-E glass was added to create a 35 cm air gap, the lateral cavity windows are closed for both winter scenarios simulations.

1st simulation- Existing building: The first simulation represents the current building with a single skylight (SS) case, with 1% openings for the side windows on the second floor during winter, which extends from January to April and from November to December. It is worth to mention that the simulation was run with a flat clear glass skylight. Results of this simulation are illustrated in Figures 26 and 27, averaged readings are shown in Tables 10 and 11.

80% acceptability: After reviewing the simulation results and referring to ASHRAE standard (ANSI/ASHRAE Standard 55, 2017): Figure 26 shows winter period simulation results for the existing building. It can be clearly noticed that April presents the highest performance regarding the total thermally comfortable hours. During April, where the 80% acceptable operative temperatures ranged between 19.6 °C – 26.6 °C: all second floor spaces show thermal comfort in 98% of WH, whilst the third floor spaces present full comfortable WH. During this month, the atrium space's average temperature was 23.5 °C, whereas the upper part average temperature recorded 26 °C.

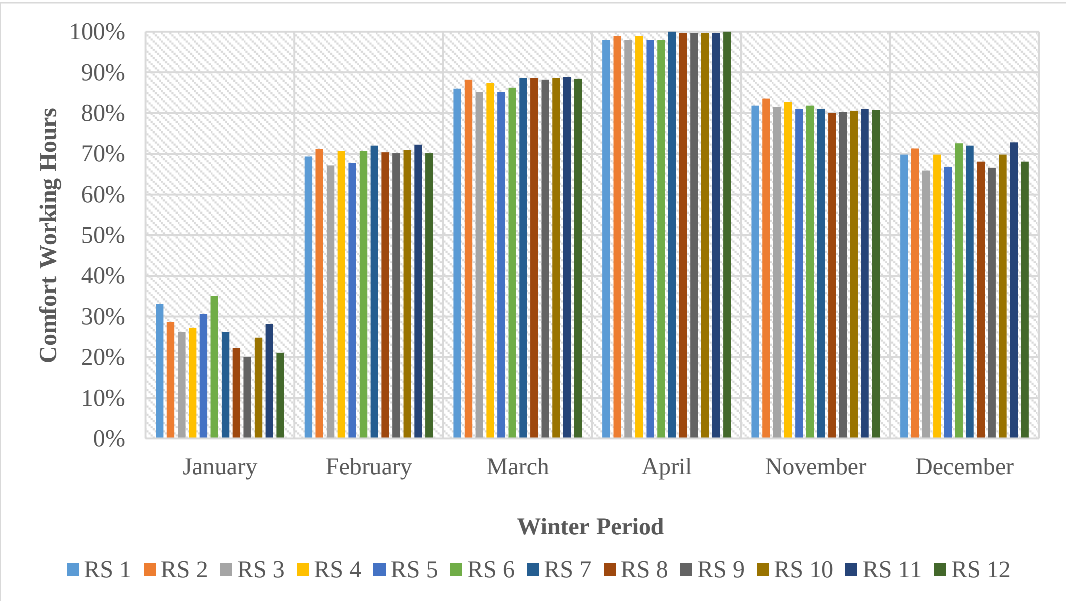


Figure 26: Winter Period Comfort WH Percentage For The Existing Building Within The 80% Acceptability Limits. Developed by the author.

The least numbers of comfortable hours are shown in January, where 18.0 °C to 25.0 °C is the comfort operative temperatures t_o range. An average of one-third only of the total WH are comfortable for the second floor spaces, however, the third floor spaces readings fluctuate between an average of 20% and 30% comfort WH. Furthermore, the second and third floor southern spaces record the highest comfort hours among the whole spaces. For the atrium space average temperature, it recorded only 18 °C, while the upper part was higher with 1 °C.

Comfort operative temperatures t_o during March are considered between 19.0 °C and 26.0 °C, during this month, an average of 87% WH for the second floor spaces locate within these limits, a slight increase of 2% can be noticed in the third floor spaces. Moreover, the comfort operative temperatures t_o of November are higher than the previous with 0.6°C, while the results of the spaces record shrinking in comfort hours for both second and third floors' spaces to reach an average of 82% only of WH. moreover, atrium space average temperature reached 21 °C and 23.5 °C for March and November respectively, while the upper part average temperature in both cases was higher with 1.5 °C.

On the other hand, February and December have a close comfort operative temperatures t_o ranges of 18.3°C – 25.3°C and 18.6°C – 25.6 °C respectively. In both months; the second floor spaces show convergent results of 78% average comfort WH, whereas during February the third floor spaces have a slightly higher comfort WH with a difference of 3% as Figure 26 shows. The atrium space average temperatures recorded 19.5 °C and 20 °C for the previous months respectively, with a 1°C increase in the upper part average temperatures.

90% acceptability: Figure 27 illustrates the percentages of the reading spaces comfort hours within the 90% acceptability limits during winter. April readings show the best comfort behavior while January readings record the least values. For April the minimum and maximum 90% thermal comfort temperatures range between 20.6°C – 25.6 °C respectively. The third floor spaces achieve a slight increase above 90% of thermal comfort during WH, whilst the second floor spaces' results achieve lower values, the northern-east and northern-west spaces record the lowest thermally comfort hours with 85% of WH.

January results show that only 12% comfort WH can be achieved in the second and third floors' spaces, it's worth mentioning that the comfort operative temperatures t_o within the 19.0 °C and 24.0 °C range. Moreover, the atrium space average temperature did not achieve the 90% comfort temperature.

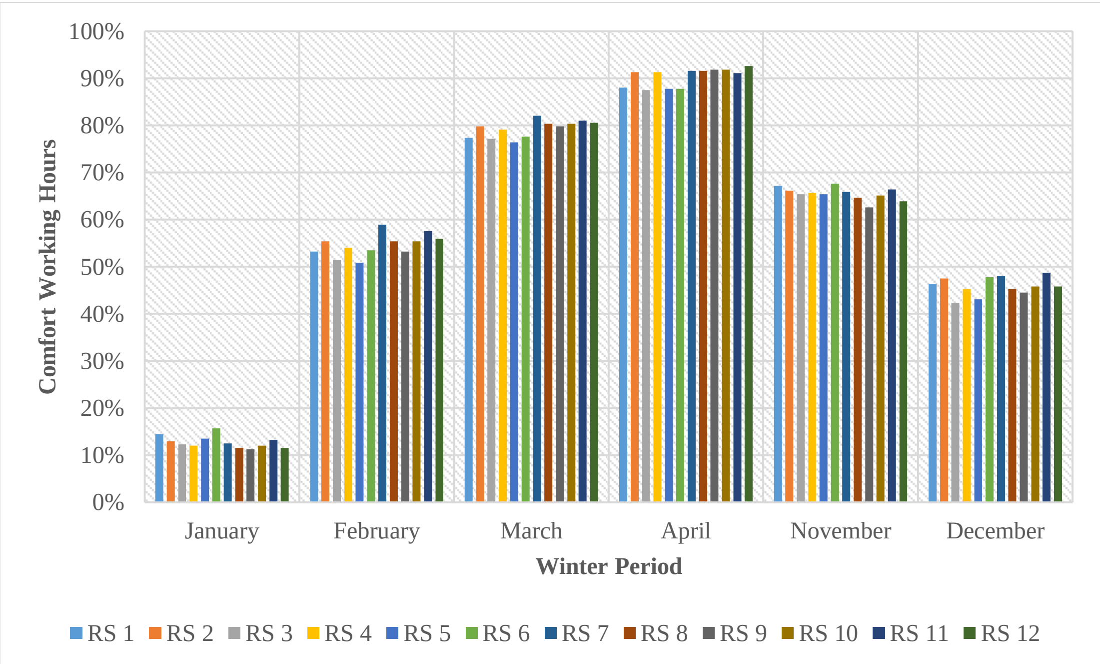


Figure 27: Winter Period Comfort WH Percentage for The Existing Building Within The 90% Acceptability Limits. Developed by the author.

For the other four months, Figure 27 presents that the comfort WH Percentage vary between 55%, 79%, 66%, and 46% in February, March, November, and December respectively, furthermore, the third floor spaces appear minor increase in comfort WH.

***2nd simulation- wintertime with Closed cavity DSS*:** The second simulation represents the building case after applying DSS, with 1% openings for the side windows in the second floor during winter which extends from January to April and from November to December, in this case, an extra glass layer was added to form a 35 cm cavity with lateral windows, all the cavity windows in this case are closed. Figures 28 and 29, Tables 10 and 11 show the second simulation outcomes.

80% acceptability: After reviewing the simulation results and referring to the ASHRAE standard. Figure 28 illustrates the winter period comfort WH Percentage for DSS case for the 80% acceptability limits. April presents the highest performance regarding the total thermal comfort hours. During April the 80% thermal acceptability operative temperatures ranged between 19.6 °C – 26.6 °C. All second floor spaces show thermal comfort in 98% of WH whilst the third floor spaces presents full thermal comfort WH. it is worth to mention that the average temperature for the atrium pace was 23 °C, while the upper parts reached 30 °C, moreover, the cavity temperature recorded 39°C.

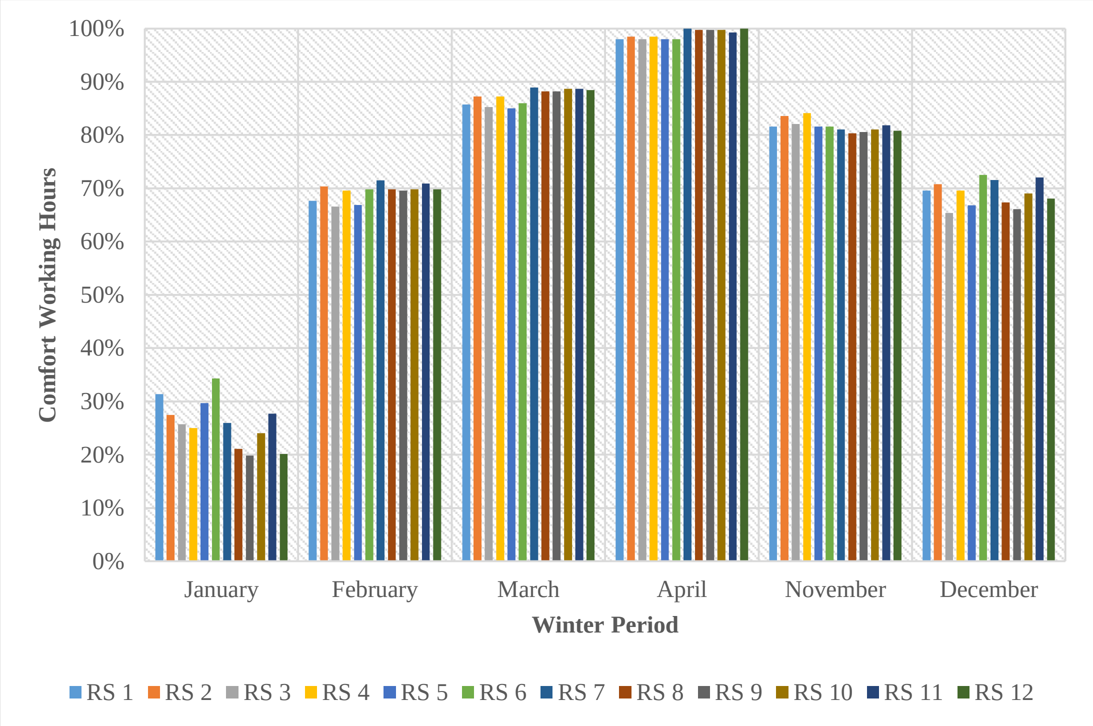


Figure 28: Winter Period Comfort WH Percentage For The DSS Case Within The 80% Acceptability Limits. Developed by the author.

The least thermal comfort hours are shown in January, where 18.0 °C to 25.0 °C are the comfort operative temperatures t_o range, one-third only of the total WH are set in the comfort range for the second floor spaces, however, the third floor spaces readings fluctuate between 20% and 30% comfort WH. Furthermore, the second and third floor southern spaces record the highest comfort hours among the whole spaces. During January, despite that the cavity average temperature reached 27 °C, the atrium space' average temperature did not exceed 18 °C.

Comfort operative temperatures t_o during March are considered between 19.0 °C and 26.0 °C, during this month; 87% of WH for the second floor spaces locate within these limits, a slight increase of 2% can be noticed in the third floor spaces. Moreover, the comfort operative temperatures t_o of November are higher than the previous with 0.6°C, while the results of the spaces record decreasing in comfort hours for both second and third floors spaces to reach an average of 80% only of WH. regarding the atrium space's temperatures: the average temperature recorded 21 °C and 23°C, while the cavity average temperature reached 35 °C and 33 °C for March and November respectively

February and December which have a close comfort operative temperatures t_o ranges of 18.3°C – 25.3°C and 18.6°C – 25.6°C respectively, in both months; the second floor spaces show convergent results, whereas during February the third floor spaces have a slightly higher comfort WH with a difference of 3% as it is illustrated in Figure 28. While the atrium average temperature was 19 °C, the cavity recorded 30 °C average t_o during February, on the other hand, in December the atrium average temperature was slightly higher whereas the cavity recorded less average temperature than February.

90% acceptability: Figure 29 demonstrates the percentages of the reading spaces comfort hours within the 90% acceptability limits during winter. April readings show the best comfort behavior whereas January readings record the least values. For April the minimum and maximum 90% thermal comfort temperatures range between 20.6°C – 25.6 °C respectively. The third floor spaces achieve a slight increase above 90% of thermal comfort during WH, whilst the second floor spaces' results achieve less values, the northern-east and northern-west spaces record the lowest thermally comfort hours with 85% of WH.

January results show that only 12% comfort WH can be achieved in the second and third floors' spaces, it's worth mentioning that the comfort operative temperatures t_o extend between 19.0 °C and 24.0 °C range.

For the other four months, the average comfort WH vary between 54%, 78%, 65%, and 46% in February, March, November and December respectively, furthermore, the third floor spaces appear slight increase in comfort WH.

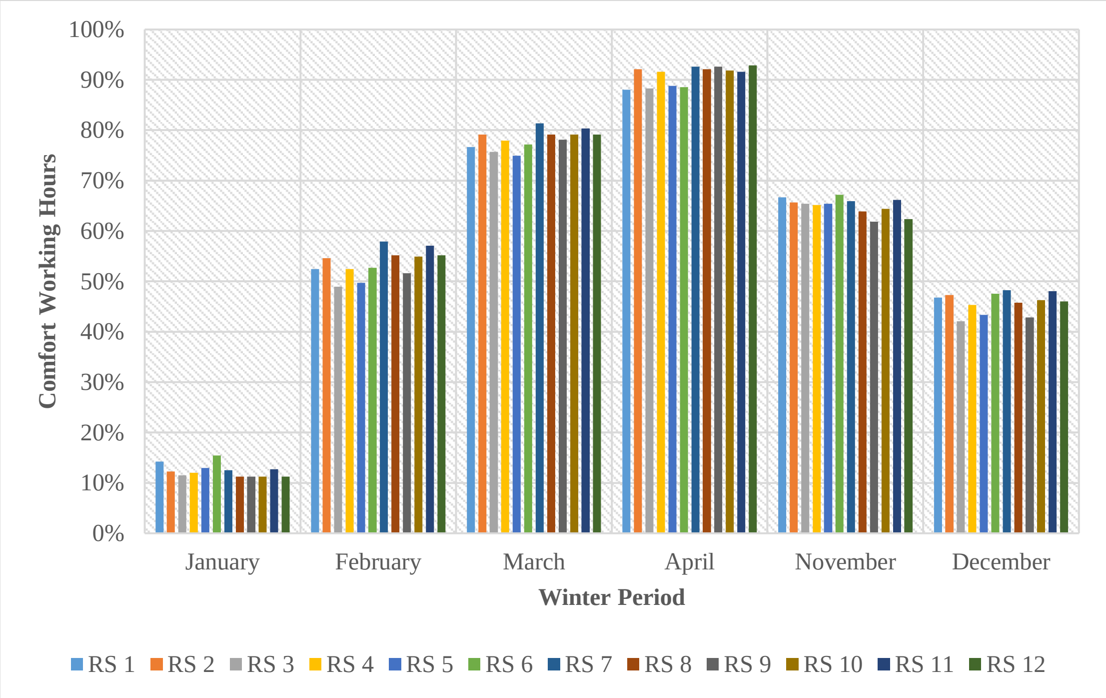


Figure 29: Winter Period Comfort WH Percentage For The DSS Case Within The 90% Acceptability Limits. Developed by the author.

Summer period simulations

In all summer period simulations, the simulation was run for the whole building which has the same characteristics and openings percentage for the lateral windows with the value of 10% for the simulated cases during summer- from May to October. To understand the effect of applying DSS, after testing the existing building, another proposal was set with upper outlets in the atrium skylight of 1.3 m x 2.0 m to extract the hot air. The total area of 7.8 m^2 for air outlets, the initial ratio between inlets and outlets was determined based on the literature recommendations.

Later on, to examine the thermal behavior of DSS an extra layer of low-E glass was added to create a 35 cm air gap, the lateral cavity windows were changed from fully closed 0% to fully open 100% with 25% intervals for each simulation.

3rd simulation- Existing building: The first simulation represents the single skylight (SS) building case with 10% openings for the side windows on the second floor during summer which extends from May to October. Figures 30 and 31, Table 10 and 11 clarify the simulation results.

80% acceptability: After reviewing the simulation results and referring to the ASHRAE standard, Figure 30 presents the summer period comfort WH Percentage for the existing building within the 80% acceptability limits. May shows the best performance regarding the total thermal comfort. During May the 80% thermal acceptability operative temperatures ranged between 20.8 °C – 30.0 °C. All second floor spaces show thermal comfort in 98% of WH. A slight decrease in the comfort hours appears in the third floor spaces which achieve comfort in 97% of the total WH. regarding the atrium space temperature, the average temperature recorded 27°C, while the upper part was higher with 4°C.

The range of acceptable operative temperatures during October is 21.1 °C – 30.3 °C, the results present close values to May with a slight difference between the spaces within the same floor; the northern-west space of the second space presents the highest thermal comfort in 99% of WH. For the third floor; four out of six spaces achieve thermal comfort in 94% of WH. The atrium average temperature reached 28 °C and it’s increased up to reach 31 °C in the top.

Where the acceptable operative temperatures in July and August locate between 23.0 °C and 32.0 °C. July presents the least values of thermal comfort hours for both the second and third floors, the second floor during July shows the maximum thermal comfort in the southern space with 30% of WH. The third floor spaces recorded only 9% of thermal comfort for the WH in the southern space while the other spaces show thermal comfort in 5% of WH. During July, the atrium space average temperature reached 34 °C and it increased 5 °C in the highest level. August presents thermal comfort in 60% of WH for the second floor spaces where this comfort is reduced in the third floor to be about 12% of WH for the most spaces, the southern space records thermal comfort in about 17% of WH. An average of 5 °C between the lower and upper levels of the atrium in August where the second floor level recorded an average of 33 °C.

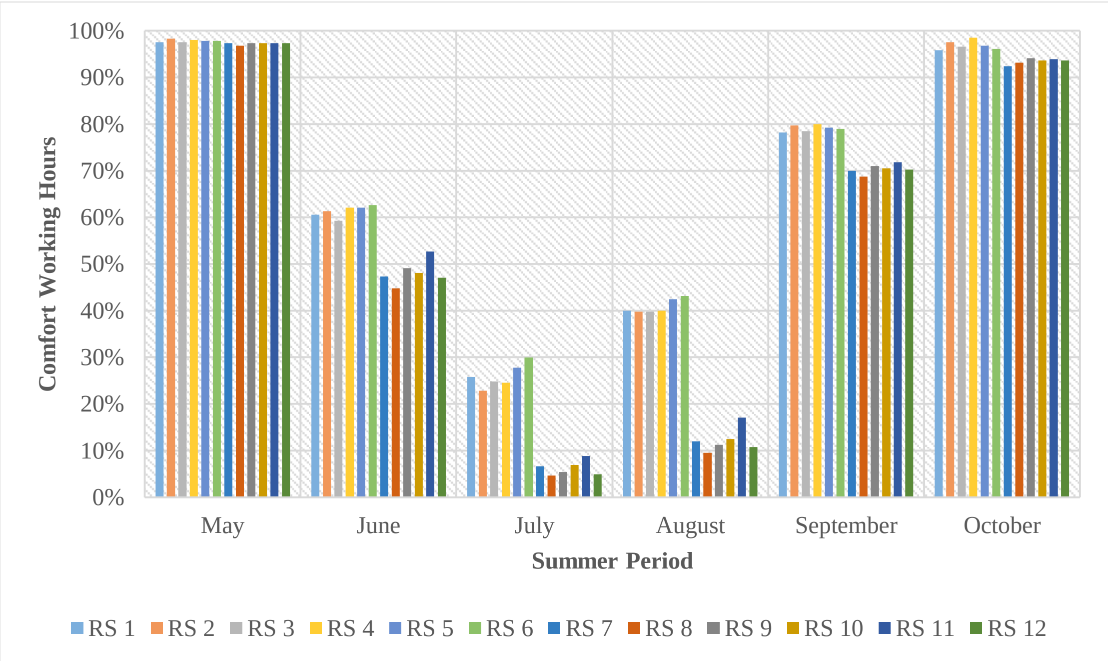


Figure 30: Summer Period Comfort WH Percentage For The Existing Building Within The 80% Acceptability Limits. Developed by the author.

September acceptable operative temperatures are set between 22.4 °C and 31.6°C. Thermal comfort is shown in the second floor spaces with 80% of WH, while third floor spaces present 70% of WH in thermal comfort. Furthermore, June accepted operative temperatures limits are 22.1 °C and 31.3 °C, within this range; 60% and 48% of WH are recorded thermal comfort in the second and third floor respectively. 32 °C was the atrium average temperature in the lower level, which increased 5 °C close to the skylight.

90% acceptability: Figure 31 presents the summer period comfort WH Percentage for the existing building in the 90% acceptability limits. May represents the best comfort behavior whereas July readings record the least values. For May the minimum and maximum 90% thermal comfort temperatures range between 21.8 °C – 29.0 °C respectively. The second floor spaces achieve about 90% of thermal comfort during working hours, both northern-east and northern west spaces reveal the best values of 94%, whilst the third floor spaces achieve less values, the northern spaces records the lowest thermally comfort hours with 85% of WH.

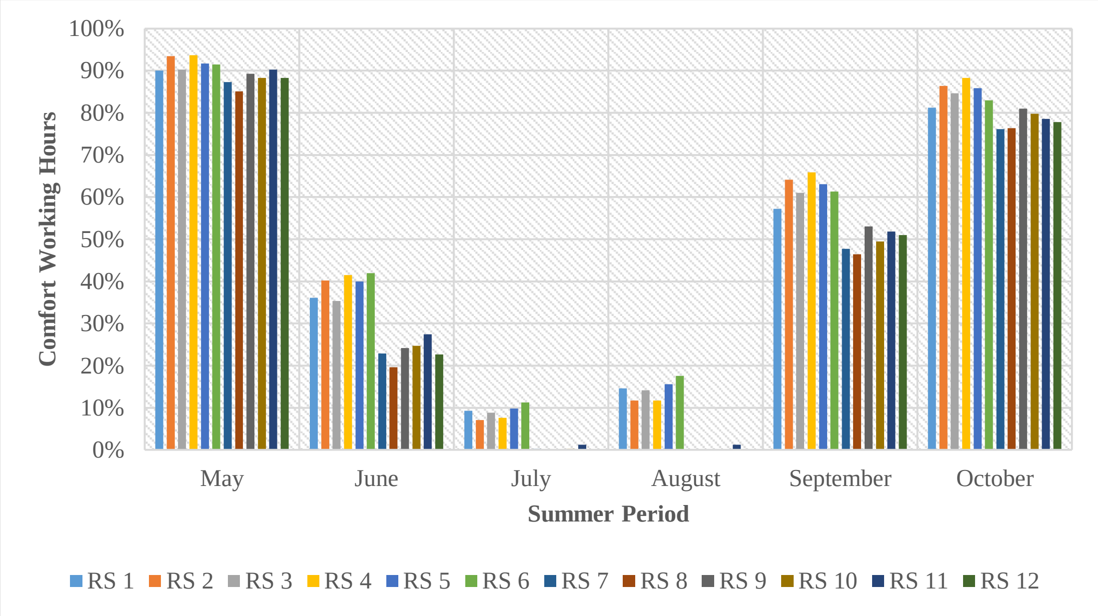


Figure 31: Summer Period Comfort WH Percentage For The Existing Building Within The 90% Acceptability Limits. Developed by the author.

In July, the minimum and maximum 90% accepted operative temperatures limits are 24.0 °C – 31.2 °C respectively. Within this range; the southern reading space in the second floor spaces achieves the best value of thermal comfort in 11% of WH. Most of the third floor spaces have no comfort hours during July, the southern space presents thermal comfort only in 1% of WH. The same results regarding August where it has the same operative temperatures limits as July. The second floor spaces comfort hours swing between 11% and 18% of WH, the southern space records the highest value. Moreover, all the third floor spaces have no comfort hours, same as July; the southern space on this floor has comfort in 1% of WH only.

June and September results show an obvious fluctuation between the same floor spaces readings as well as the two different floors. Comfort hours percentages are presented for the reading spaces in Figure 31.

4th simulation- Existing building with upper openings: the aim of this simulation is to be compared with the different scenarios of DSS, in this simulation, the upper outlets were totally opened, while the lateral windows were 10% opened for in the second floor during summer which extends from May to October. Figures 32 and 33 clarify this simulation findings, and Table 10 and 11 present the averaged readings.

80% acceptability: The simulation results for this case present that both May and October achieve convergent results for the second floor spaces which almost reached 98% comfort WH as it is shown in Figure 32, the outcomes for the third floor spaces of thermal comfort hours during October were slightly lower than May. It is worth to mention that the atrium average temperature during May and October recorded 26 °C and 27 °C, while the upper part' temperature was higher with only 1°C in both cases.

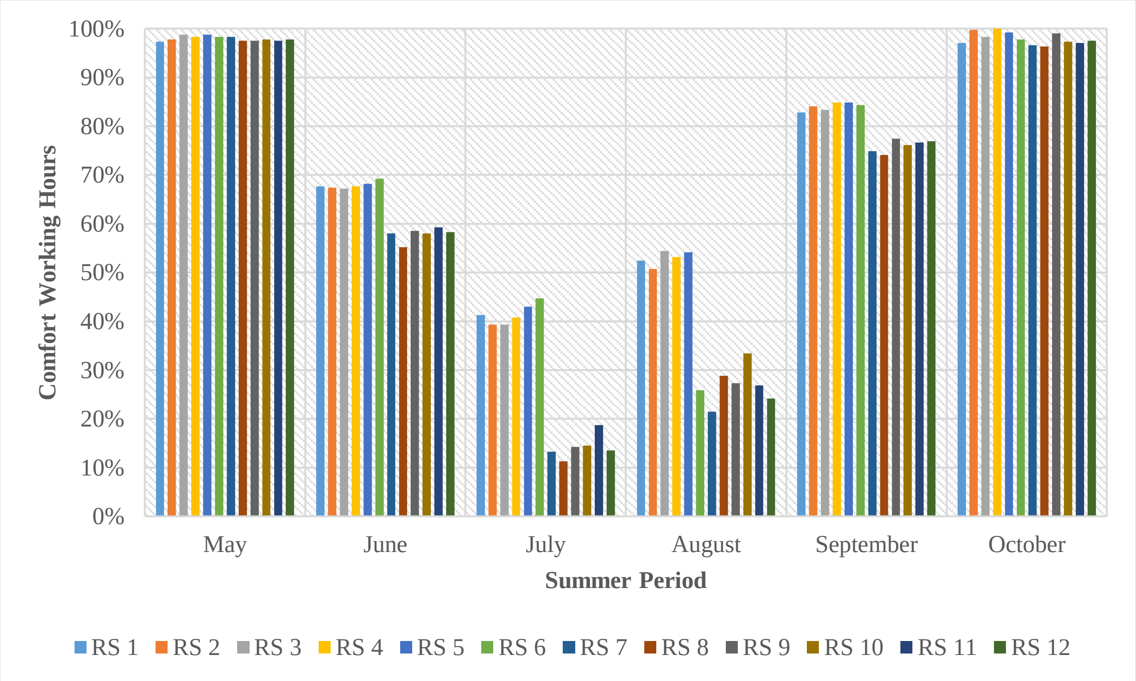


Figure 32: Summer Period Comfort WH For Opened Roof Existing Building Scenario Within The 80% Acceptability Limits. Developed by the author.

In July, comfort operative temperatures t_o were the least during summer as it is shown in Figure 32. The second floor spaces record 40% comfort WH where the highest value is recorded by the southern space with 45% comfortable WH, whereas the third floor achieved of 15% comfortable WH only, and the atrium average temperature was 33 °C. As August has the same comfort operative temperatures t_o of July; the second floor spaces barely exceed the 50% comfort WH. Moreover, although the third floor spaces have 27% comfort WH, the comfort WH in southern space reaches 33%. The atrium average temperature was the same as July while the average temperature increased only 1 °C in the highest point in the atrium.

June comfort operative temperatures t_o are limited between 22.1 °C and 31.3 °C; 68% of WH in the second floor spaces achieve comfort, while the third floor spaces temperatures were comfortable in more than half of the total WH as Figure 32 clarifies. Moreover, the atrium space average temperature reached 31 °C.

90% acceptability: Figure 33 explains the comfort WH in the library reading spaces within the 90% acceptability limits. May and October represent the best comfort behavior in this category whereas July readings are considered the worst. For the second and third spaces the two previous months almost reach 90% comfort WH same as the third floor during May, while the same floor achieve only 83% of comfort WH in October.

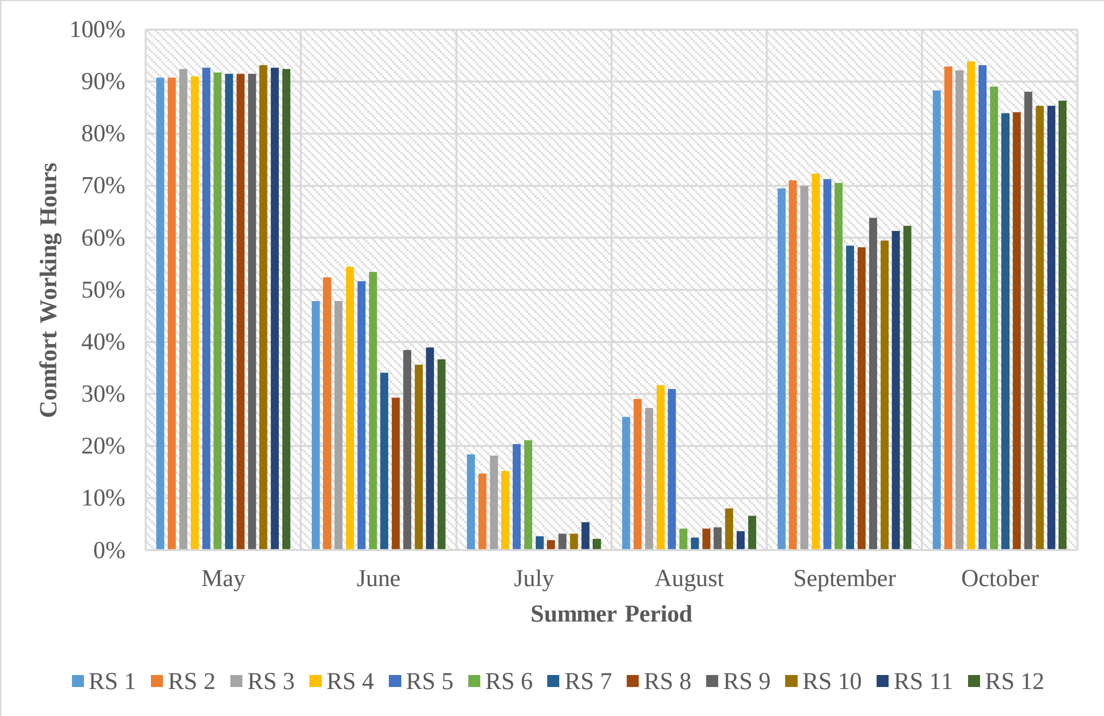


Figure 33: Summer Period Comfort WH Percentage For Opened Roof Existing Building Scenario Within The 90% Acceptability Limits. Developed by the author.

July reveals the highest values of discomfort with 85% and 97% of WH in the second and third floor spaces respectively. In spite of that, the southern space records the best value of 21% comfort WH. August comfort WH reach 27% for second floor spaces, whereas the third floor has a 95% discomfort WH. Even though, both second and third southern spaces score the highest number of comfort WH.

September results show 70% comfort WH in the second floor spaces, whereas the third floor achieves 60% comfort WH. An obvious variation between the same floor spaces reading as well as the two different floors in June as shown in Figure 33.

5th simulation- 35 cm cavity with fully closed lateral windows: This simulation represents the first proposal of the building with double skin skylight, where the depth of the cavity is 35 cm and all the cavity side windows are closed. 10% openings for the lateral windows in the second floor during summer which extends from May to

October. Results of this simulation are shown in Figures 34 and 35, with the averaged readings in Tables 10 and 11.

80% acceptability: The simulation results for this case present that both May and October achieve convergent results for the second floor spaces. As it is shown in Figure 34: the operative temperatures within the accepted range in more than 97% of WH, while the outcomes of the third floor spaces record 3% lower values of thermal comfort hours during October compared with May. The two months showed 26.5°C average atrium temperatures and 35°C, 43°C average temperatures for the higher level and the cavity respectively.

In July, comfort operative temperatures t_o were the least during summer as it is shown in Figure 34. The second floor southern space records 30% comfort WH where the highest value is recorded by the southern space with 32% comfort of WH, whereas the maximum number of comfort hours was recorded in the southern space of the third floor with 10% of WH only. As August has the same comfort operative temperatures t_o of July; the second floor spaces barely exceed the 40% comfort WH. Moreover, although the third floor spaces have 10% comfort WH, the comfort WH in southern space reaches 17% of the total WH.

June comfort operative temperatures t_o are limited in 22.1 °C and 31.3 °C; 60% of WH in the second floor spaces achieve comfort, while the third floor spaces temperatures were comfortable in half of the total WH only as it is seen in Figure 34. During July, August, and June, the average atrium temperature reached 33 °C, while the cavity temperature 53°C, the higher level of the atrium recorded 42 °C average temperatures.

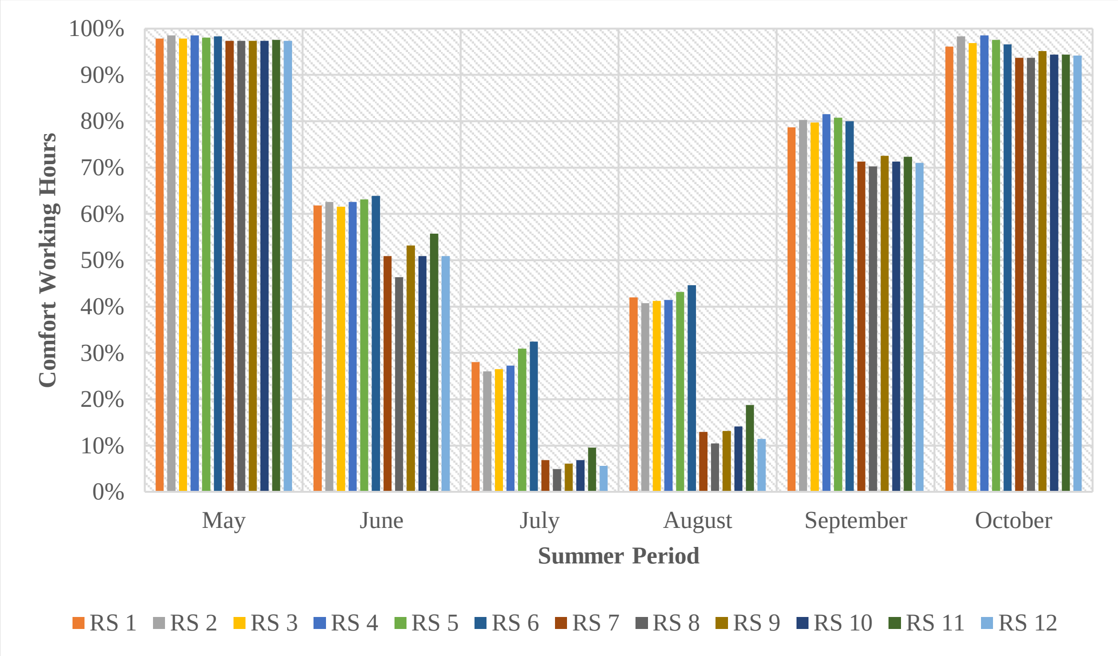


Figure 34: Summer Period Comfort WH Percentage for DSS with Fully Closed cavity Within The 80% Acceptability Limits. Developed by the author.

90% acceptability: Figure 35 clears up the percentage of comfort WH in the library reading spaces within the 90% acceptability limits. May represents the best comfort behavior in this category whereas July readings are considered the worst. For both the second and third spaces; 90% of WH are have comfortable temperatures, during October; 85% of WH are comfort in the second floor spaces while this value is decreased to 80% in the third floor.

July reveals the highest values of discomfort with 90% and 99% of WH in second and third floor spaces respectively. In spite of that, the southern space records the best value of 12% comfort WH. August comfort WH reach 15% for second floor spaces, whereas the third floor has a 99% discomfort WH. Even though, both second and third southern spaces score the highest number of comfort WH.

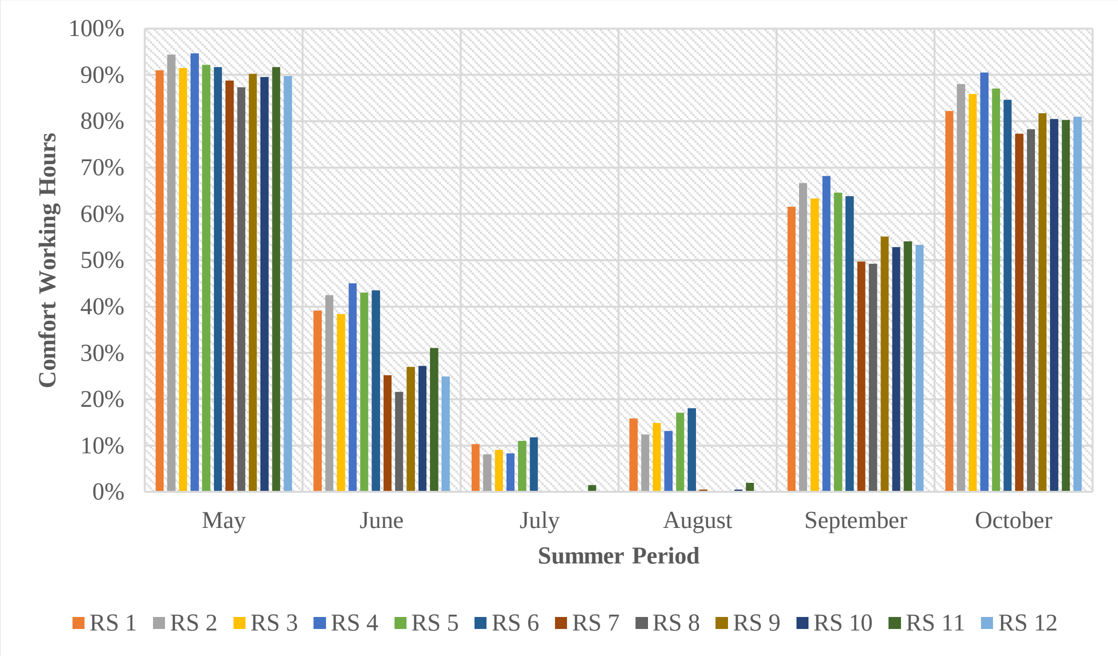


Figure 35: Summer Period Comfort WH Percentage For DSS With Fully Closed Cavity Within The 80% Acceptability Limits. Developed by the author.

June and September results show an obvious fluctuation between the same floor spaces reading as well as the two different floors. Comfort hours percentages are presented for the reading spaces in Figure 35.

6th simulation- 35 cm cavity with 25% opening lateral windows: This simulation represents the second proposal of the building with double skin skylight, where the depth of the cavity is 35 cm and all the cavity side windows are 25% opened. 10% openings for the lateral windows in the second floor during summer which extends from May to October. Figures 36 and 37 with Tables 10 and 11 clear up the simulation outcomes.

80% acceptability: The simulation results for this case present that both May and October achieve convergent results for the second floor spaces. As it is shown in Figure 36: the operative temperatures within the accepted range in more than 98% of

WH, while the outcomes of the third floor spaces record 2% lower values of thermal comfort hours during October compared with May. Moreover, the atrium average temperature recorded 27 °C, while the cavity average temperature reached 32 °C in May and October.

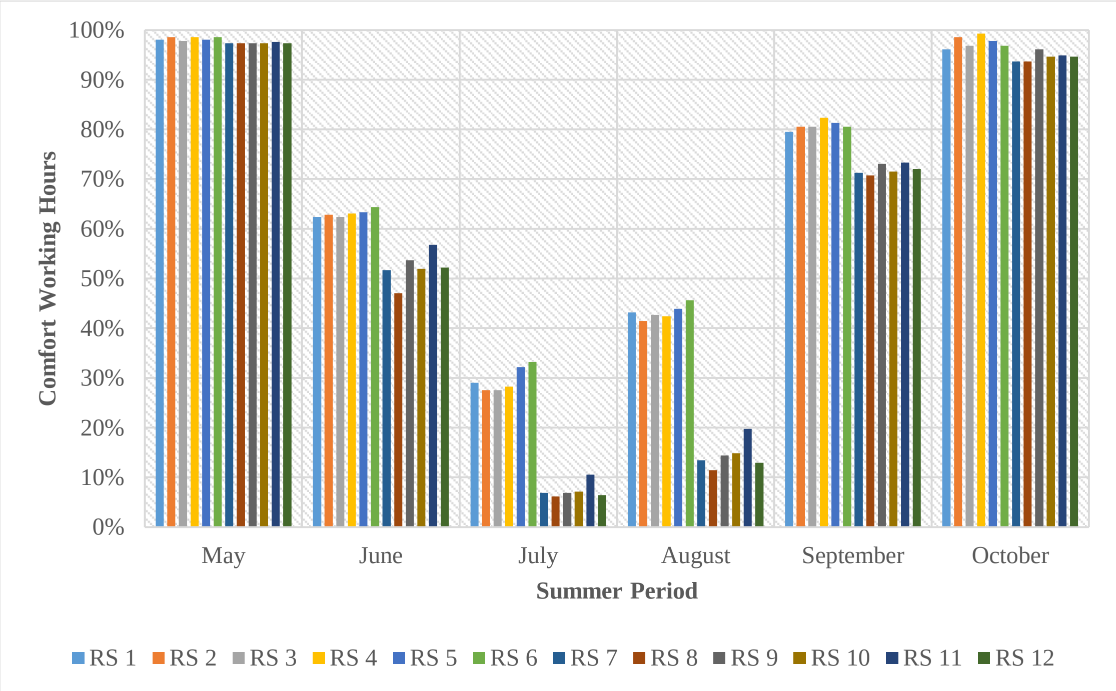


Figure 36: Summer Period Comfort WH Percentage For DSS With 25% Opened Cavity Within The 80% Acceptability Limits. Developed by the author.

In July, comfort operative temperatures t_o were the least during summer as it is shown in Figure 36. The second floor southern space records 30% comfort WH where the highest value is recorded by the southern space with 32% comfort of WH, whereas the maximum number of comfort hours was recorded in the southern space of the third floor with 11% of WH only. As August has the same comfort operative temperatures t_o of July; the second floor spaces' comfort hours reach 43% of total WH. Moreover, although the third floor spaces have a percentage of 13% comfort WH, the comfort WH in southern space reaches 20%. For both months, the atrium average temperature reached 33°C, whereas the cavity recorded an average of 40 °C.

June comfort operative temperatures t_o are limited in 22.1 °C and 31.3 °C; more than 60% of WH in the second floor spaces achieve comfort, while the third floor spaces temperatures were comfortable in more than half of the total WH as Figure 36 presents. During June and September the atrium average temperature was 30 °C and the cavity reached 38 °C.

90% acceptability: Figure 37 clarifies the percentages of comfort hours in the library reading spaces within the 90% acceptable limits. May represents the best comfort behavior in this category whereas July readings are considered the worst. For both the second and third spaces in May; 90% of WH are have comfortable temperatures, during October; a percentage of 85% of WH are comfort in the second floor spaces while this value decreases to 80% on the third floor.

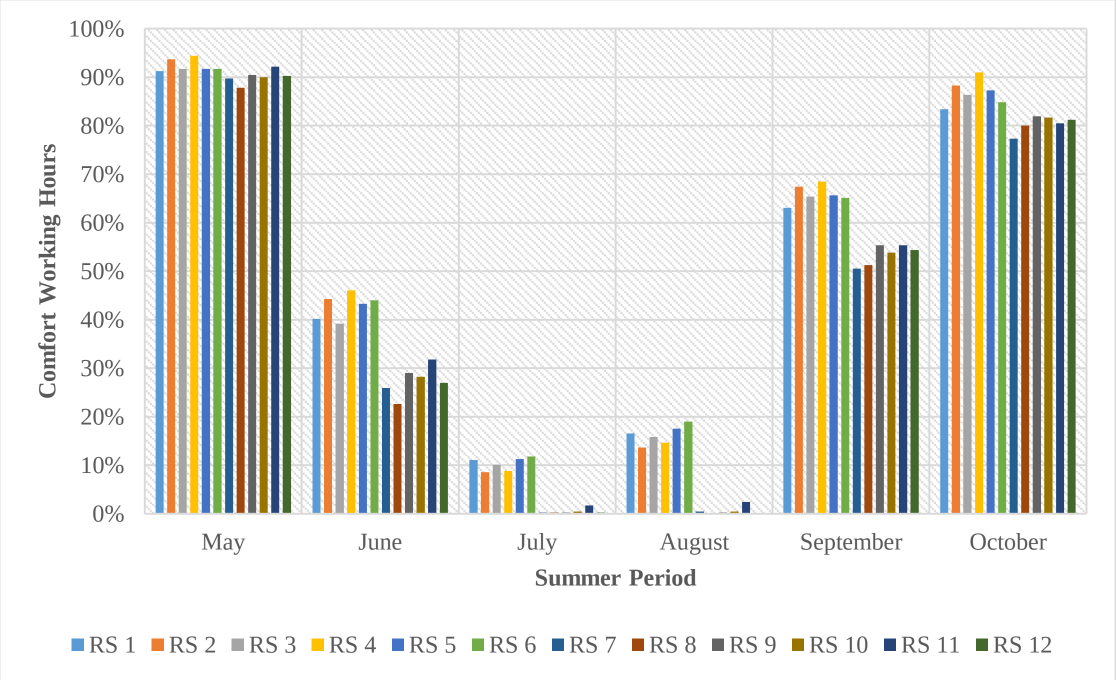


Figure 37: Summer Period Comfort WH Percentage For DSS With 25% Opened Cavity Within The 90% Acceptability Limits. Developed by the author.

July reveals the highest values of discomfort with a percentage of 90% of WH in the second floor spaces, third floor spaces don't reach the 1% of comfort WH. In spite of that, the southern space in the second and third floors record the highest values of 12% and 2% comfort WH respectively. August comfort WH reach 15% for second floor spaces, whereas the third floor has a 99% discomfort WH. Even though, both second and third southern spaces score the highest number of comfort WH.

June and September results show an obvious fluctuation between the same floor spaces readings as well as the two different floors. Comfort hours percentages are presented for the reading spaces in Figure 37.

7th simulation- 35 cm cavity with 50% opening lateral windows: This simulation represents the third proposal of the building with double skin skylight, where the depth of the cavity is 35 cm and all the cavity side windows are 50% opened. 10% openings for the lateral windows in the second floor during summer which extends from May to October. Figures 38 and 39 with Tables 10 and 11 illustrate the simulation findings.

80% acceptability: The simulation results for this case present that both May and October achieve convergent results for the second floor spaces. As it is shown in Figure 38. The operative temperatures within the accepted range in more than 98% of WH, while the outcomes of the third floor spaces record 2% lower values of thermal comfort hours during October compared with May. Moreover, the atrium average temperature recorded 27 °C, while the cavity average temperature reached 30 °C in May and October.

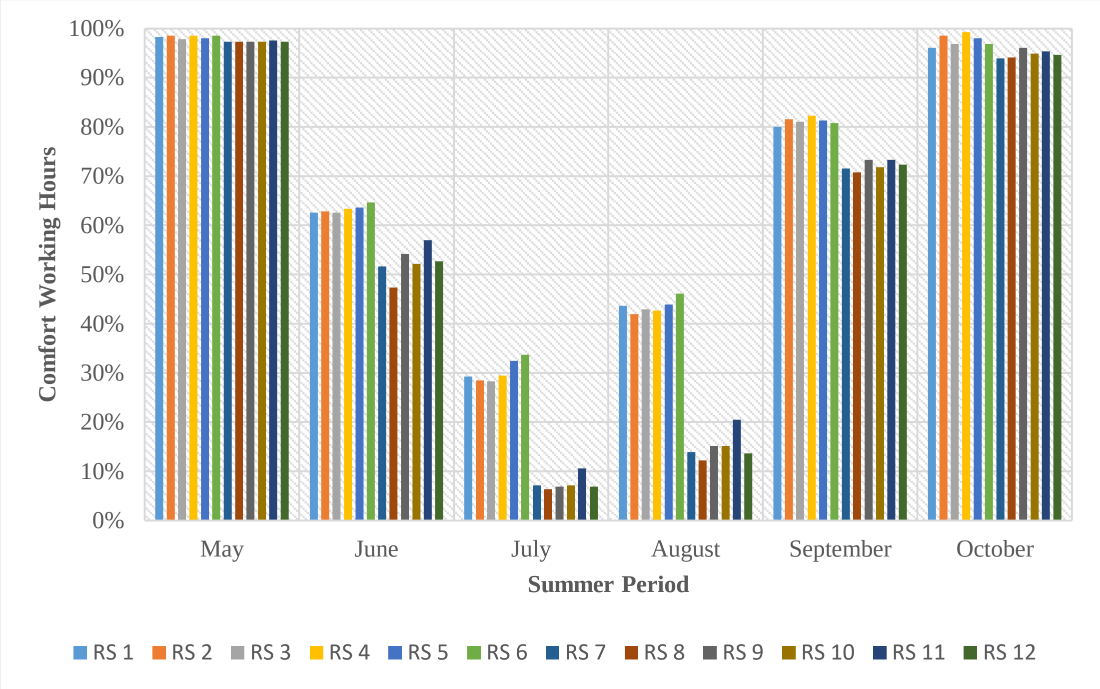


Figure 38: Summer Period Comfort WH Percentage For DSS With 50% Opened Cavity Within The 80% Acceptability Limits. Developed by the author.

In July, comfort operative temperatures t_o were the least during summer as it is shown in Figure 38. The second floor southern space records a percentage of 30% of comfort WH where the highest value is recorded by the southern space with 32% comfort of WH, whereas the maximum number of comfort hours was recorded in the southern space of the third floor with 11% of WH only. As August has the same comfort operative temperatures t_o of July; the second floor spaces' comfort hours reach 43% of total WH. Moreover, although the third floor spaces have a percentage of 15% comfort WH, the comfort WH in southern space reaches 20%. For both months, the atrium average temperature reached 33°C, whereas the cavity recorded an average of 38 °C.

June comfort operative temperatures t_o are limited in 22.1 °C and 31.3 °C; about 62% of WH in the second floor spaces achieve comfort, whereas the third floor spaces barely exceed 50% of comfort WH as Figure 38 presents. During June and September the atrium average temperature was 31 °C and the cavity reached 35 °C.

90% acceptability: Figure 39 describes the percentages of comfort hours in the library reading spaces within the 90% acceptable limits. May represents the best comfort behavior in this category whereas July readings are considered the worst. For both the second and third spaces during May; 90% of WH are have comfortable temperatures, during October; a percentage of 85% of WH are comfort in the second floor spaces while this value decreases to 80% in the third floor.

July reveals the highest values of discomfort with a percentage of 90% of WH in the second floor spaces, third floor spaces don't reach the 1% of comfort WH. In spite of that, the southern space in the second and third floors record the highest values of 13% and 2% comfort WH respectively. August comfort WH reach 17% for second floor spaces, whereas the third floor has a 99% discomfort WH. Even though, both second and third southern spaces score the highest number of comfort WH.

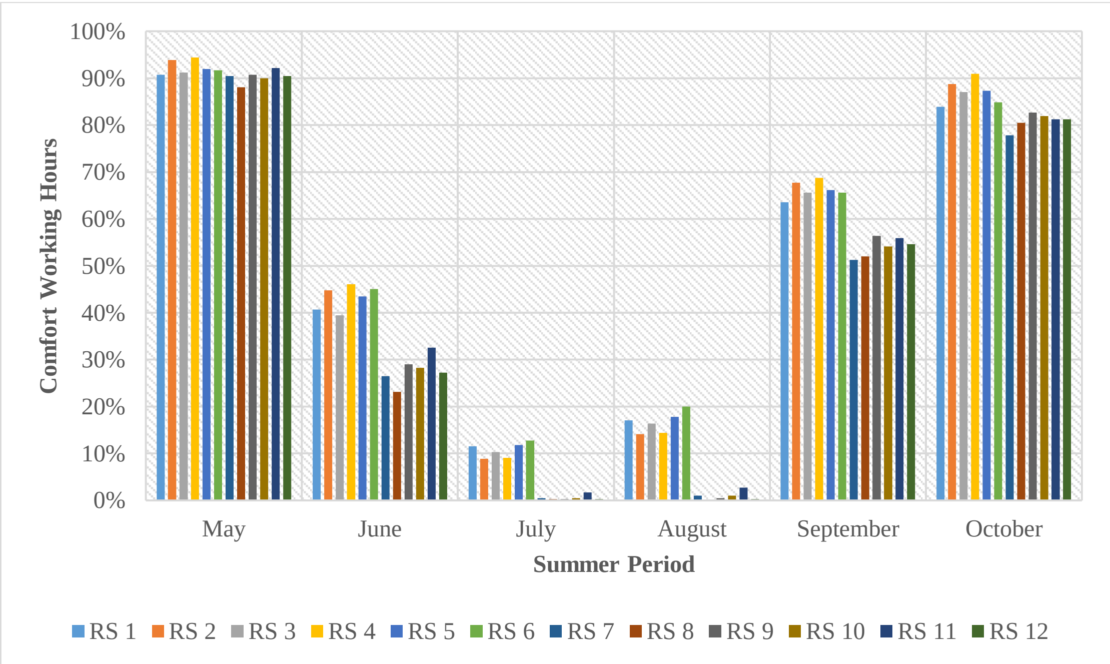


Figure 39: Summer Period Comfort WH Percentage For DSS With 50% Opened Cavity Within The 90% Acceptability Limits. Developed by the author.

June and September results show an obvious fluctuation between the same floor spaces readings as well as the two different floors. Comfort hours percentages are presented for the reading spaces in Figure 39.

8th simulation- 35 cm cavity with 75% opening lateral windows: This simulation represents the fourth proposal of the building with double skin skylight, where the depth of the cavity is 35 cm and all the cavity side windows are 75% opened. 10% openings for the lateral windows on the second floor during summer which extends from May to October. Simulation results are shown in Figures 40 and 41, with Tables 10 and 11.

80% acceptability: The simulation results for this case present that both May and October achieve convergent results for the second floor spaces. As it is shown in Figure 40: the operative temperatures within the accepted range in more than 98% of WH, while the outcomes of the third floor spaces record 3% lower values of thermal comfort hours during October compared with May. Moreover, the atrium average temperature recorded 27 °C, while the cavity average temperature reached 30 °C in May and October.

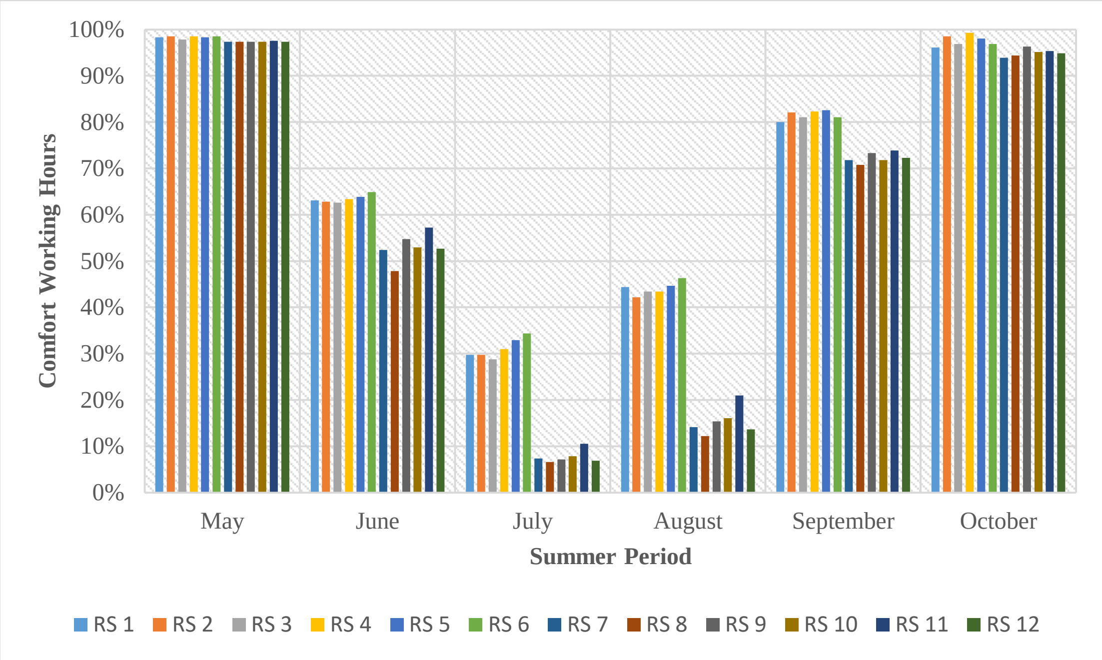


Figure 40: Summer Period Comfort WH Percentage For DSS With 75% Opened Cavity Within The 80% Acceptability Limits. Developed by the author.

In July, comfort operative temperatures t_o were the least during summer as it is shown in Figure 40. The second floor southern space records a percentage of 30% of comfort WH where the highest value is recorded by the southern space with 34% comfort of WH, whereas the maximum number of comfort hours was recorded in the southern space of the third floor with 11% of WH only. For the both months, the atrium average temperature reached 33°C, whereas the cavity recorded an average of 37 °C.

Since August has the same comfort operative temperatures t_o of July: the second floor spaces' comfort hours reach 43% of total WH. Moreover, although the third floor spaces have a percentage of 15% comfort WH, the comfort WH in southern space exceeds 20%.

June comfort operative temperatures t_o are limited in 22.1 °C and 31.3 °C; about 63% of WH in the second floor spaces achieve comfort, whereas the third floor spaces reach more than 55% of comfort WH in some spaces as Figure 40 shows. During June and September the atrium average temperature was 31 °C and the cavity reached 35 °C.

90% acceptability: Figure 41 clarifies the percentages of comfort WH in the library reading spaces within the 90% acceptable limits. May represents the best comfort behavior in this category whereas July readings are considered the worst. For both the second and third spaces during May; 90% of WH are have comfortable temperatures, during October; a percentage of 85% of WH are comfort in the second floor spaces while this value decreases to 80% in the third floor.

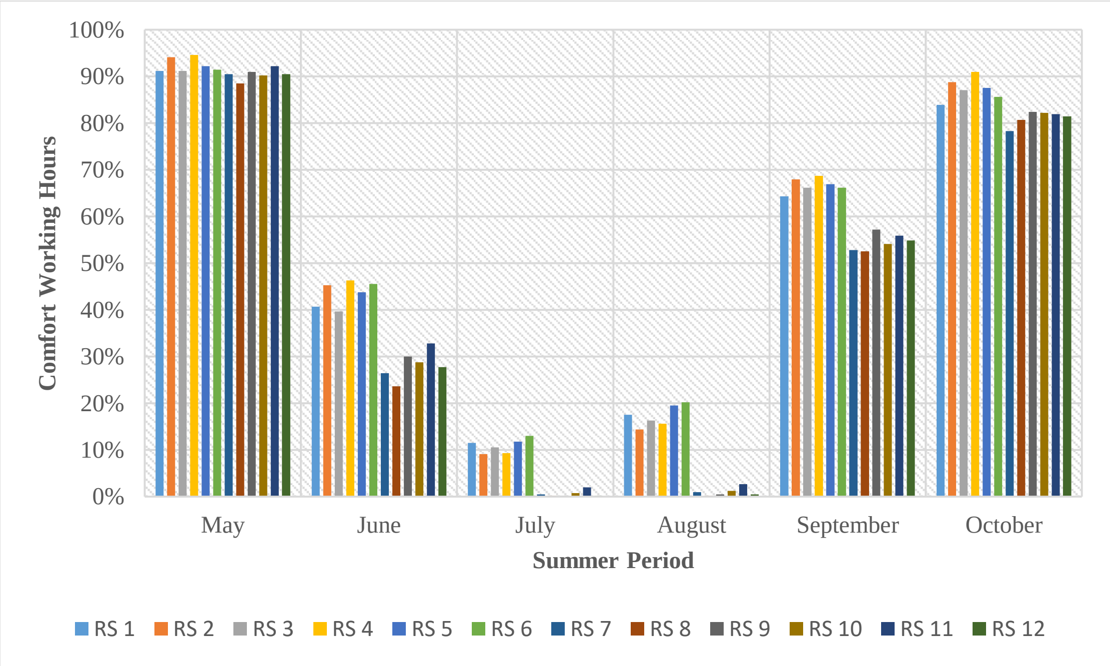


Figure 41: Summer Period Comfort WH Percentage For DSS With 75% Opened Cavity Within The 90% Acceptability Limits. Developed by the author.

July reveals the highest values of discomfort with a percentage of 90% of WH in the second floor spaces, third floor spaces don't reach the 1% of comfort WH. In spite of that, the southern space in the second and third floors record the highest values of 13% and 2% comfort WH respectively. August comfort WH reach 17% for second floor spaces, whereas the third floor has a 99% discomfort WH. Even though, both second and third southern spaces score the highest number of comfort WH.

June and September results show an obvious fluctuation between the same floor spaces readings as well as the two different floors. Comfort hours percentages are presented for the reading spaces in Figure 41.

9th simulation- 35 cm cavity with 100% opening lateral windows: This simulation represents the fourth proposal of the building with double skin skylight, where the depth of the cavity is 35 cm and all the cavity side windows are 100% opened. 10% openings for the lateral windows in the second floor during summer which extends from May to October. Figures 42 and 43, with Tables 10 and 11 clarify this simulation findings.

80% acceptability: The simulation results for this case present that both May and October achieve convergent results for the second and third floor spaces. As it is shown in Figure 42: almost all the spaces have comfort operative temperatures t_o during the whole WH.

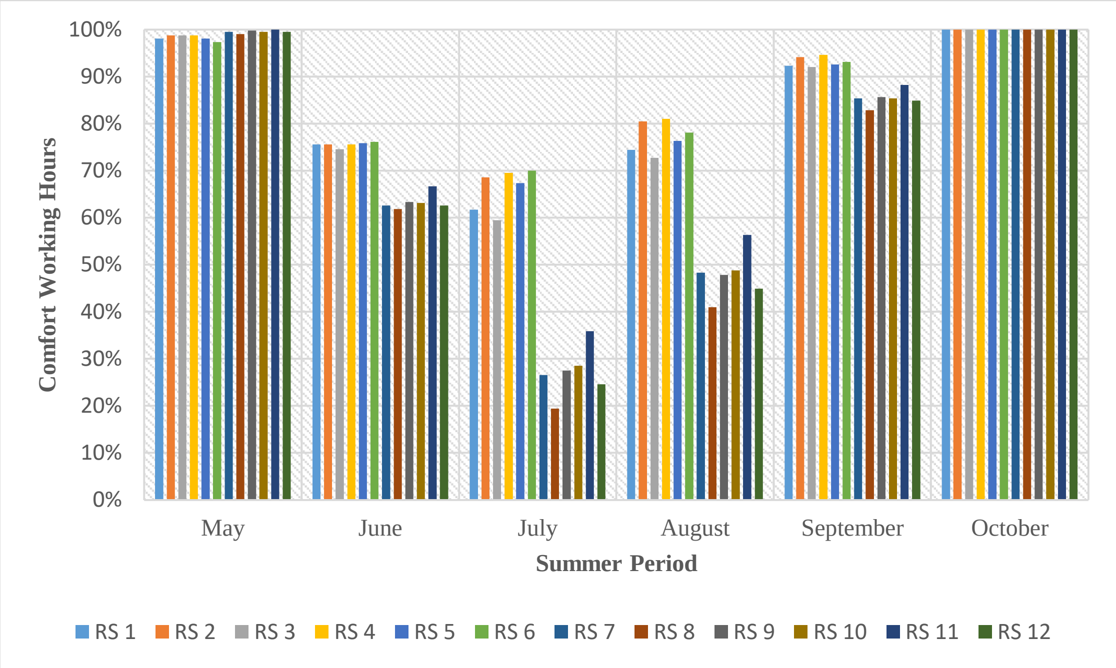


Figure 42: Summer Period Comfort WH Percentage For DSS With Fully Opened Cavity Within The 80% Acceptability Limits. Developed by the author.

In spite of the least comfort temperature results for July, but the second floor spaces achieve comfort operative temperatures t_o in more than 65% of WH, while the third floor spaces results show comfort indoor temperatures of 28% of WH, the southern space reaches comfort temperatures in 36% of WH. For the both months, the atrium average temperature reached 32°C, whereas the cavity recorded an average of 37 °C.

June and August results show convergent readings for the second floor spaces with a percentage of 75% of WH thermal comfort, whereas the third floor spaces during June record better operative temperatures than August, with 14% difference as Figure 42 shows. During June and September the atrium average temperature was 30 °C and the cavity reached 34 °C.

90% acceptability: Figure 43 shows the percentages of comfort hours for the reading spaces within the 90% acceptable limits. October represents the best comfort behavior in this category whereas July readings are considered the worst. For both the second and third spaces during October; 95% of WH have comfortable temperatures, during May; a percentage of 93% of WH are comfort in both second and third floors spaces.

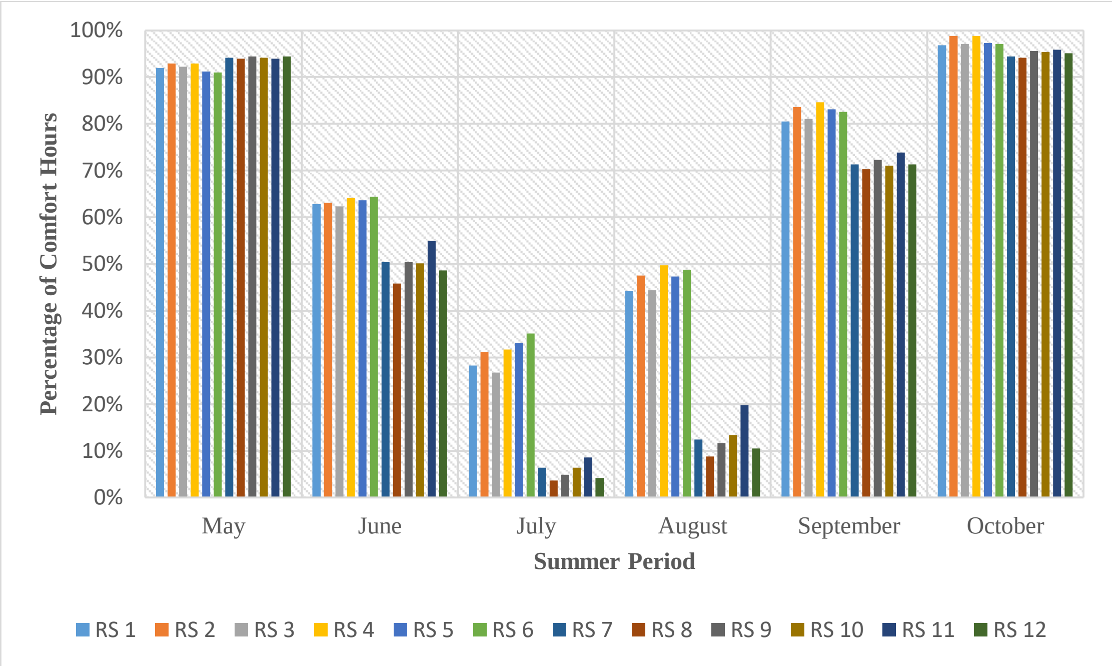


Figure 43: Summer Period Comfort WH Percentage for DSS with Fully Opened Cavity Within The 90% Acceptability Limits. Developed by the author.

July reveals comfort temperatures in 30% of WH in the second floor spaces, while the third floor spaces have comfortable temperatures in 7% of WH. In spite of that, the southern space in the second and third floors record the highest values of 35% and 9% comfort WH respectively. August comfort WH reaches 48% for second floor spaces, whereas the third floor spaces have 88% discomfort WH. Even though, the third floor southern space records the highest comfort WH.

June comfort temperatures are shown in two-thirds and half of the total WH for the second and third floors spaces respectively. September results show comfort temperatures in 80% and 70% of WH for the second and third spaces respectively. Comfort hours percentages are presented for the reading spaces in Figure 43.

3.6.1.2 Materials Selection Simulation

In this section, another three scenarios for the selected model from the previous step were tested to evaluate the effect of changing the DSS glazing materials for winter and summer respectively. The worst case months in both winter and summer were tested by changing DSS glazing materials.

***10th, 11th, 12th simulations-* winter case:** according to the previous section, January showed the least comfort WH during the winter period, hence, this section used it as a sample to test the effect of changing the DSS materials on thermal comfort WH. simulation results are obtained in Figure 44, Tables 10 and 11.

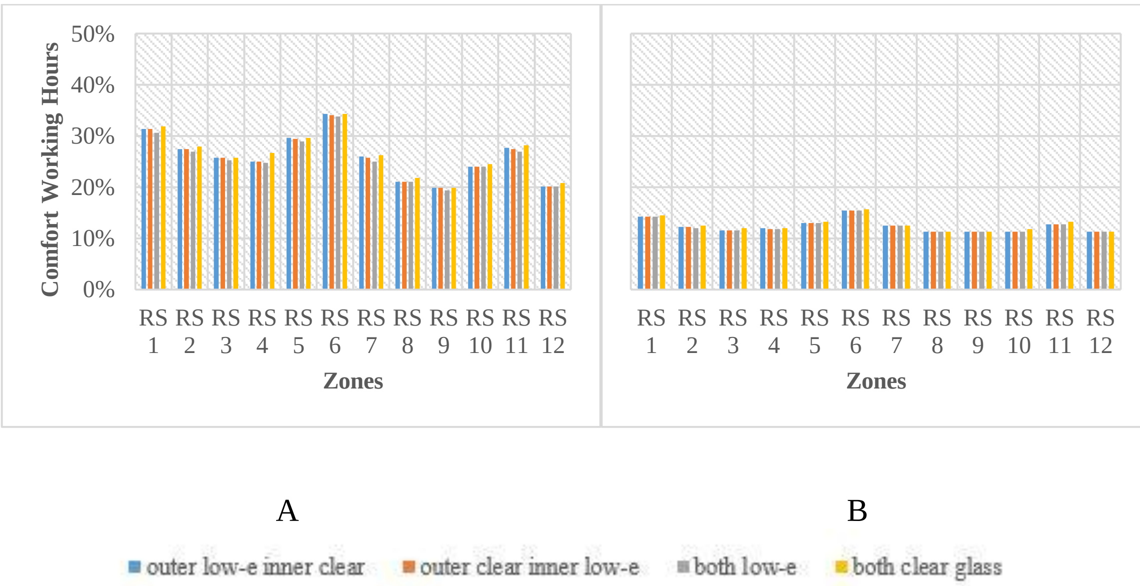


Figure 44: Changing DSS Glazing Materials in Winter Within The A: 80%, B: 90% Acceptability limits. Developed by the author.

Figure 44 A and B shows that changing the DSS glazing materials will not affect the comfort WH during January for the 80% and 90% acceptability ranges, whereas using both clear glass layers increase the comfort WH 1% from the existing building only in some spaces. Interestingly, the atrium average temperature recorded 18 °C and 20 °C between the lower level and upper level respectively for the three materials’ scenarios.

***13^{h}, 14th, 15th simulations*- summer case:** according to the previous section, July showed the least comfort WH during the winter period, hence, this section used it as a sample to test the effect of changing the DSS materials on thermal comfort WH. Tables 10 and 11 with Figure 45 present the outcomes.

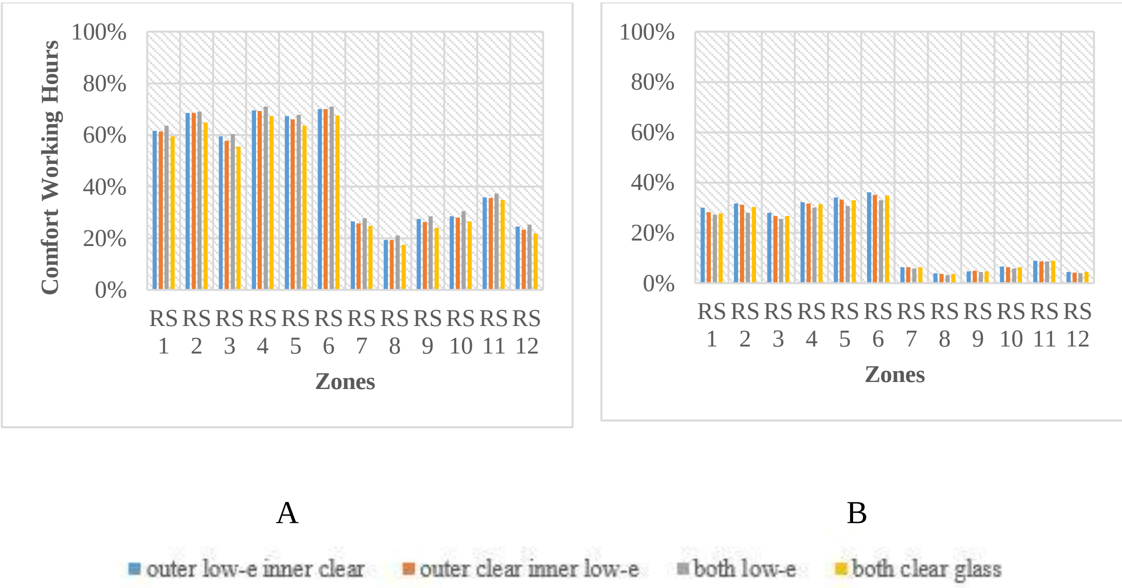


Figure 45: Changing DSS Glazing Materials in Summer Within The A: 80%, B: 90% Acceptability limits. Developed by the author.

Figure 45 A and B shows that changing the DSS glazing materials will not affect the comfort WH during July for the 80% and 90% acceptability ranges, whereas using both Low-e glass layers increase the comfort WH 1% from the existing building only in some spaces while using both clear glass decreased the comfort WH slightly. Changing DSS glazing materials recorded the same average temperature in the atrium of 32°C, while the average cavity temperature was 38°C.

3.6.2 Simulation Group 2

In this group, two design parameters related to the building ventilation strategy were tested, which are the night ventilation and changing the building inlets respectively. The library with the previous design decisions (fully opened cavity windows, Low-e external glass layer, and clear glass internal layer) was tested in different sequential scenarios for summer period; while May, October, and September reached more than 90% comfort WH, these months are excluded in this section.

3.6.2.1 Night Ventilation Simulation

16th simulation: Based on the previous simulation results, this stage was applied to the fifth scenario of the summer period which shows the best results of comfort WH Percentage during summer where the cavity windows are fully opened. Since changing the materials did not improve the comfort behavior of the building remarkably, then the study will use the first scenario for the rest parts. Moreover, the winter period is excluded. On the other hand, as May and October reached an average of more than 90% comfort WH, these two months were not studied in this section, this part of the study focuses on summer months with lower comfort WH which are July, August, June, and September respectively. Numerical simulation results are shown in Tables 10 and 11.

80% acceptability limits: Figures 46, 47, 48, and 49 show the outcomes of applying night ventilation to the reading spaces on the second and third floors during July, August, June, and September respectively. Results illustrate that operating night ventilation during this period increases the comfort WH for the studied spaces. As September already recorded high comfort WH, night ventilation slightly increased the comfort WH during this month. Figure 46 shows that comfort WH achieved a 2%

increase for the second floor spaces, whereas the third floor spaces recorded an average of 4% increase.

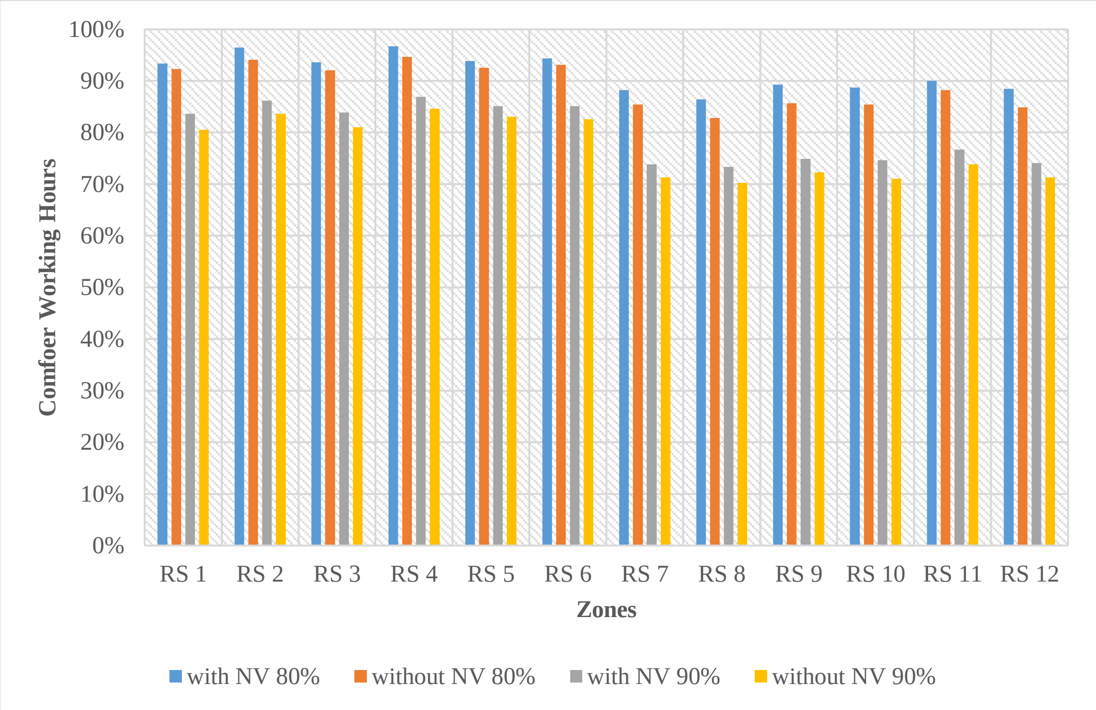


Figure 46: September Performance With and Without Night Ventilation. Developed by the author.

The effect of operating night ventilation strongly appears in the third floor comfort WH in July within the mentioned range as Figure 47 highlighted, where the southern space reached about 50% comfort WH. During July, operating day and night ventilation increases the comfort WH in the second floor spaces to an average of 75% WH, while the third floor spaces increased more than 12% average comfort WH within the 80% acceptability limits. During July, the atrium average temperature was 32°C whereas the cavity average temperature recorded 37°C.

Figure 48 presents August comfort WH in the second floor spaces which reached an average of 83% comfort WH, while some spaces almost reached 90% comfort WH.

Moreover, the atrium average temperature in August reached 31°C where the cavity average temperature was 36°C.

On the other hand, Figure 49 illustrates June results which reveal a slight difference of about 1% and 4% improvement in comfort WH for the second and third floors respectively, while for the atrium: the average temperature was 31°C for the atrium and 35°C for the cavity.

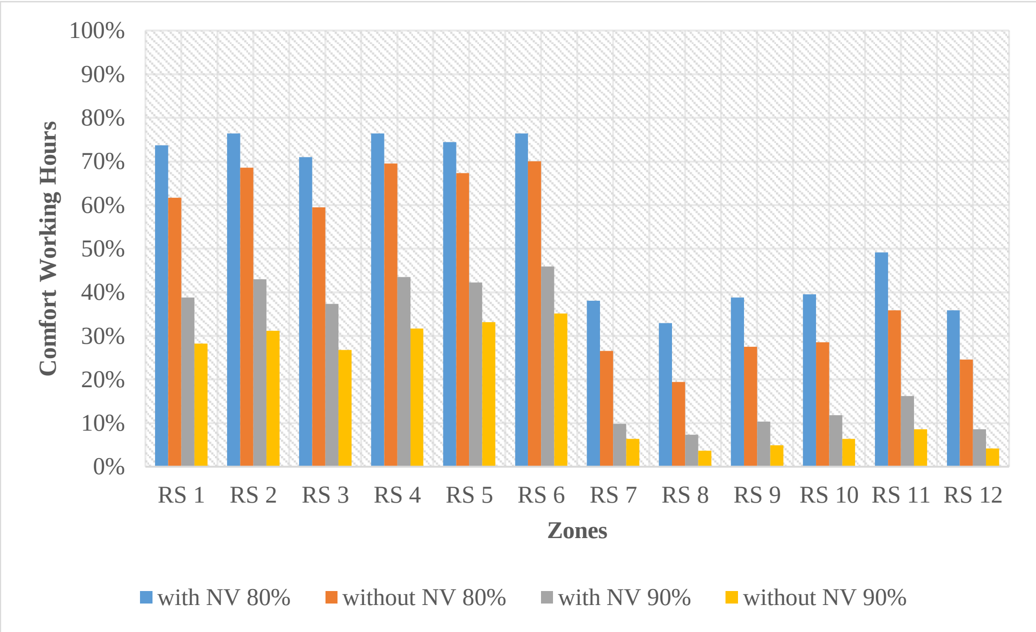


Figure 47: July Performance With and Without Night Ventilation. Developed by the author.

90% acceptability limits: On the other hand, for the 90% acceptable comfort range: the average improvement in comfort WH during September was only 3% for both floors as it can be noticed in Figure 46. The second floor spaces raised about 10% of comfort WH during July, whereas the third floor spaces have a slight improvement of 5% only as it is seen in Figures 47.

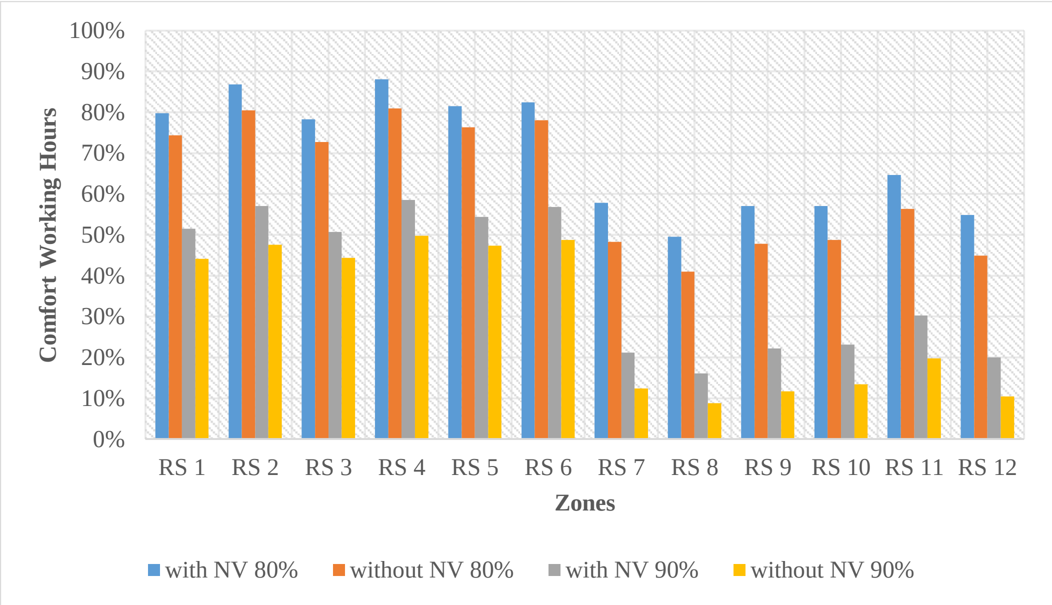


Figure 48: August Performance With and Without Night Ventilation. Developed by the author.

Third floor spaces achieved a higher improvement of comfort WH during August which exceeded the average of 20% comfort WH, while the southern space achieved 30% comfort WH, however, the second floor spaces comfort WH increased with the average of 8% as Figure 48 clarifies.

In spite of the slight increase of comfort WH in June by night ventilation operating, it achieved an average of 57% comfort WH in the third floor spaces within this range, an average of 5% increase was achieved for both spaces as it can be seen in Figure 49.

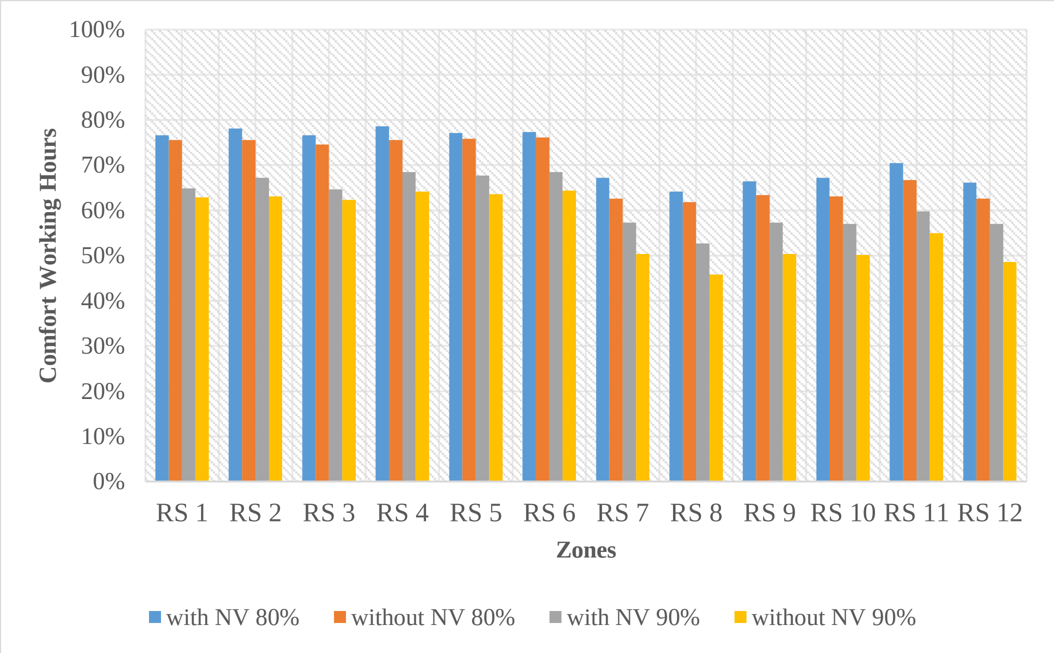


Figure 49: June Performance With and Without Night Ventilation. Developed by the author.

3.6.2.2 Building Fenestration Design Simulation

17th, 18th simulations: Based on the previous section results, operating night ventilation increases the thermal comfort WH percentage in the reading spaces for the second and third floors. For September, the reading spaces' achieved comfort WH in more than 90% of WH, thus this month was not tested in this simulation group. In this section, the simulations were run with fully opened cavity windows as well as operating night ventilation during three of summer months which are July, August, and June. In this part of simulations, the façade openings (inlets) in the second floor were changed to half opened-50%, and fully opened-100%. Moreover, the results are compared with the initial case with night ventilation and fully opened cavity outlets, where the facades' windows were 10% opened. Tables 10 and 11 present the numerical averaged comfort WH within the 80% and 90% acceptability ranges, and Figures 50, 51, 55, 53, 54, and 55 illustrate the monthly performance.

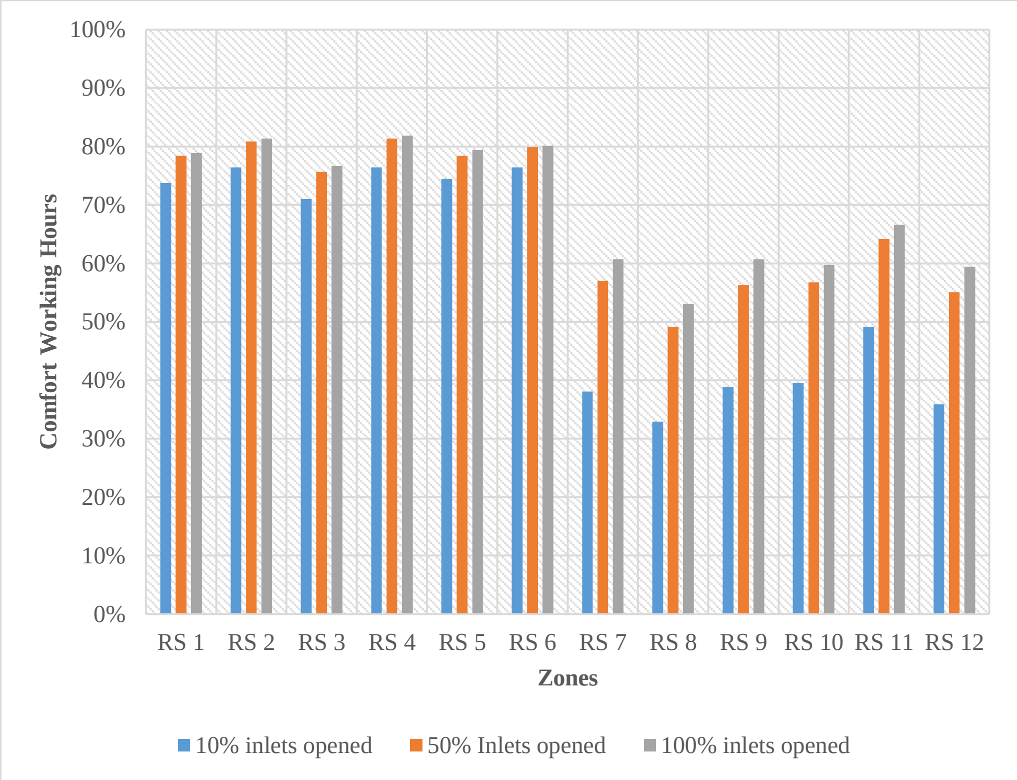


Figure 50: July Performance With Changing Inlets Openings Within The 80% Acceptability Limits. Developed by the author.

July 80% acceptability: Figure 50 appears the improvement in comfort WH Percentage in July by changing the inlets openings, the comfort WH explicitly increased when the façade windows were totally opened especially in the third floor spaces. Therefore, the third floor spaces showed a higher increase in the comfort WH, in particular, the southern space. Most of the second floor spaces achieved 80% comfort WH, whereas the third floor zones reached an average of 60% comfort WH within this range. An average difference of 3% was noticed between changing the inlets size from half to fully open. Cavity average temperature reached 36°C while the atrium temperature was 31°C in both half and full windows openings.

July 90% acceptability: Figure 51 presents the improvement in comfort WH in July, the comfort WH explicitly increased when the façade windows were totally opened. Therefore, the third floor spaces showed a higher increase in the comfort WH, in particular, the southern space. The second floor spaces achieved an average of 58% comfort WH, whereas the third floor zones exceeded the 30% average comfort WH within this range.

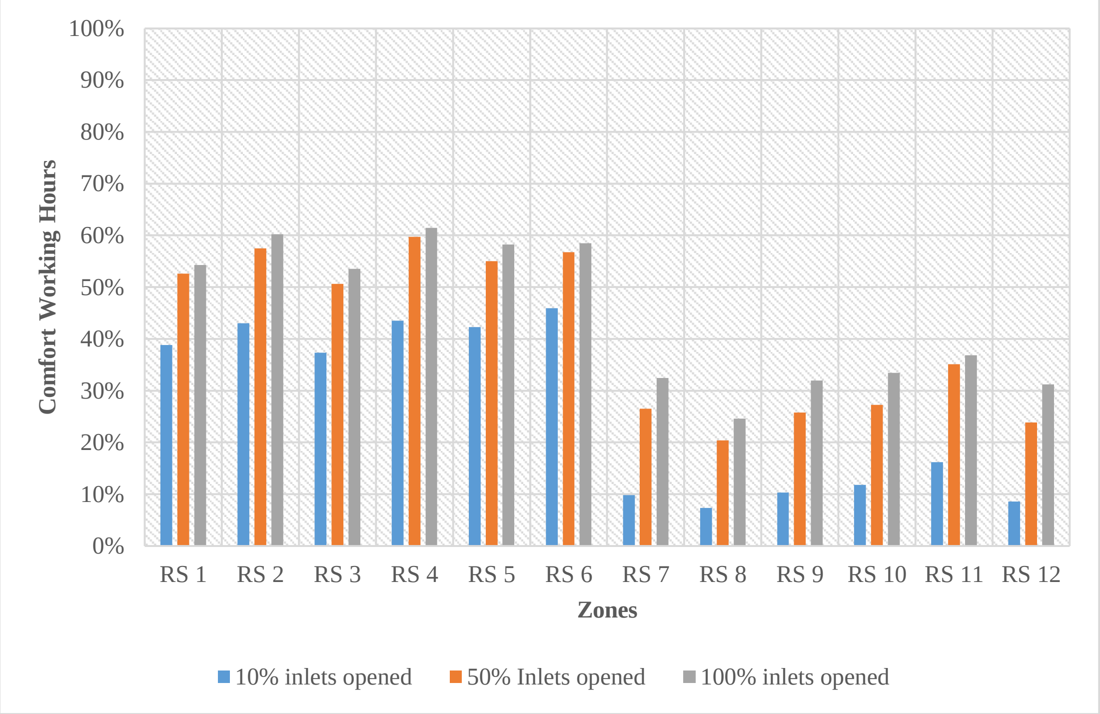


Figure 51: July Performance With Changing Inlets Openings Within The 90% Acceptability Limits. Developed by the author.

August 80% acceptability: Changing the inlets from 10% to fully open achieved a slight improvement in comfort WH during August for the second floor spaces as it is shown in Figure 52 in some spaces as the northern-west zone the increase in openings percent reduce comfort WH. On the other hand, changing the openings from 50% to 100% showed a slight enhancement in the third floor spaces. An average of 67% of comfort WH was achieved in the pre-mentioned floor by changing the openings to the higher values. Atrium average temperature recorded 31°C while the average cavity records was 6 °C for the two tested cases.

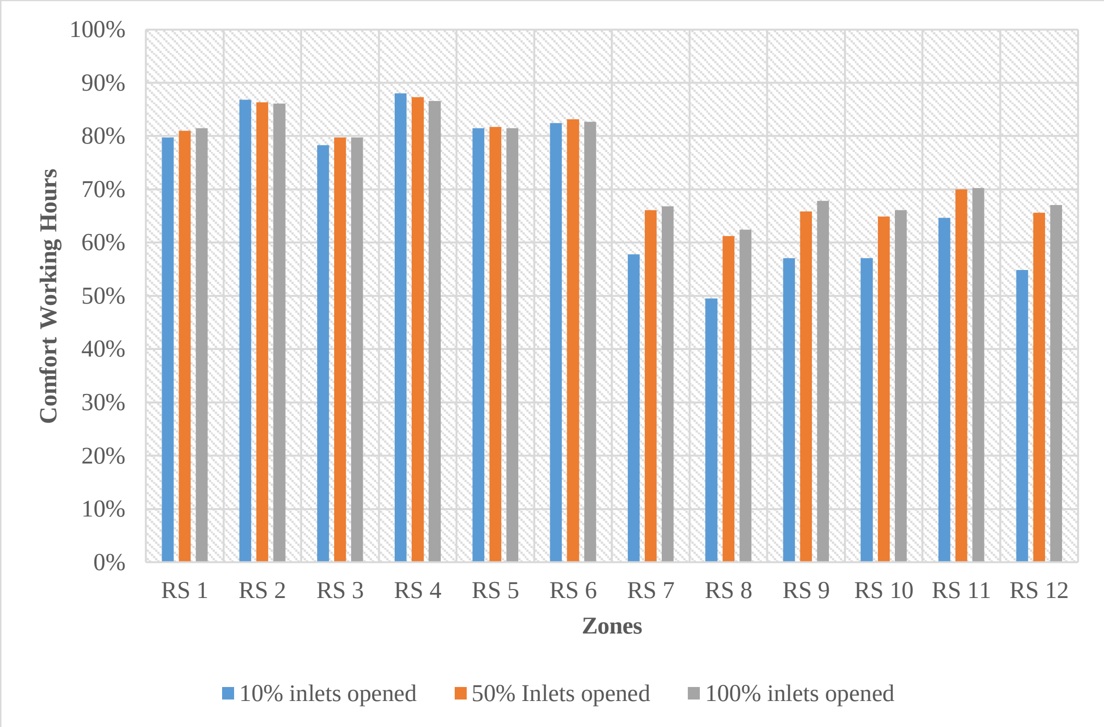


Figure 52: August Performance With Changing Inlets Openings Within The 80% Acceptability Limits. Developed by the author.

August 90% acceptability: Figure 53 presents the acceptable comfort WH within the 90% limits. The improvement in comfort WH was noticed in the second-floor spaces as well as the third floor ones, moreover, the effect of changing the inlets to 50% and 100% was higher in the third floor where the comfort WH duplicated to reach about 40% of total WH. Furthermore, the difference between half and full opened inlets is unremarkable.

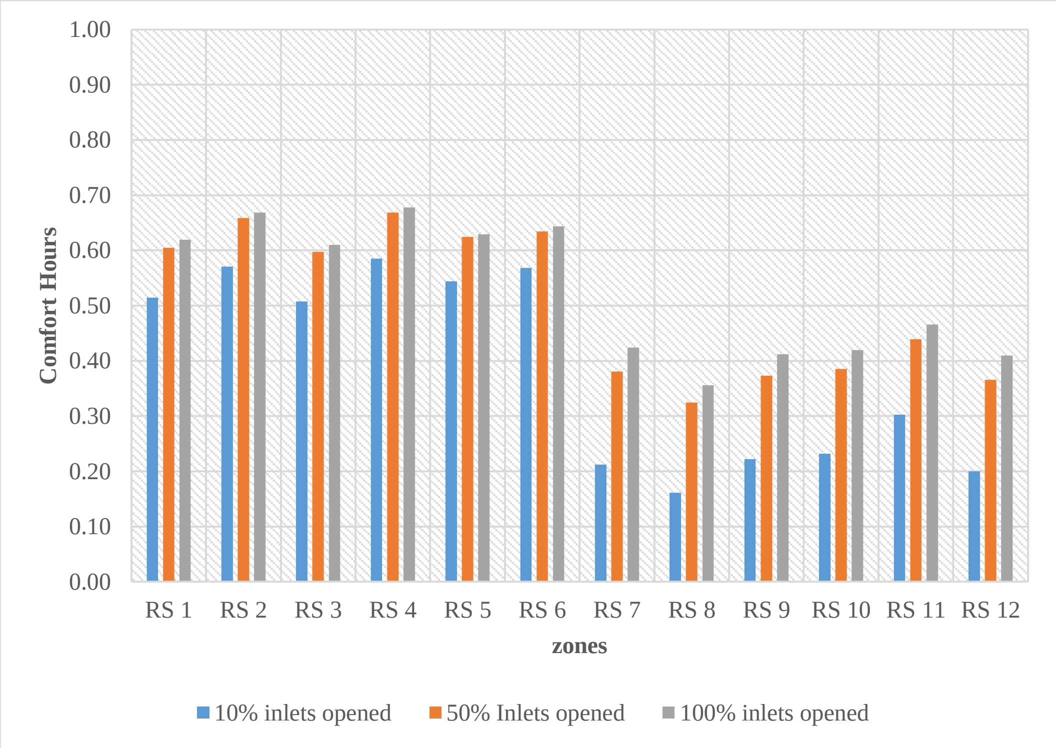


Figure 53: August Performance With Changing Inlets Openings Within The 90% Acceptability Limits. Developed by the author.

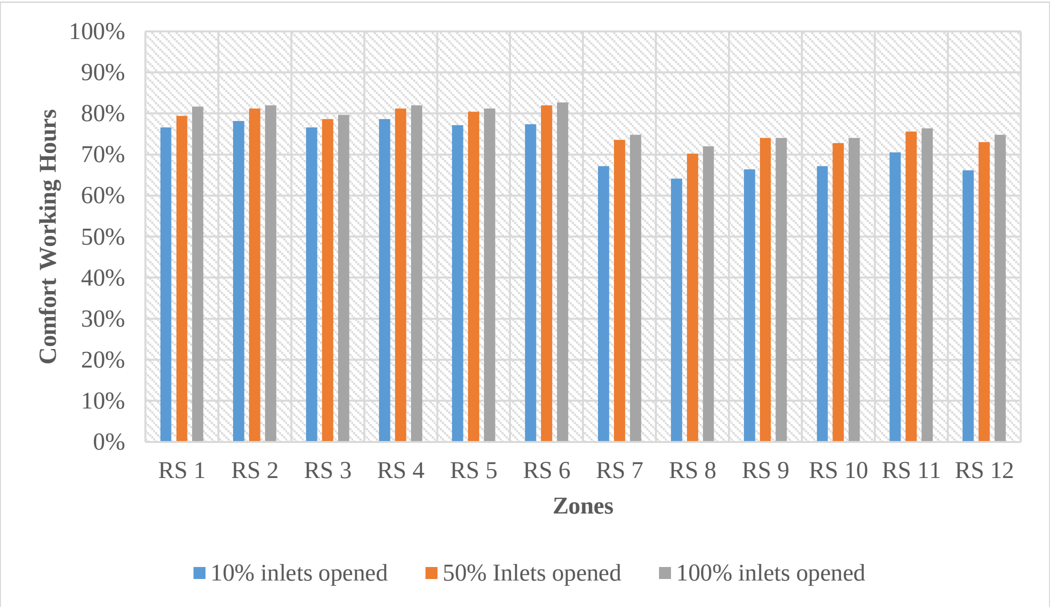


Figure 54: June Performance With Changing Inlets Openings Within The 80% Acceptability Limits. Developed by the author.

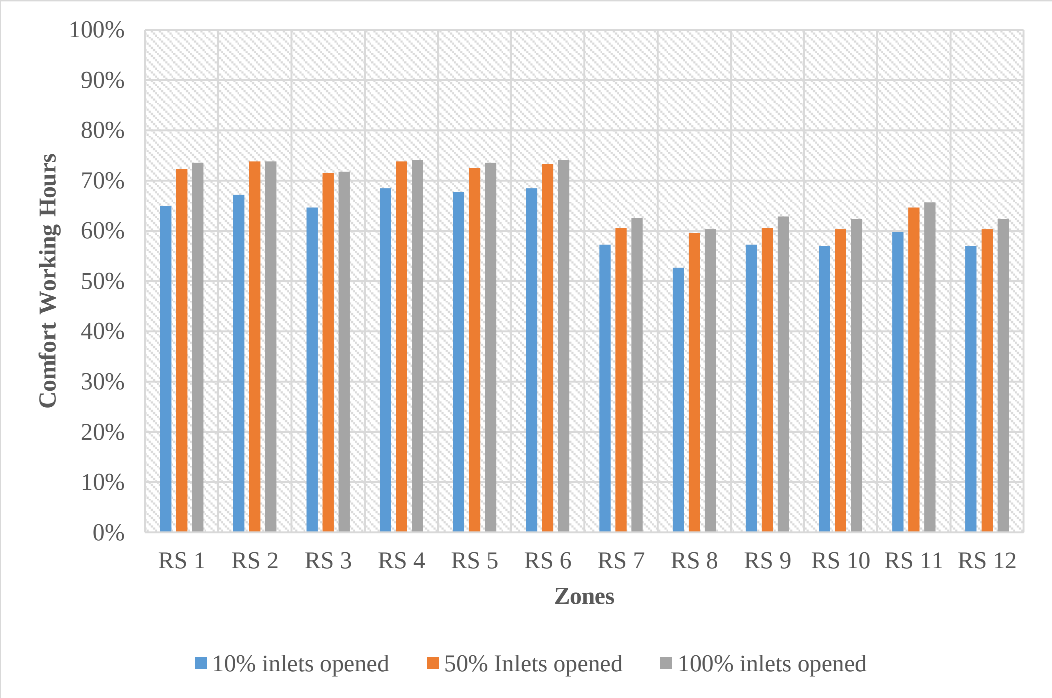


Figure 55: June Performance With Changing Inlets Openings Within The 90% Acceptability Limits. Developed by the author.

June 80% acceptability: a slight improvement of 6% only was achieved by increasing the inlets opening size during June for the second floor spaces, same as the third floor spaces where comfort WH were increased by 8% only as it is shown in Figure 54. The total comfort WH for the second floor reached 82% averaged comfort WH whilst the third floor spaces revealed 74% comfort WH. Atrium and cavity average temperatures were 30°C and 35°C respectively.

June 90% acceptability: a slight improvement of 6% only was achieved by increasing the inlets opening size during June for the second floor spaces, same as the third floor spaces as it is shown in Figure 55. The total comfort WH for the second floor reached more than 70% of the total WH whilst the third floor spaces revealed an average of 62% comfort WH.

Table 10: Average Results for The Second and The Third Floors' Spaces within The 80% Acceptability Limits. Developed by the author.

80% acceptability							Simulation Group 1																		Simulation Group 2					
	Existing Building						Cavity Fenstration												DSS Materials						Night Ventilation Strategy		Changing Inlets Openeings			
	Existing Building Case/ winter period		Existing Building Case/ summer period		Existing building case with opened roof		fully closed cavity/ winter period		fully closed cavity/ summer period		25% opened cavity/ summer period		50% opened cavity/ summer period		75% opened cavity/ summer period		fully opened cavity/ summer period		outer layer: clear glass/ inner layer: Low-e glass		outer layer: Low-e glass/ inner layer: Low-e glass		outer layer: clear glass/ inner layer: clear glass		day and night ventilation		50% opened inlets		100% opened inlets	
	simulation 1		simulation 3		simulation 4		simulation 2		simulation 5		simulation 6		simulation 7		simulation 8		simulation 9		simulation 10		simulation 11		simulation 12		simulation 16		simulation 17		simulation 18	
Months/ Floors	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd
January	30%	24%					29%	23%	Opened cavity is not used in winter period										29%	23%	28%	23%	29%	24%	Simulation group 2 is not applied in winter period					
February	69%	71%					68%	70%											Meterials changing is not tested											
March	86%	89%					86%	89%																						
April	**98%**	**100%**					**98%**	**100%**																						
																			simulation 13		simulation 14		simulation 15							
May			98%	97%	98%	98%			98%	97%	98%	97%	98%	97%	98%	97%	**98%**	**100%**	Meterials changing is not tested											
June			61%	48%	68%	58%			63%	51%	63%	52%	63%	53%	63%	53%	76%	63%							77%	67%	80%	73%	**82%**	**74%**
July			26%	6%	41%	14%			29%	7%	30%	7%	30%	7%	31%	8%	66%	27%	66%	26%	67%	28%	63%	25%	75%	39%	79%	56%	**80%**	**60%**
August			41%	12%	48%	27%			42%	13%	43%	14%	44%	15%	44%	15%	77%	48%							83%	57%	83%	66%	**83%**	**67%**
September			79%	70%	84%	76%			80%	71%	81%	72%	81%	72%	81%	72%	93%	85%	Meterials changing is not tested						**95%**	**89%**				
October			97%	93%	99%	97%			97%	94%	98%	95%	98%	95%	98%	95%	**100%**	**100%**												
November	82%	81%					82%	81%	Opened cavity is not used in winter period										Meterials changing is not tested						Simulation group 2 is not applied in winter period					
December	69%	70%					69%	69%																						
strategy1: 1% building opening							DSS outer layer: Low-e/ inner layer: clear glass																							
strategy2: 10% building opening							DSS outer layer: Low-e/ inner layer: clear glass																							

Table 11: Average Results for The Second and The Third Floors' Spaces Within The 90% Acceptability Limits. Developed by the author.

<table>
<tr><th rowspan="4">90% acceptability</th><th colspan="6" rowspan="2">Existing Building</th><th colspan="18">Simulation Group 1</th><th colspan="6">Simulation Group 2</th></tr>
<tr><th colspan="12">Cavity Fenstration</th><th colspan="6">DSS Materials</th><th colspan="2">Night Ventilation Strategy</th><th colspan="4">Changing Inlets Openeings</th></tr>
<tr><td colspan="2">Existing Building Case/ winter period</td><td colspan="2">Existing Building Case/ summer period</td><td colspan="2">Existing building case with opened roof</td><td colspan="2">fully closed cavity/ winter period</td><td colspan="2">fully closed cavity/ summer period</td><td colspan="2">25% opened cavity/ summer period</td><td colspan="2">50% opened cavity/ summer period</td><td colspan="2">75% opened cavity/ summer period</td><td colspan="2">fully opened cavity/ summer period</td><td colspan="2">outer layer: clear glass/ inner layer: Low-e glass</td><td colspan="2">outer layer: Low-e glass/ inner layer: Low-e glass</td><td colspan="2">outer layer: clear glass/ inner layer: clear glass</td><td colspan="2">day and night ventilation</td><td colspan="2">50% opened inlets</td><td colspan="2">100% opened inlets</td></tr>
<tr><td colspan="2">simulation 1</td><td colspan="2">simulation 3</td><td colspan="2">simulation 4</td><td colspan="2">simulation 2</td><td colspan="2">simulation 5</td><td colspan="2">simulation 6</td><td colspan="2">simulation 7</td><td colspan="2">simulation 8</td><td colspan="2">simulation 9</td><td colspan="2">simulation 10</td><td colspan="2">simulation 11</td><td colspan="2">simulation 12</td><td colspan="2">simulation 16</td><td colspan="2">simulation 17</td><td colspan="2">simulation 18</td></tr>
<tr><th>Months/ Floors</th><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td><td>2nd</td><td>3rd</td></tr>
<tr><th>January</th><td>13%</td><td>12%</td><td colspan="2" rowspan="4"></td><td colspan="2" rowspan="4"></td><td>13%</td><td>12%</td><td colspan="10" rowspan="4">Opened cavity is not used in winter period</td><td>13%</td><td>12%</td><td>13%</td><td>12%</td><td>13%</td><td>12%</td><td colspan="6" rowspan="4">Simulation group 2 is not applied in winter period</td></tr>
<tr><th>February</th><td>53%</td><td>56%</td><td>52%</td><td>55%</td><td colspan="6" rowspan="3">Meterials changing is not tested</td></tr>
<tr><th>March</th><td>78%</td><td>81%</td><td>77%</td><td>80%</td></tr>
<tr><th>April</th><td>89%</td><td>92%</td><td>90%</td><td>92%</td></tr>
<tr><td colspan="19"></td><td colspan="2">simulation 13</td><td colspan="2">simulation 14</td><td colspan="2">simulation 15</td><td colspan="6"></td></tr>
<tr><th>May</th><td colspan="2" rowspan="6"></td><td>92%</td><td>88%</td><td>92%</td><td>92%</td><td colspan="2" rowspan="6"></td><td>93%</td><td>90%</td><td>92%</td><td>90%</td><td>92%</td><td>90%</td><td>92%</td><td>90%</td><td>92%</td><td>94%</td><td colspan="6" rowspan="2">Meterials changing is not tested</td><td colspan="2"></td><td colspan="4"></td></tr>
<tr><th>June</th><td>39%</td><td>24%</td><td>51%</td><td>35%</td><td>42%</td><td>26%</td><td>43%</td><td>27%</td><td>43%</td><td>28%</td><td>44%</td><td>28%</td><td>63%</td><td>50%</td><td>67%</td><td>57%</td><td>73%</td><td>61%</td><td>73%</td><td>63%</td></tr>
<tr><th>July</th><td>9%</td><td>0%</td><td>18%</td><td>3%</td><td>10%</td><td>0%</td><td>10%</td><td>1%</td><td>11%</td><td>1%</td><td>11%</td><td>1%</td><td>31%</td><td>6%</td><td>31%</td><td>6%</td><td>32%</td><td>6%</td><td>29%</td><td>5%</td><td>42%</td><td>11%</td><td>55%</td><td>26%</td><td>58%</td><td>32%</td></tr>
<tr><th>August</th><td>14%</td><td>0%</td><td>25%</td><td>5%</td><td>15%</td><td>0%</td><td>16%</td><td>1%</td><td>17%</td><td>1%</td><td>17%</td><td>1%</td><td>47%</td><td>13%</td><td colspan="6" rowspan="3">Meterials changing is not tested</td><td>55%</td><td>22%</td><td>63%</td><td>38%</td><td>64%</td><td>41%</td></tr>
<tr><th>September</th><td>62%</td><td>50%</td><td>71%</td><td>61%</td><td>65%</td><td>52%</td><td>66%</td><td>53%</td><td>66%</td><td>54%</td><td>67%</td><td>55%</td><td>83%</td><td>72%</td><td>85%</td><td>75%</td><td colspan="4" rowspan="2"></td></tr>
<tr><th>October</th><td>85%</td><td>78%</td><td>92%</td><td>86%</td><td>86%</td><td>80%</td><td>87%</td><td>80%</td><td>87%</td><td>81%</td><td>87%</td><td>81%</td><td>98%</td><td>95%</td><td colspan="2"></td></tr>
<tr><td colspan="31"></td></tr>
<tr><th>November</th><td>66%</td><td>65%</td><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="2"></td><td>66%</td><td>64%</td><td colspan="10" rowspan="2">Opened cavity is not used in winter period</td><td colspan="6" rowspan="2">Meterials changing is not tested</td><td colspan="6" rowspan="2">Simulation group 2 is not applied in winter period</td></tr>
<tr><th>December</th><td>45%</td><td>46%</td><td>45%</td><td>46%</td></tr>
<tr><td colspan="7">strategy1: 1% building opening</td><td colspan="12">DSS outer layer: Low-e/ inner layer: clear glass</td><td colspan="12" rowspan="2"></td></tr>
<tr><td colspan="7">strategy2: 10% building opening</td><td colspan="12">DSS outer layer: Low-e/ inner layer: clear glass</td></tr>
</table>

3.7 Findings Discussion

For this study, which mainly aims at enhancing indoor thermal comfort for the reading spaces attached to a central atrium by utilizing the atrium’ skylight design and natural ventilation strategy around the year, two seasonal groups of scenarios were set to test the thermal comfort within the 80% and 90% acceptability limits according to ASHRAE-55 standard (ANSI/ASHRAE Standard 55, 2017). For this, the first design strategy includes developing the double skin skylight (DSS), whereas two ventilation strategies were applied as a second strategy for the cooling-time of the year, different scenarios’ simulations were compared to the existing building.

During winter which extends from January to April, and from November to December, the same thermal performance has been noticed in both of the existing building and the DSS proposal. During this period, the lateral facades’ windows were 1% opened, while the DSS’ windows were totally closed due to the low outdoor temperatures. Simulation results indicate that adding the extra layer of skylight even when the upper windows are closed did not change the thermal performance for the reading spaces which directly connect to the atrium space. Regarding the atrium space thermal behavior, the implementation of DSS did not change the indoor temperature for both the second and third atrium levels. Whereas the cavity temperatures ranged between 27 °C and 39 °C for January and April respectively, the DSS addition only elevated the upper part’ temperature, while the atrium space keeps the same temperatures for all cases, thus the atrium temperature was not influenced by the high cavity temperature which explains the same performance of the reading spaces’ thermal behavior.

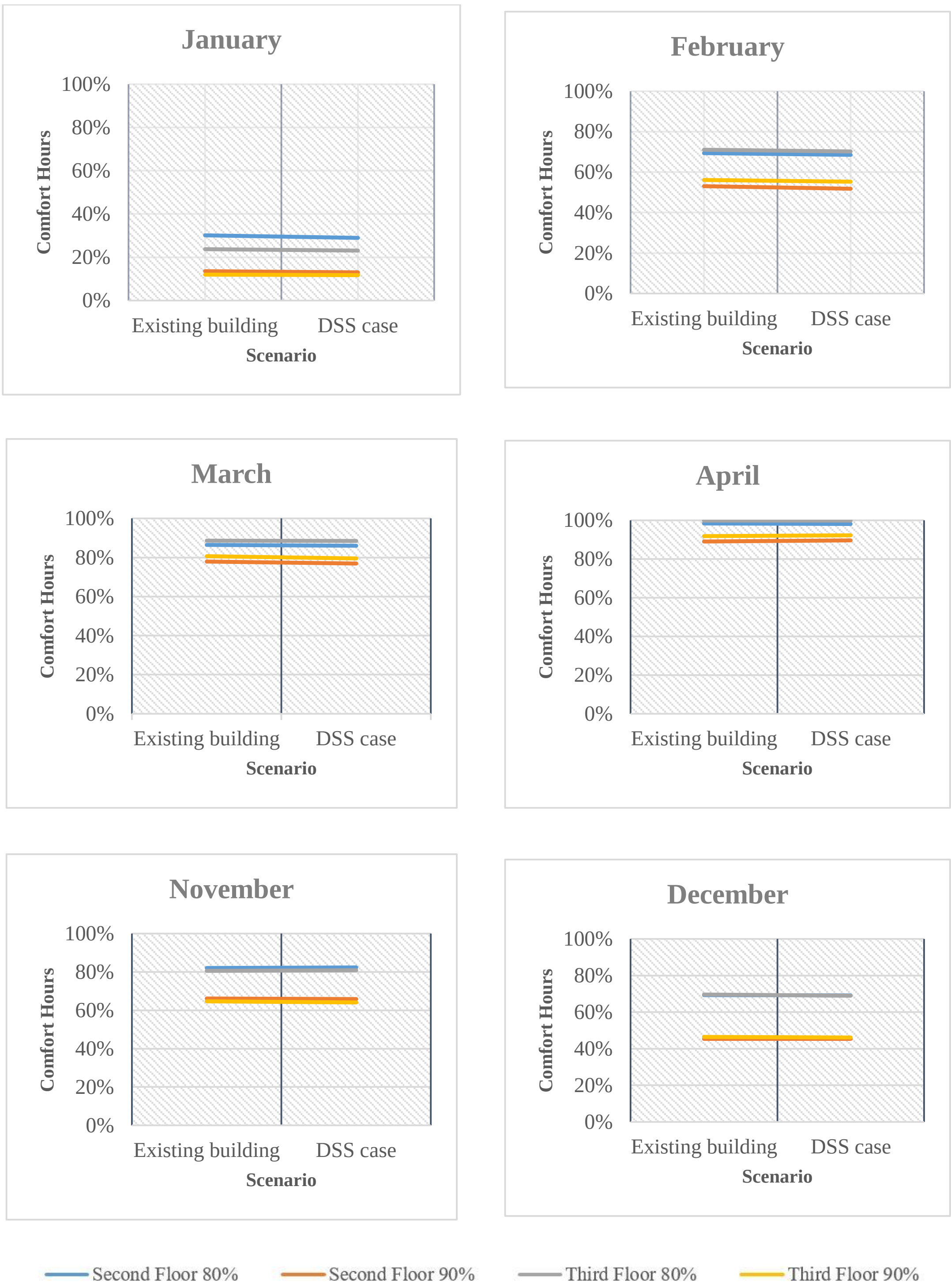


Figure 56: Winter Period Average Comfort Performance With Changing Cavity Fenestration Within The 80% And 90% Acceptability Limits For The Second and Third Floors. Developed by the author.

Figure 56 illustrates the comparison between the average comfort WH percentages during winter in the second and third floors for the existing building and the proposed case with the closed cavity DSS. January readings showed the least thermal comfort WH during the heating period, for both the existing building and DSS case, comfortable WH did not exceed 30% recorded in the second floor with 80% acceptability range, whilst the third floor readings were 24% comfort WH only for both cases. Moreover, only an average of 13% WH accomplished the 90% acceptable comfort temperatures.

February and December during wintertime achieved an average of 70% comfort WH with and without DSS, however, March WH were comfortable in 90% of WH. The best thermal performance was shown in April where the reading spaces almost achieved full comfort WH with and without the DSS proposal within the 80% acceptable comfort temperatures.

In spite of that the comfort temperatures within the 90% limits were the same for the existing building and the proposed model, comfortable WH varied between the different months. April showed the highest average of comfort in 90% WH, whereas March and November reached an average of 80% and 65% comfort WH respectively. Moreover, about half of WH were comfort in both February and December.

In general, the third floor spaces reached a higher average of comfort WH compared with the second floor spaces, this can be explained by the existence of the void spaces around the third floor which disconnect the reading spaces from the curtain wall that directly causes the heat loss to the outdoor. Furthermore, the eastern and southern spaces for both floors recorded higher comfort WH over the other spaces.

On the other hand, changing the DSS glazing materials did not affect the DSS cavity' temperature and the thermal performance of the reading spaces attached to the atrium space as well, a 1% average comfort WH difference was shown by testing various scenarios of DSS glazing materials as it is shown in Figure 46, Tables 10 and 11 in section 3.6.1.2.

During summer which extends from May to October, the thermal performance was improved with the DSS scenarios. The lateral facades' windows firstly were opened with a constant value of 10%, the comfort WH in this case were achieved by the air movement inside the building which was horizontally across the spaces. However, the atrium space recorded an average between 27°C and 34°C, whereas the upper part reached 30°C to 39°C in October and July respectively, the trapped hot air in the atrium explains the discomfort WH during the hottest months. To get a better understanding of DSS efficiency, the existing building was tested with an opened roof without DSS, the atrium space temperatures were lower with 1°C, while the upper part of the atrium space recorded 3°C to 4°C decrease. Despite the high upper temperatures, the extraction of the hot air from the skylight openings created pressure differences between the inlets and the outlets which improve the air entering from the lower openings and thus enhanced the spaces' thermal comfort. Moreover, the second floor' reading spaces showed improvement in comfort WH due to the stack effect in the atrium, but the third floor thermal enhancement was unremarkable, therefore, the DSS was implemented and tested.

The first simulation group tested the DSS windows, which were changed in five different scenarios starting from fully closed windows to fully opened windows with an interval of 25% opening percentage. Surprisingly, the implementation of DSS even with closed cavity' windows achieved a slight improvement from the original case but not from the opened-roof case, as the cavity openings' percentage increased, the atrium upper temperature was slightly decreased, and so the thermal comfort for both second and third floors raised slowly, a minor difference has been shown between the existing building and the semi-opened cavity windows, whereas the last proposal with fully opened windows showed a huge leap especially for the months with low comfort WH readings as July, August, and June in both the second and third floor spaces, where the atrium average temperature decreased 1 °C, while the upper part recorded 3°C drop, however, the cavity temperature recorded an average of 36°C during the hottest months. The heated air was trapped in the cavity, which directly was extracted by the fully-opened cavity windows.

Figure 57 summarizes the Summer period with changing cavity fenestration performance within the 80% and 90% acceptability limits compared with the existing building with and without the opened roof. For summer months with high performance, which are May and October: even that the two months achieved high comfort temperatures with the existing building case, the insertion of DSS achieved full comfort WH for both floors. Regarding the lower performance months, September revealed a 15% increase of the comfort WH for the both floors from the existing building for the 80% acceptability category where the second floor comfort hours exceeded the 90% WH.

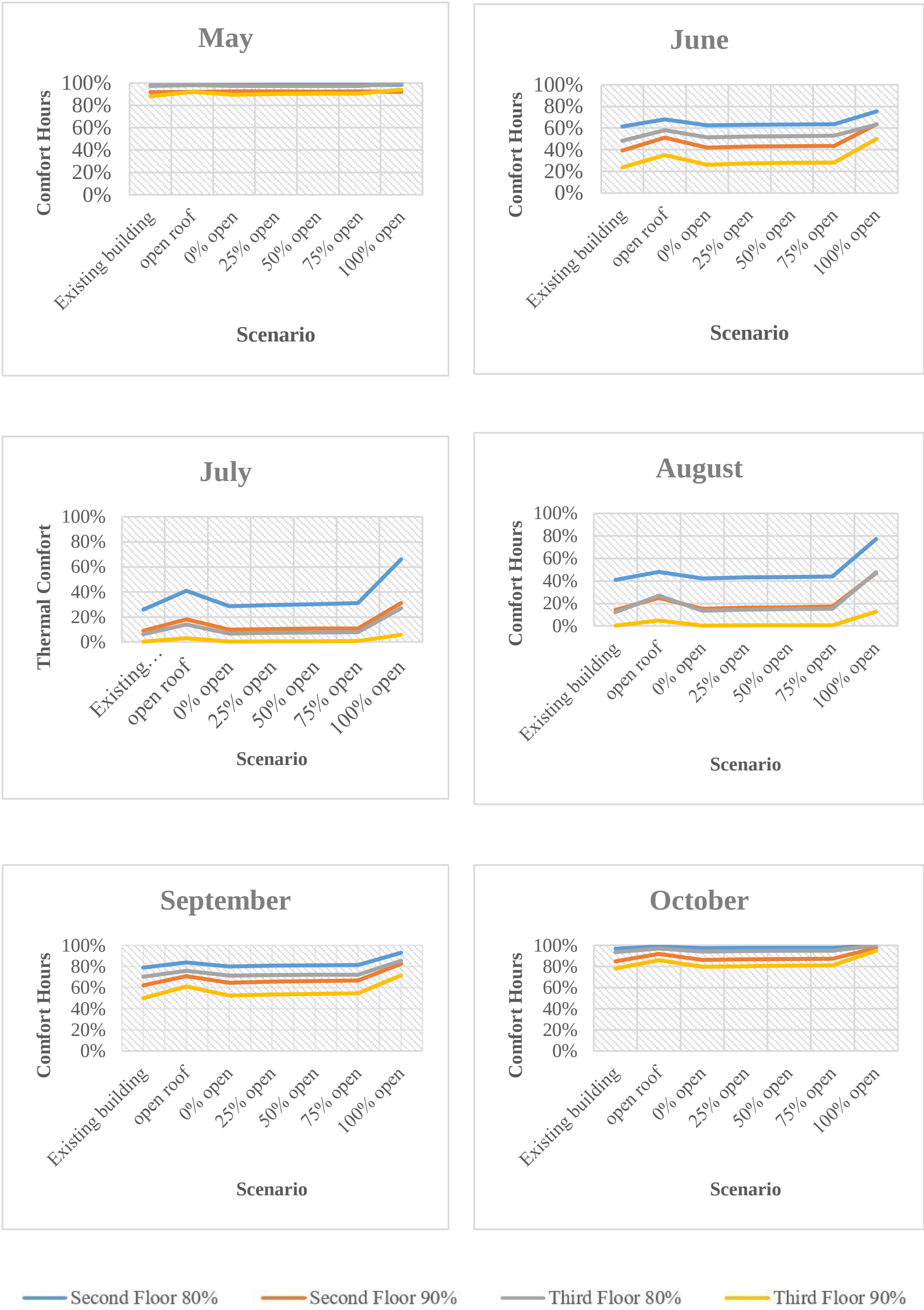


Figure 57: Summer Period Average Comfort Performance With Changing Cavity Fenestration Within The 80% And 90% Acceptability Limits For The Second and Third Floors. Developed by the author.

It can be noticed that July, August, and June recorded the least comfort hours during summer respectively. Opening the roof with the existing building improved the comfort WH in differentiated values. Whereas the implementation of DSS enhanced the results. As an example of July: the last proposal increased the second floor comfort hours by 40% from the existing building and more than 25% in case of opened roof within the 80% acceptability range, comfort hours in the third floor spaces raised about 35%, 20%, and 15% in August, July, and June respectively.

In the summertime with 90% acceptability limits, the comfort WH improvement was more noticeable in the third floor spaces. During October, the comfort WH were elevated by about 15% for both floors to become fully comfort especially in the second floor spaces. Although May’s performance had no positive effect on the second floor, the third floor performance improved to exceed an average of 90% comfort WH. The average comfort WH were increased by 25% within this category during June and September for the two floors. However, the comfort WH were elevated with the average of 33% during July and August for the second floor spaces, whereas the third floor’ comfort WH did not go beyond 13% and 6% in August and July respectively.

It can be also generalized that the second-floor spaces during summer have more comfort WH than the third floor, and that can be related to the windows' existence at this level. Regarding the orientation, the northern-west, northern-east, and the southern spaces recorded a higher number of comfort WH. Even though the upper atrium part recorded 2°C decrease, the air movement through the spaces to the atrium benefited the stack effect and the atrium average temperatures were decreased by 2°C - 3°C, which consequently decreased the spaces’ temperatures, however, the average cavity temperature reached 31.3°C during the three hottest months.

The results of materials testing during the cooling season did not reveal a noticeable change in comfort WH since the cavity temperature was not affected by materials changing, thus the ventilation rate was not progressed too. However, Low-E glass for both DSS layers recorded a slightly better performance, whereas the clear glass showed the worst.

The second simulation group was applied during summer tested the night ventilation effect and the building fenestration. The night ventilation results revealed that operating the night ventilation improved the thermal performance for both the second and third floor spaces where all the second floor zones showed an average of 75%, 83%, and 77% comfort WH in July, August, and June respectively. Moreover, the effect of night ventilation significantly increased the comfort WH in September which achieved an average of 92% comfort WH for both floors, these findings are related to the 80% comfort temperatures. Additionally, it is worth to mention that for the 90% acceptability limits, the cooling period months fluctuate between 42% and 85% for the second floor and 22% and 75% for the third level. As a result, operating night ventilation enhances the comfort WH for the two floors. Temperatures reduction can be explained by the removal of the re-radiated heat from the building' elements during the night by the air movement with the help of the atrium stack effect which consequently reduces the indoor temperature significantly. Despite the increase of comfort WH with night ventilation, the atrium space average temperature had the same average reading of 30.7°C.

The last simulation part tested the change of building fenestration, changing the building windows' openings from half-opened to fully open slightly increased the comfort WH in the second floor spaces. On the other hand, this change enhanced the comfort WH of the third floor, as it can be seen in July which became 10 times better than the existing building case within the 80% acceptability limits. The three tested months with changing the inlets' size revealed a remarkable enhancement in comfort WH, which reached an average of 82% and 67% comfort WH for the second and third floors respectively during the hottest three months. Furthermore, 65% and 45% WH achieved the 90% acceptable comfort temperatures in the second and the third floors respectively during the pre-mentioned period. The comfort temperatures recorded higher progress in the third floor spaces.

Moreover, the results showed that operating night ventilation with the full-opened cavity as well as full-opened side windows enhanced the comfort WH especially for the third floor spaces, where the third floor showed almost no comfort WH in the existing building case. Thermal performance enhancement was caused by increasing the pressure differences between the inlets in the lower level and the outlets in the cavity openings, which develops the suction on hot air from inside as well as utilizing the vertical air movement due to the stack effect of the atrium. However, the pressure differences around the outlets may increase the extraction of hot air. It is worth to mention that in this ventilation strategy the atrium average temperature recorded 31°C.

Figure 58, 59, and 60 show the improvement in comfort WH during July, August, and June respectively for the second and third floors with different scenarios.

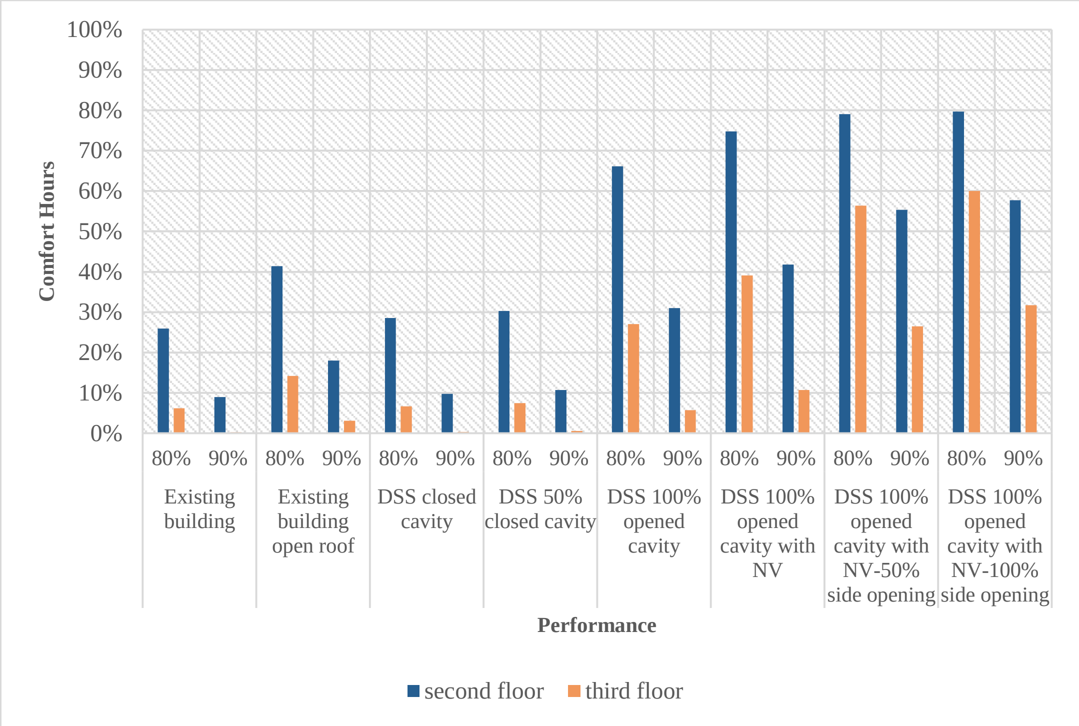


Figure 58: July thermal performance for the second and third floors with different scenarios. Developed by the author.

The same enhancement with different values can be noticed During August and June comfort WH, where increasing the inlets' size improved the comfort WH for the third floor as Figure 59 and Figure 60 respectively show.

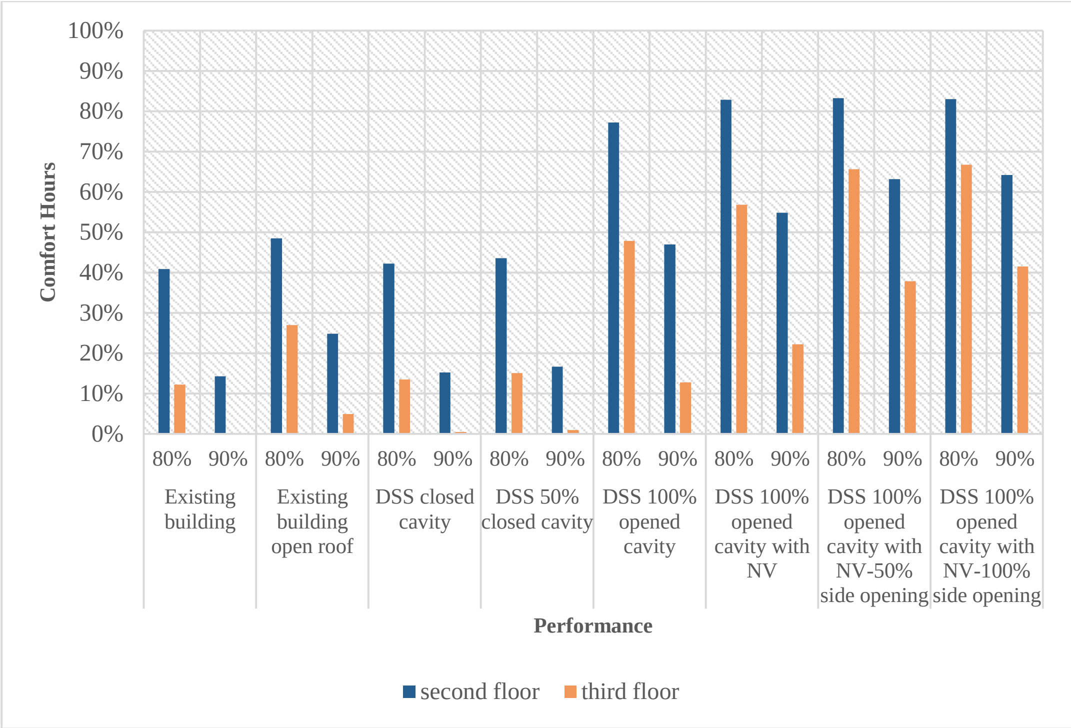


Figure 59: August thermal performance for the second and third floors with different scenarios. Developed by the author.

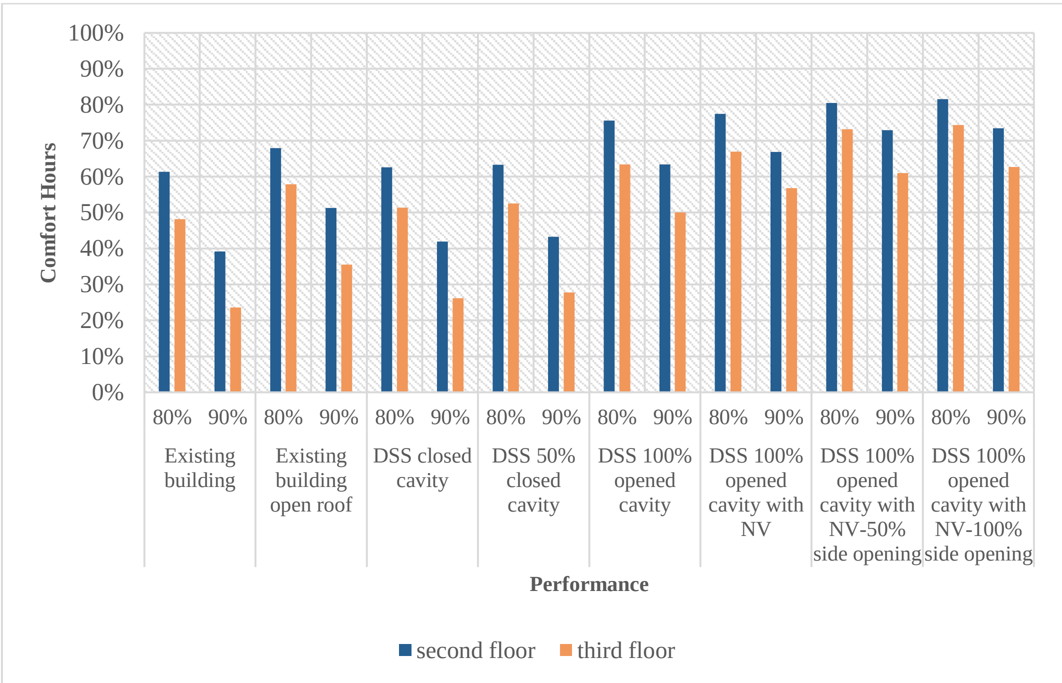


Figure 60: June thermal performance for the second and third floors with different scenarios. Developed by the author.

To summarize the above as a whole year performance: the existing building results showed the worst performance regarding thermal comfort during the peak months in both summer and winter for the reading spaces, regrettably, the implementation of DSS could not improve the thermal comfort performance during the harsh months like January and December, and that might be returned to the reason that the skylight covers a minor area of the building roof, whereas the majority of heat loss happens by the glazing facades.

However, inserting DSS improved the thermal performance during summer, later on, increasing the cavity openings (outlets) percentages improved the indoor thermal conditions till it reached the best performance with the full opened cavity for some summer months like October and May. Following that, with operating night ventilation September achieved a wide range of acceptable comfort temperatures. During the hottest summer months: the fully opened cavity with night ventilation and increasing the inlets' size, the indoor thermal conditions were noticeably improved to reach the average of 82% comfort WH in the second floor spaces and more than 60% in the third floor zones. The implementation of DSS decreased the atrium average temperature 3°C - 4°C. Figures 61, 62, and 63 show the air movement and indoor temperatures change in 21st of July at 2:00 pm where the wind speed was 4.9 m/s with south-east wind direction for the existing case, the DSS with initial openings of 10%, and the DSS with fully opened windows scenario respectively. The existing building section shows the high temperatures of the atrium space and the reading zones, where the stagnant hot air cannot be extracted, while the airflow increased for the southern space by applying the DSS with opening the cavity windows totally which reduces the operative temperatures, in addition to the air extraction from the upper cavity by the stack effect aided by the wind effect. Finally. Increasing the inlets size progress the airflow inside the building which consequently reduces the operative temperatures.

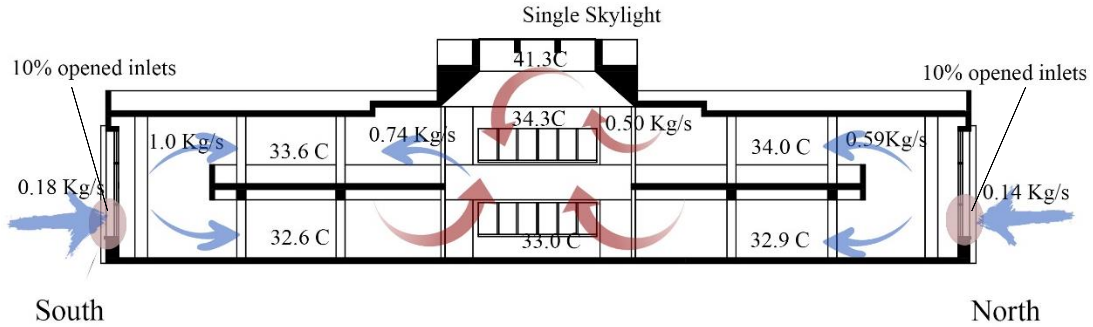


Figure 61: Airflow and Operative Temperatures' of July for The Existing Building. Developed by the author.

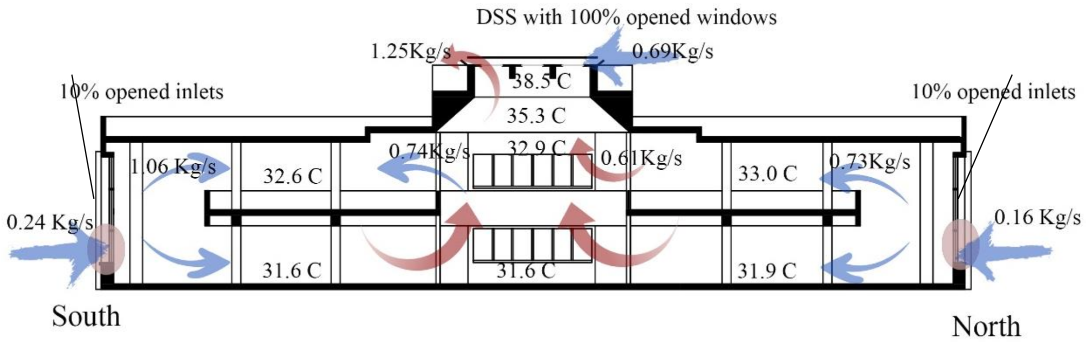


Figure 62: Airflow and Operative Temperatures' of July for The DSS Atrium with 10% Opened Inlets. Developed by the author.

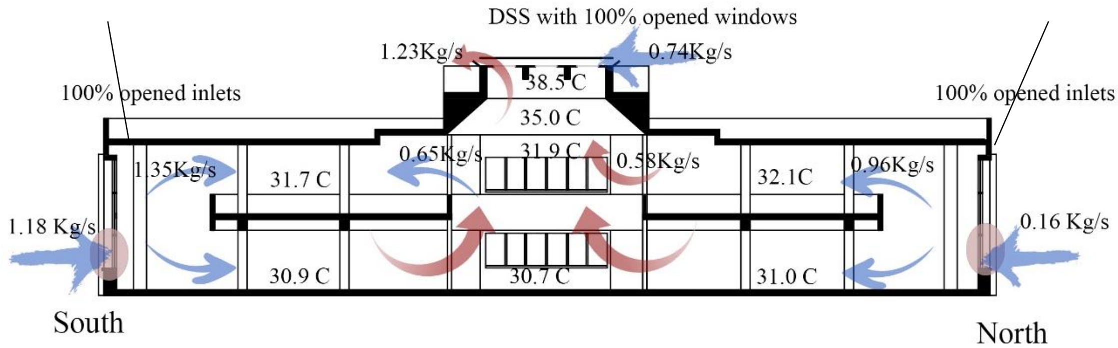


Figure 63: Airflow and Operative Temperatures' of July for The DSS Atrium with Fully Opened Inlets. Developed by the author.

In other words, the library recorded 4796 total working hours around the year, by the implementation of DSS the whole reading spaces reached an average of 77% and 66% comfort WH within the 80% and 90% acceptability ranges respectively by changing the windows opening according to the outdoor climatic conditions. To be more elaborated, the second floor spaces achieved an average of 81% comfort WH whereas the comfort WH in the third floor zones were 77% of the total WH. The minimum comfort WH were recorded in the northern space for both the second and third floor spaces with 79% and 75% comfort WH respectively. On the other hand, the best results were observed in the second and third southern reading spaces with 82% and 79% comfort WH respectively around the year, Figure 64 presents the annual average of comfort WH for the second and the third floor reading spaces by the different DSS and ventilation strategies.

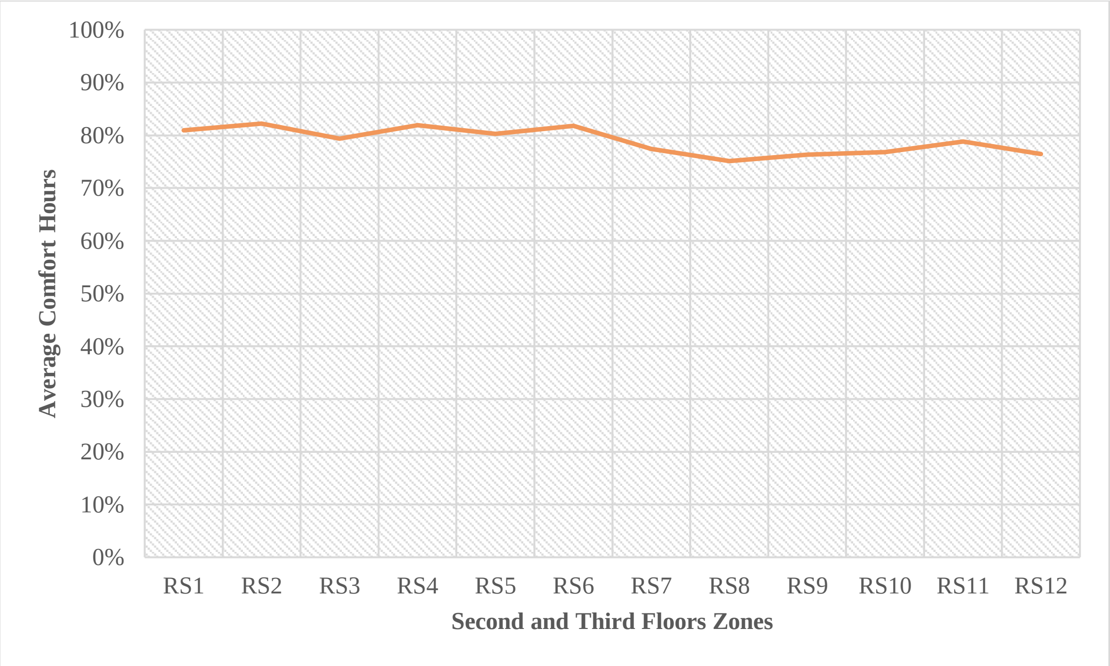


Figure 64: Yearly Averaged Comfort Working Hours for The Reading Spaces. Developed by the author.

For the whole year performance Figure 65 and 66 show that comfort WH were significantly increased during the cooling period, while the heating period kept the same performance for both floors.

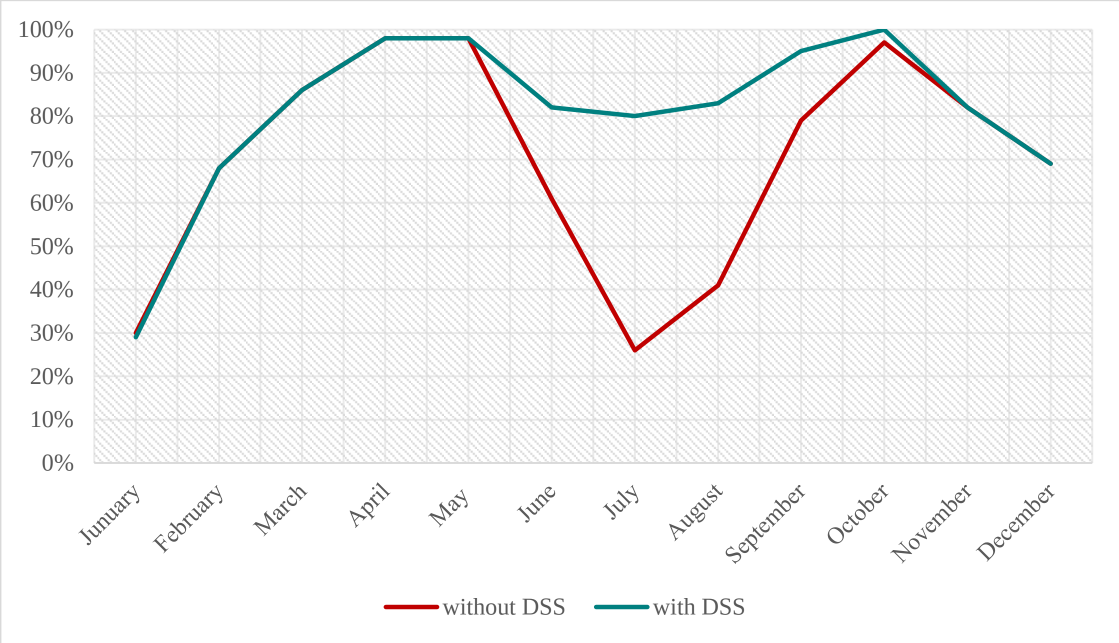


Figure 65: Second Floor Annual Improvement of Comfort Working Hours within the 80% Acceptability Limits. Developed by the author.

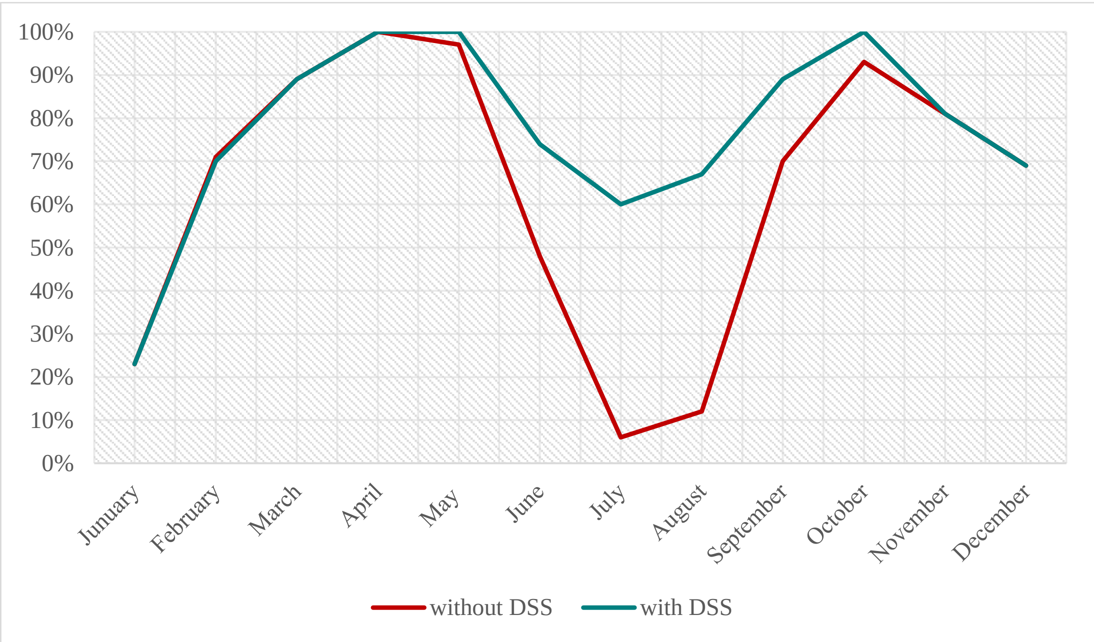


Figure 66: Third Floor Annual Improvement of Comfort Working Hours within the 80% Acceptability Limits. Developed by the author.

Chapter 4

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

A well-designed atrium utilizes the natural forces to achieve the environmental and economic benefits with respect to the exterior climatic conditions, one or more passive design techniques could be used for this purpose. Pre-design evaluation of these strategies can predict the building's performance to give the chance for solutions.

In this study, an atrium with DSS has been designed and different proposals have been categorized for improving the thermal performance in a central atrium building with top-lit skylight in Mediterranean climate as a major aim, to do that, the next step of this research evaluated the different proposals in terms of thermal comfort.

This study was conducted to bridge the gap of thermal comfort enhancement in central atrium buildings locate in the Mediterranean climate, which mainly has diverse climatic conditions around the year.

The first part presented the literature concerning atrium buildings in addition to passive design strategies, following that design strategies preparation, later, computer simulations were run and results were explained. The analysis presented the following:

After reviewing the related literature, and based on the previous recommendations for improving the atrium thermal comfort without affecting lighting performance with respect to exterior climatic conditions, the following strategies were designed. As the concept basically based on employing the atrium space to benefit the climatic conditions without inserting shading devices that decrease the lighting level, winter and summer opening strategies were set to be used during these periods. The different seasonal proposals were simulated and evaluated by comparing the current building design and the proposed models, the comparison was conducted with reference to ASHRAE-55 standard (ANSI/ASHRAE Standard 55, 2017) acceptability 80% and 90% limits.

The building achieved 77% comfort WH during the whole year WH, however, the second floor spaces recorded an average of 82% comfortable WH. seasonally, for the wintertime which extends from January to April and from November to December, where the building openings were opened with 1%; April showed the best comfort operative temperatures while January recorded the least. The Double Skin Skylight (DSS) was examined by the first simulation group with fully closed cavity first, and different materials for the DSS glazing layers, even closing the cavity windows did not increase the atrium adjacent spaces' comfort operative temperatures, the results showed the same performance of the building with and without DSS in both 80% and 90% acceptable comfort hours ranges.

The third floor spaces presented more comfort hours than the second floor ones, moreover, the southern and eastern spaces showed a slightly higher number of comfort working hours relative to the other spaces. however, changing the DSS glazing materials couldn't improve the building thermal performance, in spite of the high temperatures of the trapped air in the cavity and the atrium space, the huge size of the adjacent spaces reduced the atrium temperature utilization, on the other hand, the large glazing facades which define the reading spaces and extend on the second and third floors, increase the heat loss to the external environment due to the low outdoor temperatures.

During the summer period which extends from May to October, the building openings were opened with 10%; the existing building case showed low comfort hours during the hottest months, some of the third floor spaces did not achieve the 90% acceptable comfort temperatures. The proposed building was tested in two simulation groups; the first group outcomes revealed that the fully opened cavity' windows recorded a remarkable increase in comfort WH for the reading spaces for both 80% and 90% acceptable temperatures. Some months like May and October reached full comfort hours with and without DSS with the minimum natural ventilation, whereas the hottest months as July couldn't reach more than 65% comfort operative temperatures within the 80% acceptable range. Moreover, the second floor reached higher comfort hours relative to the third floor spaces due to the direct ventilation by the existing windows in that level, the northern-east, northern-west, and the southern spaces recorded the highest number of comfort hours among the whole spaces.

Running the second simulation group mainly focused on increasing the natural ventilation, which tested the impact of adding night ventilation, in addition to increasing the inlets' sizes. The results indicated that operating full day ventilation (day and night) during September achieved more than 95% comfort working hours, whereas the mid-season months; July, August, and June respectively, still need more improvement. The outcomes of changing inlets' size during the hottest months presented a remarkable improvement in comfort working hours, where it reached the average of 80% comfort working hours for the whole months, this improvement returns to the high air pressure difference between the inlets in the second floor and the cavity openings' outlets. Moreover, the acceptable comfort temperatures significantly increased especially for the third floor spaces to reach 60% comfort working hours, after it was only 6% without the DSS implementation.

As a result of the whole study, the implementation of DSS presented higher enhancement in comfort temperatures for the atrium adjacent spaces in summer more than winter. During the coldest months, the building needs heating. However, during the mild months of summer like May and October; the building reaches full comfort performance only by opening the windows 10% even with fully opened cavity windows. While during the hotter month of summer, September comfort working hours can be obtained with operating night ventilation incorporation with fully opened cavity' windows and 10% opened inlets. On the other hand, the hottest summer months can achieve 80% comfort working hours with fully opened inlets as well as fully opened cavity' windows, to reach full comfort hours fans can be used, moreover, its recommended to insert window mesh screen to prevent insects while utilizing natural ventilation.

Applying DSS can achieve total comfort WH for one-fourth of the year (three months) by changing the opening sizes based on the outdoor climatic conditions, whereas increasing the ventilation rate with more openings size and whole day ventilation can achieve an average of 80% comfort WH for the rest three summer months. Even that the DSS did not improve the winter period thermal performance but the warm winter months like April can achieve full comfort WH, whilst other winter months reached an average of 70% comfort WH by closing the building windows. January results cannot be improved by utilizing the atrium design, thus heating systems should be used.

4.2 Recommendations for Further Research

Conducting this research, brought recommendations to the scene to be studied in future work, some of these recommendations are:

- The possibility of evaluating different skylight designs as changing the widths of the cavity, as well as testing other glass types and properties, moreover, different forms and shapes with the possibility of testing inclined skylight could be tested.
- Combining the evaluation of visual comfort with thermal comfort for the DSS.
- The possibility of integrating the DSS with other passive design strategies to improve winter performance.
- Conducting further studies related to the atrium design in the Mediterranean climate with different configurations.

REFERENCES

Ab Ghafar, N., Gadi, M., & Adam, M. (2019). Evaluation of thermal and solar performance in atrium buildings using sequential simulation. *Energy and Environment*, *30*(6), 969–990. https://doi.org/10.1177/0958305X18813684

Abdullah, A. H., & Wang, F. (2012). Design and low energy ventilation solutions for atria in the tropics. *Sustainable Cities and Society*, *2*(1), 8–28. https://doi.org/10.1016/j.scs.2011.09.002

Abuseif, M., & Gou, Z. (2018). A Review of Roofing Methods: Construction Features, Heat Reduction, Payback Period and Climatic Responsiveness. *Energies*, *11*(11), 3196. https://doi.org/10.3390/en11113196

Aflaki, A., Mahyuddin, N., & Mahmoud, Z. A. (2015). A review on natural ventilation applications through building fac components and ventilation openings in tropical climates. *Energy & Buildings*, *101*, 153–162. https://doi.org/10.1016/j.enbuild.2015.04.033

Ahmad, M. H., & Rasdi, M. T. H. M. (2000). *Design principles of atrium buildings for the tropics*. Penerbit UTM.

Al-Obaidi, K. M., Ismail, M., & Abdul Rahman, A. M. (2014). A study of the impact of environmental loads that penetrate a passive skylight roofing system in Malaysian buildings. *Frontiers of Architectural Research*, *3*(2), 178–191. https://doi.org/10.1016/j.foar.2014.03.004

Al-Obaidi, K. M., Ismail, M., & Rahman, A. M. A. (2014). A review of skylight glazing materials in architectural designs for a better indoor environment. *Modern Applied Science*, Vol. 8, pp. 68–82. https://doi.org/10.5539/mas.v8n1p68

Al-tamimi, N. A. (2015). Toward Sustainable Building Design : Improving Thermal Performance by Applying Natural Ventilation in Hot – Humid Climate. *Indian Journal of Science and Technology*, *8*(28), 1–8.

Alberto, A., Ramos, N. M. M., & Almeida, R. M. S. F. (2017). Parametric study of double-skin facades performance in mild climate countries. *Journal of Building Engineering*, *12*, 87–98. https://doi.org/10.1016/j.jobe.2017.05.013

Aldawoud, A. (2013). The influence of the atrium geometry on the building energy performance. *Energy & Buildings*, *57*, 1–5. https://doi.org/10.1016/j.enbuild.2012.10.038

Alibaba, H. Z., & Ozdeniz, M. B. (2016). Energy Performance and Thermal Comfort of Double-Skin and Single-Skin Facades in Warm-Climate Offices. *Journal of Asian Architecture and Building Engineering*, *15*(3), 635–642. https://doi.org/10.3130/jaabe.15.635

ASHRAE, *ASHRAE/ANSI Standard 55-2017 Thermal environmental conditions for human occupancy*. 2010, American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.

Aram, R., & Alibaba, H. Z. (2019). Thermal Comfort and Energy Performance of

Atrium in Mediterranean Climate. *Sustainability*, *11*(4), 1213. https://doi.org/10.3390/su11041213

Bahaj, A. S., James, P. A. B., & Jentsch, M. F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings*, *40*, 720–731. https://doi.org/10.1016/j.enbuild.2007.05.006

Baharvand, M., Hamdan, M., Ahmad, B., & Safikhani, T. (2013). Thermal Performance of Tropical Atrium. *Scientific Journal of Riga Technical University. Environmental and Climate Technologies*, *12*(1), 34–40. https://doi.org/10.2478/rtuect-2013-0014

Bangalee, M. Z. I., Lin, S. Y., & Miau, J. J. (2012). Wind driven natural ventilation through multiple windows of a building : A computational approach. *Energy & Buildings*, *45*, 317–325. https://doi.org/10.1016/j.enbuild.2011.11.025

Barbosa, S., & Ip, K. (2016). Predicted thermal acceptance in naturally ventilated office buildings with double skin façades under Brazilian climates. *Journal of Building Engineering*, *7*, 92–102. https://doi.org/10.1016/j.jobe.2016.05.006

Barbosa, S., Ip, K., & Southall, R. (2015). Thermal comfort in naturally ventilated buildings with double skin façade under tropical climate conditions: The influence of key design parameters. *Energy and Buildings*, *109*, 397–406. https://doi.org/10.1016/j.enbuild.2015.10.029

Bianco, V., Diana, A., Manca, O., & Nardini, S. (2018). Numerical investigation of an inclined rectangular cavity for ventilated roofs applications. *Thermal Science and Engineering Progress*, *6*(February), 426–435. https://doi.org/10.1016/j.tsep.2018.02.016

Chang, P. C., Chiang, C. M., & Lai, C. M. (2008). Development and preliminary evaluation of double roof prototypes incorporating RBS (radiant barrier system). *Energy and Buildings*, *40*(2), 140–147. https://doi.org/10.1016/j.enbuild.2007.01.021

Chen, D., & Chen, H. W. (2013). Using the Köppen classi fi cation to quantify climate variation and change : An example for 1901 – 2010. *6*, 69–79. https://doi.org/10.1016/j.envdev.2013.03.007

Chen, Y., Tong, Z., & Malkawi, A. (2017). Investigating natural ventilation potentials across the globe : Regional and climatic variations. *Building and Environment*, *122*, 386–396. https://doi.org/10.1016/j.buildenv.2017.06.026

Chenari, B., Carrilho, J. D., & Gameiro, M. (2016). Towards sustainable , energy-ef fi cient and healthy ventilation strategies in buildings : A review. *Renewable and Sustainable Energy Reviews*, *59*, 1426–1447. https://doi.org/10.1016/j.rser.2016.01.074

Ciampi, M., Leccese, F., & Tuoni, G. (2003). Energy Analysis of Ventilated Roofs in Summer Cooling of Buildings. *International Conference on Innovations in Building Envelopes and Environemental Systems*, (September). https://doi.org/10.1007/978-3-642-17387-5_2

Dickson, A. (2004). *Modelling Double-Skin Facades*. University of Strathclyde, Glasgow UK.

Ding, W., Hasemi, Y., & Yamada, T. (2005). Natural ventilation performance of a double-skin façade with a solar chimney. *Energy and Buildings*, *37*(4), 411–418. https://doi.org/10.1016/j.enbuild.2004.08.002

Douvlou, E., & Pitts, A. (2000). Glazed spaces in the Mediterranean climate: design of glazing and shading devices in atria. Architecture, City, Environment: Proceedings of PLEA, 292-293.

Douvlou, E. D. (2004). Climatic Responsive Design & Occupant Comfort : The Case Of The Atrium Building In A Mediterranean Climate.

Environmental Design Solutions Limited, Tas, Awww.edsl.net/ (2018, accessed 2 February 2018).

Faggianelli, G. A., Brun, A., Commission, A. E., Wurtz, E., Commission, A. E., & Muselli, M. (2013). *Assessment of natural ventilation potential for summer comfort in buildings on Mediterranean coastal zones*.

Fini, A. S., & Moosavi, A. (2016). Effects of “ wall angularity of atrium ” on “ buildings natural ventilation and thermal performance ” and CFD model. *Energy & Buildings*, *121*, 265–283. https://doi.org/10.1016/j.enbuild.2015.12.054

Frontczak, M., & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment*, *46*(4), 922–937. https://doi.org/10.1016/j.buildenv.2010.10.021

Gagliano, A., Patania, F., Nocera, F., Ferlito, A., & Galesi, A. (2012). Thermal performance of ventilated roofs during summer period. *Energy and Buildings*, *49*, 611–618. https://doi.org/10.1016/j.enbuild.2012.03.007

Galal, K. S. (2019). The impact of atrium top materials on daylight distribution and heat gain in the Lebanese coastal zone. *Alexandria Engineering Journal*, *58*(2), 659–676. https://doi.org/10.1016/j.aej.2019.05.013

Gan, G. (2010). Interaction Between Wind and Buoyancy Effects in Natural Ventilation of Buildings. *The Open Construction and Building Technology Journal*, *4*, 134–145.

Göçer, Ö., Tavil, A., & Özkan, E. (2006). Thermal Performance Simulation Of An Atrium Building. *In Proceedings of ESim Building Performance Simulation Conference*, pp. 33–40.

Grabe, J. Von, Svoboda, P., & Bäumler, A. (2014). Window ventilation efficiency in the case of buoyancy ventilation. *Energy & Buildings*, *72*, 203–211. https://doi.org/10.1016/j.enbuild.2013.10.006

Hien, W. N., Gabriela, O., Tan, E., & Jusuf, S. K. (2017). Indoor Thermal Comfort Assessment Of Naturally. *Journal of Architecture and Built Environment*, *44*(1), 53–59. https://doi.org/10.9744/dimensi.44.1.53-60

Hung, W. Y., & Chow, W. K. (2001). A Review on Architectural Aspects of Atrium Buildings. *Architectural Science Review*, *44*(3), 285–295. https://doi.org/10.1080/00038628.2001.9697484

Hussain, S., & Oosthuizen, P. H. (2012). Numerical investigations of buoyancy-driven natural ventilation in a simple atrium building and its effect on the thermal comfort conditions. *Applied Thermal Engineering*, *40*, 358–372. https://doi.org/10.1016/j.applthermaleng.2012.02.025

Ibrahim, S. H., Baharun, A., Abdul Manan, M. D., & Abang Adenan, D. A. (2013). Importance of thermal comfort for library building in Kuching, Sarawak. *International Journal of Energy & Environment*, *4*(6), 1003–1012.

Ji, Y., & Cook, M. (2005). Atrium - assisted natural ventilation of multi - storey buildings. *Proceedings of the 10th International Conference on Indoor Air Quality and Climate*, 1311–1315. Retrieved from http://usir.salford.ac.uk/15845/

Jomehzadeh, F., Nejat, P., Kaiser, J., Badruddin, M., Yusof, M., Ahmad, S., … Muhammad, W. (2017). A review on windcatcher for passive cooling and natural ventilation in buildings , Part 1 : Indoor air quality and thermal comfort assessment. *Renewable and Sustainable Energy Reviews*, *70*, 736–756. https://doi.org/10.1016/j.rser.2016.11.254

Laouadi, A., Atif, M. R., & Galasiu, A. (2002). Towards developing skylight design tools for thermal and energy performance of atriums in cold climates. *Building and Environment*, *37,* 1289–1316.

Lau, S. S. Y., Zhang, J., & Tao, Y. (2019). A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus. *Building and Environment*, *148*, 579–599. https://doi.org/10.1016/j.buildenv.2018.11.032

Lee, S., Park, S. H., Yeo, M. S., & Kim, K. W. (2009). An experimental study on airflow in the cavity of a ventilated roof. *Building and Environment*, Vol. 44, pp. 1431–1439. https://doi.org/10.1016/j.buildenv.2008.09.009

Li, D., Zheng, Y., Liu, C., Qi, H., & Liu, X. (2016). Numerical analysis on thermal performance of naturally ventilated roofs with different influencing parameters. *Sustainable Cities and Society*, *22*, 86–93. https://doi.org/10.1016/j.scs.2016.02.004

Li, Z. R., Ai, Z. T., Wang, W. J., Xu, Z. R., Gao, X. Z., & Wang, H. S. (2014). Evaluation of airflow pattern in wind-driven naturally ventilated atrium buildings : measurement and simulation. *Building Services Engineering Research and Technology*, *35*(2), 139–154. https://doi.org/10.1177/0143624412474941

Liang, N., Kong, Q., Cao, Y., Zheng, W., & Yang, Q. (2019). Thermal Performance of an Atrium with Hybrid Ventilation and cooled air supply. *IOP Conf. Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/268/1/012088

Liu, C., Bian, J., Zhang, G., Li, D., & Liu, X. (2018). Influence of optical parameters on thermal and optical performance of multi-layer glazed roof filled with PCM.

Applied Thermal Engineering, Vol. 134, pp. 615–625. https://doi.org/10.1016/j.applthermaleng.2018.01.117

Liu, C., Zhou, Y., Li, D., Meng, F., Zheng, Y., & Liu, X. (2016). Numerical analysis on thermal performance of a PCM-filled double glazing roof. *Energy and Buildings*, *125*, 267–275. https://doi.org/10.1016/j.enbuild.2016.05.002

Liu, P., Lin, H., & Chou, J. (2009). Evaluation of buoyancy-driven ventilation in atrium buildings using computational fluid dynamics and reduced-scale air model. *Building and Environment*, *44*(9), 1970–1979. https://doi.org/10.1016/j.buildenv.2009.01.013

López-Pérez, L. A., Flores-Prieto, J. J., & Ríos-Rojas, C. (2019). Adaptive thermal comfort model for educational buildings in a hot-humid climate. *Building and Environment*, *150*, 181–194. https://doi.org/10.1016/j.buildenv.2018.12.011

Mirrahimi, S., Mohamed, M. F., Haw, L. C., Ibrahim, N. L. N., Yusoff, W. F. M., & Aflaki, A. (2016). The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot-humid climate. *Renewable and Sustainable Energy Reviews*, *53*, 1508–1519. https://doi.org/10.1016/j.rser.2015.09.055

Modirrousta, S., & Boostani, H. (2016). Analysis of Atrium Pattern , Trombe Wall and Solar Greenhouse on Energy Efficiency. *Procedia Engineering*, *145*, 1549–1556. https://doi.org/10.1016/j.proeng.2016.04.195

Moosavi, L., Ghafar, N., & Mahyuddin, N. (2016). Investigation of Thermal Performance for Atria : a Method Overview. *MATEC Web of Conferences*, *66*, 00029 EDP Sciences.

Moosavi, L., Mahyuddin, N., Ab Ghafar, N., & Azzam Ismail, M. (2014). Thermal performance of atria: An overview of natural ventilation effective designs. *Renewable and Sustainable Energy Reviews*, *34*, 654–670. https://doi.org/10.1016/j.rser.2014.02.035

Moosavi, L., Mahyuddin, N., & Ghafar, N. (2015). Atrium cooling performance in a low energy of fi ce building in the Tropics , a fi eld study. *Building and Environment*, *94*, 384–394. https://doi.org/10.1016/j.buildenv.2015.06.020

Moosavi, L., Mahyuddin, N., Ghafar, N., Zandi, M., & Bidi, M. (2018). Numerical prediction of thermal and airflow conditions of a naturally ventilated atrium and validation of CFD models. *Journal of Renewable and Sustainable Energy*, *10*(6), 065101. https://doi.org/10.1063/1.5037386

Najafabadi, F. A., & Alibaba, H. Z. (2013). *Effect of Atrium on Thermal Comfort*.

Nasrollahi, N., Abdolahzadeh, S., & Litkohi, S. (2015). Appropriate Geometrical Ratio Modeling Of Atrium For Energy Efficiency In Office Buildings. *Journal of Building Performance*, *6*(1), 95–104.

Nugroho, A. M. (2009). Solar Chimney Geometry for Stack Ventilation in a Warm Humid Climate Solar Chimney Geometry for Stack Ventilation. *International*

Journal of Ventilation, *8*(2), 161–173. https://doi.org/10.1080/14733315.2006.11683841

Omar, A. I., Joseph, V., Etienne, V., Damien, D., & Idriss, A. I. (2017). Energy Saving Potential with a Double-Skin Roof Ventilated by Natural Convection in Djibouti. *Energy Procedia*, *140*, 361–373. https://doi.org/10.1016/j.egypro.2017.11.149

Omrani, S., Garcia-hansen, V., Capra, B. R., & Drogemuller, R. (2017). Effect of natural ventilation mode on thermal comfort and ventilation performance : Full-scale measurement. *Energy & Buildings*, *156*, 1–16. https://doi.org/10.1016/j.enbuild.2017.09.061

Palma Rojas, D. (2013). Atrium building design : key aspects to improve their thermal performance on the Mediterranean climate of Santiago de Chile. *International Journal of Low-Carbon Technologies,* *9*(4), 327–330. https://doi.org/10.1093/ijlct/ctt009

Pitts, A. (2013). Thermal Comfort in Transition Spaces. *Buildings*, *3*(1), 122–142. https://doi.org/10.3390/buildings3010122

Raji, B., Tenpierik, M. J., & Dobbelsteen, A. Van Den. (2016). An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates : A case study in the Netherlands. *Energy & Buildings*, *124*, 210–221. https://doi.org/10.1016/j.enbuild.2015.10.049

Roslan, Q., Halipah, S., Affandi, R., Nasrun, M., Nawi, M., & Baharun, A. (2016). A literature review on the improvement strategies of passive design for the roo fi ng system of the modern house in a hot and humid climate region. *Frontiers of Architectural Research*, *5*(1), 126–133. https://doi.org/10.1016/j.foar.2015.10.002

Roslan, Q., Ibrahim, S. H., Affandi, R., & Mohd Nawi, Mohd NasrunBaharun, A. (2016). A literature review on the improvement strategies of passive design for the roofing system of the modern house in a hot and humid climate region. *Frontiers of Architectural Research*, Vol. 5, pp. 126–133. https://doi.org/10.1016/j.foar.2015.10.002

Rundle, C. A., Lightstone, M. F., Oosthuizen, P., Karava, P., & Mouriki, E. (2011). Validation of computational fl uid dynamics simulations for atria geometries. *Building and Environment*, *46*(7), 1343–1353. https://doi.org/10.1016/j.buildenv.2010.12.019

Sarbu, I., & Pacurar, C. (2015). Experimental and numerical research to assess indoor environment quality and schoolwork performance in university classrooms. *Building and Environment*, *93*, 141–154. https://doi.org/10.1016/j.buildenv.2015.06.022

Sharples, S., & Bensalem, R. (2001). Airflow In Courtyard And Atrium Buildings In The Urban Environment : A Wind Tunnel Study. *Solar Energy*, *70*(3), 237–244.

Shetabivash, H. (2015). Investigation of opening position and shape on the natural cross ventilation. *Energy & Buildings*, *93*, 1–15.

https://doi.org/10.1016/j.enbuild.2014.12.053

Sozer, H. (2010). Improving energy ef fi ciency through the design of the building envelope. *Building and Environment*, *45*(12), 2581–2593. https://doi.org/10.1016/j.buildenv.2010.05.004

Su, Y. (2017). Improvement of Ventilation and Thermal Comfort Using the Atrium Design for Traditional Folk Houses-Fujian Earthen Building. *World Academy of Science, Engineering and Technology International Journal of Urban and Civil Engineering*, *11*(4), 469–477.

Sunanda, W., Budiarto, R., & Budiarto, R. (2018). Performance of Glazing Materials for Atrium in Hot & Humid Climate. *MATEC Web of Conferences*, *186*, 02007.

Tabesh, T., & Sertyesilisik, B. (2016). An Investigation into Energy Performance with the Integrated Usage of a Courtyard and Atrium. *Buildings*, *6*(2), 21 https://doi.org/10.3390/buildings6020021

Tanaka, H., Okumiya, M., Tanaka, H., Young, G., & Watanabe, K. (2009). Thermal characteristics of a double-glazed external wall system with roll screen in cooling season. *Building and Environment*, *44*(7), 1509–1516. https://doi.org/10.1016/j.buildenv.2008.07.014

Tong, S., & Li, H. (2014). An efficient model development and experimental study for the heat transfer in naturally ventilated inclined roofs. *Building and Environment*, *81*, 296–308. https://doi.org/10.1016/j.buildenv.2014.07.009

Wang, F., & Abdullah, A. H. (2011). Investigating thermal conditions in a tropic atrium employing CFD and DTM techniques. *International Journal of Low-Carbon Technologies*, *6*(3), 171–186. https://doi.org/10.1093/ijlct/ctr005

Wang, L., Huang, Q., Qi, Z., Xu, H., & Yuen, R. K. K. (2017). Role of atrium geometry in building energy consumption : The case of a fully air-conditioned enclosed atrium in cold climates , China. *Energy & Buildings*, *151*, 228–241. https://doi.org/10.1016/j.enbuild.2017.06.064

Wang, Z., Yi, L., & Gao, F. (2009). Night ventilation control strategies in office buildings. *Solar Energy*, *83*(10), 1902–1913. https://doi.org/10.1016/j.solener.2009.07.003

Yang, Y., Wu, H., Yang, L., Xu, T., Ding, Y., & Fu, P. (2019). Thermal and day-lighting performance of aerogel glazing system in large atrium building under cooling-dominant climates. *Energy Procedia*, *158*, 6347–6357. https://doi.org/10.1016/j.egypro.2019.01.273

Yasa, E. (2015). Evaluation of the Effect of the Different Distances between Two Facades Natural Ventilation on Atrium Buildings with DSF and. *Procedia Engineering*, *121*, 667–674. https://doi.org/10.1016/j.proeng.2015.08.1064

Zhou, J., & Chen, Y. (2010). A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China. *Renewable and Sustainable Energy Reviews*, *14*(4), 1321–1328. https://doi.org/10.1016/j.rser.2009.11.017

Zingre, K. T., Wan, M. P., Tong, S., Li, H., Chang, V. W. C., Wong, S. K., … Leng Lee, I. Y. (2015). Modeling of cool roof heat transfer in tropical climate. *Renewable Energy*, *75*, 210–223. https://doi.org/10.1016/j.renene.2014.09.045

Zingre, K. T., Wan, M. P., Wong, S. K., Toh, W. B. T., & Lee, I. Y. L. (2015). Modelling of cool roof performance for double-skin roofs in tropical climate. *Energy*, *82*, 813–826. https://doi.org/10.1016/j.energy.2015.01.092

URL 1: https://knowledge.autodesk.com/support/revit-products/getting-started/caas/simplecontent/content/passive-design-strategies.html

URL 2: https://en.climate-data.org/asia/cyprus/famagusta/famagusta-3770/

URL 3 https://library.emu.edu.tr/en/about-us/floors-virtual-tour-and-photos